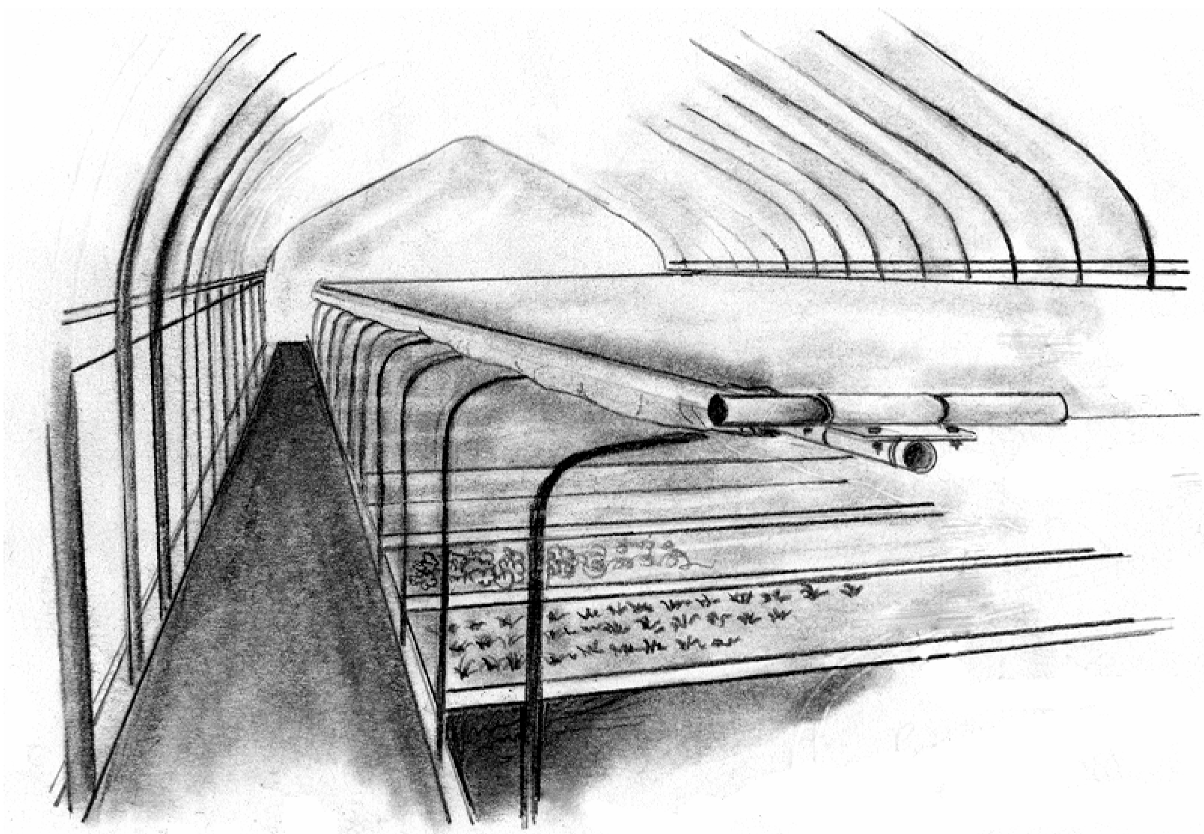
High Tunnels

Using Low-Cost Technology to Increase Yields, Improve Quality and Extend the Season



By Ted Blomgren and Tracy Frisch

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Introduction

High tunnels are inexpensive, passive solar structures designed to extend the growing season and intensify production. By protecting crops from potentially damaging weather conditions (frost, temperature fluctuations, precipitation, wind, or excess moisture that delays planting or cultivation), high tunnels also reduce risk and enhance the quality of the harvest. They enable farmers to tap discerning markets hungry for local products and thus become more profitable.

High tunnels have other benefits. They can help farmers better utilize labor by providing work in bad weather and potentially creating year-round positions. Due to the protected microclimate inside the structure, high tunnel crops tend to be of higher quality and produce higher yields than field-grown crops. As plants inside high tunnels tend to experience less disease and insect pressure, fewer pesticides are used.

High tunnels—simple, plastic-covered, tubular steel structures—rely mainly on the sun's energy to warm the soil and air. Their name is derived from the fact that they are high enough in which to stand up. European and Asian farmers have used high tunnels for decades but this low cost growing environment is relatively new in North America. In recent years, more and more farmers are experimenting with their use.

Typically high tunnels forgo mechanical systems such as heaters, fans, and lights. Partially because of the absence of these amenities, high tunnels are less costly to build. Often, however, their frames are identical to more conventional greenhouses. Because high tunnels are far less capital intensive than greenhouses, it usually takes less time for them to pay for themselves. In addition, high tunnels are typically classified as temporary agricultural structures for purposes of property assessment and taxation, since they lack a concrete foundation or footings.

Co-author and Pennsylvania farmer Steve Moore suggests several rules for high tunnel design:

- Capture as much natural solar energy as possible.
- Conserve as much energy as possible.
- Keep it simple, both mechanically and managerially.
- Design and operate for minimal economic risk and a quick payback.

Unlike greenhouse culture, where crops may be grown hydroponically or in flats or pots on benches, crops in high tunnels are almost always grown in the ground. High tunnels can be configured in a variety of shapes (i.e., Quonset or gothic) and sizes (narrow or wide, short or long, single bay or multi-bay), and can be semi-permanent, temporary or movable structures.

There are also differences between four-season high tunnels (also called "hoop houses" or "passive solar greenhouses") and three-season high tunnels such as Haygroves. Four-season structures—the conventional single bay high tunnel—typically cost about \$2 to \$3/ ft^2 compared to \$0.75 to \$1.25/ft^2 for a three-season high tunnel. The farmer case studies and text that follow will illuminate the differences between these two types of structures.

In the Northeast, high tunnels are well suited for the production of high value crops including salad mix, baby spinach, fresh market tomatoes, cucumbers, red peppers, basil, cut flowers, raspberries, strawberries, and more. And dwarf tree-crops like sweet cherries can be produced in larger multi-bay tunnels (like Haygroves). Farmers may construct high tunnels to complement their existing agricultural operations or turn to high tunnels as the centerpiece of a new stand-alone business.

While we want to demonstrate how high tunnels may be a reasonable option for farmers wanting to extend their growing and marketing seasons, high tunnels are not for everyone. They are tools, not ends in themselves. To be an appropriate investment, high tunnels must suit a farmer's goals and resources. Each grower needs to critically examine the pros and cons of high tunnels in the context of their own situation.

Some farmers have no interest in extending the season. A couple farming at Persephone Farm in Oregon eloquently expressed this perspective (see the September 2006 issue of *Growing for Market*). They relish their off-season downtime and look forward to selling out and shutting down for the year. And they are cognizant and accepting of the trade-offs inherent in their decision.

This manual is intended to provide farmers, agricultural developers, and farm advisors with a realistic depiction of some of the applications for high tunnels in Northeastern agriculture. We aim to assist farmers and those who work with farmers in determining if and how to make use of high tunnels. As a decision-making aid, this publication provides both general principles and specific, in-depth examples as guidance. The manual should enable more farmers to use high tunnels effectively, enhancing productivity, net income, and quality of life, and avoiding some of the pitfalls of earlier adopters.

The information and concepts we have chosen to present are based largely on the observations and experimentation of farmers who grow in high tunnels in the Northeast from southern Pennsylvania to northern Vermont. We have profiled six farmers, and also have drawn from the experiences of several others. The extensive farming experience of two of the three authors has also provided much of the basis for this publication.

Case Study: Cramer's Posie Patch

Ralph Cramer and his son and business partner, Keith, are well-known southern Pennsylvania cut and dried flower farmers. They are also pioneers in the usage of multi-bay high tunnels. Ralph serves as the Eastern U.S. sales agent for Haygroves, manufactured in Great Britain. Their one acre of Haygrove high tunnels complements the other 49 acres of annuals, perennials (15 acres), and woody ornamentals (4.5 acres) that include 130 varieties of flowers at Cramer's Posie Patch.

Ralph Cramer's parents, Lewis and Mary, were also Lancaster County farmers. Lewis teased his wife Mary about her "little flower growing hobby" so she began to keep records of the profit from her flowers and (unbeknownst to him) his tobacco. The next year, when he saw the figures, he wasn't laughing anymore, said Keith. The couple developed several famous lines of cockscomb that their son and grandson continue to raise and sell as improved varieties.

Ralph bought an additional farm in another part of the county and continued to grow flowers on its silty loam fields. Land quality is very good on this current site, and two streams allow for overhead irrigation of direct seeded annuals when rainfall is low. However, compared to the old farm perched on top of steep hills, this farm is somewhat of a "frost magnet" with a shorter growing season, and the coldest field is also their wettest. The farm is classified as Zone 6B or a cold Zone 6, with fall frost around the first week of October and the last frost free date around May 15.

Before they purchased their first Haygrove, they were looking for some sort of multi-bay season extension structure. At a West coast meeting of the Association of Specialty Cut Flower Growers, the Cramers saw a homemade light-weight structure. Using it as a model, they built their own 1/6 acre tunnel, but a 20 mile per hour wind blew it down.

Keith explains why their experimental high tunnel failed. "The hoops in our homemade structure were made from rebar inserted through PVC pipe (to protect the plastic from rubbing), but the rebar was not strong enough to resist the wind pressure. We also had aligned our tunnels in a North/South configuration—which placed them sideways to the prevailing winds, making them even more vulnerable. We had no experience or advice about venting tunnels to prevent damage. We had no top rail or gantry of any type, thus the ropes could not be pulled tight to prevent the plastic from shifting and becoming a spinnaker in the wind."

Primed to grow in a multi-bay high tunnel, the Cramers discovered Haygroves and they traveled to England to see where they were commercially available. The structure impressed them, as did the Haygrove company's responsiveness to farmers' needs and ideas.

By enabling them to sell cut flowers both earlier and later and greatly improving size and quality in some cases, Haygroves have boosted the Cramers' business far out of proportion to the growing space they cover. With these structures, the Cramers achieve larger blooms and greater stem length for certain species and protect their flowers from disease and wind injury.

For many years the farm had only sold dried flowers. But the market for dried flowers is "soft," and storing dried stock hurts cash flow and takes up considerable barn space. The Cramers had trialed fresh flowers as an afterthought, but wholesalers needed to see quantity. By 2001, four years after they decided to seriously grow fresh cuts, they accounted for more than half of total sales. Producing both fresh and dried flowers for different markets has given the Cramers a broader range of options than they previously had.

Most of the Cramers' fresh cuts go to 20 major wholesale florists in the mid-Atlantic, from New York's Finger Lakes region to Washington, D.C. Downward price pressures and the logistics of getting a truck into and out of the city by 7 A.M. have led them to avoid New York City buyers. A typical buyer will receive delivery of 20 buckets of flowers from Cramers' Posie Patch once or twice a week.

Working with large-scale wholesale buyers can be demanding. Early every morning, Keith faxes an availability list to these buyers. Each buyer's order becomes a cut list assigned to the farm's eight-person field crew. They cut, grade, and do quality control as piecework in the field. Availability lists are saved to guide planning for the next year's planting.

Bouquet makers who sell to big box stores like Costco are another category of buyer that take a significant volume of their flowers. For some flowers, these buyers are looking for different characteristics than the wholesale florists, providing the Cramers with a market for smaller stems.

Cramer's Posie Patch also ships dried flowers to designers and florists nationwide; sells seeds to commercial growers and three large seed companies (Gloeckner, Germania and Johnny's); and has a small, dried flower retail shop at the farm.

Large multi-bay tunnels make sense for the Cramers' production needs. With routine sales of 800 bunches at a time, they would rapidly clear out a single 30' x 100' high tunnel. Smaller, single-bay high tunnels are also less accessible for tractors and so require more hand labor.

The cost per square foot under cover is lower in Haygroves than in single-bay high tunnels. A one-acre Haygrove costs about $28,000 (2006 price), including shipping and polyethylene film and the Cramers expect 15 to 20 years of use.

The Cramers take full advantage of the ability to manage each high tunnel bay independently. This flexibility allows them to tailor venting, shading, and irrigation practices to the temperature and humidity requirements of individual crops that fill a bay. With some experimentation, they identified species that are especially rewarding for them to grow in Haygroves. These include cockscomb, sunflowers, chili peppers, lisianthus, dahlias, and hydrangeas.

Cockscomb (*Celosia*) is the hallmark flower of Cramer's Posie Patch. Keith's grandparents selected this seed, and he and his father continue to do. In two bays the farm grows cockscomb as a cut flower. Once *Celosia* plants are established, warm temperatures (80°F) will promote flowering better than cool temperatures (below 50°F). Height of cockscomb is significantly greater, 4' to 4-1/2' in the Haygrove versus 3' in the field. The Haygrove also permits harvest to begin around July 6, a month earlier than field-grown.

This four or more week harvest advantage and superior quality brings a price that is 30 to 40% higher ($4.15 per bunch versus the $2.95 bunch price). They have been able to maintain that high wholesale price for all cockscomb stems cut during the season, whether grown in the tunnel or the field. This represents a huge increase in profit.

Chili peppers grown in Haygroves have become an important element of the farm's product mix. High tunnels allow them to grow bigger peppers, early harvest, and 3' stems (compared to 14" or 16" for field-grown). In the tunnel most chili harvests begin in the first week of August rather than at the first frost (late September or early October) in the field. They grow the chilies in the warmest bay, which they vent less and irrigate more than the other bays.

In the Haygroves, the first sunflowers are harvested 3-1/2 weeks earlier. Local sunflowers are most in vogue in May, June and the first part of July, and early sunflowers help with perennial sales. The Cramers grow seven visually identical varieties of pollenless sunflowers with different maturation dates. Their early sunflowers get them in the door with their customers so they can sell other species of early field-grown flowers. They double crop sunflowers, so after the early crop is done, they remove the plants, make new holes in the plastic, and seed sunflowers for harvest after the frost.

During Hurricane Isabelle and other catastrophic wind and rain events, cut flower plantings in the Haygroves were barely affected. With their tunnels fully vented for the high winds, the tops kept approximately 80% of the soil dry. The tunnels diffused the wind as it moved through them. Straight line winds and saturated soil combined to level outdoor crops, including transplants on black plastic mulch. Sunflowers inside remained safe and sound while those in the field were uprooted.

The Cramers could not grow marketable lisianthus outside, but do so consistently in the Haygroves, where they raise 1/6 acre of the flower in four colors. This high-value, rose-like cut flower species requires prolonged cool temperatures to develop stem length but cannot tolerate frost. They moderate temperatures by keeping the lisianthus bay open unless frost threatens, covering the beds in white plastic to reduce soil warming, and using shade cloth. In the Haygroves, lisianthus stems reach 3' in length (versus 9" in the field). "My customers are not interested in anything shorter than 20-24" stems," says Keith.

Hydrangeas (*Paniculata grandiflora*) are the first woody perennial the Cramers have tried in the Haygroves. They have been rewarded with more rapid growth and impressively large flower clusters. The trial was so successful, the Cramers have added a full bay (approximately 600 plants) of the variety 'Limelight.'

Making the right decision about when to cover multi-bay high tunnels is critical in regions with the possibility of late snowfall. The Cramers want to get the biggest jump on production that they can. Yet if they cover the tunnels too early, they run the risk that a late snowstorm will damage the structure, as they are not engineered for snow load. In their southern Pennsylvania location, they generally cover the tunnels around April 7 and plant them in mid-April. In the Spring of 2003, the structure withstood 5" of wet, heavy snow. They were able to "bump it off" without incident.

They aim to 'hibernate' (remove) the tunnel plastic in mid-October. They bring the top poly from two adjoining tunnels into the shared leg row, cover it with black plastic row mulch to prevent UV degradation, and secure it with tomato twine. They remove the doors and store them in the barn. Over the winter, they leave the side curtains hanging on the structure.

The first year they grew in the Haygrove, the Cramers gave their crew responsibility for recording daily high and low temperatures in each bay. This data taught them that the normal temperature fluctuation is okay. They monitor the tightness of the ropes monthly. During thunderstorm season, they keep the tunnel fully vented for temperature control, with doors open and the roof clipped in the open position. As this is also the proper way to vent for high winds associated with thunderstorms, storms require no special intervention.

Blessed with good Lancaster County soils, the Cramers use a one-size-fits-all fertilizer program, the same in the Haygroves as outside. They apply a 19-19-19 fertilizer at the rate of 50 pounds of actual nitrogen per acre. After incorporating the fertilizer, they chisel plow, disc and lay plastic mulch.

For their Haygrove plantings, the Cramers use a flat plastic bed layer to apply 5' wide plastic mulch over a 4' wide planting area. They can just fit four of these beds per 24' bay. These are not raised beds because their raised bed shaper/plastic layer cannot squeeze four beds into a bay. They vary the color of the plastic mulch depending upon whether they want to warm or cool the soil. Chiseling in the fall helps the soil dry out faster in the spring, when they do most of their soil preparation and the plastic mulch laying. They would like to fully prepare the beds in the fall but winter winds loosen the plastic mulch.

Only transplants, set by hand, are used in their Haygroves. First, to correctly space holes in the plastic mulch, they use the waterwheel from a transplanter behind a tractor. While transplants mitigate risk, they require much more labor. In contrast, in the field they direct seed about 80% of their annuals—with two acres of seeding scheduled every two weeks. Only about five acres of flowers are transplanted in the field.

As controlling foliage wetness is a major high tunnel benefit, the Cramers only use drip irrigation in the Haygroves. “We don’t want to make it rain inside a tunnel,” explains Keith. Using transplants makes it feasible to use drip tape. Were they to direct seed, they would need to cultivate, which would damage drip tape. They use double drip tape per bed.

Haygroves vent high and provide excellent air exchange, therefore humidity is not a problem. Alex Hitt, who grows organic heirloom tomatoes in Haygroves and in single-bay tunnels in Graham, North Carolina, attributes the reduced disease of plants in the Haygroves to their superior ventilation. The internal humidity is similar to outside conditions when vented.

Powdery mildew is more prevalent under the dry conditions common to these high tunnels. The Cramers sometimes have powdery problems in the field during dry periods of the season as well. *Oxidate* and *Zerotol* are hydrogen peroxide products that they have used successfully to control this disease. As an added bonus, these pesticides have zero re-entry periods. They prevent powdery mildew from spreading by exploding the spores so they can’t attach to plant tissue. Existing powdery mildew growth—which has a grey powdery look—is not affected by these products; therefore, detecting this disease problem early is essential as flowers with grey mildew are obviously not marketable.

Under the Haygroves (as with greenhouses), dry season pests like aphids and spider mites are accentuated. The structures offer a perfect micro-climate and protect these pests from rain washing them away. Keith relies on chemical pesticides to control these pests, such as the broad-spectrum organophosphate *Orthene* against aphids and several different miticides in rotation to avoid resistance.

In retrospect, the Cramers realize that a simple procedure would have eliminated weed pressure in the leg rows between bays. Before drilling the tunnel legs into the soil, they recommend making a shallow furrow (for runoff control) and pinning down narrow strips of black weed barrier fabric. In the absence of this prophylactic action, the Cramers apply *Roundup*. In the growing beds, plastic mulch eliminates the need for mechanical cultivation or herbicide applications, although some weeding must be done by hand in the plant holes.

Mid-weight floating row cover protects tender transplants coming from the greenhouse. Their crew lays this row cover over low wire hoops straddling the beds. Eventually, when the transplants outgrow the hoop, the row cover is removed. They use wide enough fabric to reach from one side of the bay to the other. When they pull it off, they move it to the center of the bay (keeping it out of the leg row where it could get wet), between the second and third beds.

These covers must be carefully managed to control excessive temperature and humidity. The Cramers learned the hard way. “The first year, we cooked over 4,000 sunflowers,” Keith recalls. In the spring, they can avoid excessive heat and provide adequate airflow just by opening the doors. A west wind keeps the air moving. When they have a stretch of cloudy weather followed by sun, they find it is important to remove the row cover and let the breeze in the doors. This dries out the plants’ micro-environment, preventing disease. It also hardens off the plants.

Haygrove recommends that the doors of the tunnel be aimed at the prevailing winds usually from the West. This satisfies ventilation needs and protects the structure from severe winds. Many greenhouse designs suggest a North-South orientation for even sunlight on the plants because the trusses create quite a bit of shade. High tunnels have a lot less overhead steel to shade plants. Adequate light has not been an issue in the Haygrove tunnels.

The Cramers use shade cloth on lisianthus to reduce ambient temperature and elongate the stems by reducing light. Rather than covering the top of the high tunnel with shade net, they put it underneath—inside the tunnel. If it were outside, venting would become more difficult. Keith explains, “Our shade net is rolled out on top of ropes that we tie across the bay. They are approximately 7 feet above the soil, so we can walk under them. If needed, we can move the shade across the bay and store on the north side to give full sun to the crops.”

After four years of use, the Cramers are replacing their polyethylene cover with an improved greenhouse film called Luminance. It is designed to deflect a portion of infrared rays, reducing the highest temperatures in the tunnel. Some light is lost with this feature so to offset the loss, Luminance diffuses light, sending the available light into the plant canopy at different angles.

Cramer’s Posie Patch faces some difficult choices in charting its future course. One weak link is labor. Eight Mexican laborers legally brought into the country on the federal government’s H-2A Agricultural Guest Worker Visa Program constitute the farm’s field crew. Keith tolerates the program’s “red tape nightmare because it provides the qualified, legal, dependable workers needed to operate profitably.” To add more workers would require building more housing, and adding septic, electric, and other infrastructure. Alternatively, they could reduce outside production and rely on fewer workers.

Haygrove Tunnels have fit nicely with the farm’s recent shift in emphasis to fresh cut flowers. The novelty of having local flowers earlier than other area growers makes the Cramers popular with the major wholesale florists they supply. Being the first local grower with certain crops creates a definite customer loyalty. At the end of each season, most of his customers tell Keith, “Don’t forget me next year when you have the early stuff!”

Enterprise Budget for Cockscomb in One Bay (1/6 Acre) of a One Acre Haygrove Tunnel at Cramer's Posie Patch

Fixed Costs			
Construction Costs		**Materials**	**Labor**
High tunnel construction			$3,000
High tunnel frame		$25,000	
	Subtotals	**$25,000**	**$3,000**
	Total Construction Costs		**$28,000**
Fixed Costs			
High tunnel construction (divided by 15 years)			$1,867
Interest (construction financed at 7% for 15 years)			$980
Taxes, land, office expenses, fees			$222
	Total Fixed Costs		**$3,069**
	Total Fixed Costs per Bay (1/6 Acre)		**$511**
Variable Costs per Bay (1/6 Acre)			
Materials and Machinery			
Seeds and growing out plugs			$357
Fertilizer, lime and compost			$10
Irrigation supplies			$68
Plastic mulch and row cover			$90
Pesticides			$70
Poly covering (divided by 4 years)			$200
Delivery costs			$230
	Subtotal		**$1,025**
Labor Costs ($11/hr)			
Cover installation and removal			$110
Bed preparation and fertilization			$22
Transplanting, laying drip tape and mulch			$380
Pruning, trellising, irrigating, spraying, venting			$220
Harvesting, grading, packing			$2,400
Sales and delivery ($14 to $20/hr)			$366
High tunnel clean-up			$132
	Subtotal		**$3,630**
	Total Variable Costs per Bay		**$4,655**
		Total Costs per Bay	**$5,166**
		Revenues per Bay*	**$20,125**
		Net Returns per Bay	**$14,959**

*Revenues are based on a harvest of 4,800 bunches per bay and a selling price of $4.15/bunch (plus a total of $105 in delivery fees).

Prior to the first fall frost, the Cramers' customers start to look to other suppliers in California, Holland, and South America. The uncertainty of the first frost date is a concern for their customers since they need to have a continuous supply of flowers. The summer season is very intense for all involved, with daily availability updates and a compressed schedule. Keith says that most of his customers look forward to the more relaxed environment of standing orders, even though the product is not quite as nice or nearly as fresh.

Timing the late season crop is an on-going challenge since the hard frost is unpredictable.

Moreover, by the time that hard frost ends the harvest, the wholesale market has weakened so it is difficult to get the higher prices needed to justify tunneled production. With only an acre of tunnels, the Cramers cannot protect both the quantity and diversity of product that their wholesalers demand. For these reasons, the Cramers have decided concentrate on getting a jump on the harvest early, rather than keeping it going after the fall frost.

Case Study: Weaver's Orchard

Weaver's Orchard in Berks County, Pennsylvania is a third generation, 100-acre family farm. Like many tree fruit growers trying to survive in today's competitive environment, Ed Weaver believes in diversification and direct marketing. The farm grows a number of fruits and vegetables to complement the primary crop of apples. The farm's on-site market has become a primary sales outlet and the farm offers a pick-your-own option for small fruits (such as blueberries, strawberries, and brambles) and for peaches, apricots, plums, nectarines, cherries, apples, and pears. With these features to attract a good clientele to the farm, the business is able to sell half of its farm's production retail.

Ed's grandparents purchased the farm in the 1930s where they grew vegetables, fruits, and tobacco. Under Ed's management, the farm produced tree fruit, vegetables, and strawberries until ten or twelve years ago, when he added blueberries and brambles.

Sweet cherries have been an important crop on the Weaver Farm for three decades. In the late 1990s, frustrations with standard rootstocks convinced Ed to expand their acreage with new dwarfing rootstocks. The dwarf trees come into full production much more quickly and are easier to manage. But when his first dwarf trees began producing, cherry yields were hurt by frost, rain, and birds. The damage was so great that Ed decided he had to find a way to protect the crop or else remove the trees.

Searching for a way to protect the trees led the Weavers to discover Haygrove multi-bay high tunnels at a spring 2003 trade show. Subsequently, Ed took a growers' tour to England to see how these tunnels are used on another continent. Full of enthusiasm, that spring the Weavers constructed their first multi-bay tunnel over seven-year-old dwarf sweet cherry trees. The three-bay tunnel covered 0.6 acre; each bay is 28' x 300'. In 2004, the Weavers constructed a 0.9 acre Haygrove over five-year-old cherry trees. These tunnels were longer, with two 28' x 450' bays and one 20' x 450' bay. Each bay accommodates two rows of trees, spaced 9' apart in the row and 15' between rows.

In two years, the Weavers had put almost one-third of their sweet cherries under plastic. Later, they added more Haygrove tunnels for growing tabletop strawberries, brambles, blueberries, and 1/3 acre of tomatoes.

During some years, Haygrove tunnels can mean the difference between an abundant high quality crop and virtually no crop. On this southeastern Pennsylvania farm, losses might reach as high as 90% in the uncovered orchard blocks, while only 2 or 3% of the crop is lost on trees protected by the Haygroves.

Cherries remain one of Ed's most promising crops under plastic. Beyond affording protection from adverse weather and birds, they offer other significant benefits. For a number of reasons, cherries grown under Haygroves tend to have higher fruit quality. Their quality also lengthens shelf life.

The Haygroves' minimal frost protection has been enough to protect the earliest varieties, which flower when temperatures can still drop below freezing. These structures can advance the ripening of early cherry varieties up to one week. And earliness can raise the price 30 or 40 cents a pound or more.

Rain is an important risk factor for a delicate fruit crop like cherries. Excess rain at or near harvest time is a major cause of crop loss in the uncovered cherry blocks. Rain-induced cracking and disease makes cherries unmarketable. Rain at the wrong time also causes other problems in the field.

Keeping rain out with the tunnels and using drip irrigation to even out moisture levels has been an effective solution. High tunnel coverage provides insurance that the orchard will provide a consistent supply year after year, which is no small matter when it comes to retaining its place in the market.

The multi-bay tunnels make it possible to leave cherries on the tree longer, so they can reach optimal size and maturity. For uncovered cherry plantings, a grower's only defense against the threat of rain has been to pick early. Staying on the tree longer makes the cherries sweeter and bigger. Ed Weaver estimates as much as a 20% potential weight gain in the tunnel-grown cherries harvested. This enhanced yield helps pay for the costs of the tunnels. On the other hand, increased heat under cover around harvest time can soften cherries and reduce their quality, so proper venting of the tunnels is crucial.

Bad weather ordinarily prevents farm tasks from being performed in a timely fashion and interrupts harvest. However, inside the Haygroves, farm employees can work even when it is raining or wet. Similarly, the rain is less of a deterrent for U-pick customers when they can harvest cherries under cover.

In addition to protecting the fruit from disease by keeping off precipitation and preventing lingering wetness, Haygroves have also reduced bacterial canker at Weaver's Orchard. This disease organism can enter pruning wounds. The Weavers prune their trees following the cherry harvest and leave the Haygroves covered until late August, after the wounds have healed.

Plastic bird netting around the perimeter of each tunnel—to close off the sides and ends—is sufficient to keep birds out of the trees. Bird damage and consumption in an average year destroys about 15 to 20% of the cherry crop outside of the tunnels and, in a dry year, bird damage can be greater.

Counter to these benefits are the ways that Haygrove structures complicate cherry production. Much of the work relates to the plastic itself. The structures must be covered each spring and uncovered in late summer. And the down side of keeping rain off a crop is the need to irrigate.

The Weavers use bumblebees to ensure pollination. Early flowering can occur when it is still too cold for honeybees to be active. And these bees can become disoriented in high tunnels. Honeybees fly repeatedly to and from their hive, while bumblebees spend the entire day away from their colony. Advance (six weeks) notice is required to order bumblebees and the timing of an order can be changed if blooms are slower than anticipated.

Erratic weather conditions call for more intensive tunnel management. Venting is fairly easy, but requires vigilance. If it gets hot or if a thunderstorm threatens, the Haygroves must be vented. When rain is forecast, the tunnels must be closed down.

It can be inconvenient to work around and inside the Haygrove structure and for a tree fruit grower, this disadvantage is magnified. Because the tunnels are 14' or 15' high at the peak, the cherry trees must be pruned back to 12'. Putting up Haygroves over existing trees is awkward, though doable.

The tunnels are spacious enough to drive a tractor inside for fertilizer application, spraying, and mowing. At Weaver’s Orchard, a granular fertilizer is applied in early March, before the tunnels are skinned, so that precipitation will water it in. Growing season fertility is provided with fertigation. All watering is done with drip irrigation.

Weaver’s Orchard is situated on rocky soil and the terrain is uneven. The soil and topography make erecting Haygroves or any other type of tunnel a challenge.

None-the-less, Ed Weaver believes that the Haygroves are paying for themselves. More importantly, these structures are allowing the farm to lessen the risk of crop loss and have profitable, high quality cherry harvest every year. He estimates that an increase in the value of the crop by just $0.40 per pound will pay for the annual cost of the tunnel over its lifetime.

Given the investment, Ed counsels other growers to maximize the efficient use of space in Haygroves. He was unable to do so with his first Haygrove structure as it was constructed over an existing cherry planting and that orchard block was not spaced at the optimal high density.

They have almost doubled tree density in the new blocks they are planting with the intention of covering them with Haygroves. Ed noted that new studies have demonstrated how cherry growers can intensify production by increasing the fruiting to vegetative wood ratio. They hope to develop more fruiting wood in each tree by paying more attention to tree training.

Yields depend a great deal on the variety. Rainier, a superior tasting variety, has performed at the top. It also commands a higher price and Weaver’s Orchard sells pre-picked Raniers for $4.99 per pound, a dollar per pound more than dark cherries. They have 100 producing Rainier trees in their Haygrove (and none in the field). At 30 pounds of production per tree and 400 trees per acre, Ed extrapolated a yield of 12,000 pounds per acre and a $30,000 gross income at the pick-your-own price of $2.50 per pound. Ed estimates that this is about twice the outdoor yield of varieties that produce consistently. However, accurate comparisons with outside production are difficult, given differences in age and varieties.

On the other hand, about half of the Weavers’ trees in the 2004 Haygrove tunnels s are varieties that are especially challenging to pollinate. Even outside of the tunnels, these varieties characteristically produce a good crop only two years out of three. But in the Haygroves, their production was down a surprising 85% in 2005. By bringing in more bees and planting more varieties as pollinators in the block, they are trying to address this problem. Recent releases of self-fertile varieties are also relevant. The shortfall in fruiting reduced yields by about $5,000 an acre (wholesale gross revenues) and cut net income by at least $3,500 per acre.

Despite some disappointing yields in the 2004 block, Ed remains optimistic about growing cherries in these multi-bay high tunnels. They have solved some otherwise intractable problems—most significantly those caused by rain and birds. And with several years of experience and investigation, he has good ideas about approaches to cultural practices, varietal selection, and planting density to overcome other snags in his plan.

Ed also is exploring the value of Haygrove production for other crops. Berries are important in the crop mix at Weaver’s Orchard, though the Weavers are new to growing berries in Haygroves. Their protection from birds and rain has reduced damage and disease and improved quality for all types of berries. In the high tunnels, both the blueberries and brambles also produced “super vigorous" canes heavy with fruit that required either temporary or additional trellising, respectively. Ed calls this "a good problem!" Blueberries ripened earlier (three to four days to a week or more) than field grown berries, but the farm did not gain much added value with earliness for this crop.

The Weavers have the least experience with bramble production in the Haygroves as their first crops under plastic were harvested in 2005. Summer and fall bearing bramble crops—Black Raspberry, Primacane Red Raspberry, and Floricane Red Raspberry—were successful. The biggest benefit is that the cover keeps the canes and fruit dry. Pickers don't have to wait until the dew has dried, and with fewer blemishes, the fruits are easier to pick. Shelf life has increased, with no mold evident a day after picking. Ed wonders, though, if the lower productivity of black raspberries, compared to reds, justifies the cost of planting in the Haygroves.

Ed has experimented with several strawberry production systems, including day-neutral varieties and June-bearing varieties in tabletop production. He is optimistic about growing tabletop strawberries, which are common in the United Kingdom. This system gives the grower flexibility in timing the fruiting of the crop. Plants are started in trays on pallets in another hoop house. At blossom, they are moved to the Haygrove. After production ends, they are returned to the other hoop house. Planting date, pinching primary buds, temperature, and the date the plants are moved to the Haygrove are among the factors the grower can manipulate to alter the harvest date.

By keeping rain off the plants with the tabletop system, the Weavers have been able to grow a June-bearing strawberry crop with a longer shelf life and no pesticide application. They retailed their crop for $1 more per quart. The Weavers' experience with ever-bearing (day-neutral) strawberries grown in the ground was less promising, as they were afflicted with disease problems. Ed Weaver is eager to experiment with growing strawberries that ripen out of season, in May, and in the Fall.

Enterprise Budget for Sweet Cherries in a One-Acre Haygrove Tunnel at Weaver's Orchard

Fixed Costs			
Tunnel Construction Costs		**Materials**	**Labor**
High tunnel construction (220 hrs. x $10/hr)			$2,200
High tunnel frame		$25,000	
Irrigation		$630	
	Subtotals	**$25,630**	**$2,200**
	Total Tunnel Construction Costs		**$27,830**
Cherry Tree Establishment Costs		**Materials**	**Labor**
Trees (@ $10.25)		$4,100	$2,300
Stakes and guards		$1,312	
Fertilizer, pesticides, etc.		$237	
	Subtotals	**$5,649**	**$2,300**
	Total Cherry Tree Establishment Costs		**$7,949**
Summary of Annual Fixed Costs			
High tunnel construction (divided by 15 years)			$1,855
Interest (construction financed at 7% for 15 years)			$974
Taxes, land, office expenses, fees			$295
Cherry tree establishment (divided by 15 years)			$530
	Total Fixed Costs		**$3,654**
Variable Costs			
Materials and Machinery			
Fertilizer and lime			$47
Bees for pollination			$220
Pesticides			$244
Poly cover (divided by 4 years)			$1,000
Marketing Costs			$800
	Subtotal		**$2,311**
Labor Costs ($8 to $12/hr)			
Poly cover installation, removal, venting			$1,200
Pruning, irrigating, spraying			$158
Harvesting, grading, packing			$3,706
Sales and delivery			$880
	Subtotal		**$5,944**
	Total Variable Costs		**$8,255**
		Total Costs	**$11,909**
		Revenues*	**$17,780**
		Net Returns	**$5,871**

*Revenues are based on yields of 5,760 lb/acre and an average wholesale price of about $2.10/lb. The Weavers wholesale nearly half the total crop to their own farmstand, and then retail the cherries for an average of $4/lb, increasing their revenues by $1.90/lb, or by just over $4,200 (after marketing costs) in profits per acre. Because not all the cherry trees produced a full crop, yields were reduced by about 50%, having a large impact on net returns.

Case Study: Cedar Meadow Farm

Steve and Cheri Groff, and their three children, live in Holtwood, Pennsylvania, in southern Lancaster County. On rolling land near the Susquehanna River, they produce 210 acres of small grains and vegetables including no-till tomatoes, pumpkins, and sweet corn. Steve has become known for his success with a permanent cover cropping system in which he establishes vegetable crops without tillage and makes use of cover crops and crop rotations as a way to save soil, reduce pesticides, and increase profits.

Like many no-till farmers, Steve has noted that because soils remain colder under no-till conditions, they tend to produce later crops. Steve grows nine acres of no-till tomatoes, and his inability to capture the lucrative early market had been a frustration.

Steve had been growing some tomatoes in a 15' x 96' high tunnel for nearly seven years, and was pleased with the benefits a high tunnel offers including earliness, improved fruit quality, and increased yields. But he wanted to produce his early tomatoes on a much larger scale. So, four years ago, Steve built a one-acre, multi-bay Haygrove tunnel.

Steve's decision to purchase the Haygrove tunnel was based primarily on economic considerations. The initial cost of the structure, 6 mil plastic cover, and mulch, with about 250 hours of labor for assembly, was about $30,000. On a square-foot basis, that was less than half what a high tunnel would have cost him to build. Steve calculates the annual cost of maintaining his acre of Haygroves at $4,000. This figure includes one-third of the cost of the polyethylene film, which he replaces every three years, labor for covering the structure in the spring and uncovering it in the fall, and labor for venting.

Steve was also attracted to the scale of the Haygrove. One multi-bay unit would give him an entire acre of tomatoes under cover. Finally, he liked the fact that the structure was tractor-accessible, giving him greater flexibility to perform tillage and other operations with machinery.

Steve's tunnel has six bays that are 24' wide and 300' long. To maximize its use, Steve planted 6,000 plants in the first season, but the result was tall and leggy plants. He sought to control the vegetative growth by reducing nitrogen rates and watering, which did seem to retard growth but also resulted in smaller tomatoes.

The next year, Steve reduced the plant population to 4,800 plants per acre and was pleased with the results. In his first year, Steve planted into bare ground and had a difficult time with weeds despite using herbicides. In the second season, he formed raised beds and installed a woven plastic ground cover, which resulted in a warmer soil and effective weed suppression. He plans to maintain the beds permanently and to reuse the mulch and stakes.

Steve now makes weekly nitrogen applications through a drip irrigation system, and vents to control excessive growth. He irrigates three times each week, providing 3 pounds per acre of nitrogen per watering. In the past, he used calcium nitrate and liquid nitrogen. Now that he has established permanent, mulched beds, he will use a complete fertilizer beginning soon after planting.

Steve sets his plants out during the third week in April, and harvests from the first week of July until early November. So far, he has been pleased with the variety, *Mt. Spring*, finding that it performs well for a much longer period inside the tunnel than it does in the field, but also continues to trial other early varieties. In the future, Steve plans to use row covers inside the tunnel in early spring to extend the season even longer. He is also looking into options for supplemental heat as a means to prevent frost injury and to boost spring growth.

Steve has used bumblebees to get better pollination but questions if they are necessary, especially since he likes to occasionally vent on windy days to control plant growth and lower humidity.

In his first year, Steve had yields of 2,400 25-lb boxes (60,000 lb.) of #1s and #2s. In his second year—after fine-tuning crop spacing, fertilization, and irrigation—tomato yields increased to 3,400 boxes per acre, 70% of which were #1s. His four-year average annual yield for Haygrove-grown tomatoes was 71,531 pounds.

Steve's second season in the Haygrove tunnel was a particularly wet one, and yields of the same tomato variety in the field were only 1,200 boxes per acre. The three-fold increase in tomato yields was just one of the benefits of the tunnel. The quality of tunnel-grown fruit has been vastly superior to field-grown fruit. "We see it every time we bring high tunnel tomatoes into the grading room and compare them with field-grown tomatoes," says Steve.

Steve has found the effects of severe weather and disease pressure to be noticeably reduced inside the tunnel. He sprays occasionally, finding that he gets good coverage by using an air-blast sprayer from both ends. The natural movement of air inside the tunnel helps deliver the pesticide to plants in the middle of the structure. Last year, Steve struggled with a bacterial problem, and is re-evaluating his use of the permanent ground cover and stakes that may harbor the pathogen over the winter. He has also struggled with spider mites, and is seeking an alternative to miticides for their control.

Although Steve is experimenting with raspberries in one bay of the tunnel, he is not planning on rotating out the tomatoes. He has considered relocating the tunnel if he finds that tomato pest populations increase to unfavorable levels, but he estimates that may cost up to $4,000. He believes that the experience of erecting the tunnel the first time will enable him to reduce the time required to build the tunnel a second time from 250 hours to about 200 hours.

Since Haygrove tunnels are not designed to withstand more than a few inches of snow, they were a good choice for Cedar Meadow Farm as Steve wasn't looking for an over-wintering structure. He wanted to begin production after snowfall was no longer a threat, and finish the season before winter. To prepare for winter, he removes the sheets of plastic, placing them in the gutter of every other bay, a job that takes about 20 labor hours to complete. He wraps them in black plastic to prevent decay from ultraviolet radiation.

Installing the plastic in the spring is a big job. Six people can do it on a calm day, but eight is better, especially if it becomes breezy. Steve says that the key is to be prepared for that calm day when plastic installation will go smoothly. He estimates that installing the plastic cover and end-wall doors takes about 50 labor hours every spring.

Once the tomatoes are planted, it is important to ventilate the tunnel properly, which Steve describes as an art that comes from experience. "You have to make venting decisions based on temperature, wind speed and direction, and the stage of crop growth," he said. "During initial fruit-set—the most critical time—I look at the hourly forecast on the Internet. During that six-week period, I literally baby-sit the tunnel."

Like other high tunnels, multi-bay units are ventilated manually, but instead of rolling up the sides and ends, the plastic on a multi-bay is pushed up, and held in place by adjusting the tension on the ropes that hold the plastic down. During the early season, when days are warm and nights are cold, ventilation is time-consuming. Steve estimates that ventilation takes from 15 minutes to two hours of his time every day for the first six weeks of the season.

Beginning around June 15, Steve opens the tunnel and removes the doors for the rest of the season. If high winds are expected, Steve fully vents the tunnel, as Haygrove recommends, to avoid damage to the structure. When properly constructed, these tunnels are designed to withstand 70 mph winds. Steve had some experience with high winds—in the field, tomatoes and sweet corn had blown down but his tomatoes in the multi-bay tunnels remained unscathed.

Steve believes that he has realized his objectives with the Haygrove tunnel. He has found a cost-effective way to produce good yields of high-quality tomatoes in the early and late periods of the tomato season, when prices are at their peak. And, by being in the marketplace in the early part of the season, he is able to continue selling tomatoes from the field.

However, Steve cautions growers who are considering a purchase of this kind to do their homework. If winter production is one of your goals, choose another structure. If you have a particularly windy site, consider a different structure. But if you are looking for a three-season structure that is tractor-accessible and relatively inexpensive, the Haygrove may be a good choice for your farm.

Case Study: Intervale Community Farm

Member-owned Intervale Community Farm (ICF) is located in the heart of Burlington, Vermont, on the site of the city's last dairy farm. It was started in 1990 as a not-for-profit Community Supported Agriculture (CSA), and currently has nearly 500 members. Andy Jones has been the farm's manager since 1994. Andy, assistant farmer Becky Maden, and a staff of seven seasonal employees produce 20 acres of vegetables, flowers, and berries for member households. The farm is one of the oldest CSAs in Vermont, and is the single largest.

The Intervale is a 1,500-acre flood-plain delta at the mouth of the Winooski River, and is home to twelve other small farms, creating what Andy describes as a "collegial and supportive community of farmers and entrepreneurs." The farm sits on a level, well-drained soil that is suited to vegetable production. Although the weather at the Intervale is slightly moderated by Lake Champlain, the growing season is still relatively short. It is considered a cold Zone 5 or a warm Zone 4, with the average last frost on May 12, and first fall frost on October 1.

The farm's produce is distributed for about 22 weeks, from mid-June to early November. Members visit the farm each week during that period to pick up their shares and harvest their own flowers, herbs, peas, beans, berries, and cherry tomatoes. The weekly share includes baby salad greens, carrots, broccoli, cucumbers, and tomatoes, among other vegetables.

Andy says that the field-grown tomato season lasts five to six weeks—from early August through mid-September. Because member surveys indicated that tomatoes are favorite crops, Andy started using high tunnels in 1999 to ensure a steady supply of tomatoes to his shareholders.

ICF has a total of six tomato tunnels. Four are 14' x 96' units. Two measure 14' x 144', and have sides that are about 18 inches higher than in the other four. The gothic-shaped structures were made by Ledgewood Greenhouses in New Hampshire. Andy selected the structure for its strength, snow-shedding design, and economical cost, which was about $0.90 per square foot.

The frame cost between $1,200 and $1,250, not including the roll-up sides. The taller sidewalls added a couple hundred dollars to the purchase price but are well worth the price. In 2003, the four-year, six-mil greenhouse plastic that Andy uses costs about $350 for a 28' x 100' piece. The total cost of the high tunnel, including structural steel, wood for end-walls and sideboards, hardware, and the labor to construct it, was approximately $2,000 for a 14' x 96' house. Andy calculates a yearly cost of $400 to own the 14' x 96' structure, basing this figure on a ten-year payback. However, the metal tubing of the frames should last much longer. Andy estimates that the wood parts of the structure (hip boards, baseboards, and end walls) need replacing every 10 years.

Andy seeks a nice mid-size (7 to 10 ounce) red tomato for the bulk of the production. For the taller tunnels, which are trellised overhead, ICF has been using the 'Buffalo' variety and is currently trialing replacement greenhouse cultivars that are as flavorful and productive. In the shorter tunnels, where the tomatoes are trellised with a basket weave method, the main red tomato has been 'Jetstar.' This cultivar has a beautiful appearance, moderate size, and good flavor. 'Jetstar' is less resistant to *Fulvia*, though, so Andy continues to look for others. 'Big Beef' is a pretty good choice, but runs a bit larger than Andy likes for the CSA. Andy's trials of 'Fabulous' from Seedway looked favorable, though the fruit are not quite as tasty as 'Big Beef' or 'Jetstar.'

Some other types of tomatoes—heirlooms and other colors—are also grown at the farm, but these tomatoes represent no more than one-quarter of the total. Popular heirlooms are 'Cherokee Purple' and 'Rose d'Berne' which is pink. Every year a few new yellow and orange cultivars are tried, but the perfect combo of size, yield, and flavor is still elusive.

Andy sows his first tomato seeds during the first week of March. He seeds into row trays, and then, about two weeks later, pots into 4" square cells. The first tomato transplants are set out on May 1, about eight weeks after seeding.

Each tunnel has four beds. Tomatoes are planted in rows 42" on center, except for the two inner rows, which are just 34 to 36" apart since both rows are trellised overhead to the ridgepole. For winter greens production, they divide each tunnel into two outer beds 30" wide and two inside beds 36" wide, with three one-foot wide aisles.

The beds are usually rototilled in the spring, although when the residue is not heavy, they may be hoed instead. They add two to three cubic yards of compost per tunnel (roughly 65 cubic yards per acre) and other soil amendments as indicated by soil test results.

In addition to the compost, they generally apply 50 lbs. of greensand, a little over 20 lbs. of azomite and, for calcium, about 25 lbs. of gypsum. Often they spread a little nitrogen starter fertilizer at a rate equivalent to 30 lbs. N per acre to give the early May planting a boost. Lately, they have been using a dehydrated chicken manure called *Cheap Cheap* from North Country Organics as their early nitrogen source. With a 4-3-3 analysis, this product provides a bit of soluble phosphorus and potassium as well.

The beds are covered with black landscape fabric, each outfitted with a single drip irrigation line. The same fabric has been in use for seven growing seasons and appears to be going strong. A 15' x 100' piece costs about $100.

X-shaped holes cut about 4" x 4" in the landscape fabric allow for easy transplanting. He has also tried cutting longer slits, but the strands of fabric tend to impede rapid planting as they pull free in later years. While burning makes tidy holes, Andy does not like burning plastic, and he and his crew found the razor-sharp edges of the torch-made transplant holes to be abrasive and objectionable. He said, "250 holes per house, 6 houses a year, 10 years per sheet of fabric…you get the idea."

Andy transplants one row of tomatoes down the center of each bed, using a 18" in-row spacing. This gives a plant population of about 250 plants per 14' x 96' tunnel.

Tomato irrigation is primarily accomplished with 0.6 gal/hr drip line. At transplanting, they typically soak the tunnel with an overnight watering. After that, the plants automatically receive about 25 to 30 minutes of water per day. A battery-powered timer ($35 from the local hardware store) controls the watering so no one has to remember to water. Once the fruit begins to ripen, they reduce watering to around 15 minutes a day. By mid September, they generally stop watering the tomatoes altogether.

Andy now uses determinate varieties in the shorter tunnels so that their vines don't overrun the structure. He uses a stake-and-weave system, where a stake is placed between every other tomato plant in the row. Andy finds that the effort of staking and stringing is rewarded by an increase in the proportion of marketable fruit and by easier harvesting. He prunes his tomatoes, removing all the suckers and leaving one leaf spur below the first flower cluster.

In the taller houses Andy uses an overhead trellis, prunes each plant to a single leader, and uses clips to hold the tomato vine to the trellis. Andy recommends taller structures because they offer more choices with respect to variety selection and because they give better air circulation. The additional air volume also helps to keep temperatures up in cooler spring and winter conditions.

Andy's planting schedule reflects his desire to extend his outdoor field production. Each year, about half the tunnels are planted early (from the end of April to early May). These are intended for the first four weeks of the harvest season. These tunnels have back-up heating units that are only used during very cold nights. The other houses are planted in mid-to-late June, and are harvested beginning at the end of August and continuing through the end of September. In between those picking windows are the field tomatoes, if the weather cooperates.

The tunnels have helped reduce insect pest and disease incidence in Andy's tomatoes. Insects in the tunnels have not been a problem, despite the absence of any kind of rotation. Diseases that were chronic problems in the field, such as the leaf blights caused by *Septoria* and *Alternaria*, are no longer a concern. An exception, however, is leaf mold, caused by the pathogen, *Fulvia fulvum.* This disease is particularly problematic where temperatures and relative humidity inside the tunnel have been high, chiefly in the late summer and autumn. Basket weaving, though beneficial in many ways, inhibits air circulation and field cultivars that are most suitable for basket weaving don't have the *Fulvia* resistance that some of the greenhouse varieties have.

The tunnels are ventilated by means of roll-up sides. There are no gable end vents and the tunnels' 8' x 4' doors (on one or both ends) are not deliberately used to manage air movement. The chief management activity associated with the tunnels is the time required for temperature and ventilation management. Andy estimates that during the "high maintenance phase," about a half an hour per day is dedicated to environmental management for the six-house complex. Spring tomatoes are pollinated with Class 'C' bumblebee hives. Late crop tomatoes rely on wind through the rollup sides to set fruit.

Andy has been very pleased with his yields. His six tunnels, along with about 800 field tomato plants on a quarter acre, are enough to provide each of his 500 members with 30 to 40 pounds of tomatoes over a period of eight to ten weeks. Harvest begins in earnest in mid-July, and winds down in late September, in time to plant a crop of fall salad greens. Andy estimates the cash value of the tomato crop at around $30,000 (17,500 pounds at $1.75 per pound).

Years of ICF member surveys have shown that tomatoes are always within the top five most popular crops and contribute one of the largest percentages to the overall CSA share value. Therefore it has made sense to invest in high tunnels to ensure success. Andy thinks the tunnels might also be suited to trellised cucumbers and red peppers, but he has settled on tomatoes because they are the crop most valued by his members.

“With high tunnels, our members are pleased because we can provide them with more and better tomatoes over a longer period of time,” said Andy. “And we are pleased because content members are likely to renew their memberships. Our financial stability stems from repeat business—it’s far easier to make happy customers than to find new ones.”

To increase the return on his investment in high tunnels, Andy has begun using them to grow cold-hardy greens offered as part of a winter CSA share. This share also includes stored squashes, cabbage, and root crops from ICF, supplemented with products from other local farms, such as organic eggs, goat cheese, and apples.

The kales, mustards, Tatsoi, Mizuna, arugula, and spinach are on Andy’s short-list of hardy greens. Though ICF has experimented with other hardy greens such as Claytonia, Sylvetta arugula, Mache, and so forth, so far the standard field salad greens have outperformed them for ICF.

To prepare for the winter shares, Andy removes the tomato vines, twine, stakes, and plastic mulch by the end of September. In his experience, a winter salad crop must be direct-seeded in early October to be successful. Crop growth will be slow during the late fall because of the cooler temperatures and shorter day length. In unheated and unlit structures, most crop growth must occur before the end of November. After that period until the day length begins increasing again, Andy says, development virtually stops, except during particularly sunny days, and the crop temporarily enters a kind of suspended animation.

Andy’s goal is to have a succession of salad greens harvests throughout the winter. Nevertheless, a single planting date is sufficient. The high tunnel is essentially a winter warehouse of salad greens. Once established, they will be available for harvest throughout the winter, as long as they are not exposed to extreme cold.

To help reduce the risk of freezing injury, Andy covers the crop with a medium-weight row cover that he suspends over low wire hoops. In his experience, the greens he grows are hardy down to about 21°F. So far, Andy has not felt the need to add supplemental heat. Nighttime temperatures inside the tunnel are generally 5 to 10°F warmer than outside temperatures, and the covers add another 5 to 10°F of warmth. As heat radiates from the soil, it is trapped under the low cover, offering protection to the plant canopy.

Andy direct-seeds his salad greens with a single row Planet Junior seeder. He had previously used a six-row pinpoint seeder for all these crops except for spinach. He counts on just one harvest, but sometimes a second cutting may be made in the early spring. By mid-February, when daylight exceeds ten hours, the crop shows signs of renewed growth. The mustard family crops do reasonably well through much of December, except for the kales which can thrive throughout the winter. Spinach is the mid-winter standout, and ICF is considering quitting all other green crops intended for harvest January or later.

To water their high tunnel greens, they set up Netafim DAN microsprinklers (these sprinklers don’t put out much water) and soak the houses for 24 to 48 hours prior to planting. After that, they water overnight about once a week until later fall. The lack of irrigation water during winter months is a problem at ICF with its very sandy soil. Andy imagines that February and March yields would be greater if irrigation were possible. Given the opportunity, he supposes they would water once every three or four weeks during the winter.

Andy has also used the farm’s heated 30' x 96' greenhouse for winter greens production. Even without supplemental heat, he saw significantly better greens growth in the greenhouse than the high tunnels. Andy suspects that the larger thermal mass afforded by the greenhouse structure provides a more consistent growing environment than the much narrower hoop house frames. This suspicion is reinforced by the fact that the taller hoop houses do better in the winter than the shorter versions.

The value of convenient mid-winter ventilation also has become apparent to Andy. He is currently examining the feasibility and cost of adding a small exhaust fan and louver to each hoop house for winter use. Last winter, which was warmer than usual, ICF had some disease problems in spinach that were largely a result of warmer, humid conditions. Andy has found the roll-up sides to be somewhat impractical for winter use, when a tight seal is often desired shortly after venting.

Enterprise Budget for a Six-Month Tomato Crop in a 2,000 sq-ft High Tunnel at the Interval Community Farm

Fixed Costs

Construction Costs		**Materials**	**Labor**
Site prep (tractor time, labor)		$60	$48
High tunnel layout		$10	$48
Frame & construction		$5,000	$576
Lumber, hardware, and labor		$800	$384
Endwall finishing		$250	$144
Water service		$50	$12
Irrigation (valve, tape, water timer, header, fittings)		$100	$32
Backup heater		$225	
Other -- weed mat		$200	
Other -- harvest containers		$200	
	Subtotals	**$6,895**	**$1,244**
	Total Construction Costs		**$8,139**
Fixed Costs			
High tunnel construction (divided by 15 years)			$543
Interest (construction financed at 7% for 15 years)			$285
Taxes, land, office expenses, fees			$800
	Total Fixed Costs		**$1,627**
	Total Fixed Costs (six-month tomato crop)		**$814**

Variable Costs (six-month tomato crop)

Materials and Machinery			
Plants			$700
Fertilizer and compost			$175
Irrigation supplies			$10
Stakes, string, clips			$200
Heater fuel			$75
Bees for pollination			$100
Poly covering (divided by 4 years)			$200
Misc. supplies, repairs, maintenance			$150
	Subtotal		**$1,610**
Labor Costs ($12/hr)			
Bed preparation and fertilization			$144
Transplanting, laying drip tape and weed mat			$144
Site mowing and weeding			$144
Pruning & trellising			$576
Harvesting, grading, packing			$480
High tunnel clean-up			$120
Annual maintenance			$96
Environmental management			$360
	Subtotal		**$2,064**
	Total Variable Costs		**$3,674**
		Total Costs	**$4,488**
		Revenues*	**$8,750**
		Net Returns	**$4,262**

*Revenues are based on a tomato yield of 3,500 lb per 14 X 144' high tunnel. The tomatoes are assigned a value of $2.50/lb, and revenues were $8,750.

Case Study: Star Light Gardens

Almost half an acre of intensive production in five high tunnels (17,500 square feet) complements an acre of field grown salad crops and other vegetables at Star Light Gardens, located one half hour south of Hartford, Connecticut. Mixed baby greens, mesclun, and tomatoes as well as arugula, basil, and pea tendrils are currently David and Ty Zemelsky's main tunnel crops. Close to year round sales of freshly harvested produce from this micro-farm provide the couple with their livelihood. Each had another career before they made a quick transition to farming in the late 1990s.

David always had a passion for gardening. In the years before he and Ty started their own farm, David deepened his horticultural know-how by lending a hand to an aging friend and long-time organic farmer. At the time, he did not imagine that pursuing his avocation would enable him to quit his day job.

Listening to his friend's tales of winter growing pioneer Eliot Coleman prompted the Zemelskys to make a 500 mile round trip pilgrimage to Coleman's Four Season Farm on Maine's Penobscot peninsula in October 1999. Ty said, "We didn't even know what questions to ask." They bought Coleman's *Winter Harvest Manual* and Ty, who describes herself at the "instigator," decided that there was no reason they couldn't start their own business using this model.

With their children grown, the Zemelskys had been exploring ways to be self-employed together. They were about 50 years old and fit enough to be running marathons. They wanted to find "good honest work" that was compatible with their values and provided a reasonable livelihood. A home-based enterprise was attractive to Ty who, as a visual artist, found working alone in her studio to be too isolating.

To build their first high tunnels, they took out a home equity loan. By Thanksgiving of that year, their son (a landscaper) had prepared the site and they had erected their first two high tunnels. They remember the date—April 9, 2000—of their very first greens harvest, from seeds sown in February. When June rolled around, with a small field planted outside and restaurants buying their produce, David left his school psychologist job for good.

Within two years, David and Ty had put up a total of four 30' x 96' high tunnels on a North-South axis. Next, they hired the local greenhouse fabricator to construct a 30' x 144' structure on an East-West axis, making it their warmest and brightest tunnel. All are gothic style.

Their first two high tunnels are skinned with double layers of plastic inflated with a small blower fan. Initially none of the tunnels had heat. After a few years, they decided to install a forced air oil furnace in one of these original tunnels to facilitate early tomato production. Ducts transport hot air to an adjacent tunnel. They have no inclination, however, to put heat in their other three tunnels.

The Zemelskys chose high tunnel design options that maximize passive ventilation. They set 30" roll up sides about 2' above ground level to protect young plants from cold blasts of air. Directly below the roll-up is the high tunnel baseboard. Plastic film covering the tunnel below the baseboard is buried in a trough in the ground. On each high tunnel, both gable ends have large doors that fully open. Under cold winter conditions, these passive venting systems are not feasible. David and Ty say they would have opted for ridge vents if they were more affordable.

In their first four tunnels, the Zemelskys experimented with two types of fans. Above the doors, each of these tunnels has a louvered vent on one gable end and a big exhaust fan mounted at the other. A thermostat triggers the louvers to open and let fresh air in. This automatically turns on the fan. They set the thermostat at 80°F for winter greens.

Horizontal airflow (HAF) fans are the second type they had installed. This conventional greenhouse ventilation system is comprised of four window fans hung from the trusses, with one pair blowing air up one side and the other pair blowing it down the other side. Their purpose is to keep air circulating inside, particularly on cloudy winter days when the tunnels are closed. After the Zemelskys stopped growing fall and winter lettuce (their mildew-prone crop), they eagerly stopped running these fans and significantly cut their high electrical consumption.

Ingredients of the Zemelskys' salad mix changes with the seasons and every year they experiment with new varieties. Their hardier, sturdier winter mix contains about eight different kinds of cold-hardy brassicas (including 'Siberian' and 'Dino' kale), and various Asian greens such as Tatsoi and Mizuna. Claytonia—which thrives in cold, low light conditions—is a winter favorite. Arugula accounts for as much as 30% of their sales. Pea tendrils are another important cool weather crop. Some of their seed comes from High Mowing, a small Vermont seed house that only sells open-pollinated, organic seeds. Wild Garden Seed in Philomath, Oregon is the source for chervil and mixed mustards they like called, 'Morton's

Mild Mustard Mix.' Johnny's Selected Seeds is another source.

Timing is very important for winter production since the growth rate of crops decreases to almost a standstill in the weeks leading up to winter solstice. To work around this cycle, the Zemelskys have learned to sow greens from early September through October 7 for winter harvest in their location. They start slower growing crops like spinach, chard, and beet greens earliest. For spring harvest, they have planted late into November and in February. With the exception of tomatoes, all of their high tunnel crops are direct seeded.

Intensive production and double or triple cropping requires ample nutrient availability. Before fall planting, David applies an inch of a purchased certified organic leaf-based compost. In the spring, he adds more compost as well as some organic fertilizer into the tomato transplant holes. The Zemselskys also make their own compost by windrowing leaves from local landscapers. Since these composts are low in nitrogen, David supplements them with a purchased fertilizer product from North Country Organics and alfalfa meal for extra nitrogen content. They test the soil periodically as required by their organic certification agency.

David used to roto-till the soil but he has discontinued that practice because he feels it damages soil structure and brings up weed seeds. Instead, he uses shallow tillage to prepare the planting beds. He is experimenting with a small power harrow, a tool that does not invert the soil. Alternatively, he uses hand tools for soil preparation: a saddle hoe to remove debris and old plants, a wheel hoe with a cultivator attachment, and a broad fork. Before planting, he rakes the seedbed and firms up the top layer of soil with a mesh roller.

Over the years, the Zemelskys have found weeds to be quite challenging. Weeds slow harvest and compete with the crops. Certain tenacious cool season weeds, like chickweed, have been very difficult to overcome. Stale seed bedding followed by flaming is proving to be the best prevention for weed proliferation. After preparing the seedbed, David irrigates and, when the weeds emerge, he cooks them with a propane backpack flamer. David is learning to leave two weeks between getting the beds ready and planting the crop to allow time for this technique.

After using a four-row pinpoint seeder for several years, David graduated to a newer six-row model that has built-in rollers. He said the six-row seeder is an improved model that is more forgiving than the four-row one. He recommends a plastic cover over the seed trays for keeping soil from kicking into each bin, and Johnny's incorporated that suggestion. He said, "At first it didn't seed well, but the company got the kinks out of it, for the most part."

With any of the pinpoint seeders, monitoring the operation of the seeder is critical in David's experience. He makes sure the shaft is turning and the belt has not jumped onto a different pulley as this determines how much seed is sown.

To achieve the intensive production he aims for, David prefers to grow his greens in blocks rather than rows. Rows allow for cultivation with a hoe, whereas blocks do not. He explained that seeding in blocks requires successful implementation of stale seed bedding to reduce the weed seed bank. If an area is too weedy, he can still use his six-row pinpoint seeder, filling only two of the six hoppers in order to skip two rows for every row he seeds.

Like others with a similar mix of crops, the Zemelskys use two different watering methods. For their summer crops like tomatoes and peppers, drip irrigation helps conserve their extremely limited water supply. With the aid of electronic timers, they irrigate three times a day—in the middle of the night and early morning hours—in order to load up the soil with water before it gets too hot.

With their greens seeded in blocks rather than rows, drip irrigation is not feasible. David is slowly converting his overhead irrigation to a product called "Ein Doers" that is sold by various dealers. Four rows cover a 30' wide tunnel. He also uses a conventional rotating sprinkler, mounted on a tripod, and another conventional sprinkler that goes back and forth.

After sowing, the late plantings are protected with a medium-weight, spun polyester row cover to assist the crop in germination. This microclimate warms the soil 2 to 3°F. Sometimes their plantings under the row cover experience some dieback. When the seedlings reach a certain size, the row cover is suspended over wire hoops pressed into the ground. The hoops prevent the row cover from chafing the fragile leaves and freezing onto the plants. This structure also keeps condensation off the plants.

The Zemelskys begin their high tunnel greens harvest in November and December. For the first few years, they harvested throughout the winter without a break. They have since stopped selling greens in January. By winter solstice, short day length and low light have considerably reduced plant growth, so they take a needed break while they wait for more re-growth to occur. By early February, with the sun higher in the sky and the light intensifying, they resume harvesting and also reseed some beds as necessary to ensure a strong March and April harvest.

Harvesting salad mixes constitutes a major portion of their labor. The dense, good quality crops at Star Light Gardens can be cut with more speed and the Zemelskys can cut almost 30 pounds per hour, compared to 20 pounds an hour in a more average stand. Ty used to be the main cutter but an old back injury was aggravated by all the bending. Now David does most of the harvesting, with the aid of a harvest cutter and a net bag in a laundry basket.

For the greens harvest, they cut with good, small, light-weight kitchen knives into nylon nets (from a fishing supply company) placed in laundry baskets. They wash the greens in the net bags and then run the bag through the spin cycle of a standard washing machine. They mix the greens to their standards or for special orders in a home-made mixer. If a batch of salad mix grows too big, they sell it as braising mix.

A couple of winters ago, the Zemelskys ceased trying to grow lettuce in the winter. David says that lettuces are too susceptible to powdery mildew under low light and high humidity conditions to be worth the trouble of growing in winter. They also grow too slowly after their August planting, requiring a full week longer than Brassicas, and are not nearly as cold hardy. Since Ty and David market their produce as local and seasonal, their customers readily accepted their explanation, without “batting an eye.” Always experimenting, they may try seeding lettuce in February for the spring harvest.

In 2006, a visit to Bryan O’Hara’s low tunnels in eastern Connecticut sparked a fundamental change in Star Light Gardens’ cropping philosophy. *(See section on Low Tunnels, page 38.)* In mid- and late September that year, David planted lettuce outside in low tunnels. He says his goal is to have enough field-grown lettuce to supply their markets through Thanksgiving, and then start harvesting in the high tunnels. The system appears to be working, though he will need to tinker with crop timing in both of these growing environments.

Pea tendrils are a money-making crop that the Zemelskys grow wherever they can fit it in, such as around the colder edges of their high tunnels and between the rows of tomato plants until they fill out. While pea plants cannot handle freezing the way hardy Brassicas and Claytonia can, they do well in cool fall and late winter conditions.

A pound of ‘Dwarf Grey Sugar Pea’ seed costs $1.30 and yields about five pounds of tendrils on 5" high pea plants. The Zemelskys plant 10 to 15 pounds of seed per week. David and Ty sell the pea tendrils alone for $13 a pound. Occasionally they add them to salad mix for more weight. David says, “Pea tendril pesto has regular basil pesto beat, and so much earlier!”

They have also added micro-greens to their marketing mix. They have found that these greens have already helped their bottom line.

Depending upon how early their field dries out, they transition to harvesting field-grown greens sometime in April or early May. The transition between high tunnel and field production can be a challenge. They have attempted to overwinter field greens in low tunnels, but the results have not been consistent.

Initially the Zemelskys only produced salad greens in the tunnels, leaving them vacant in the summer. In their fourth year, they added tomatoes and basil. Tomato transplants go into the high tunnels from March until early April and the tomato harvest lasts from June through early October. They must quickly pull out the tomato plants in time to reseed the tunnels to fall greens.

The Zemelskys make a wire trellis for the tomatoes using the support structure of the high tunnel. They typically use double leaders, pruning each plant to two main stems. The rows run the length of the tunnels, with nine rows fitting their 30' width, though David is considering growing fewer rows. In order to get earlier tomatoes, they may heat one tunnel to 60°F. This year, they began experimenting with grafting tomatoes. They specialize in heirloom varieties for their discerning customers and also grow some indeterminate greenhouse cultivars. Chefs order tomatoes by color.

Star Light Gardens has been very successful in marketing. Restaurants were originally the mainstay of their sales, but after several years of farming, they added farmers’ markets and the Yale University Sustainable Dining Program to their customer base.

Connecticut has few farmers in relation to its population, and organic, fresh, and unique produce is in great demand. The Zemelskys consciously aim to differentiate their produce from generic products, and they trial new varieties every year. They have been able to maintain their wholesale price for salad mix at $8 per pound. David said, “There is no competing product. What you get from California does not compare with what we have.”

The Zemelskys enjoy a nice relationship with chefs and find it advantageous at their scale not to rely on a distributor or purveyor. They get new accounts by visiting restaurants or when chefs find them through the Northeast Organic Farming Association of Connecticut (NOFA-CT). “Chefs are movable people,” said David, “We can gain or lose accounts when they change jobs.”

Currently they wholesale to about two dozen restaurants. Their weekly delivery route also includes four stores (including a family-owned IGA and natural foods stores).

They first tried selling at a farmers' market in 2004, when the founder and manager of a new market in New Haven recruited them. A couple of years later, they joined another farmers' market an hour away, which began when the sponsoring organization of the first market expanded its reach. Farmers' markets have been lucrative and sociable for the Zemelskys, and have also resulted in contacts with chefs and other buyers.

The Zemelskys have also been selling a significant amount of their production to Yale University since 2004 when it began piloting local food in one dining hall. The University is willing to pay 50% more than the going rate to obtain locally grown, preferably organic, food. Yale buys a third to a half of their salad greens during the late fall and early winter.

Enterprise Budget for a Six-Month Brassica Greens Crop in an Unheated 3,000 sq-ft High Tunnel at Starlight Gardens

Fixed Costs

Construction Costs		Materials	Labor
Site preparation, bulldozer			$1,500
High tunnel construction			$600
High tunnel frame		$3,000	
Lumber and hardware		$400	
Endwall finishing			
Water and electrical service		$311	$100
Irrigation		$150	
Exhaust fan and louvered vent		$750	
Bed preparation		$150	
Other (horizontal air flow fans)		$330	
	Subtotals	**$5,091**	**$2,200**
	Total Construction Costs		**$7,291**
Fixed Costs			
High tunnel construction (divided by 15 years)			$486
Interest (construction financed at 7% for 15 years)			$255
Taxes, land, office expenses, fees			$225
	Total Fixed Costs		**$966**
	Total Fixed Costs (six-month winter season)		**$483**

Variable Costs (six-month winter season)

Materials and Machinery		Cost
Seeds		$46
Fertilizer, lime and compost		$78
Plastic mulch and row cover		$75
Heater fuel and electricity		$25
Beneficials and pesticides		$10
High tunnel poly cover (1/2 year)		$110
Delivery costs		$175
	Subtotal	**$519**
Labor Costs ($20/hr)		
Poly cover installation and removal		$75
Bed preparation and fertilization		$160
Planting		$60
Irrigating and managing row cover		$20
Harvesting		$750
Washing and packing		$300
Sales and delivery		$420
	Subtotal	**$1,785**
	Total Variable Costs	**$2,304**
	Total Costs	**$2,787**
	Revenues*	**$6,000**
	Net Returns	**$3,213**

*Revenues are based on a Brassica greens yield of 0.25 lb/sq-ft or a total of 750 lb per cutting in the Zemelsky's 3000 sq-ft high tunnel. The greens were sold at $8/lb. Arugula, which sells for $11/lb and is not as cold resistant as some other brassicas, was not included in this accounting.

Case Study: Slack Hollow Farm

Twenty-five years ago, Seth Jacobs and Martha Johnson started Slack Hollow Farm in the Taconic foothills in Argyle, New York, located a little over an hour Northeast of Albany. In their early years, they did all their fieldwork with horses and depended heavily on hand tools. Today, with 15 acres in vegetable production, the farm claims three small tractors, numerous implements, a box truck, a greenhouse, and two high tunnels. Seth and Martha grow a wide range of vegetables and salad greens that they sell at two substantial producer-only farmers' markets and to wholesale accounts. Their primary high tunnel crops are spinach and other salad greens, produced in the late fall through spring, and tomatoes and basil, grown in the warmer months.

The first of their two tunnels is a 21' x 120' gothic-shaped structure manufactured by Ledgewood Greenhouses. They built it in 1995 from a kit and estimate that it cost between $6,000 and $8,000. This relatively simple tunnel does not have electricity, heat, or fans, and uses roll-up sides for ventilation. It has an East-West orientation. In this structure, they utilize a two-crop rotation. They grow tomatoes and basil from early May through late September or early October, and spinach from mid-October through early April.

Seth and Martha stopped growing tomatoes in the field about ten years ago because the yield and quality of their tunnel-raised tomatoes is so much better. Their farm in Argyle is in Zone 4, providing relatively little time to for a field-raised crop to develop. Also disease pressure in field-grown tomatoes is high, reducing marketable yields and profitability.

Seth and Martha have been growing spinach during the winter for four years and the system they have developed works well for them.

As a certified organic farm, compost has been the basis of Slack Hollow Farm's fertility program. In the past, they added farm-made manure-based compost at the rate of 10 tons per acre by running their manure spreader down the middle of the tunnel. New organic regulations require long intervals before harvest, so now they only apply compost in April, prior to planting the tomato crop. (A foliar spray of Epsom salts for magnesium on tomatoes is their only other nutrient input.)

After removing the tomato vines and trellises at the end of September, they roto-till the soil with a tractor-mounted tiller to prepare a good seedbed. Time permitting, they will flame-weed before seeding, but even when they can't get to it, weeds appear to be under control. Martha direct-seeds the spinach using a one-row Planet Junior seeder, producing remarkably straight rows. She aims for 12 to 16 seeds per foot, with rows four inches apart.

'Space' is the variety they prefer because of its leaf type, eating qualities, yield, and cold-hardiness. Spinach is very winter-hardy. "No temperature can kill it," Seth says.

Protecting the spinach plants with floating row cover is essential. They use up to four layers of mid-weight spun polyester row cover to buffer the crop from sub zero temperatures. The aim is to manage the freezing of the crop and soil during very cold periods, as this would interfere with or prevent harvest.

In the unheated tunnel, they get at least three harvests of spinach during the winter, taking cuttings on a given section about 60 days apart, depending on the amount and length of sunshine and the temperature. For plants harvested on December 20, the shortest day of the year, a second harvest will be ready during the last week of February. Production all but ceases between December 20 and January 30, so spinach is stockpiled for that period. A bed cut at the end of February will be ready for another cutting in early April. At this point, they take their last harvest, so they can renovate the tunnel in preparation for tomato planting.

They cut most of the spinach plant, leaving one or two new leaves behind, harvesting by holding the prostrate leaves up with one hand, and cutting with the other.

The first cutting of the winter spinach is of the highest quality, and the sugar levels seem to be higher. Customers notice that it is sweeter than outdoor in season. Leaf quality goes down with each cutting, but the taste remains unsurpassed. And it is still superior to what is found in grocery stores at that time of year.

Their markets for winter spinach and other greens include a large food co-op in Albany, with which they have had a very long relationship, and a large farmers' market that operates throughout the winter. If they expand their winter production, they would add more markets, or perhaps start a winter CSA. Currently, retail spinach prices are in the range of $10 to 12 per pound. They expect to harvest a total of 1,000 to 1,500 pounds of spinach from the unheated 21' x 120' tunnel, generating sales of $10,000 to $15,000 during the winter.

In 2004, Seth and Martha constructed a second high tunnel which some might consider more a soil-based greenhouse. Its North-South orientation was determined by their existing field layout. The 30' x 120' gothic-shaped structure was made by Rimol, a company that provides valuable technical assistance. Unlike their first high tunnel, they had this one built by professional contractors. It cost about $25,000 to build, including the structural steel, the heating and venting systems, cover materials, and labor.

For ventilation, they outfitted the structure with thermostatically controlled automatic roll-up side curtains and gable-end vents. These features cost only a few hundred dollars more than a big exhaust fan and there is no power bill. Four standard greenhouse fans improve interior air circulation during warm weather and for fall germination. Access is provided by large tractor doors and, in winter, by a small people door that opens inward so snow shoveling or plowing is not required.

They covered the structure with a single layer of plastic. On the end-walls and roll-ups they used a woven poly with 90% light transmission which is much more durable and long-lasting than normal greenhouse film. They opted for extra-heavy bows spaced 5' on center, rather than the standard 4' spacing because the cost was lower. In-ground heat tubes circulate hot water to warm the soil and root zone.

Several other growers now produce spinach for winter farmers' markets in their area, and competition has increased. To take full advantage of their winter marketing opportunities and to more fully satisfy their customers, they decided to expand their crop mix to include a range of less hardy salad greens. Building a new structure has made this diversity more possible. Seth said, "We would like to increase production during a time of year when competition from other local producers is lower."
They have been using their new tunnel to grow a variety of cold-hardy greens including arugula, Tatsoi, Mizuna, kale, radishes, turnips, beets, Swiss chard, and Bok Choy, as well as spinach. Some of these crops are seeded with a pinpoint seeder. Between the lateral beds (not raised) wooden boards focus foot traffic in very narrow paths. (They grow the tomato crop in rows running the long way.) They use the same production techniques here as in the unheated tunnel as well as the same general rotation. The addition of heat in this structure gives them more flexibility with planting dates.

This new heated high tunnel has benefited their spinach crop in several ways. While growing winter spinach in the original high tunnel, Seth and Martha found that they could not harvest early in the morning or during very cold days because the leaves would be frozen and quite wilted. The addition of a small amount of ground heat enables them to harvest spinach during these cold periods.

During a very high wind event in late February 2006, they lost the plastic on their older high tunnel. The plastic film on this house needed replacing and the pine hip boards had rotted, Seth noted. (Now all wooden parts in Slack Hollow Farm high tunnels are made of Eastern white cedar.) The loss of the plastic occurred right after they had finished the first cutting of their winter spinach. This crop was lost to cold burning.

At the same time, two beds of spinach planted around December 15 were maturing in the new, ground-heated tunnel. "We got astounding yields," said Seth. They cut these spinach beds on alternate weeks from the end of February until the last week in April and were able to supply their farmers' market from a much smaller planting. "Production far surpassed the unheated high tunnel," Seth said.

Even with the in-ground heating system, row cover remains an essential element of winter growing at Slack Hollow Farm. In the heated high tunnel, daily covering and uncovering with medium-weight floating row cover is required to prevent overheating during the day. To streamline the application and removal of the row cover, this winter they plan to construct a hand-cranked roll-across covering system within the high tunnel. *(See inner coverings section, page 52.)*

At Slack Hollow Farm, the decision to equip a new high tunnel with ground heat was intuitive. *(See heating section, page 49.)* Seth felt that for a tunnel covered with a single layer of poly, such a in-ground heating system would be significantly less expensive to run than heating the air.

Seth and Martha have always used a single layer of plastic because they believe it has a smaller environmental footprint or impact than two layers. *(For a different view, see Single vs. Double Layer in Selecting Your Structure section, page 31.)* It transmits more light, results in half as much plastic to dispose of, and averts the need for electricity to power an inflator blower. It is less resource-intensive to use lightweight row covers inside—which lasts for many years. Seth stressed that they do not use high tunnels to grow a warm weather crop out of season. They also do not use plastic mulch.

Seth estimates that a quarter to a third of the farm's revenues come from their two high tunnels. He expects that the new (more costly) tunnel will pay for itself within two to three years. It is very inexpensive to operate, requires no machinery except for tractor tillage twice a year, and takes only about 12 hours per week of labor, yet produces very high yields.

He anticipates $25 to $30 in sales per square foot.

Seth and Martha attribute much of their initial interest in winter production to their desire to offer year-round employment to their farm manager, Colleen Converse. She is, in turn, responsible for most of the winter harvesting and marketing.

“Our expansion into winter production has been employee-driven,” Seth said. They are able to travel in the winter because the manager can handle the farm, and they can also cut back in summer by placing more emphasis on winter markets. And year-round high tunnel production has also evened out the farm’s income.

Seth and Martha like tunnels so much that they actually have a third tunnel, 30' x 48', that they use as their washing and packing shed. With the wash station end covered with three layers of shade cloth in the warmer months, it is comfortable all summer, and far more pleasant than a dark barn. An added benefit is no property taxes as assessed on this temporary structure.

Enterprise Budget for Winter Spinach Crop in an Unheated 2,500 sq-ft High Tunnel at Slack Hollow Farm

Fixed Costs

Construction Costs		**Materials**	**Labor**
Site preparation, bulldozer			$1,000
High tunnel construction			$2,100
High tunnel frame		$5,000	
Lumber and hardware		$500	
Endwall finishing		$400	
Water service			$850
Irrigation		$700	
Bed preparation		$240	
	Subtotals	**$6,840**	**$3,950**
	Total Construction Costs		**$10,790**
Fixed Costs			
High tunnel construction (divided by 15 years)			$719
Interest (construction financed at 7% for 15 years)			$378
Taxes, land, office expenses, fees			$1,377
	Total Fixed Costs		**$2,474**
	Total Fixed Costs (six-month winter season)		**$1,237**

Variable Costs (six-month winter season)

Materials and Machinery		**Cost**
Seeds		$50
Compost		$200
Irrigation supplies		$50
Row Cover		$100
Poly covering (divided by 4 years)		$90
Packaging		$30
Delivery costs		$560
	Subtotal	**$1,080**
Labor Costs		
Bed preparation and fertilization		$500
Seeding		$48
Irrigating		$100
Harvesting, grading, packing		$1,500
Sales and delivery		$1,500
High tunnel clean-up		$100
	Subtotal	**$3,748**
	Total Variable Costs	**$4,828**
	Total Costs	**$6,065**
	Revenues*	**$12,000**
	Net Returns	**$5,935**

*Revenues are based on a spinach yield of 1,000 lb in a 21 X 120' high tunnel. The spinach was sold at $12/lb. Yields were reduced this season because a severe storm damaged the plastic cover. Revenues the previous year were $15,500 on yields of 1,550 lb and a selling price of $10/lb.

High Tunnels and Marketing

One of the primary reasons for adding high tunnels to a farm is to increase marketing opportunities. High tunnels enable growers to extend their marketing season. And because crops grown in high tunnels are usually of better quality, they usually command a higher price and attract quality-conscious shoppers.

Producing a crop in a high tunnel is typically more costly than growing it in the field, due to the structure's capital costs and increased manual labor requirements. On the other hand, when calculating the cost per pound or bunch produced, high tunnels often come out ahead. Depending upon the year and the crop, high tunnel yields tend to be significantly higher than those for field production. The more controlled environment favors production quantity and quality. And when outdoor yields are severely impacted by weather, pests, or other factors, the comparison can be particularly striking.

Since the investments in high tunnel crops are greater, it makes sense for farmers to maximize the returns on high tunnel crops through a deliberate choice of marketing strategies. Small farmers often find direct marketing to be essential, whether through farmers' markets, farm stands, Community Supported Agriculture (CSA), and even restaurant sales. Out-of-season production can pose significant challenges for marketing but it can also offer tremendous potential for creating a profitable niche.

Boosting Value

There are many ways to enhance the value of production. When direct marketing at farmers' markets or to chefs or small retailers, product diversity can enhance sales and put a farm in a preferred position. Since an individual customer will only use a finite amount of one product, a farmer can boost the food dollars spent by each buyer by offering more products. Most direct marketers raise a variety of crops during the growing season, and this can also be an effective strategy during the extended season.

For direct sellers, good signage, a friendly and positive demeanor, and attractive product presentation will probably be adequate for creating an effective image. Home-grown promotions that take a little time but cost little or nothing can also help create a buzz. Farmers can pitch their stories to the media with press releases or phone calls suggesting why they are of interest. Writing a newspaper column or getting a gig as a radio show guest will also increase public exposure. A public open house or tour for chefs are other means to make an impression on potential or current customers.

Packaging, labeling, websites, brochures, ads, or other forms of branding may play a role in adding value, depending on the market outlet. Any of these items may be helpful in the right situation. For example, a brochure is indispensable for CSA farmers like Andy Jones in recruiting members annually. Steve Groff belongs to a grower co-op selling tomatoes and other crops to supermarket chains. A life-size cut-out of Steve for display in the supermarkets helped create demand for the group's produce. As wholesalers with 50 acres of high-value crops in production, the Cramers can justify having a couple of websites where buyers can view their flowers and learn about the seed varieties they sell. For most small-scale growers, high expenditures on a lot of costly professional marketing materials are usually not warranted.

Farmers' Markets

With minimal investment, farmers' markets give farmers the opportunity to represent their farms and their products directly to the public. Good farmers' markets can be very competitive marketplaces; however, they also gather together far more shoppers for a compressed period of time than most individual farm stands. Successful farmers' market vendors develop relationships with their customers. They establish loyal followers who are not distracted by lower prices offered by other farmers at peak harvest.

The competition inherent in successful markets also speeds up the spread of appropriate innovations like high tunnel production methods. With shoppers comparing the various sellers, willingness to learn and flexibility to change are important attributes for farmers whose primary outlet is the farmers' market. Seth Jacobs has tried to position Slack Hollow Farm ahead of the curve. He was the first in his market to grow large quantities of spinach all winter in an unheated high tunnel. As other farmers adopted this practice, he anticipated the next opportunity by constructing a ground-heated tunnel to expand and diversify his winter production.

Taking Initiative to Extend the Farmers' Market Season

When farmers decide to use high tunnels to lengthen their harvest, they may not find a ready market awaiting them. For instance, farmers who rely on mid-season farmers' markets may have no outlet in early to mid- spring, late fall, or throughout the winter. Without a good market outlet, there is no point in extending the season.

Waiting for a market to appear is not practical. Instead, many farmers are taking initiative to develop or strengthen markets to serve their needs. Farmers need not organize markets single-handedly. Some of the best farmers' markets are joint projects of the farmer members and community advocates or enthusiasts. Farmers generally do need to stay involved to ensure the market will continue to work for them.

One of the most promising strategies for farmers growing in the winter is starting an indoor winter farmers' market. With proper planning and publicity, these new markets are finding receptive audiences. Our region now boasts at least four weekly winter markets, all started between 2002 and 2006. Fresh spinach, brassicas, salad mix, and sometimes kale and chard are popular winter items, and unless there is a large producer in attendance, greens usually sell out early in the market day.

Some farmers' markets only run from mid-June through September. Such a short time frame is not conducive to the creative use of high tunnels. For regular farmers' markets to start earlier in the spring or continue later into the fall, farmers must have appealing foods and other products to sell at these times.

A farmers' market will not attract a critical mass of shoppers if spring greens are the only product for sale. Vegetable farmers who are extending the season might want to recruit farmers who sell meats, poultry, cheeses, and other animal products, as well as bakers and processed and prepared food makers to create diversity and interest at a market.

Pick-Your-Own

Under the right circumstances, fruit grown in high tunnels can be an ideal crop for a pick your own operation. Of the fruit with which we are familiar, fall raspberries and sweet cherries seem to be especially good candidates. The appropriateness of pick-your-own depends on a farm's location, the temperament of the farm operator and farm family, and the capacity of the farm to accommodate large numbers of customers and their vehicles. Another consideration is the timing of the harvest season for a particular type of fruit. Even when fully vented, the temperature in single bay high tunnels can become stifling in warm weather.

Ed Weaver has found the climate protection offered by his multi-bay high tunnels to be attractive to his pick-your-own fruit customers. The quality of his sweet cherries is much improved, and even in inclement weather, customers can come and harvest protected from the weather. Due to the potential for spreading disease, pickers need to stay out of plantings when leaves and fruit are wet, even though rain may have ceased. Because of these factors, high tunnels enhance his customer base.

Community Supported Agriculture (CSA)

Instead of increased profit, the most important benefit for the Community Supported Agriculture farmer's livelihood may be risk mitigation. A CSA farmer might not be able to isolate the actual economic return from a high tunnel since CSA members pay a lump sum for their share of the entire harvest.

CSA members agree to share the financial risks with the farmer when they purchase a share in advance. It is in the interest of the CSA farmer to minimize the production risks inherent in agriculture and deliver the vegetables the members expect. Otherwise members may become disgruntled and the future of the CSA may be jeopardized.

For example, CSA farmers in northern climates often use high tunnels to ensure an adequate and sustained tomato crop. The added warmth of a high tunnel may permit an earlier harvest, and will guarantee production even in a cold year. By avoiding precipitation and associated disease, high tunnels will often keep the crop going longer. In a rainy year, high tunnel tomatoes usually significantly outperform field tomatoes. All of Andy Jones' high tunnel production goes to his CSA members. Having a consistent, high quality tomato crop helps keep Andy's members happy and coming back year after year.

Starting the CSA harvest earlier in the season or extending it later into the fall can also be achieved with high tunnels. A longer season may well allow the farmer to command a higher price per share. A CSA farmer might also use high tunnels to increase the diversity of produce at the growing season's start, even in a wet, cold spring. All of these uses can help a CSA farm differentiate itself and attract a loyal membership.

Some farmers have organized winter CSAs using high tunnels to produce greens. Winter CSAs can be as simple or complex as the farmers wish. In Wisconsin, a farmer started a stand-alone spinach share. He delivered spinach every couple weeks to Madison customers over the course of the long cold winter.

In a more typical winter CSA, fresh salad ingredients like high tunnel-grown spinach, brassicas, and even lettuces complement storage vegetables like carrots, onions, beets, parsnips, rutabagas, and winter squashes. Winter CSAs tend to provide vegetables to their members less frequently than growing season CSAs. Biweekly or monthly deliveries from December through March are typical.

A winter CSA need not be very demanding of the farmer's time. Providing off-season cash flow may give winter CSAs value beyond the relatively low income they bring in. Another benefit of a winter CSA is allowing the farmer to amortize the capital costs of the structure over multiple crops per year.

Some CSAs are collaborations among two or more farmers. Some CSA farmers are not interested in continuing production into the winter, but have the ability to grow sufficient storage crops to serve a CSA. A high tunnel farmer who grows greens during the winter could join forces with such a farmer. This sort of CSA partnership presents a direct sales opportunity for a high tunnel grower in areas where there are no winter farmers' markets.

Selling Directly to Restaurants and Specialty Stores

To gain acceptance with chefs and specialty stores, farmers find that interesting, superior tasting and exotic varieties are a real draw. Careful variety selection also "adds value," entitling the producer to higher prices. The Zemelskys have maintained strong prices for their tomatoes with an upscale chef clientele by growing heirloom tomato varieties. The fact that such varieties may be less productive, don't travel or store well, or may be more delicate makes them less attractive for many farmers, but these characteristics also open up a niche for small farmers who depend on direct marketing. Since these finicky crops are not easily mass marketed, they have not been embraced by supermarket chains or produce distributors. Specialty stores and independent restaurants can use these varieties to distinguish themselves from chains by offering these kinds of specialty vegetables.

Wholesaling

Effective wholesaling requires appropriate volumes of consistent products. The task of the wholesaler is finding customers who appreciate what they have to offer. In good wholesale situations, quality matters, and high tunnels can help guarantee the desired quality. Getting a jump on the season and providing reliable delivery and service are other attributes that create enduring relationships with wholesale customers. Early production gets Cramer's Posie Patch in the door with brokers who would otherwise look elsewhere for their suppliers. And the high quality flowers they grow in their tunnels help them keep their customers all season long.

Some buyers are interested in purchasing from farms in the region as a way to gain their own customers' loyalty. For instance, Hannaford, a Maine-based grocery chain, recently stepped up its locally grown program with the hope of attracting more farmer suppliers and capitalizing on their efforts with a customer campaign.

A group of Lancaster County growers, including Steve Groff, have developed a wholesaling relationship with a regional supermarket chain in Philadelphia and its suburbs. High tunnels gave the group an edge in dealing with this buyer. The Haygroves afford more consistent production and higher quality, two critical factors for supermarkets that are staking their future on excellence in their produce departments. In addition, the group is able to supply tomatoes beginning early in the spring, and extending late into the fall, long after field production in the region has been shut down by frost and disease pressure.

Site Considerations

It is a good idea to give careful consideration to where a high tunnel will be built. Success with the structure is highly dependent on its location. The high tunnel should be conveniently accessible, where water and electricity (if desired) can be supplied without excessive cost. A well-drained site is essential, and the site should be graded to divert water. The site should offer full sun and protection from the wind.

Check local zoning ordinances and permit requirements before you proceed. Under most local zoning ordinances, high tunnels are viewed as "temporary" structures that do not require a building permit. Similarly in most jurisdictions, high tunnels are not assessed as a property improvement and therefore are not taxed.

Utilities

Clean water that is free of sediment and chemical contamination must be reliably available in sufficient volume throughout the year—or at least during those months when plants will be growing. "Dirty" water may spread pathogens, blocks emitters in drip irrigation tape, and can even stain the high tunnel's poly covering.

Electricity is not a requirement for high tunnels as they are strictly defined. Most are covered with a single layer of plastic and therefore do not need an inflation fan to create the airspace between double layers of film. Similarly, passive ventilation is generally adequate. If you decide that electricity is desirable, site the high tunnels close enough for an economical connection with the electrical grid or consider using solar panels *(see "Photovoltaic Inflation Systems" on page 48).*

If use of a backup heating system is anticipated, the tunnel should be accessible to fuel delivery vehicles, and a fuel storage site should be identified.

Tunnel Access and Room for Expansion

High tunnels are relatively labor-intensive structures and require frequent access. In most situations, there is an advantage to locating high tunnels close to the farmhouse and established work patterns. Truck and tractor access is essential for moving product and supplies in and out. Proximity to the washing area, packing shed, and processing and distribution area will simplify the operation.

When considering where to locate your first high tunnel, keep in mind that you may want to add more tunnels in the future. As one grower put it, "High tunnels seem to like company." Make sure that your layout provides a logical plan for expansion, while also accommodating farm traffic and snow removal.

With his array of six 14' wide high tunnels, Andy Jones suggests placing tunnels as far apart as they are wide. Ted Blomgren suggests leaving alleyways that are at least as wide as the high tunnel is tall to prevent the shadow from one structure from falling on the adjacent structure.

Air Movement and Orientation

An ideal high tunnel site allows the free flow of air in summer and provides protection from cold wind in winter. For both passive and mechanical ventilation systems to be effective, the site should be open. Adequate ventilation will help remove hot air from the high tunnel. It will also remove excess moisture, reducing leaf wetness and foliar diseases. Creating favorable environmental conditions will result in healthier plants. Avoid cold pockets (i.e., the bottom of a hill) and areas of turbulence from adjacent hills or tree lines.

Good high tunnels are sturdier than they look. But a constant pounding and shaking from the wind can be hard on a structure (not to mention a farmer's nerves). Orienting the gable end to face the prevailing wind helps limit the structure's exposure. A windbreak is a good idea, especially for winter growing, as long as it doesn't affect sun exposure.

Water Movement and Drainage

High tunnels are most successful when they are built on well-drained sites. Removing excess water from around the high tunnel is absolutely necessary. Run-off from a high tunnel roof and from rain and melting snow can be significant. An inch of rain falling on a 30' x 96' house, for example, works out to be 0.6 gallons per square foot, or 1,728 gallons over the entire structure. This water and ground water should be diverted by a swale around the high tunnel. If there is uphill runoff, it is wise to divert this water before it reaches the high tunnel. Ideally, the tunnel should be at least a foot above grade of the land around it. A high tunnel water plan should be designed for the worst-case scenario of frozen ground with lots of rain.

In addition to surface water, subterranean water and seasonal springs must be avoided or dealt with. Ground water will wreck havoc on your crops, potentially causing devastating problems such as disease, secondary insect infestations, denitrification of the soil, and heat loss, among other problems.

Level and Square

High tunnels need not be on a level site. A little slope is okay, and a very gradual slope from one end to the other can actually be advantageous. This allows better flow when using low-pressure drip tape (with the headers and manifolds at the top), and offers the ability (if needed) to blend the high tunnel into the existing terrain without as much excavation. This slope also facilitates the addition of gutters if you want to collect or facilitate the removal of rainwater.

Too great a slope, however, can compromise the structural integrity of the high tunnel. Heavy snow loads that bear asymmetrically on a structure may cause its collapse. And your structure should be square. Kit greenhouses with pre-drilled holes for purlins, for example, will not align properly if the structure is out of square.

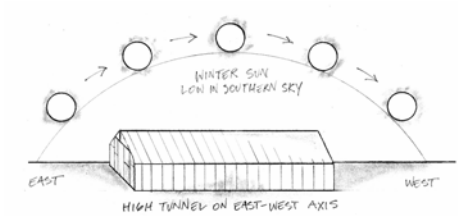
Exposure and Orientation

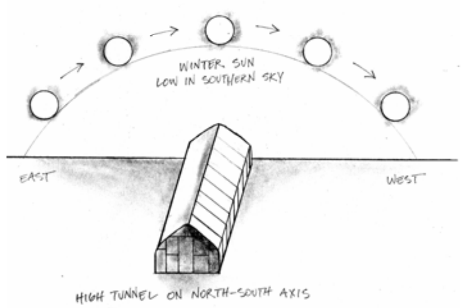
The site should be free from shade, as the first principle of high tunnel growing is ensuring full sun. Unless you are already attuned to the sun's movements, you'll be surprised to learn of the changes in its path across the sky over the course of a year. Hills, trees (even deciduous trees), and buildings can greatly restrict sunlight in the winter when sun is low on the horizon. Use a good sun chart such as the one in "The Passive Solar Energy Book" by Edward Mazria or at www.mysundial.ca/tsp/sun_charts.html.

Traditionally, greenhouses are oriented along a North-South axis to avoid shading. If you are certain that you will only be growing during the warmer months, this orientation will be acceptable. However, if you wish to maximize sunlight energy during the low light period of winter, it makes sense to orient high tunnels along an East-West axis. The Zemelskys, who grow year round in five high tunnels in Connecticut, found that their newest structure—the only one oriented East-West—outperformed their four others which are on a North-South axis.

When the sun arcs low across the southern sky during the winter months, solar radiation strikes the plastic of a North-South house at an oblique angle. When sunlight strikes at an oblique angle, some of the radiation is reflected outward and is lost. Solar gains in a high tunnel are greatest when solar radiation strikes the cover at a 90 degree angle.

During the winter and early spring, an East-West orientation improves this angle of incidence, more effectively capturing solar radiation. And a gothic-shaped structure captures this incoming radiation better than a Quonset structure except when the sun is high overhead, as it is during summer.





True South is different from magnetic South. In southeast Pennsylvania, for instance, it is 7 degrees West of magnetic South. It is better to orient a little East (i.e., 10 degrees) to facilitate more solar energy earlier in the day and warm up the high tunnel quicker.

Capacity of Soil to Support the Structure

Most greenhouses and high tunnels use ground posts that are installed into the ground two to four feet deep. Ledge, boulders, coarse stone, or other obstructions can hamper installation. If rock cannot be removed, holes must be bored with a rock drill as Ed Weaver did in constructing his multi-bay high tunnels.

A firm base is needed, especially at the bottom of the ground pins and concrete. Extensive excavating and/or previous fill must be completely settled or the ground pins will need to be placed to an undisturbed depth to avoid settling of the high tunnels.

Agricultural Capacity of the Soil

As a base, any coarsely textured, well-drained soil should be appropriate for high tunnel production. Clay soils are the least desirable base for high tunnels because they don't drain well, thus remaining colder, and because they are more prone to the build-up of salts *(see salinity discussion on page 56)*. However, growers have been able to make do with a wide variety of soils, amending and improving them as they are able, in order to successfully grow in these special environments *(See "Soil Management" on page 54)*. It is more economical to enrich soil in existing high tunnels to boost yields and enhance plant resilience than to add more high tunnels.

Selecting Your Structure

Setting out to build a high tunnel is no different from any other capital project. The steps prior to construction—planning, financing and funding, and ordering—are often the most difficult. The actual building project is relatively simple and can be exciting. The completion of any project has rewards of satisfaction and future profit.

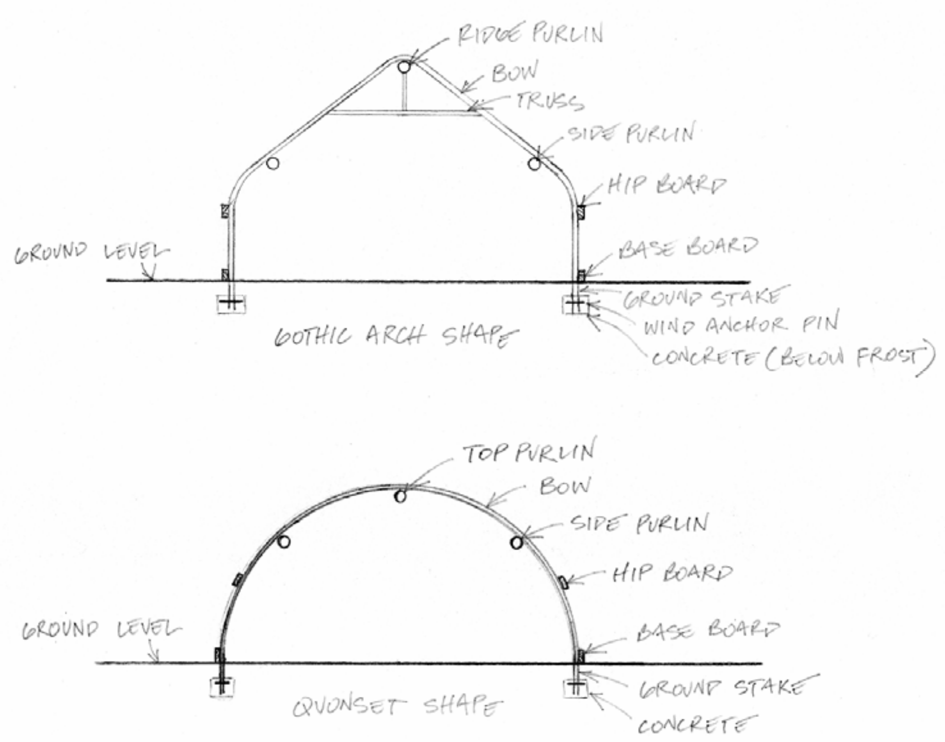
In shopping for a high tunnel, and here we focus on single-bay structures, a grower will need to select from an array of designs, sizes, and special features. Different materials and construction methods can also be used. Experienced farmers have weighed the advantages and disadvantages of these options for their climate, markets, production aims, and bottom line.

Quonset or Gothic-shaped Structures?

The shape of a tunnel affects its performance. It will have an effect on lighting (and shading), energy gain, growing space, and ventilation.

Single-bay high tunnels come in two primary shapes: Quonset and Gothic arch *(see diagram below).* The Quonset shape is relatively short and squat with a rounded roof and sloped sides, while the Gothic, like a cathedral, has a high pointed peak and straight sidewalls. Unheated Quonset structures can also serve as cold frames for overwintering nursery stock. Multi-bay high tunnels, including the Haygrove structure described in this manual, are usually a series of interconnected Quonset-shaped tunnels. Gothic type tunnels have several advantages compared to Quonset models. In many circumstances, these advantages easily offset their greater cost.

A Gothic-shaped structure readily sheds snow because of the steep pitch of its roof. Quonsets, especially those with PVC bows, need to be swept free of snow to prevent collapse. When snow threatens, some growers set up 2" x 4"s as temporary props under the ridge pole, purlins, or bows of their Quonset-shaped high tunnels. PVC tunnel owners are wise to remove their plastic for the duration of the snowy season.



Match your structure's design load to local conditions of snow and wind. Some greenhouse suppliers can select design specifications appropriate to your county. In the first winter, one northern farmer's high tunnel—purchased from a southern supplier—was destroyed in a snowstorm, along with the perennial plant material inside.

The taller sidewalls of Gothic tunnels offer more usable space along the sides for crop production and growth and for working comfort. For trellised crops like tomatoes, Gothic-style tunnels provide adequate height both for the interior and perimeter rows. The headroom over the edge beds in a Quonset tunnel may be so low that even a short person is uncomfortable when using a walk-behind seeder, for instance.

The Gothic shape also contributes to better air exchange and moisture control, and thus a superior growing environment. The greater height of Gothic tunnels allows for better ventilation through higher gable-end vents. Gothic arch roofs tend to have enough of an angle to help shed water that condenses on the interior, instead of dripping on the plants below.

In Quonset tunnels, since the whole structure is curved, opened roll-up sides expose some of the crops growing along the side to precipitation and other adverse weather conditions. This defect can be partially alleviated by purchasing extended ground posts.

Footprint

High tunnels come in many sizes, in widths from 14' to over 40' and in incremental lengths. A width to length ratio of 1:2 is ideal for passive solar gain *(See Mazria's "The Passive Solar Energy Book").* However, you get more for your money with a 30' x 96' high tunnel than a 30' x 60' structure.

Narrower tunnels will experience more heat loss than wider tunnels because of their perimeter to growing area ratio. A 10' x 90' tunnel has a 200' lineal perimeter and a 900 square foot growing area, whereas a 30' x 70' tunnel also has a 200' lineal perimeter and 2,100 square foot growing area. The second structure has 133% more growing area, and less than half the ratio of perimeter (or heat loss potential) to growing area. Wider tunnels also tend to be taller and provide improved ventilation and interior air circulation.

Under northern growing conditions, even 30' wide high tunnels can be sufficiently ventilated with roll-up sides and large gable-end vents and doors. In warmer climates, in tunnels with tall, dense crops like tomatoes, narrower tunnels (20' to 26') may more effectively reduce stale air in the middle of the structure without mechanical ventilation.

Size

How big should your high tunnel be? Consider not just how much growing space you expect to use now, but also what you'll want a few years into the future. A well-built tunnel will last at least 20 years.

Another important factor in determining the size of high tunnel to purchase is the amount of additional workload you are prepared to take on. Steve Moore estimates that a 30' x 96' high tunnel that is intensively planted with multiple crops can take 10 hours or more of labor each week after initial set up and skill development. Marketing time is additional. When a farm uses a simple cropping pattern, like Slack Hollow Farm's winter spinach system, regular management time can be greatly reduced.

To get the most from your investment, it might make more sense to start with a short, wide house (i.e., 30' x 48') and add on later than to buy a 16' x 96' high tunnel that may quickly outgrow its usefulness.

Also when determining the size of tunnel to build, take into account how the structure will fit on your property. What are the site possibilities? How much land is available and what is its topography? It is critical to have enough room around the tunnel for easy access with vehicles and equipment, snow removal, water drainage, and ventilation; to avoid shading; and to allow for future expansion *(See "Site Considerations" on page 26).*

Selecting Materials

The Frame

Historically, wood was commonly used to frame greenhouses, but it is has gone out of fashion because of its relatively high maintenance cost and the availability of steel greenhouses. Pete Johnson, a year round grower in North-central Vermont, is an exception. He is currently growing tomatoes and salad crops in a very large high tunnel which he framed with Eastern white cedar and other local trees. For most growers, steel is the best material for a high tunnel frame. The best greenhouse structures are made of high tensile strength steel covered with a very good galvanized coating to prevent rust.

An alternative to steel for the structural members of a high tunnel is polyvinyl chloride (PVC) pipe. Price is PVC's only real advantage compared to steel. Mainly it is used in farmer-built tunnels. Tunnels whose bows are made of PVC pipe are more prone to collapse under snow load and wind. Only narrow high tunnels with a Quonset-shape and smaller walk-in or caterpillar tunnels can be constructed of this weaker material. It should be noted that PVC is a persistent poison that harms human and animal health and pollutes the environment during manufacture and disposal *(See "The Trouble with PVC" on page 31).*

Bow spacing will depend upon the overall design of the tunnel, the anticipated snow load, and the strength and capacity of its component steel. Although a 4' bow spacing is used fairly commonly, with trusses placed on every other bow, growers are increasingly turning to 5' bows that utilize trusses on every bow.

(See "Bending your Own Frames" on page 43.)

Baseboards and Gable-ends

Most high tunnels use wood for baseboards, hip boards and gable-end framing. For the gable-end, another option is steel. While more costly, it will not need to be replaced and is easy to work with. For the baseboard, recycled plastic lumber, that is rot and insect resistant, is another comparatively expensive alternative.

In selecting the type of lumber to be used for the baseboard and hip board, consider their rates of decay. Finding lumber that is affordable, durable, and sustainably harvested is a challenge and trade-offs are inevitable. For example, redwood is very expensive and unsustainable.

Other more accessible choices, (depending on location) include rot-resistant wood species such as the cedars, cypress, black locust, and Osage Orange. White oak can also be used, though it will need to be replaced after about eight years, the second time you replace the tunnel's polyethylene film. Cheaper but less attractive options are hemlock, pine, and spruce, listed from most to least rot-resistant.

The Trouble with PVC: A Cheap but Unsustainable Material

Polyvinyl chloride (a.k.a. vinyl or PVC) is a chlorinated hydrocarbon, like DDT and dioxin. During PVC production and disposal, very large quantities of hazardous organochlorine chemicals are produced unintentionally and released into the environment. As a result of its intrinsic hazards, PVC is under intense scrutiny in many countries, by governments as well as environmental and health advocates.

PVC is virtually impossible to recycle because each PVC product contains a unique mix of additives. Even in Europe, where PVC recycling is more advanced than in the U.S., less than 3% of post-consumer PVC is recycled. And even most of this tiny fraction of PVC is merely "down-cycled" into other products, so the amount of virgin PVC produced is not reduced.

The production of chlorine for PVC uses as much energy as 80 medium-sized nuclear power plants would generate. Chlorine production is an extremely energy-intensive process that consumes about 1% of the world's total electrical output.

Among the toxic chemicals produced during the PVC lifecycle are chlorinated dioxins, chlorinated furans, PCBs, hexachlorobenzene, and octachlorostyrene. Workers and communities are exposed to high levels of the toxic substances released into water, air, and soil due to PVC production. These toxic substances are also released when PVC is incinerated.

As a group, toxic by-products of PVC production are highly persistent. These chemicals do not degrade in nature, so they build up in the environment. Transported by wind currents and water, their presence has been documented even in the most remote regions of the globe.

Since these chemicals are fat-soluble, they build up in the tissues of living organisms. In species high on the food chain (like humans), the levels of these chemicals can be millions of times greater than in the environment. In mammals, these chemicals easily cross the placenta and concentrate in breast milk.

Some of the toxic chemicals produced when PVC is made are dangerous even at extremely low doses. For instance, at doses in the low parts per trillion, dioxin causes damage to fetal development, and the immune and endocrine systems, and impairs reproduction. Cancer and brain and nervous system damage are also associated with exposure to these organochlorines.

In its pure form, PVC is rigid and brittle. To make flexible vinyl products, large quantities of plasticizers called "phthalates" are added. Phthalates cause cancer, infertility, testicular damage, reduced sperm count, suppressed ovulation, and abnormal development of male reproductive tract in lab animals. Like the organochlorine byproducts of PVC production, phthalates are pollutants that bioaccumulate (i.e., persist in the environment) and are found in the tissues and fluids of the human population. As they are not chemically bonded to PVC, but merely mixed in when the vinyl is formulated, they eventually leach out into air, water, and other substances with which the vinyl comes in contact.

Pure PVC is not stable, so lead, cadmium, and organotins are added to stabilize vinyl used in construction and for other extended-life applications. These stabilizers, which are toxic and persistent in the environment, are released when vinyl is formulated, used, and disposed.

(Source: Thorton, PhD, Joe. Environmental Impacts of Polyvinyl Chloride Building Materials. A Healthy Building Network Report.)

Due of the dangers of exposure to human and animal health, CCA (chromated copper arsenate) pressure-treated wood has not been produced for most residential and general consumer uses since 2004. Two Canadian government agencies, Environment Canada and Health and Welfare Canada, consider arsenic to be a "non-threshold toxicant" (i.e., a substance for which there is believed to be some chance of adverse health effects at any level of exposure). Arsenic leaches out into soil and is taken up by plants. Organic farmers are prohibited from using arsenic-containing pressure-treated lumber.

Borates are one of the arsenic-free wood treatment alternatives already on the market. Treating oak with approved borate products may lengthen its lifespan to 12 years. Steve Moore has treated oak with sodium tetraborate and sodium octaborate, both of which may meet organic standards if from mined sources. He uses these food grade borate products as they can be readily and inexpensively obtained from local chemical suppliers. Borate wood preservatives such as Boracare can be purchased from pesticide distributors. They penetrate into the wood much more effectively than the food grade materials dissolved in water.

End walls can be made of plywood (painted is best), twin wall polycarbonate sheets ($1.50/ft^2), other structured sheets, or just polyethylene film ($0.10/ft^2). Of course, opaque materials like plywood prevent light transmission.

Twinwall polycarbonate is an extruded ribbed high-tech plastic with double walls for added insulation. It is sold as structural sheeting. For high tunnels, it has an application for the gable-end walls. As a hoop house covering, it compares favorably with both polyethylene and glass. It transmits up to 83% of light (more than two layers of polyethylene film), and insulates 40% better than glass, but weighs one-sixteenth as much and won't shatter. It is very durable and cuts easily with a saw. It is far more expensive than poly but costs less than glass.

Plastic Film

By far the most common covers for high tunnels of all types are made of polyethylene. UV resistant greenhouse-quality polyethylene is far superior to common construction-grade polyethylene. It transmits light better; is more resistant to wind, heat, and yellowing; and has a longer life.

It is important to replace poly film as recommended. For instance, after four years, standard 6-mil plastic loses about 15% of its ability to transmit light. This is particularly significant during winter production, especially in cloudy climates.

Greenhouse film treated with anti-condensate additives prevents condensation drips. Infrared re-radiant (IR) materials are added to film to reduce overnight heat loss. In the U.S., metal halides are typically used to treat the film, while in Europe phosphorous and boron compounds fill this function.

Chris Wien, at Cornell University, points out that "films that lack an additive which blocks infrared radiation can allow so much heat to escape on cold clear nights that temperatures in high tunnels are lower than they are outside the tunnel. You can have instances in which the plants inside freeze before plants just outside the greenhouse. It is very important that polyethylene films used on high tunnels have an infrared blocker added to prevent such a problem."

Anecdotal evidence suggests that the frost forming on the inside of the plastic on a high tunnel is an excellent reflector of infrared radiation. Steve Moore thinks that it may be equal in value to special infrared AC plastic in unheated structures. In heated structures (where the interior frost is not present), infrared AC plastics undoubtedly retain heat better.

New designer greenhouse films are now entering the market. When the Cramers replaced the film on their Haygrove multi-bay tunnel, they chose *Luminance THB* (thermal heat barrier) poly which costs 10% more than ordinary greenhouse film *(See www.bpiagri.com/hort-luminance.htm)*. Using infrared blockers, this enhanced poly reduces excess daytime heat and scorching while also helping to minimize heat loss at night. It also increases light diffusion, making more light available to plants to increase photosynthesis and yields. In particular, it is recommended for ornamentals and nursery stock and has been shown to improve tomato yields. However, the manufacturer cautions that it is not the best choice for early spring growth.

Steve Moore experimented with several types of plastic film over a multi-year period on two adjacent high tunnels. He compared double layers (inflated) of the standard 6-mil 4-year film with infrared re-reflectants and anticondensate to single layer *Coeava*, a 7.8 mil film with reportedly an 8-year useful life.

In south central Pennsylvania, a high tunnel with two layers of 6-mil, 4-year standard poly was warmer by an average of over 6°F during the winter, and had superior plant growth compared to high tunnels with a single layer of 7.8 mil high performance plastic. Steve suspects that this difference in thermal performance between the two types of film would be less significant in a warmer climate or under late fall or early spring conditions.

In carrying out this experiment, Steve had thought that the lower insulating ability of a single layer of poly could be offset by using more layers of row cover inside the structure. He also hoped to gain the benefit of enhanced light transmission and save money by not using another layer of high tunnel covering. But neither of these theories proved correct. In the dead of winter, the double walled tunnel stayed warmer and outperformed the single layered tunnel.

Double Versus Single Layers

A double layer of poly film with inflation between the layers provides insulation and reduces heat loss by 40% according to Aldrich and Bartok (see NRAES publication, "Greenhouse Engineering,"). Along with increasing heat retention, the second poly layer reduces the light level by about 10% so a balance must be reached. Low light levels cause plants to become weak and leggy, and slow down growth. As an alternative to double poly layers with an inflation fan, some farmers use multiple layers of floating row covers, which more drastically decrease light transmission. Unless these covers are removed during the day, crop production may suffer.

Many farmers have found it sufficient to use a single layer of polyethylene on their high tunnels. However, in the winter, these high tunnels will have greater heat loss and will be colder than tunnels with a double layer of poly. And where a heating system is used, significantly more fuel will be needed if just a single layer of poly film is employed. Using a double layer requires electricity to run a small blower fan. An alternative to being connected to the electrical grid is a modest solar power system. *(See "Photovoltaic Inflation Systems" on page 48 and "Getting the Right Pressure on Your Inflation" on page 46.)*

Disposal and Recycling of Agricultural Plastic Films

Plastic film must be disposed of when its useful life is over, presenting the farmer with a disposal problem. Polyethylene covers on high tunnels and greenhouses make a significant contribution to the growing problem of waste plastics. Polyethylene film has rapidly replaced more durable materials in many farm applications. Plastic bags and covers are used to store hay and ferment animal feeds such as silage and haylage, and palletized goods are shrink-wrapped. Most of these plastic films are produced from low-density polyethylene (LDPE #4) resins.

The most environmentally sound disposal option for these plastics is recycling, which is discussed below. Most agricultural plastics are not recycled, however, in part because recycling opportunities are few and far between. Surveys in New York and Pennsylvania suggest that about half of agricultural plastics are burned and the remainder are buried or dumped on-farm. These states, like many others, do not restrict the on-farm disposal of plastics. Therefore, farmers have no economic or legal incentive to transport these materials to a regional transfer station or other central collection facility for recycling or controlled disposal (at a landfill or incinerator).

Burning agricultural plastics in open fires or burn barrels is a burdensome and unpleasant job. It is also highly polluting and carries short- and long-term health risks. A chemical fact sheet cautions firefighters to wear a self-contained breathing apparatus where there is a risk of exposure to burning polyethylene and states that fumes from molten or burning polyethylene can cause respiratory irritation, headache, and nausea.

Low temperature combustion of plastic film that occurs in on-farm burning produces soot and other noxious emissions and also leaves toxic residues. These emissions are far in excess of those released by municipal waste incinerators that burn at very high temperatures and are equipped with mandatory pollution control devices. An early 1990s study for the US EPA reported that 20 times as much dioxin, 40 times as much particulate matter, and many times more metal emissions resulted from open burning of household waste in barrels compared to municipal waste incinerators.

Since that study, the gap in emissions from open burning versus incineration has grown exponentially due to stricter pollution control standards for incinerators imposed since 1995. Between 1990 and 2000 emissions of toxic compounds called dioxins and furans declined by about 99% and heavy metals by more than 90% in 66 large municipal waste incinerators.

On-farm burial removes refuse from sight, but decomposition is extremely slow and the potential exists for movement of water-soluble breakdown products into groundwater. Leaving discarded plastic lying around is unsightly and gives a negative impression about agriculture. Pools of water that form in the plastic film serve as mosquito breeding grounds.

Municipal disposal in landfills or incineration is a better alternative for disposing of waste plastics than on-farm burning, burial, or non-disposal. Farmers often reject this option because of the expense, time, and logistics involved.

Another disposal method—pelletizing waste agricultural plastic into fuel nuggets—has been under investigation by at Pennsylvania State University researchers since 1995. The “densified” fuel pellets would generate energy when burned with coal in boilers. These pellets would also eliminate the problem of densely compacted plastic bales causing “hot spots” that damage incinerator equipment. When highly contaminated plastics are used to make the pellets, more toxic emissions result, sometimes exceeding regulatory limits. One hypothesis is that dirt and debris limit air movement to the combustible materials—a problem that increases when plastic mulches are wet.

Originally researchers envisioned “co-firing” small burners with these waste plastic pellets and coal for heating greenhouses and for other farm applications. But pollution concerns may require that the pellets be burned as a tiny portion of the total mix in a large industry or municipal incinerator. The toxicity of ash from burning plastic fuel pellets on the farm is another area of concern.

Recycling is a superior way to dispose of agricultural plastics. Recycling programs are underway in the Northeast US and Canada for handling most types of plastic resins used in agriculture, though their geographic coverage is spotty. In the absence of such a program, some farmers are stockpiling their waste plastic film until they have access to a recycling program. A trip to purchase equipment or supplies may serve as an occasion to bring waste plastic to a distant recycling program.

In the Northeast, two successful agricultural plastic recycling programs stand out as models for government initiatives and individual entrepreneurs. A polyethylene nursery film collection program was started in New Jersey around 1997. This state-run collection program collects “clean” bundles of nursery and greenhouse films. Its Mt. Holly site accepts film from out-of-state growers. In its first five years, with 100 to 125 growers participating, almost 1.8 million pounds of nursery film was recycled. The $20 to $25 per ton fee is substantially less that the $60 per ton landfill tipping fee.

With an initial aim of reducing farmers' tipping fees, Lancaster County farmer Daniel Zook started a viable agricultural polyethylene collection business that is now actually paying $80 to $100 a ton for waste polyethylene. In 2005 (its fifth year), Zook Plastic Recovery sold 500,000 pounds of plastics. Zook set up the program with Trex, a company that reprocesses the material into plastic lumber for decking. Besides guaranteeing a market, this firm guided Zook through start-up and helped him purchase a cardboard baler. Zook holds month-long waste plastic collection drives each spring and fall and for a couple weeks in the summer. He also accepts plastic at other times. After he bales this plastic, he has it hauled to a Trex factory in Virginia.

A 2003 Cornell report lists several other agricultural plastic recycling efforts. A plastic lumber re-processing facility based in Prince Edward Island, Canada, is capable of handling "dirty" LDPE plastics used in dairying. A nationwide, industry-sponsored network collects high-density polyethylene pesticide containers. In the US and Canada, an industry-sponsored program based in Ontario, Canada, picks up, pays for, and re-processes polystyrene nursery flats and trays.

The recycling of agricultural plastics lags behind other types of recycling due to several barriers. Municipal waste transfer stations cannot easily accommodate loose plastic film, which is bulky and difficult to handle. Any collection site must be equipped to bale the material separately.

The quality of agricultural plastic film is often compromised by contamination of dirt, moisture, or debris. Contamination reduces the marketability and/or the price paid. For example, the Trex Company pays less than one-fifth its standard rate for plastics that require pre-cleaning. This company has installed a $10 million wash line to clean dirty plastics and also has a pick line to remove debris.

The black and white agricultural films used for mulch bags and wrapping are not much in demand by plastic recyclers as the pigments must be greatly diluted to manufacture marketable plastic lumber. This is relevant to high tunnel growers because, in many regions, the bulk of agricultural film is used by dairy farms and feed producers, and greenhouse film alone might not be abundant enough to support a collection program.

Agricultural plastics are also more costly and inefficient to collect than urban plastics, because they are dispersed across the countryside and farmers dispose of these plastics sporadically and seasonally. Since concentrated quantities of agricultural plastics are more attractive to recycling markets, recycling programs may need to be organized into regional or statewide programs.

Farmers are more likely to participate in recycling where there is a nearby collection system, where burning and dumping are prohibited, and where tipping fees for solid waste disposal are significantly higher than for recyclables. Regional and statewide recycling programs may be most appropriate given the capital costs for recycling equipment, the sporadic and seasonal nature of plastic removal, the dispersed feedstock for recycling, and the critical mass of materials needed to attract industry.

Despite these challenges, opportunities for new private and public recycling efforts abound. While greater farm use of polyethylene is increasing the magnitude of the disposal challenge, high oil prices are also creating greater demand for waste plastics. Farmers who use agricultural plastics should consider taking an active role in making recycling an easier choice for other farmers in their region.

This section was adapted in part from Levitan, Lois, and Barros, Ana. "Recycling Agricultural Plastics in New York State." March 11, 2003. 2nd ed. Environmental Risk Analysis Program. Cornell University. http://environmentalrisk.cornell.edu/C&ER/PlasticsDisposal/AgPlasticsRecycling/. Personal communications with plastic recyclers and reports from Penn State provided additional background.

Multi-Bay Tunnels

Multi-bay high tunnels are a special category of tunnel. The most prominent manufacturer of this type of tunnel is the British company, Haygrove Ltd. As fruit farmers in Herefordshire, England, Haygrove found single bay tunnels inadequate for field-scale crop protection. With multi-bay tunnels in Spain as an inspiration, it developed its own model.

In Spain, where the climate is mild, multi-bay tunnel frames can be rather weak. Haygrove tunnels improved on the original Spanish tunnel concept by making them appropriate for use in the U.K. Since they were first introduced in 1996, their use has spread to 30 countries, from Norway to Australia, and by 2006, they were protecting over 7,000 acres of crops.

Like other high tunnels, Haygroves enable the farmer to extend both ends of the growing season. They also prevent rain, wind, and hail damage, reduce pesticide use, and avoid the loss of harvest days due to precipitation.

In terms of environmental management, Haygroves vent more fully than typical single-bay high tunnels. Haygrove's lacing system holds the polyethylene cover securely in place while allowing a grower to vent the tunnels up to 8' or 10' high. This design feature virtually eliminates the problem of excess tunnel heat and humidity.

Haygroves are three-season structures. They are not designed to support a heavy snow load. In temperate regions, the polyethylene film should be removed for the period of time during which snowfall is possible. The film is "hibernated" by pulling it off the hoops, down onto the Y of the legs, and covering it with black plastic that is secured with twine. This eliminates any chance of snow damage to the tunnel and protects the film from UV exposure when not in use. At the beginning of the next growing season, the film is remounted on the hoops and secured with the rope lacing.

Haygroves can withstand relatively high winds. Each Haygrove leg and anchor has an auger welded to it, and these are drilled 30" into the soil; cement is not used. This keeps Haygrove tunnels from lifting out of the soil, something that can happen with single bay tunnels that are not cemented into the ground. During high winds, Haygroves should be left fully vented. This decreases pressure on the tunnel by allowing some of the wind to move through the tunnel while still shielding the crops from its full force.

Most growers in temperate climates vent (open) and close their tunnels every day for the first six weeks or so of the season and then leave them completely vented for the majority of the growing season. No special attention to venting is required during the period when severe thunderstorms are most likely. Daily venting and closing is again practiced during the fall.

Haygrove tunnels concentrate the run-off in the leg rows between the bays, and this water must be controlled. Prior to construction, most growers form shallow swales that are covered with weed barrier cloth. The legs are then drilled into the soil through small slits in the cloth.

Haygroves are sold in various bay widths and heights to accommodate a range of needs. The structures are tall enough for tractor access and dwarf tree-fruit production. The Haygrove design allows adjacent bays to be managed for different microclimates, with curtains dividing bays with cool and warm crops. The configuration of these tunnels provides for easy expansion of growing area to the sides or ends.

These tunnels retail for about half the cost of traditional, single-bay high tunnels. The minimum Haygrove purchase is a half-acre; however, a full trailer load contains two acres and the delivery cost is the same whether the trailer is full or not.

Construction time is faster for these multi-bay structures than for traditional high tunnels. Typically, growers report 250 to 300 man-hours to construct an acre-sized Haygrove compared to 75 or 100 hours for a 30' x 96' tunnel (1/12th acre). Construction involves relatively few tools and no lumber. Along with delivery, Haygrove provides on site hoop bending and construction training for customers. Since these tunnels follow the natural contours of the land, there is no need for heavy equipment to prepare a level site.

Inferior Multi-Bay High Tunnels

One farmer decided to buy a less expensive multi-bay structure to save money, and regrets his purchase. Rob Hastings, the owner-operator of Rivermede Farm in Keene Valley, New York (in the Adirondacks), may be one of the most Northern-most farmers in the Eastern U.S. to grow crops in a multi-bay high tunnel. He grows fall raspberries, everbearing strawberries, and cut flowers (for October weddings) in the structure and also has five heated and unheated single bay high tunnels.

After going on the Haygrove grower tour in England, he was sold on this type of high tunnel. Based solely on economic considerations, he opted to buy a cheaper model from another company (which we will refer to as "Brand X"), instead of a Haygrove, which it superficially resembled. He purchased a four-bay structure that covers a quarter acre for under $7,000; each bay measured 26' x 100'. A Haygrove covering a third acre would cost $12,000, in part because the shipping is the same whether one buys an acre or a fraction of an acre.

"There are many subtle differences that you can't see in the catalogue," says Rob, explaining his disappointment at the weaknesses of the structure he selected. He has had to modify and reinforce the high tunnel in order for it to function. Contrasting the two companies, he characterizes Haygrove as "farmers turned metal benders" and Brand X as "metal benders who happen to make products for farmers."

While on the tour in England, he watched how quickly the Haygrove went up. The Brand X structure took much longer to assemble and construction was far from smooth. "There is no comparison," Rob observes. A major difference is that Haygroves can be constructed out of extra-long pieces because they are shipped from the United Kingdom in a container and then delivered as a unit to the customer. Haygrove personnel come and bend the hoops on the farm.

Brand X's multi-bay high tunnel consists of multiple pieces that need to be bolted or screwed together. For instance, there are five pieces in each Brand X hoop while a Haygrove hoop comes as a single piece. “I had to find a flat surface on the farm to assemble the hoops so they would not be twisted.” Each of these joints presents a weak spot, and Rob has experienced a plethora of failures around these joints. “I had to double screw every hoop where it joins the Y post,” he says. “It either tore out the tek screw or bent them.”

Rob has identified various annoying design flaws in the Brand X. In a Haygrove the hoops rest on the Y post and no water can get in and freeze. The Brand X structure allows water to enter and freeze. Haygroves have a peg at the top of each Y post for tying the rope to that keeps the plastic film on. The Brand X lacks the peg and there is nothing to tie to.

The Haygrove has an effective way to finish off the end walls ands simultaneously provide wind bracing. The Brand X structure comes with a reinforced plastic end wall which has not been satisfactory. “The flopping plastic acts like a gigantic sail tied down with an anchor,” observes Rob. He plans to do some cross bracing to shore up the plastic.

The lack of technical support is another major frustration. “Brand X barely knew I had bought one,” he says. “When I called, I was talking to someone who was clueless and who was not a farmer.” Rob recommends other farmers learn from his mistakes and “invest in the best.” “I’m sorry I didn’t ask questions,” he concludes.

Single-Bay Tunnels in the Haygrove Style

Haygrove’s newest product is the “Solo” single bay tunnel. It comes in sizes appropriate for the smaller grower. Typical dimensions are 24' x 200' and 28' x 200", though various widths and lengths are available. This Quonset-shaped structure is built of 14 gauge galvanized steel hoops. Its poly cover is secured to the framework with the same rope lacing system used on Haygrove’s multi-bay tunnels and therefore provides excellent venting. With a minimum 10' height at the peak, it has a large air volume for its size. Being a single-bay tunnel, the Solo seals well for maximum season extension. Like other Haygroves, it is sold as a three-season structure and is not engineered for snowload.

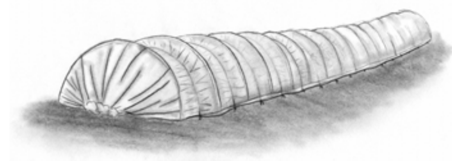
Solos can be erected on hills or uneven sites and compared to other single-bay tunnels, much less construction time is required. As with Haygrove’s multi-bay high tunnels, no carpentry or extra materials are required. While Solos are single-bay tunnels, they can be built on double prong anchors (8" between bays) to cover large areas.

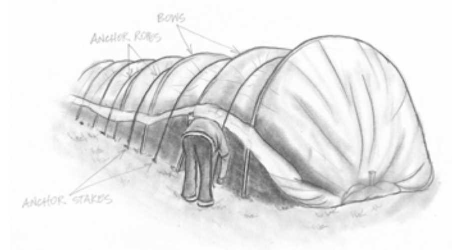
A Solo package, including the poly film cover and 12 mil roll-up doors for both ends, costs about $1 per square foot, or about half the cost of a more conventional high tunnel.

Walk-in Tunnels (Caterpillars)

Walk-in tunnels are inexpensive alternatives to the greenhouse-like structures that come to mind when thinking about high tunnels. For an equivalent area under cover, they cost less than a quarter of the price of a more traditional high tunnel. With respect to environmental modification, they are intermediate between traditional high tunnels and the low tunnels commonly used by vegetable growers. *(See “Low Tunnels” on page 38.)*

Due to their segmented appearance, some growers call these structures “caterpillar tunnels” *(see diagram)*. They have been used to grow vegetables, cut flowers, greens, and herbs.





The size of walk-in tunnels is variable. They range from 8' to 18' in width and cover two to four beds. Their length may be from 24' to 300' or more, depending on the length of beds they are intended to cover and limits to the sizes of available covers. The flexible tunnel length enables a grower to construct a walk-in tunnel virtually anywhere on the farm because it can be sized to fit into a farm’s existing bed system. The tunnels are tall enough to walk in and are accessed by ducking under the sides anywhere along their length (hence their name).

Bows for walk-in tunnels may be made from PVC, electrical conduit, or galvanized steel hoops. To erect the tunnel, the bows are either slipped over ground stakes made of rebar or tubular steel, or the bows are set directly into the ground about a foot deep. Bows are spaced six to ten feet apart, depending on the site’s wind exposure. It is best not to construct the tunnel broadside to the wind, but if that is unavoidable, the tunnel will serve as an effective windbreak for crops planted on its lea side.

A 1/4" rope tied from hoop to hoop is used to form a ridge purlin. The purlin is attached to heavy-duty ground stakes at both gable ends. The structure is quite “loose” when uncovered; much of the tunnel’s structural integrity comes from the cover and the way it is secured to the ground.

Walk-in tunnels may be covered with greenhouse plastics, heavy spun-bonded fabrics such as Typar, or shade cloth. The cover should be matched to the intended use of the structure. The less expensive Typar might be the better choice, for example, if the goal is to give a boost (or provide insect protection) to cool-season crops such as spring greens. Greenhouse plastic would be the better choice for an early planting of tomatoes. And shade cloth might be selected for rooting strawberry tip cuttings.

The covering is held fast by 1/4" ropes that are drawn over the top of the structure (Canastoga wagon-style) and are secured to stakes or earth anchors in the ground. These ropes give the structure its segmented, caterpillar-like appearance. The edges of the plastic are left loose, but the covering should be sized so that there are at least two feet of extra material on each side. In particularly windy locations, the covering may be secured by placing rocks or small sand bags on the edges of the plastic. At the gables ends, the plastic is bunched together using rope, and the rope is tied to a secure stake. The tunnel's dimensions should be configured to fit commonly available greenhouse films or floating row covers.

While they have many advantages, starting with their cost, walk-in tunnels are really three-season structures. The wide bow spacing that keeps them cost-effective greatly reduces their snow load capacity, so the covering should be removed before winter. However, walk-in tunnels with a bow-to-bow spacing of 4' and a width of 10' have reliably withstood snow.

Walk-in tunnels must be ventilated manually to avoid excessive temperatures. During the coldest periods of the year, sections of the sides (the cover) are propped up with short "Y" shaped props or branches cut for the purpose. When temperatures warm, the sides may be rolled up along the entire length of the tunnel. Clamps or tall "Y" props can help hold the rolled up plastic in place. The sides must be rolled down when high winds threaten.

These tunnels are highly portable. They may be erected and dismantled relatively quickly. For example, two 200' long units built to cover three beds of lettuces were erected by Ted and Jan Blomgren and a co-worker over the course of a morning.

One way to reduce the annual costs of construction and dismantling is to leave the caterpillar tunnel in place from year to year, and to develop a list of tunnel crops around which a crop rotation plan might be developed.

Walk-ins are highly adaptable structures. They may be built over existing crops, or over bare ground for a later planting. They may be built in the fall, left uncovered during the winter, and then covered in the spring for an early planting. Or they may be used to cover tomatoes during the spring and summer, and then taken down and reconstructed over an existing fall spinach crop.

Caterpillar Tunnels at Windflower Farm

Ted and Jan Blomgren have found many uses for walk-in tunnels to produce vegetables and cut flowers. On Windflower Farm in Easton, New York, they construct some of their caterpillars with metal bows spaced 10' apart, and others using PVC bows spaced 6' to 8' apart. At any given time in the growing season, the Blomgrens may have as many as 9,000 to 12,000 ft^2 of walk-in tunnels on their farm, with the typical tunnel 200' long. Most are covered in 6 mil greenhouse plastic obtained from Farm Tek, "the only source of very long plastic" of which they are aware. Their other walk-ins are skinned in Typar.

Caterpillars have become important on Windflower Farm because they are easy to construct and cover, and are inexpensive, while providing many of the benefits of a multi-bay structure like a Haygrove. Steel hoops and plastic film for one of their 16' x 200' tunnels cost them about $1,500, about one-third the cost of a Haygrove multi-bay high tunnel. In addition, air flow in caterpillars is excellent—better than in a more expensive, conventional high tunnel—as caterpillars open fully like a Haygrove. (But unlike a Haygrove, management of high winds in a caterpillar requires closing the sides.)

To get high quality fruit early from their first planting, Ted and Jan transplant zucchinis and cucumbers into walk-in tunnels on May 1. These tunnels span three beds that are six feet on center. Early harvests of both of these vegetables are important in meeting their goal of delivering a diversity of "real vegetables" (as opposed to salad greens) to their New York City-based CSA membership.

Cucumbers, planted two rows per bed into black plastic (or six rows across a tunnel), start yielding a substantial harvest by the end of June. The zucchinis go into bare ground, with one row running in the middle of each of the three raised beds. Each row of zucchini is sandwiched between rows of quick Asian greens. These greens will be harvested by the middle of June just as the zucchinis are filling out the space. By the end of the first week of July, the zucchini harvest is going strong.

On May 1, tomato transplants are planted into three beds in walk-in tunnels for first harvest in July. Using the hybrid variety 'Mountain Spring' as their mainstay, Windflower Farm gets a high quality fruit that bears well over a long period of time. In 2005, they harvested from their May 1 planting until late October. They have also produced eggplants and bell peppers in walk-in tunnels.

The Blomgrens initially experimented with walk-in tunnels to protect China asters from aster yellows, a disease transmitted by leafhoppers. The alfalfa fields that surround Windflower Farm are leafhopper habitat. Ted says they skinned these tunnels with Typar because “We thought we could get away without rolling up the sides,” something that wouldn’t be possible for plastic-covered tunnels which trap heat more effectively. “Now, tarnished plant bug is our only insect problem,” says Ted.

Besides preventing aster yellows, the tunnel environment produced China asters with stems three feet long. Short-stemmed cut flowers are not desirable and Ted and Jan realized that the extended stem length was a benefit that tunnels could provide other cut flowers. The absence of wind and reduction of light in the walk-in tunnels are two factors associated with longer stems.

Windflower Farm currently grows stock, snapdragons, godetia, larkspur, Bells of Ireland, and lisianthus in walk-in tunnels to achieve much earlier blooms and longer stems. They have come to prefer walk-in tunnels to regular high tunnels. They are also convinced that plastic film is superior as a tunnel cover to Typar except for mid-summer production. In the summer, they use Typar to protect against insects, diffuse the brightness of the sun, and shelter the flowers from wind.

Though they are moving away from Typar, Ted stresses that it has two virtues. It costs about half as much as plastic, and its light weight makes it easy to use. “I can cover a 200-foot tunnel myself,” he said. It takes a minimum of two people to install a plastic cover.

On walk-in tunnels built for fall lettuce and salad mix, they may still use Typar as the cover. Ted and Jan sometimes build tunnels over beds where they have already set transplants. Using a marking rod, they pound in stakes at 10' intervals and then lower hoops over the stakes. For an inside cover, they use a midweight fabric, such as 0.9 ounce Covertan, suspended over low wire hoops. They harvest mature lettuce from these unheated tunnels as late as Thanksgiving. Ted cautions that this design has no capacity to bear snow.

Caterpillar Tunnels at New Minglewood Farm

In 2004, Chris Lincoln grew half his tomato crop at New Minglewood Farm in walk-in tunnels. Better yields and a higher percentage of #1s have convinced him to raise his entire tomato crop in these tunnels. This year, he used four 100' long tunnels to grow 800 row feet of heirloom tomatoes for retail sale at a farmers’ market and to restaurants.

Chris notes higher yields, higher quality, a longer harvest season, and cleaner fruit as benefits of growing fresh market tomatoes in these tunnels. He also counts the low cost of the tunnels and the ease of moving them to different sites on the farm as advantages to walk-in tunnels when compared to more permanent, stationary high tunnels.

Getting earlier tomatoes was not the overriding factor in adopting this growing environment. New Minglewood’s typical tomato schedule (reported for 2005) is as follows: Seed on March 28, transplant on May 16, begin picking on July 23, last harvest on October 18, first killing frost on October 21.

In 2005, they sold 5,885 pounds of tomatoes with an average of 11.8 pounds per plant on their 500 plants. (Production varies considerably among the diverse heirloom varieties grown at this farm.) At \$3/lb. for #1 fruit, and \$2/lb. for seconds, Chris and his wife, Tammara Van Ryn, grossed almost \$16,000 on this crop, produced in one-eighth of an acre of caterpillar tunnels.

Chris used 1-1/2" diameter Schedule 40 PVC pipe, rather than steel, for bows. The bows are spaced every 6' and placed on rebar stakes, with a rope and another pair of stakes in between. His tunnels are 10' wide, which allows just two rows of tomatoes per tunnel.

Ideally, he said, the tunnel would be 2' wider, with a corresponding increase in height to accommodate the indeterminate varieties that he grows. As it is, when the plants fill out, they are a bit crowded and grow into the sides and roof of the tunnel. The actual size is perfect for determinate tomatoes, which he does not grow.

Wind is the biggest threat to the walk-in tunnel design, but built properly, they seem to hold up adequately. Unlike a more conventional high tunnel, where the plastic is attached directly to a steel frame, walk-in tunnel plastic is held down by ropes secured to the earth by means of rebar stakes or earth screws. Like the Blomgren’s structures, Chris uses ropes over top of the plastic and secured to long rebar stakes driven deep into the ground. If these ropes are not secure, wind can cause damage. To prevent wind damage, it is critical that these anchors are long and stout enough to hold the ropes.

Chris believes that walk-in tunnels have been more time-consuming for New Minglewood Farm than regular hoop houses would be. This is mainly due to the labor involved with setting up and covering these tunnels before tomato planting and disassembling them later in the year after the plants have been removed.

Another regular task during the spring and fall is opening and closing the sides, depending on sun, rain, and temperature. To vent, Chris rolls up the plastic and clips it to a rope. Once the weather warms, the sides stay up all summer.

In 2006, Chris mulched with black landscape fabric. He used a weed barrier fabric to accelerate tomato development, suppress weeds, and prevent soil splash on the plants. He chose a 6' wide fabric and covered the 2' wide space between tunnels as well as all the ground inside of the tunnels, enabling him to locate the tomato rows at the intersection of two pieces of the fabric. This arrangement eliminated the need to burn or cut plant holes into the fabric.

Low Tunnels: An Alternative to High Tunnels

In some climates, low tunnels can be an inexpensive alternative to high tunnels for cold weather season extension. Low tunnels are simple, protective structures consisting of wire hoops covered with polyethylene or fabric row covers. Though more labor intensive, with well-planned beds, they can be assembled with just a small investment.

On Tobacco Road Farm in Lebanon, Connecticut (about an hour east of Hartford), organic market growers Bryan and Anita O'Hara have over an acre of low tunnels for extending fall vegetable production and growing a variety of baby and braising greens and other vegetables throughout the colder months. The low tunnels are removed in late spring to allow for easier field production. The O'Haras complement their low tunnels with two small 14' and 16' wide high tunnels used for seedling production.

The couple markets their mixed vegetables and maple syrup cooperatively with Bryan's father. Their stand always sells out at the two Saturday farmers' markets their family attends from early May through Thanksgiving. The nearby Willimantic Food Co-op, which just tripled its store area, is their other major outlet and has a standing order with them.

Several factors, including southern exposure and wind protection, help make low tunnels feasible for impressive season extension at Tobacco Road Farm. The low tunnels at the farm are situated on a sloping, southwest facing field. Conifer windbreaks mitigate the prevailing west wind. A third environmental advantage to this site is a large damned river the size of a small lake located beyond a grove of trees next to the field.

But this is not a snow-free environment. While most snowfall is light, the O'Haras may receive as much as 8" or 10" of snow at a time. And though snow usually melts in a few days, their low tunnels have been covered by snow for a month, without harmful effects on the plants inside. However, when the tunnels are covered in snow, harvest is impossible.

The O'Haras have been using these inexpensive tunnels for about 10 years at an annual cost of about 7.5 cents per square foot ($3,000/acre) to extend their growing and harvest season. At first, their goal was to push fall production later. Driven by strong customer demand for the good-tasting, cold weather-grown greens and their need for farm income, they just kept on expanding their off season production. Bryan said, "We realized that these plants are winter annuals. They have no disease and insect pests when we grow them out of season."

The seeding dates for their winter and spring low tunnel crops are astonishing late. They continue planting through the beginning of December and start up again in February. All these crops—which include lettuces, Asian greens, spinach, kales, Claytonia, scallions, beets, carrots, dandelions, parsley, and arugula—are direct seeded with an Earthway seeder. Normally, harvest continues until Christmas and then resumes in March. The mild winter of 2005-06 allowed them to harvest at intervals in January and February as well.

At Tobacco Road Farm, beds are standardized at 3' wide, separated by 8" wheel tracks. For this bed width, the wire hoops must be at least 80" long. The hoops are about 24" high at center. The minimum hoop size is 3/16" round stock. Either steel or galvanized will do. Wire hoops are spaced 2' to 2.5' apart. The tunnels are covered with two layers of plastic at frost, usually in early October. In March, the warming sun prompts the removal of the plastic film and its replacement with Agribon. This spun polyester row cover breathes and lets water pass through. Both the plastic and the fabric row cover are held down with up to a dozen 6 ml black plastic sand bags.

Bryan buys 20' lengths of steel wire at a local metal shop and has them chop it in thirds, precisely the length he needs. Bryan has used the same steel wire for over 10 years. Chafing from surface rust only occasionally causes rips in the Agribon row cover, while also helping to stick the cover onto the hoops. Galvanized steel is much more expensive.

For ease of operation, the beds are covered in 40' sections. Wind build up makes longer sections unmanageable, and with the length of this low tunnel, two people working together can uncover a whole field in little time. Bryan uses two layers of cheap 1.5 mil construction grade plastic. A 200' length of this film will suffice for two 40' sections. To close the ends, 50' of plastic is needed to skin 40' long low tunnels. The ends are bunched up and pulled tight to create tension over the top of the hoops.

Bryan is an enthusiastic missionary for the environmental control provided by low tunnels. They prevent excess precipitation from damaging germination and ruining crops, and protect crops from wind and cold. Bryan has measured a 35°F gain on sunny days. The low tunnels should be vented if the outside temperature reaches about 70°F and opened to catch precipitation if excessively dry. In 2005, Bryan kept the beds uncovered until the extremely late first frost on October 21, a lapse he came to regret since 20" of rain that month broke all records. If the beds had been covered, the crops would not have been devastated and it would have been more possible to control chickweed with cultivation.

Irrigation is rarely required until later in winter. The plants seem to like it drier in winter, Bryan explained, noting two mechanisms that plants use to withstand cold temperatures: desiccation and mineralization of their sap to reduce their freezing point. These mechanisms make these crops extremely sweet-tasting in the winter.

In the central Connecticut climate, snow build up has not been a problem for the low tunnels. The hoops are pushed down by snow load, but pop up, pushing off the snow, as soon as the sun begins melting it. Snow accumulation on the wheel tracks insulates the low tunnels, provides a windbreak, and also holds down the row cover.

For several years, Bryan has been selecting Asian greens and arugula for cold hardiness. This breeding has yielded quick results, boosting winter survival from 10% to 100% in arugula just by collecting seed from planted that made it through the winter. For his first breeding experiments, Bryan seeded three adjacent beds of Mizuna, Tatsoi, and Miruba. He replanted the next year from the seed he harvested from the Mizuna mother plants which successfully over-wintered. Each year he collects seed from subsequent generations of plants interbred from the three cultivars that survive the winter. The hybrid seed selected from a large gene pool produces very vigorous plants with much greater cold tolerance. He can stagger seed production by altering when he harvests for salad mix.

Chickweed is the biggest weed problem in winter low tunnel production. Before they grew year round, the O'Haras used to tolerate chickweed in their fields over the winter so now they are grappling with a huge seed bank. Seeding crops very late in the fall allows late tillage, reducing chickweed germination, and the Asian greens sown on December 2 were their cleanest over-wintered crop.

At Tobacco Road Farm low tunnels have a variety of advantages:

- Low tunnels are very inexpensive and quick to install. Bryan estimated that two people could cover over an acre in two days.
- In the spring, low tunnels are more easily cooled than high tunnels to prevent bolting.
- Low tunnels are easily converted from plastic to cloth covers.
- Low tunnels allow farmers to manage water, protecting crops and soil from excess rain and wind. A slight slope allows water to run off the tunnels.
- Low tunnels allow farmers to grow without insect and disease pressure.
- Since low tunnels are closer to the earth, they provide more heat to the plants in the day. Bryan said they are 3° to 5°F warmer than ambient temperature on cold nights, similar to their high tunnels.
- Cold growing conditions enhance the taste of the crops.
- Low tunnels convert readily for regular summer production, allowing triple cropping.
- Soil preparation and other tractor operations can be carried out in the field prior to quick installation of the low tunnels.
- As they are easily removable, low tunnels reduce soil salt build up.

The O'Haras also recognize that low tunnels have the following disadvantages, some of which are common to high tunnels as well:

- The biggest issue is that low tunnels are more labor intensive. To hoe, harvest, or irrigate, the coverings must be removed.
- Low tunnels cannot be automated and require a lot of bending to manage the cover, causing worker discomfort.
- Low tunnels restrict access compared to high tunnels. One can't harvest on a cold, windy day.
- Cut lettuce grown under plastic film-covered low tunnels (or high tunnels) is very delicate and wilts quickly. This is one reason to convert to a fabric covering like Agribon.
- Low tunnels provide a perfect environment for chickweed, the ultimate winter weed.
- The plastic cover on low tunnels must be vented during warm sunny late fall and winter days.

(An earlier version of this profile appeared in "Growing for Market.")

Construction Tips

Hoop house construction can be as exacting or casual as you like. However, not paying attention to initial details can cost extra time in the long run, and the resulting structure may not look as nice or stand as long.

Two people with good construction skills can erect a 30' x 96' high tunnel in about a week. The 75 to 100 hour estimated completion time assumes that all materials are on site. Setting up the metal frame, installing baseboards and hipboards, roll-up sides, and building endwalls are included. Additional time will be required for site preparation, utility installation and covering the tunnel with polyethylene film.

Most manufacturers provide instruction manuals with the frame and technical support if needed. Some, however, are less helpful than others in their support so inquire before selecting a company. The most important step is to make certain that the site is square and uniformly pitched or level. If this is done carefully, the frame should install easily.

Instead of step-by-step instructions for constructing a high tunnel, here we offer tips to save you time and money. We hope these recommendations enable you to complete your project with less stress and more confidence.

Start with an adequate selection of tools to make the construction process a pleasant one. Tools to assemble include the following:

- level, level string, chalk line, and transit;
- long-handled mallet or sledge hammer for driving ground stakes;
- post-hole digger for endwall posts;
- cordless drill and drill bits (plus spares) for the various size fasteners you plan to use;
- good step ladder;
- socket set;
- drift punch or pipe wrench;
- miter saw or circular saw;
- speed square;
- hacksaw or saws-all;
- power cord; and
- tape measures (12', 25', and 100').

An experienced high tunnel builder advises: “a cordless drill (preferably one with ample batteries) will be your best friend for fastening those millions of quarter inch bolts and nuts.”

Batter Boards

It is important to set up batter boards at the start of high tunnel construction *(see Diagram 4 below)*. The small amount of extra time involved will be well-rewarded by the increased ease of construction. The use of these semi-permanent building markers is described at www.dulley.com/deck/deck01.shtml.

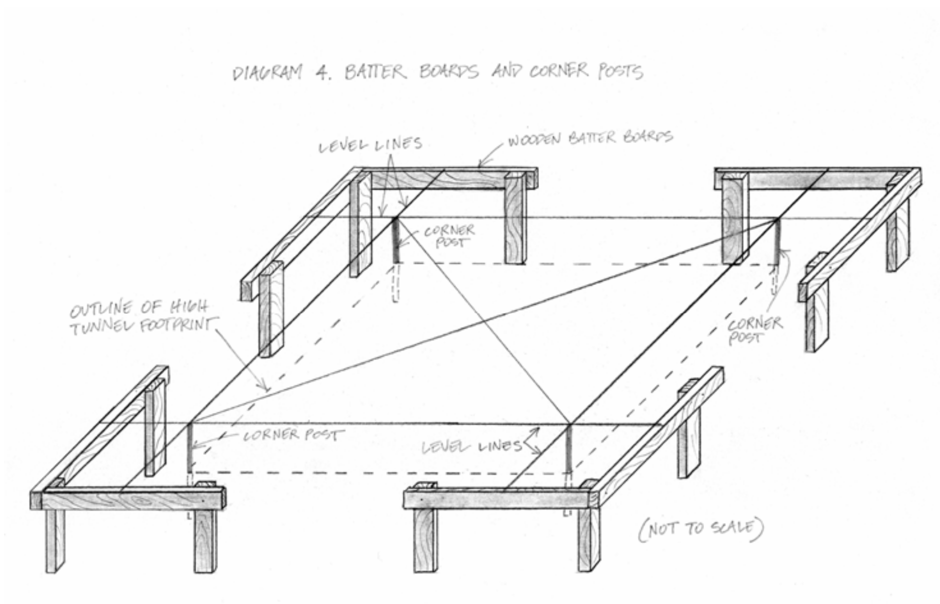
Batter boards define the corners and heights of the high tunnel. They allow you to erect the structure with confidence whenever you are ready. There is nothing worse than grabbing an hour here or there to work on a high tunnel only to find that someone bumped the stake and all your work is now out of line.

Ground Posts

As farmers, we are striving for a loose, well-structured soil in which to grow our plants. But we need a medium with the opposite characteristics to support a building. (If you have concerns about your site and its ability to support a high tunnel, check with a qualified professional.)

A high tunnel’s foundation is provided by ground posts, which are steel pipes partially buried in the ground. On rocky ground, in high wind areas, or where significant ground disturbance occurred during site preparation, a little additional support may be warranted. In these specific situations or for extra stability, a couple shovels of cement will effectively keep ground pins in place.

A sledgehammer is commonly used to drive in short ground posts. Most companies provide a protective piece

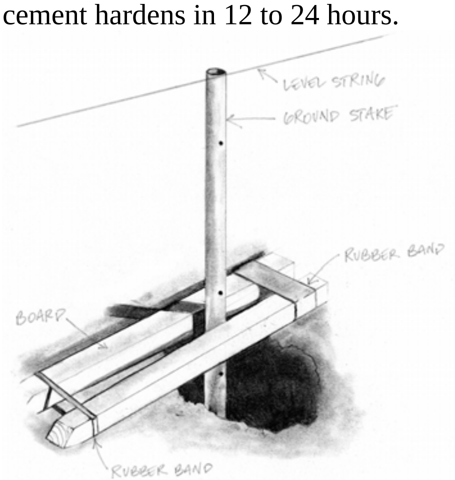


to put in the pipe to protect the end from being damaged or "doughnuting." For a taller structure with extended ground posts, John Biernbaum (who researches and teaches about high tunnels at Michigan State University) has found that a post or fence pounder works better.

The ground posts at the four corners should be solidly cemented in. For tunnels over 70' long, also cement in the intermediate ground posts in the middle of the long sides. Cement must be placed below the soil freeze zone, as the freezing action can force the ground pin up out of the ground. You may want to use caution when employing cement as this may move the structure into a 'permanent' classification.

Steve Moore suggests a good way to keep the ground posts in place so they don't pull out of the cement or slide down: pre-drill the ground posts within 2" or 3" of the bottom and insert a 4" to 6" piece of rebar.

The ground posts need to be in the right location and at the right height. A jig made with two old boards and some broccoli-type rubber bands or thin bungee cords will align the posts with the strings between the batter boards that outline the high tunnel. *(See diagram below.)* It will also keep the posts at the desired height. This simple device is removed once the cement hardens in 12 to 24 hours.



To ensure that the posts are placed at the correct height, use a transit, hose level, or laser level. Then take down the batter boards and run a high-strength nylon mason cord between the corner ground posts. Pull the string as tightly as you can to minimize droop over the long distance. Be careful; if a tight nylon string breaks, it can hurt someone as the end whips past.

The bows – and therefore the ground posts – of most high tunnels are spaced on 4', 5', or 6' centers. A wooden template with notches at 4' (or whatever the bow spacing is) eliminates the need for the time-consuming and awkward task of measuring from bow center to center. Ledgewood and Rimol provide their greenhouse customers with these spacers. They are also easy to make. John Biernbaum regards them as essential for construction.

Alternatively, Steve Moore recommends measuring from the same side of a post every time to attain an accurate center measurement. Taping the end of the measuring tape to the corner ground post is one simple way to do this. A level should be used to ensure the posts are vertical/plumb. A post level that has bubbles at 90 degree angles is useful because both directions can be seen at once.

Bows

Bows typically consist of two or three shorter pieces of metal tubing. Preassemble bows loosely. Do not tighten the bolts. This loose bow assembly will help in purlin installation. (Purlins are horizontal pieces typically made of pipe that is a smaller diameter on one end (swedged) to fit inside the next pipe.)

Historically, pike poles were used to push up large sections of timber framing for barns. Pike poles also have a place in erecting high tunnels.

Raising a heavy bow on a wide tunnel (20' or wider) is best accomplished with at least three people. One person stands at each leg of the bow, and a third pushes the bow up in the air with a pike pole. This is heavy work. Each bow will need to be picked up and wiggled onto the spline/ground posts. Use one or two pike poles to keep the bow assembly from falling while the crew wiggles it onto the ground posts.

Purlins

Purlins help stabilize the high tunnel. They are bolted to the bows, along the length of the structure. Typically a 30' tunnel will have five purlins, including the ridge pole.

The purlins can be attached once the bows are loosely assembled and in place. A platform is much safer than ladders and saves a tremendous amount of time and energy. Use a hay wagon, truck bed, or scaffolding, especially if you can pull it along as you go!

A drift punch or pipe wrench can be used to help align bow and purlin holes. As you attach the purlins, tighten all bow bolts, except those that connect the bow to the ground pin. Finally, when you are at the end bow, with all the purlins in place, you are ready to "plumb" the gable end to straighten the entire bow/purlin assembly.

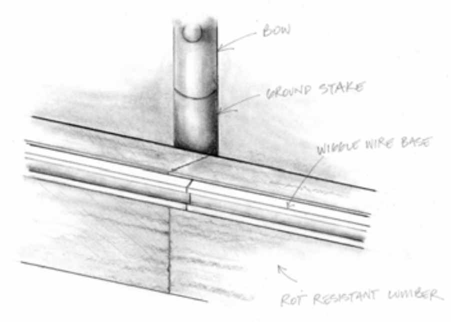
Attach one string with a plumb bob to the top point of the outside edge of the last bow, and a second ground string to the outside edge of the bottom bow. Allow the plumb bob string to come within 1/8" of the ground string.

A good way to adjust and hold the high tunnel plumb is to attach a come-along to a large immovable object like a tree or truck and then attach a rope or chain from the come-along up to the bow. A come-along's ratcheting mechanism and its steel cable allow for quick and precise alignment of the tunnel. Now you can tighten all remaining bolts and install the wind braces.

Baseboards

The baseboards sit on the ground along the sides of a high tunnel. They are bolted to the ground posts. Use 1.5" x 8" lumber for baseboards.

Consider sourcing your lumber from local family-owned and operated sawmills. Often boards from these mills are sawn several inches longer than their designated length, rather than being trimmed down to an exact, even foot measure. This extra length will allow you to cut the ends at a 45 degree angle for joining together at the bows with a 1/4" machine bolt *(see diagram below).*



Use a long 1/4" bit to drill out the holes for the bolt through the wood from the inside of the high tunnel. This added length is helpful when attaching framing to bows.

Machine bolts are superior to carriage bolts for attaching the poly hold-down strips to the baseboard. Carriage bolts are often used for this purpose, but they rust fast. When the baseboard needs to be replaced, sometimes the nuts are stuck in place and won't turn. With a wrench on either side of the nut and bolt, the machine bolts will break off much faster and easier than hack sawing carriage bolts, which only turn in the wood.

While bolts may be better for attaching the base boards and hip boards to the bows, galvanized pipe straps can also do a good job, as long as the pipe strap is also tek-screwed to the bow. Ted Blomgren recommends using a washer on the wood screw.

The frame will be complete after the hip board (2" x 6" lumber) along with "poly lock" or "wiggle wire" base is attached to the bows approximately 5' or 6' off the ground. (Poly lock is the trade name for an extrusion for attaching the polyethylene film to the structure. It serves the same purpose as wiggle wire.) This will serve as the point of attachment for the plastic covering.

The hip board should be inspected at each change of polyethylene to make sure it will be sound for another four or five years. Farmers should be aware of rot and ready to replace the baseboard as necessary; the plastic need not be removed to do so.

Gable Ends

Doors should be large enough for ventilation and easy access. They can span even the full width of the high tunnel. To maximize airflow and accessibility, some farmers construct removable end walls. A smaller, personal door that opens inward makes a convenient winter passage.

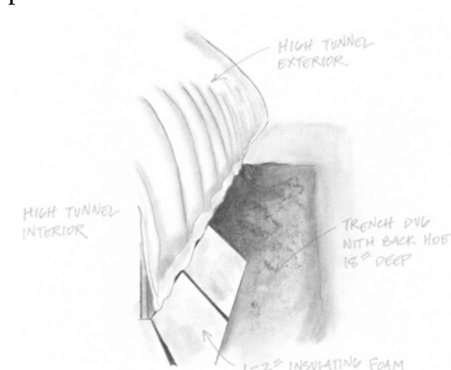
Unless the high tunnel will have very wide doors, some tasks such as adding compost, tilling the soil, and installing utilities are best accomplished before the gable ends are closed in and access is restricted.

Gable end framing can be done with steel or wood. If using wood, either select one of the rot-resistant species recommended for the baseboards *(see materials section)* or be prepared to replace the wood as needed. Steve Moore uses rough sawn 2 x 4s to frame the gable end. When the wood rots right at the soil line where moisture and air meet, rather than take apart the whole assembly, he just pounds in a U-shaped steel fence post and lag or machine bolts it to the post that had rotted off. "This buys me a good many more years service," he says.

If you use a rigid gable-end covering, such as polycarbonate, the outside of the baseboard will need to be flush with the outside of the bow. To make it flush, attach an 8" piece of universal corner (a thin-walled piece of angle iron with multiple holes for bolting) with the same bolts that hold the side baseboard.

Insulation

In cold climates, insulation can make a significant difference in the performance of high tunnels. In Zone 6, burying 1" thick by 2' wide rigid foam (i.e. polystyrene) isolates frozen ground from growing areas. The thickness and depth of insulation should be modified according to your climatic zone. This foam should be buried at an angle to gain more benefit from the thermal mass of the earth. The angled placement also makes installation easier and allows space for the cement support at the bottom of the ground pin *(see diagram below).* Insulation can also be used in pathways and along the lower portion of the sidewalls.



Hiring Out Construction

For some farmers, hiring an experienced crew to do the installation may be the best option. The estimated labor cost for basic high tunnel construction used to be fifty cents to one dollar per square foot. However, due to inflation, the labor bill for high tunnel construction in previous years may not be relevant for estimating costs under current conditions. Like any construction project today, expect skilled contractors to be expensive.

Bending Your Own Frames

Rather than purchasing a hoop house kit, some farmers choose to bend their own. A good role model for this activity is Ed Person of Ledgewood Greenhouse. This New Hampshire farmer went from bending frames for his own use to developing a substantial independent business that sells and delivers high tunnel frames throughout the Northeast.

For savvy shoppers, fabricating a high tunnel steel frame can save money. It also allows farmers to realize a better design idea, satisfy unique needs, or add onto an existing high tunnel.

Ted and Jan Blomgren bent several Gothic arch high tunnel frames for their farm. Three people worked for about the equivalent of one week fabricating the jigs and bending and drilling the component parts for three and a half 30' x 96' high tunnels with trusses.

At the time, they were able to make their own high tunnel frames for a third of the cost of a kit, thanks to a farmer friend's tip about a supplier of economically priced steel. Ted cautions though that purchasing steel from a local chain link fence supplier might actually cost more than buying a kit with pre-bent, pre-drilled steel.

The Blomgrens' bows consisted of two long side pieces with a shorter, smaller diameter piece at the ridge. In all, they used three sizes of steel pipe—1.9", 1.6" and 1.3" diameter for bow, small ridge bow, and purlins, respectively—to fabricate all the high tunnel components including trusses. The only new tools they needed were a chop saw and drill press outfitted for cutting and drilling steel. After four years, there is no rust at the bends and the galvanized coating has not popped off.

They built the two jigs needed for bending the steel for the bows by replicating a bow they had removed from their existing high tunnel. To bend the steel, they placed a jig, made of two-ply 3/4" plywood and lumber, on the level cement floor of their garage, braced against its foundation. For the easier, shallow bend, they were able to use their sedan with a steel cable attached to the trailer hitch. The more acute portion of the bow required the weight and traction of their heavy John Deere tractor. To compensate for the springback in steel, they bent it until it fit a pattern they had outlined on the floor.

Bending the bows for a high tunnel can be a simpler process. For example, Thomas Christenfeld, a neighbor of the Blomgrens, bent the bows for his Quonset-style greenhouse using a silo as a jig. He stuck one end on one of the hoop bolts that holds the concrete panels of the silo together and bent the other end around the silo. Two people are needed to get a good enough bend in the pipe and that it probably only works for a single piece hoop. Thomas notes, "You cannot get any real bend in the ends of the pipe so two pieces stuck together leaves a flat part on top of the hoop house, which is far from ideal in a snowy climate."

Another Way to Bend Your Own

Kevin Loth, who is contractor as well as a farmer, has fabricated his family's 20' x 200' Quonset-style high tunnels near Lincoln, Nebraska. The Loths have two heated greenhouses and two year round high tunnels. By bending his own bows, he was able to get twice as much ground under cover than if he purchased kits. His calculation included what he paid a helper but not his own time. He said if you don't drill the bows, you could probably bend them in a day, though set up might take a couple of days.

With a borrowed pipe bender, he made bows out of the 15 gauge metal pipe used as a chain-link fence top rail. He saved considerably on the pipe by purchasing it by the bundle of 91 pipes. Because the pipe comes in 21' lengths, he had to swedge together one and a half lengths for each bow. While a swedging tool can be expensive, often when you buy fencing steel, one end comes already swedged.

His finished tunnels are Quonset-shaped, 10' high at the peak. Their bows are 4' on center, and they have two purlins but no trusses.

Kevin has attached the purlins and bows in several ways. Holes should be drilled prior to bending the bows. For the less technically adept, purlin clamp connectors (available from greenhouse suppliers) or pipe clamps (from plumbing supply outfits) preclude the need to drill holes for the bolts attaching the purlins. Getting these holes to line up properly can be difficult. Moreover, the very act of drilling holes weakens the steel.

While the purlin connectors are aluminum, Kevin dismisses concern about mixing metals as the tunnel's steel is galvanized. He thinks this is less of an issue than drilling holes as that action exposes ungalvanized steel and weakens the structural pieces. Also he noted that the ends of the bows are in contact with corrosive cement and soil acids.

Covering a High Tunnel

Farmers employ several methods for getting the unwieldy expanse of polyethylene film over the top of large hoop house structures and evenly attached. The size of your crew helps determine which methods are most feasible. The most important rule of thumb is never attempt to cover a tunnel on a windy day.

Covering a large (i.e., 30' x 96') high tunnel with a single layer of poly should take four or five people two or three hours. There is a learning curve so the first few times may take longer.

Method A: Pull over the end.
For this method, four or five people and a center-folded roll of polyethylene are required. (You can order your polyethylene folded in several ways.)

The first step is unrolling the plastic. To do this, set up a pair of cinderblocks a few feet further apart than the length of the roll of polyethylene. For a 12' tube, set the blocks about 14' apart. Then put a pipe in the tube. Make cardboard washers about 1' square to put on the ends of the pipe. The washers serve to protect the ends of the rolled up polyethylene from abrasion against the cinderblocks when you unroll it. This set up should allow the plastic to freely unroll.

The next step, getting the plastic over the tunnel, requires five people. One person is stationed on a ladder at a gable end of the high tunnel. Wearing a hooded sweatshirt is recommended to avoid plastic rubbing and to counteract the static electric generated by moving the plastic film over head. The center of the end of the poly is passed to the person on the ladder. The film unrolls as it is pulled up the ladder. Two people on the ground hold the corners and walk along side the tunnel as the plastic is unfurled. Meanwhile the person on the ladder does a sort of butterfly swimming stroke, bringing the plastic overhead so that it clears the peak without getting caught.

The two people walking along the sides can have an exceedingly long way to pull the plastic. When they reach the middle of a long tunnel, two more people standing at the original gable end should assist pulling the plastic along. These additional people also help keep the plastic from becoming a sail if a sudden gust of wind comes along.

After the whole tunnel has been covered, it’s time to even out the plastic. The selvage edge must be even for the entire length of the tunnel and should be 12" or longer. You don’t want the edge to run out!

If you are putting a second covering on, just tack it on the first layer using just a couple strategically placed poly fasteners (i.e., wiggle wire) and repeat the process with the second covering. Otherwise, proceed to the next step.

Once you are satisfied that the plastic is even on the edge, temporarily secure the plastic in place at three or four points on each side. The most common method for securing the plastic is wiggle wire inserted into a U channel. An alternative assembly is homemade—wood attached with drywall screws every 6" to 8".

Now you are ready to fully secure the single or double layer of plastic. The person on the ladder inserts wiggle wire from the top down on one of the gable ends. Next the plastic film at the other gable end should be pulled and that plastic “tacked” down. Once one gable-end plastic is permanently attached and the other gable end has been “tacked” in place (with a short wiggle wire), one side can be attached for a distance of about three bows. Remember to keep a constant selvage (waste) edge. Another person (or two) starts on the opposite side of the first group and both groups attach side plastic down to the end and finish the gable end. The reason for the staggered start and attachment is to avoid see-sawing the plastic side to side. The lead attachers must always keep the selvage edge the same while the other side pulls the plastic to match.

Getting all of the wrinkles out is not important if you are going to inflate. It is important not to pull the poly film so tight that the wiggle wire in the U channel perforates the new plastic.

A variation on the pull-over-the-end method of covering a high tunnel is used by the Kilpatrick family. They set up the plastic on scaffolding at one end of the tunnel as described above. “Make sure the scaffolding is above the peak of the structure. While one person pulls the plastic down the length of the high tunnel, the others assist from the ground.” Philip and Michael Kilpatrick have found that for work on the purlins, scaffolding mounted on a cart is far more convenient than using a ladder.

Method B: Ridge-roll.
This is one of the two ways that the Blomgrens cover their tunnels. (The other way is described in Method C.) Both methods involve climbing up the high tunnel and thus entail danger. Use these methods at your own risk.

Covering a high tunnel with a lean crew (four people) necessitates a different method. Once again, make sure to obtain greenhouse plastic with its fold down the center so it will unfurl properly.

In this technique two people carry the entire roll of poly up to the top of the high tunnel. A bucket loader is handy for this purpose. Before climbing up, they insert a pipe into the cardboard tube to assist in unrolling it. With the roll sitting on the top purlin, they temporarily fasten it on the gable end of the tunnel. Then they proceed to walk it down the tunnel, making use of the side purlins, walking the roll along as they go. By the time the pair has walked halfway down the tunnel, the plastic will have begun unfurling, with half falling down one side and half down the other. (This unrolling procedure will go much more quickly if the high tunnel is designed so that the ridge purlin is situated on top of the bow. This is an atypical purlin placement and is only advisable for tunnels that will never be covered with a double, inflated layer of poly.)

Meanwhile the two other people, who are on the ground, are starting to tentatively connect the poly to the hip board just above the roll up sides.

After the plastic has been unrolled along the entire length of the tunnel, the two people who have been walking the ridge with the roll of poly temporarily connect the poly with wiggle wire at the top of the second gable end. They then climb down and join the two folks on the ground. With two people on each side of the tunnel, they square up the plastic, and then begin attaching the plastic along the top of the roll up sides. With the two teams working on opposite sides of the tunnel, they start at one end, and work toward the other end.

They then finish the gable ends, taking up the slack and smoothing out wrinkles, before permanently attaching it there. They trim off the excess plastic at the gable ends so it doesn't flap in the wind. To complete the covering, the roll up sides must be attached.

Method C: Over the side.
Like the previous method, this covering procedure used by the Blomgrens has safety and liability issues. As an alternative to climbing over the tunnel frame, Steve Moore suggests attaching grommets to the plastic and using ropes to pull it over the structure.

For a big tunnel (30' x 96' or 150'), at least eight people are needed for this method. Start by unrolling the plastic (without unfolding it) along the side of the high tunnel. If there is a risk of the slightest wind, it is best to be on the windward side of the tunnel.

After the plastic has been unrolled, people station themselves at regular intervals along the tunnel. They each take hold of what will become the far edge of the poly. Pulling this edge, they climb up and over the tunnel. With enough people, the weight of the poly is distributed and not burdensome to anyone.

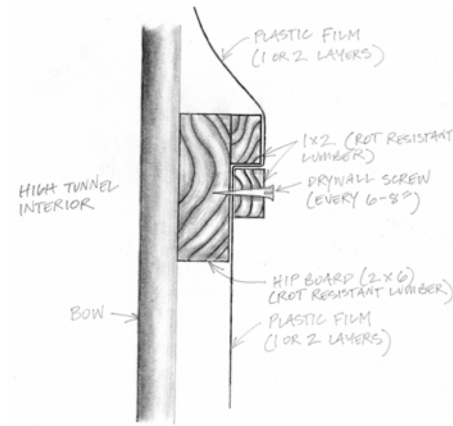
Once the plastic is over the top of the structure, it is squared up, and then temporarily fastened to the gable ends. They then proceed as in the above description, with teams starting from opposite sides of one end and both working toward the far end.

There is an alternative to climbing up and over the greenhouse. Ropes may be attached to the plastic along its side. Clips available from greenhouse suppliers can be used to secure the rope to the plastic. Alternatively, wrap tennis balls in the plastic and use them to help fasten the rope. Toss the ropes over the tunnel structure and, once on the other side, pull the plastic over.

Tips for Attaching the Plastic

Single poly can be difficult to keep on a structure because there is no tension from an inflation fan to reduce flapping. Steve Moore has used wide poly strapping placed between every other bow and attached to the baseboard to keep the cover in place. This increases the longevity of the plastic film, and also reduces a farmer's worry about losing the plastic on the tunnels (and sleep) on windy nights.

If you choose to use wooden batten boards to fasten the plastic to the hip board, you would be wise to use a pair of batten boards one above the other with the plastic outside of the top one and behind the bottom one. This more effectively locks the poly in place. *(See diagram below.)*



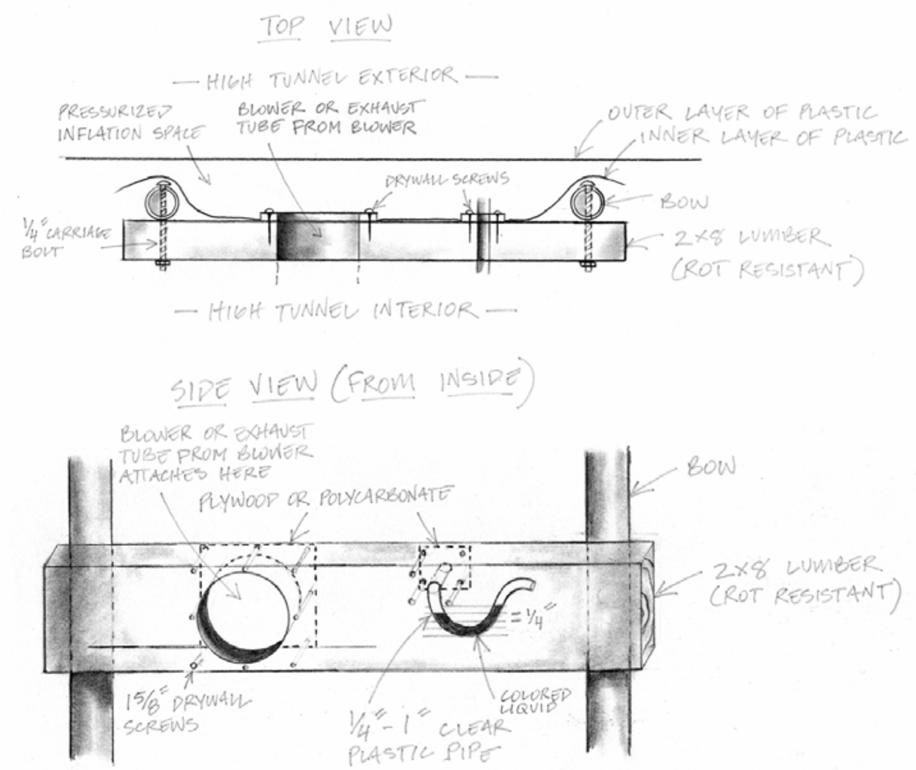
After you have to undo rusty screws or other failing attachments to remove old poly, you will probably come to believe that wiggle wire is a bargain at a $1 per foot. When attaching new poly with wiggle wire, don't pull the poly too tight (or over inflate). The wiggle wire will actually cut perforations (corresponding to the wiggle wire) in the new cover if there is too much tension. This applies to double layers of poly, too.

When attaching plastic to battens (thin boards less than 1/2" x 1-1/2"), use double headed nails—rather than regular nails—for easier removal. Galvanized screws are another option.

Getting the Right Pressure on Your Inflation

Correct pressure ensures a balance between over and under inflation. By providing sufficient tightness of the plastic, flapping is minimized. If the plastic is stretched too tightly, light transmission is reduced. Simply put, correct pressure increases the life of the plastic and its ability to transmit light.

A manometer is an instrument used to measure the pressure of a gas. For high tunnels with a double poly layer, it is useful for determining the proper inflation pressure. Steve Moore makes his own homemade manometer using this simple procedure.



On the inside of the tunnel, attach a 2" x 8" (or wider) board with carriage bolts to two of the bows at a 4' to 6' height. (This board can be used to mount the inflation fan as well.) After covering the high tunnel with the first layer of poly, a 4" to 6" square piece of polycarbonate is attached with drywall screws to the wood before the tunnel is covered with a second layer of poly.

From the interior of the tunnel, drill a hole through the wood, the inside layer of plastic and the small piece of rigid material. From the inside, push a clear flexible plastic tube (available by the foot at most hardware store) into the wood, allowing the tube free access to the air between the layers. The tube's internal diameter can be from 3/4" to 1". Caulk around the tube so that it is airtight to prevent leaks.

Let the tube form a "U" with one of the top legs of the U going through the wood. Attach the other top of the U tube to the board and fill the bottom of the U with a colored liquid (blue washer fluid or colored water). Mark level horizontal lines ¼ of an inch apart on the board next to the U portion of the clear tube. If the interior air level of the U is ¼ inch higher than the inflation side of the U, then the pressure is about right. The liquid level on the side of the U that is attached to the board should be 1/4 " lower than the side of the U that is open to the inside of the tunnel.

Adjust the pressure by using a damper on the intake of the inflation fan. You can make a damper with a flat piece of metal, like an old can lid (taped to keep from cutting yourself). Insert a screw through the top edge of the metal lid. Attach it tightly enough to the intake of the inflation fan that it will stay in place at various degrees of opening.

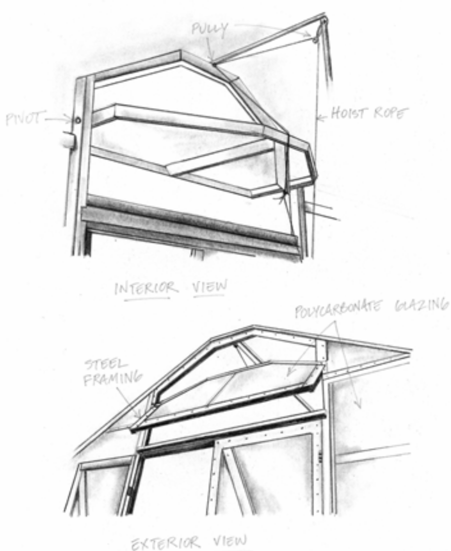
Steve has used solar power to run the inflation fan and his monitoring equipment.

Environmental Management

Ventilation and Cooling

Venting to reduce humidity is more important than keeping the tunnel closed to boost the temperature. The sacrifice of a few degrees in favor of lower humidity will contribute to overall plant health.

High tunnel ventilation is usually accomplished by the passive movement of air through the structure. The air movement through tunnels occurs through roll-up sides, gable-end doors and vents, ridge vents, and removable end walls. *(See below.)*



For growers who also work off the farm, an automated vent is essential. Motorized louvers are readily available, and probably pay for themselves relatively quickly, but solar openers are good alternatives to motors.

The height of roll-up sides should be considered when selecting or designing a high tunnel. The higher the sidewall, the greater the potential air movement through a tunnel. Sidewall height depends in part upon the design of the tunnel. For instance, straight sidewalls—the norm for Gothic structures—allow for higher roll-up sides than curved walls. Longer ground pipes or leg extensions on the bows of Quonset tunnels add height to sidewalls. Gothic tunnels also allow for bigger gable-end vents over the door than Quonset tunnels. Caterpillar tunnels and multi-bay tunnels like Haygroves provide superior venting, since entire sidewalls can be pushed up to allow air passage in both structures.

To prevent tender plants from being blasted with cold air when roll-up sides are vented, some growers are installing a low protective sidewall 12 to 18" above ground level. Poly film, clear acrylic, and polycarbonate have all been used for this purpose. Roll-down side curtains offer another solution.

Large gable-end vents and doors and removable end doors help maximize venting with no energy cost. Retrofitting is feasible, but planning ahead for optimal ventilation during the design phase is best.

Ryan Voiland at Red Fire Farm near Amherst, Massachusetts, purchased a 35' x 120' Harnois greenhouse kit because it seemed the best option for ridge venting. The roof comes to a higher peak in his model than in others. A 24" wide flat piece of plastic at the ridge moves to open the vent. The opening mechanism is powered by a small motor that is activated by a thermostat.

The frame with the ridge vent costs considerably more than a frame without one. Since the frame was also more complicated, Ryan hired a greenhouse builder to erect it. To access the ridge vent, his tunnel has a catwalk on top of the frame. Covering the ridge-vented tunnel with plastic is challenging and follows a different procedure.

Ridge Vents

In ridge-vent systems, cooler air enters the high tunnel through roll-up sides or gable-end openings, and hotter air rises and exits through the ridge vent. These systems work very well, but few high tunnel growers seem to use them, as they are more expensive to purchase and install. Ridge vents can be manually or mechanically operated. Some growers have even constructed their own ridge vents.

An alternative to an expensive full-length ridge vent is a series of small roof vents which act as chimneys to vent out hot air. For several years, Ken-Bar has made an inexpensive roof-installed vent for high tunnels that is available from Farm Tek for a little over $200. These vents have an actual 30" x 14" opening and should be installed every 20' to 25'. A $50 solar vent opener eliminates the need for a noisy motor and an electrical hookup. *(See “Green-house Supplies” on page xx.)*

Although Ryan is satisfied with the venting of his large tomato high tunnel, he said he would not opt for a ridge-vented structure again due to the costs and complications of construction. He believes that an exhaust fan could adequately serve the same function.

Fans

Multi-bay and walk-in tunnels can be vented very effectively, but the narrower openings in more traditional high tunnels sometimes constrict airflow. While passive venting is usually sufficient in well-designed high tunnels, several circumstances prompt some high tunnel growers to turn to fans to cool their tunnels, reduce humidity, and improve air circulation.

Photovoltaic Inflation Systems

By Steve Moore

Most traditional hoop houses or high tunnels have only one layer of poly film as a covering, so no blower fan is used. But thermal performance is far better in dual covered structures.

Heated greenhouses typically use two layers of poly film and require a blower. Inflation has two functions. First, it creates a dead air space for insulation. Secondly, it provides turgor to the covering. Keeping the plastic at the right tautness prevents stretching which reduces light transmission. It also prevents tearing.

There are a variety of energy sources to power an inflation fan or blower. For example, Amish farmers sometimes run inflation fans on compressed air to keep within the bounds of their faith. Otherwise, most applications require electricity.

However, not infrequently, high tunnels are located at a distance from grid-connected electrical service. Hook-up can be costly. The alternative we have used is solar photovoltaics—electric power from the sun. Our independent solar power system has worked well for many years.

We used a 32-watt Unisolar flat photovoltaic panel ($210), a Morningstar charge controller, two 6-volt golf cart batteries ($70 - $80 each) and a 12-volt blower fan. With renewable energy, it is cheaper to reduce energy demand than to produce more energy. We were lucky in finding such a fan through a military surplus outlet. This 4-watt blower fan ($20 when available -- see resources) has a very low amperage draw.

The rest of the system is built around the electric demand, in this case, the blower. The blower runs 24/7 so backup batteries are required for nighttime and long stretches of cloudy days. More northerly locations with shorter winter days may require a bigger solar panel and more battery storage capacity.

The two 6-volt batteries are wired in a series resulting in a 12-volt current which is compatible with the charge controller's needs and the solar panel output. In southeast Pennsylvania, the 32-watt solar panel was sufficient to keep the batteries charged for our long-term storage needs (times of little or no sun) and to power the blower and some monitoring equipment. We used a rather expensive charge controller so we could build on it for further expansion of the solar system. Otherwise, several small and inexpensive models ($35 to $100) would be more than adequate.

It is important to protect the batteries from cold. We all have experienced how cold reduces battery efficiency, when we try to start our car on very cold days. With this concern in mind, we chose to place them in a box below grade in the ground in the high tunnel where the earth's constant temperature moderates the cold. We also wanted to get them out from under foot and reduce the chance of spilling or puncturing the cases and releasing battery acid.

You must ventilate your battery box as explosive hydrogen can be a byproduct of battery charge and discharge cycling. We do this with a few holes in the plywood lid. By sizing it big enough, we get double duty out of our battery box. It also functions as an irrigation distribution box to add or change drip tape manifolds and other needs.

The production of trellised summer crops such as indeterminant tomatoes and cucumbers with lots of foliage can reduce air movement. Stagnant masses of humid air result in greater disease incidence. To avoid potential crop loss, it is not surprising that some growers opt for fans.

For winter production, when roll-up sides are buttoned down and doors firmly latched, gable-end vents may be too small to do the job. In this situation, an exhaust fan mounted high at one gable end coupled with a louvered vent at the other can help remove hot air and free moisture and reduce relative humidity in the structure. The louvered opening is controlled with a motor and thermostat.

In addition to an exhaust fan, Slack Hollow Farm uses four small fans hung from purlins to move air in a circular pattern in the 30' x 120' high tunnel. Commonly used in greenhouses, these horizontal airflow (HAF) fans create a gentle air current that moves and mixes air.

The Zemelskys had four HAF fans installed in each of their four 30' x 96'. high tunnels for a cost of $330 per tunnel, including the wiring. In the summer, the added air flow benefits their mostly heirloom tomato crop. However, for winter greens production they do not run these fans. The Zemelskys also use a gable-end exhaust fan in four of their five high tunnels.

Heat stress

Heat stress can be a problem for plants growing in high tunnels that are inadequately vented. When leaf surface temperatures get too hot, photosynthesis and other metabolic activities shut down. Plants close their stomata and stop transpiring. If overheating is allowed to continue, plants will grow poorly, and may eventually die.

A high tunnel full of plants will stay much cooler than an empty one. Transpiring plants release water into the air producing natural evaporative cooling. This is also why misters work well to lower the temperature and why trees, in addition to providing shade, cool down a city street.

Shade cloth is commonly used by greenhouse growers to reduce the interior temperature of the structure. But shade cloth has less applicability to high tunnel growing. In the Northeast, for many summer crops it will reduce light availability too greatly, resulting in poor overall growth and leggy plants.

Shade cloth does make sense for certain species of cut flowers in high tunnels. In southern Pennsylvania, the Cramers effectively use shade cloth in one bay of their Haygrove high tunnel to grow cool-loving (but long-season) lisianthus. This material moderates high summer temperatures and reduces light diffusion, producing the elongated stems required by the market.

Heating

High tunnels are normally defined as unheated greenhouses. Their primary sources of heat are solar energy and the ambient heat of the earth. Farmers don't use high tunnels to grow warm season crops significantly out of season; instead, they use them to extend the normal season by a period of several weeks. With the additional protection of internal row covers, adequate growing conditions for cold weather crops can be attained, even during the winter months.

For warm season crops such as tomatoes and cucumbers, a standby heating unit can be brought into a high

In-Ground Radiant Heat

In-ground, radiant heating tends to be a less energy-intensive approach than air heating for any structure, whether it is a building, greenhouse, or high tunnel. While relatively costly to install, in-ground systems, which circulate a heated fluid, consume less fuel than heating air, reducing fuel consumption and costs over time. Heating the root-zone stimulates seed germination and root development. In a radiant heating system, a water-antifreeze mixture is heated and circulated with small pumps through polyethylene tubing buried in the ground.

Slack Hollow Farm had been growing year-round in a high tunnel that had neither artificial heat nor electricity. But in their new 30' x 120' high tunnel, Seth Jacobs and Martha Johnson (with the assistance of a plumber) installed a radiant heating system that uses standard, off-the-shelf technology. Seth buried PEX tubing 18" deep, in rows 12" apart, using about a dozen 300' loops for the 30' x 120' tunnel. (Each loop consists of an outgoing and return stretch of tubing.) A 1:1 propylene glycol/water mixture, heated by an oil-fired hot water heater, circulates in the tubing. The heat spreads upward and outward in the soil at a 45-degree angle above the tubing. Once the heat is turned on, it takes about 10 to 12 hours to heat the soil 6" below the surface.

In designing their heating system, they were concerned that the antifreeze mixture circulating in the buried PEX tubing would be too hot for their crops. As a protective measure, they designed their system with all the "bells and whistles," including dampening valves and return-flow mixing. These added features have proven unnecessary in their application in part because the heater itself can be turned down to 110°F.

For the first winter (2005-06), they chose 47°F as the target soil temperature at a 6" depth. Under the row covers at night, the lowest air temperature was 27°F. It took a single tank of oil (275 gallons, costing $500) to maintain this soil temperature. With the onset of longer days in mid-February, they were able to stop burning oil for the rest of the winter (even though temperatures were cold). They found that the soil 6" down could gain 5°F on a sunny day.

In 2005, before the heating system had been installed, they grew tomatoes in their high tunnel without heat. They warmed the soil to 70°F for their spring 2006 tomato crop, consuming three-quarters of a tank of oil in several weeks during that cold spring. In both years they started wholesaling tomatoes around July 11.

With just one year of experience with their in-ground heating system, it is too early for Seth and Martha to draw conclusions about the economic feasibility of this application. In order to cut fuel requirements, they plan to insulate the soil around the tunnel's perimeter to a depth of at least 18". The temperature they will eventually choose for soil temperature in mid-spring for summer tomato production is still in question; they hope next year's trials will help them come to an answer.

tunnel as a temporary safeguard against extreme cold. But when growers install a permanent heating system, they begin to transform their high tunnels into something more akin to a greenhouse.

Nonetheless, farmers are constantly experimenting, and there is much to be learned from their attempts to create superior and cost-efficient growing conditions. While the pros and cons of conventional greenhouse heating systems are beyond the purview of this manual, one example of the use of in-ground heat is presented on page 50. Such a system has applications for growers who wish to minimally heat the soil in their structures just enough to prevent freezing.

Relative Humidity and Temperatures in a High Tunnel

Water condenses on the inside surface of a high tunnel or greenhouse cover when the outside temperature drops below the dew point. Free moisture in the air changes to a liquid state, the same way that dew is formed. When this condensation drips, it can damage plants and promote disease. Droplets of water on the plastic film reflect light away from the tunnel.

High relative humidity increases condensation. Evapotranspiration by plants contributes to the humidity level. Ventilation or heating can reduce moisture levels in the air.

High tunnel temperatures can be measured for the air, soil, or plants. Ventilation directly influences air temperature. Plant metabolism and growth processes affect plant temperature. The intensity of solar radiation affects the temperature of the first inch or two of the soil, but soil temperatures at greater depths are constant. Plant scorching may be influenced more by the intensity of solar radiation than by air temperature.

Adapted from Film Facts, www.bpiagri.com/hort-luminance.htm

Interior Row Covers

Floating row covers are commonly used to further protect plants from cold weather within high tunnels. They are either laid directly over plants or suspended over wire or pipe hoops in the form of low tunnels. Some farmers use plastic film to create tunnels within tunnels. This is a good use for old greenhouse film, as long as it is not so degraded as to prevent adequate light transmission. But plastic, whether new or used, traps moisture and overheats the enclosed space more readily than fabric row covers, and therefore must be opened or ventilated daily.

Alternatively, spun-bonded synthetic fabrics may be used. These include Remay, Typar, Agribon, Agrofabric, and Covertan. These row covers come in a various sizes and weights. Weights range from 0.5 to 2 ounces per square yard. Heavier materials cost more and are less apt to tear. Some are even rip-stop reinforced. The less the fabrics weigh the less cold protection they offer, but the more light they transmit. Because of this trade-off, the jury is out regarding the best weight row cover to choose under different conditions.

In Maine, Eliot Coleman prefers lighter weight materials as they allow more light to penetrate and warm the soil during the day than heavier row covers which provide a few more degrees of frost protection. He does not want to have to open and close inner covers daily. In contrast, while farming in Pennsylvania, Steve Moore used the heaviest weight fabrics for winter high tunnel production. He appreciates its increased insulating ability and durability and has come up with several streamlined systems for moving this material.

In Connecticut, the Zemelskys have used light- and mid-weight spun polyester row cover to assist the crop in germination and protect their hardy greens for winter production. Andy Jones, in Burlington, Vermont, typically covers his winter greens with a single layer of mid-weight row cover, though on occasion he adds a second layer when “super cold” conditions are expected. At Slack Hollow Farm in upstate New York, as many as three or four layers of a medium-weight row cover protect spinach and other greens in the dead of the winter.

At Slack Hollow, the covers are usually removed during the day. Seth Jacobs explains that, in order to take full advantage of solar gain, the ground needs to be exposed to incoming sunlight so it warms up the groundmass, and then insulated from the cold air at night. This concentrates the stored heat from the sun in the ground but eliminates the small layer of air under the cover. “On bitter cold, very cloudy days we might leave some or all of the covers on during the day, but we feel we should uncover whenever possible for maximum light on the plants, and heat gain in the soil,” he said.

Steve Moore follows the same logic as Seth Jacobs for row cover management. On warm, sunny days, he rolls back the covers, while on cold and cloudy days he tends to leave the covers on. However when there is a string of two or more cloudy days, he finds it important to vent on “the best days” as air movement helps prevent and control disease.

In contrast, at the Intervale Community Farm in Vermont, Andy Jones explained that their row cover management is less intensive. “We wait to put them on until fairly late (around late November), but only plan to remove them at harvest or for other chores.”

In a class of its own is Tufbell, one of the heaviest, longest-lasting row cover materials on the market. Made of polyvinyl alcohol, its characteristics are more conducive to winter horticulture than the more common spun polyester. It increases air and soil temperature by 5 to10°F and leaf temperature by 2 to 6°F, yet does not overheat in 90°F weather. It allows 92 to 95% light transmission. Only minimally degraded by sunlight and reinforced against rips, it lasts at least five years or longer if protected in storage from mice and other nest builders. It can also be sewn and washed. However, at 22.5 cents per square foot, it costs more than twelve times as much as Argibon 19 (which costs 1.6 cents per square foot).

Over a period of several years, Steve Moore experimented with a variety of materials in two different configurations, using them as inner grow tunnels on 5' wide beds and also as a 14' wide covering (half the tunnel’s width). He tested the performance of used plastic (greenhouse film), Agribond products, Typar, Agribell, Low-e (1/4 inch foil faced bubble wrap), thermal curtain material, Aluminet, and several others.

He found that used plastic was almost as good as very costly alternatives in terms of thermal protection and heat retention. In fact, he concluded that it is the most economical and environmental choice. He also found that covering half of the high tunnel (14' width in a 30' house) performed better than covering one 5' bed at a time, regardless of the materials used.

The tunnels within a tunnel averaged approximately 18°F warmer than outside temperatures. However, the temperature difference for the five coldest nights was about 26°F. “This is significant,” said Steve. “We want the most protection on the coldest nights.”

Steve was puzzled by some of his temperature readings. He has recorded an outside temperature of 17°F below zero when the temperature in the inner grow tunnel was 17°F above zero. The lettuce growing there was perfectly good and harvested for sale. He attributes the survival of the lettuce to some of the freeze protection mechanisms noted in the section on cold stress physiology and to the effects of super cooling.

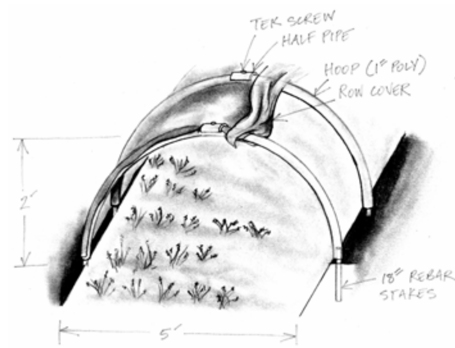
Supporting Interior Tunnels

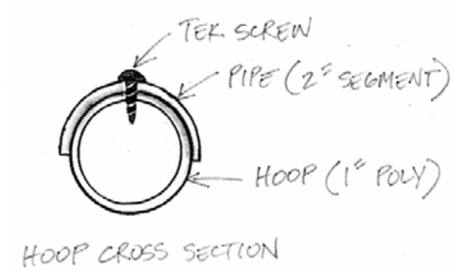
The Zemelskys and other farmers protect their winter crops by laying their “floating” row covers directly on newly seeded ground or over the top of growing crops without any supporting structure. But some growers have experienced a need to support their covers.

For low tunnels in the field, farmers often use hoops of 8 or 10 gauge galvanized steel wire to span their beds. Heavy gauge high tensile livestock wire can also be used. Usually the hoops are about 2' tall and are placed 4' apart. However, for winter production in high tunnels, several growers have noted that steel hoops are not appropriate because they are not tall enough to prevent the cover from touching the crop canopy. Generally plant tissue that comes in direct contact with frozen row cover will become marred and may eventually die.

Steve Moore makes hoops with 8 foot lengths of used polypropylene water pipe (3/4" to 1-1/4" diameter). The pipe ends of the 8' lengths are placed over 18-inch pins pushed three-fourths of the way into the ground on the edges of beds. Row covers may be suspended over these hoops just as would be done in the field.

Attaching the row cover to the bows facilitates ventilation and access to beds for harvest and other horticultural tasks. For each bow, cut a 2" piece of water pipe in half lengthwise. Using either a tek screw or drywall screw, fasten one of these small segments of pipe onto the top of each bow, sandwiching the polyethylene film between. *(See diagrams below.)* To open these mini tunnels, the cover is flung over one side. On a sunny day, the southern exposure is readily ventilated.





Steve closes off the ends of his mini-tunnels with half circles of twinwall polycarbonate or waste polyethylene film. The tunnels themselves are covered with used greenhouse plastic cut to size. Each tunnel spans a single 5' bed, and is about 3' tall.

His tunnels within a high tunnel stay 15 to 20°F warmer than minimum outside temperatures in winter. In sunny weather, he finds it essential to roll or pull up the plastic to reduce unwanted heat within the low tunnels.

The plastic is also pushed out of the way for weeding, watering, and harvesting.

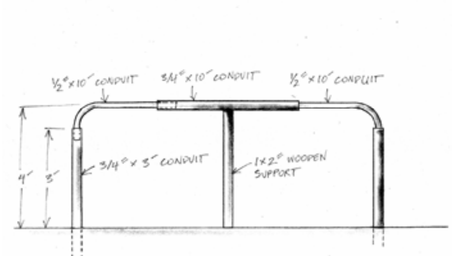
Some of his 30' wide high tunnels are laid out with a center aisle flanked on either side by beds running laterally across the tunnel *(see "Interior Tunnel Layout" on page 57).* Using this configuration, Steve is able to cover half of the cropping area (one side of the entire tunnel) with a single large sheet of row cover.

To suspend the row cover above the crops, Steve uses a long, rail-like hoop. He finds the larger, wider tunnel within the tunnel to be more effective in retaining heat than the smaller, single 5' bed inner tunnels. He has even created a roll-up mechanism for convenient venting and re-covering.

His framework for suspending the floating row cover is made of 1/2" or 3/4" thinwall electrical conduit. These metal pipes are spaced 4' on center to line up with the high tunnel bows. Steve bends one end of this metal pipe to a 90 degree angle to support the framework at a height of 30". He supports the middle of the 14' laterals with a piece of PVC pipe and uses a 2" x 4" to attach each metal conduit to a bow. Row cover can be laid loosely over this framework and scrunched up against the sidewall to open up the growing beds. Alternatively, Steve uses a swedged pipe—the kind used for roll-up sides—spanning the length of the high tunnel, to make a roll-up for the row cover. This roll-up is outfitted with a hand crank.

John Biernbaum created a row cover suspension frame almost 4' high for taller crops in his latest teaching and demonstration high tunnel at Michigan State University. *(See Diagram 12.)* The tunnel itself is 30' wide with 25' long lateral beds. Aisles on both sides in the colder and wetter edges conserve the center area for growing. The design uses a horizontal member for every bow and bed, both of which are 4' on center.

DIAGRAM 12. SUPPORT FRAME FOR INTERIOR POLY FILM OR ROW COVER USING EMT CONDUIT



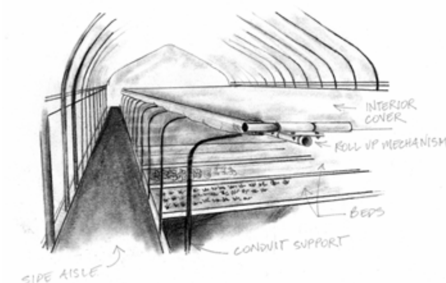


DIAGRAM 12. INTERIOR COVER SUSPENDED OVER EMT CONDUIT SUPPORTS

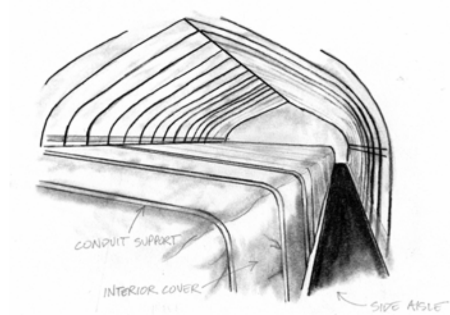


DIAGRAM 12. INTERIOR COVER SUSPENDED OVER EMT CONDUIT SUPPORTS

For horizontals, two 10' pieces of 1/2" conduit, each with a 90 degree bend on one end, cover 18' of the 25' bed length. A piece of 3/4" conduit in the center spans the remaining 7'. The ends of the 1/2" conduit fit inside of the 3/4" conduit. The 5' vertical support pieces (one at each end of horizontals) are made of 10' long 3/4" conduit cut in half. They are driven about 20" into the ground. The bend of the horizontal conduit raises the height a bit more.

Freeze Damage in Plants

There are three stages of freezing. As it gets colder, first the water in the soil freezes. Next, the water between a plant's cells freezes. Finally, water inside a plant's cells freezes, usually killing the plant.

Freezing of Water in the Soil
Water freezes at 0°C (32°F), yet, in the soil, dissolved solids lower the freezing point of water. When soil water freezes, it actually leaves particles and solutes behind.

In the process of freezing, water expands. While this can cause physical damage to the plant root, at times root cells are able to withstand pressures of up to 1000 atmospheres. This ability to withstand pressure varies seasonally and has been shown to increase with cold hardening. Freeze hardening is not completely understood. It is believed that the seasonal storage of sugars, sugar alcohols, and proteins within the cell aids in lowering its freezing point.

In addition to increased pressure, the frozen ground also prevents plants from taking up water. If they cannot replenish the water they lose through transpiration and other processes, they will die of desiccation (drying out). Winter wind can rob water from plant tissues, exacerbating the requirement for water. Both high tunnels and greenhouses are very effective in protecting against this type of desiccation.

Freezing of Inter-Cellular Water
When water changes phase (i.e., from liquid to solid), it releases significant amounts of energy. Freezing water literally releases heat!

In addition, in freezing temperatures, plants actually expel water from their cells into intercellular spaces. This increases the solutes within the cell, lowering the freezing point of cellular water and protecting the cells. This protective action can keep a plant from structural damage, even if it looks wilted or appears to be frozen.

Freezing of Intra-Cellular Water
Under most circumstances, when the temperature gets cold enough to freeze the water inside a plant's cells, the plant dies. It is ice crystal formation that kills the plant and not freezing per se. Rapid freezing of cells can occur without ice formation. Supercooling can also alter the freezing point, but this is a poorly understood process.

In Walking to Spring, their book about high tunnels on their farm about 100 miles southeast of Louisville, Kentucky, Paul and Alison Wiediger recommend keeping high tunnel plants on the dry side in the cooler months. "We don't let them wilt, but we don't keep them really turgid either…Dry conditions allow plants to accumulate more sugars in their cells, and acclimatize the cells to the cold."

"We can go in the cold frame on a sub-freezing morning (say below 20°F) and all the plants look dead—lying on the ground, you know the frozen look! But by 10 AM or so, especially if the sun is out, they are all upright and beautiful again. It breaks your heart the first time you see it, but it invokes wonder two or three hours later."

"Last year we had the soil at a good moisture level in mid-November and we didn't need to water until February…When we need to water [in the winter], we watch the weather forecast for a window of several days and nights above freezing. We water on the first day of that window, so that by the time the freezing temperature returns, the plants have adjusted to the extra water."

Soil and Crop Management

Soil Management

Most high tunnel growers produce their crops in the soil on which the tunnel rests; therefore, the quality of the soil under your tunnel will be critical to your success. Given that you will spend a good deal of money to construct a premium growing structure, it makes sense to complete the job by making certain the soil environment is also a superior one.

A coarsely textured, well-drained soil is best for high tunnel production. Clays, because they drain and warm relatively slowly and have a tendency to accumulate salts, are the least desirable soils for high tunnels. *(See "Salinization" on page 56.)* However, growers have been able to make do with a wide variety of soils, amending and improving them over time.

The structure of the soil in the relatively small space under a tunnel can be dramatically altered. The addition of substantial amounts of compost or leaf litter will increase the organic matter in the soil, thereby increasing the soil's capacity to provide oxygen, water, and nutrients to the crop.

To lighten heavy clay soils, organic matter can be added in a variety of forms, besides finished compost. For example, aged wood shaving with leaves or a small amount of manure or another organic nitrogen source can improve the structure of a heavy soil. Avoid fresh wood shavings as they will tie up soil nitrogen. John Biernbaum improves the soils in his high tunnels with significant amounts of animal bedding from weekend livestock shows on campus. This bedding has a low concentration of manure.

Monitoring Soil Health

A good monitoring program evaluates the physical and biological composition of your soil as well as its chemical makeup.

Several important indicators of soil physical health are easy to monitor. To determine if your soil is compacted, for instance, you can use a penetrometer, a tool that measures resistance to penetration. Although these devices are expensive, they can sometimes be borrowed from your local Extension office. You may make an effective penetrometer at home by putting a simple handle on a straight piece of rebar. The tip should be sharpened to a dull point. You should be able to push it at least 12 inches down into the soil before encountering resistance.

You can also check plant rooting depth. If you observe plant roots to be growing horizontally at a shallow depth, then the soil is probably too compacted for good root penetration or water drainage, and should be loosened by some form of tillage. When preparing the soil for planting or when removing crop debris, take the time to determine if earthworms are present and at what level.

Traditional chemical analyses are as important in tunnels as they are in the field. Nutrient and organic matter levels, soil pH, and electrical conductivity (salts) should all be measured periodically.

Adding Nutrients

High tunnel production is intensive, with faster growth than typically found in field production. In some cases, three or even many more successions of crops are grown in a tunnel during a single year. (Greens growers can produce as many as eight crops per year in the Northeast.) Because of this intensity, high tunnel soils benefit from relatively high applications of compost, fertilizer and other soil amendments. Similarly, large applications of organic matter are also beneficial.

Farmers approach nutrient management in high tunnels in a variety of ways, many of which are similar to their field practices. One notable absence from high tunnels is the practice of cover cropping, even on farms that employ cover crops in their fields. Farmers have offered several reasons for the lack of interest in cover cropping in high tunnels: first, there is no risk of erosion inside a tunnel; second, space is at a premium; and third, windows of time for cover cropping are minimal, particularly for farmers who use their tunnels year-round. Some cover crops could potentially serve as over-wintering habitat for pest species.

Many farmers rely heavily on compost as the foundation of their fertility programs. A balanced compost added to a good soil can provide the range of nutrients required for crop development, and some farmers depend upon it exclusively for fertility. Too much of a good thing can create its own problems, however. Using too much compost is not only expensive; it can also lead to the build-up of salts and outbreaks of root-feeding arthropods such as tiny symphylans.

Several farmers reported adding large amounts of compost to a new high tunnel, and then adding modest levels thereafter. For a new tunnel at Slack Hollow Farm, compost was added at the rate of 10 tons per acre. The Blomgrens also load up at the onset. Then, before each new crop, they spread just five gallons of compost per 40 square foot bed—a layer of less than an eighth of an inch. They add this compost to enhance microbial activity, nutrient availability, and soil water-holding capacity. These quantities improve the soil's structure, but don't affect soil texture. Compost must be free of viable weed seed.

Composted manures typically have an excess of phosphorus in relation to nitrogen. If compost is applied at a rate designed to meet crop nitrogen needs, phosphorus will be oversupplied. Farmers who have recognized this problem are reducing their compost applications and applying alternative sources of nitrogen. When determining fertilizer rates, they are sure to credit the compost for the nutrients it has supplied.

When soils are cool in the spring, microorganisms are not converting nitrogen to an available form fast enough to sustain good plant growth. This is the time to consider adding a soluble nitrogen source, such as Chilean nitrate (guano).

Just as periodic soil testing is advisable, it is also wise to have compost tested for nutrient availability, pH, and the presence of substances like salts or toxics that could be detrimental to crops. (A persistent herbicide called chlorpyralid has contaminated composts containing lawn clippings and other materials.) Farmers can request test results from commercial composters or submit compost samples to laboratory services like Dairy One.

Some farmers manage soil fertility more strictly by the numbers and with less bulky materials. Fertigation, with soluble fertilizers injected into a drip irrigation system, is the basic program employed by many farmers who operate in controlled or managed environments, such as high tunnels and greenhouses. Growers, like Keith Cramer at Cramer's Posie Patch in Pennsylvania, incorporate a chemical fertilizer into the soil prior to bed preparation. Steve Groff, also in Lancaster County, Pennsylvania, also uses his drip irrigation system to supply his high tunnel tomato crop's nutrient needs.

Like fertigation, foliar feeding makes soluble nutrients immediately available. Two farmers in this project foliar feed Epsom salts, kelp, and fish products respectively. This practice can be used with a variety of micronutrients as well.

Day Length Affects Flowering

If you extend the season at either end to achieve earlier or later harvest dates, some cut flowers will not perform as anticipated. Plant physiologist Chris Wien, a Cornell professor, realized that day length was the culprit when his several of season extension trials failed.

He attempted to get sunflowers to bloom in the spring rather than summer and he started *Rudbeckia hirta* (Black-eyed Susan) late to get fall flowers. To prevent mishaps, he suggests experimenting on a small scale before you decide to grow a flower cultivar off-season. He found that seed catalogs are not always correct on this point.

(See "Daylength affects rudbeckias, sunflowers," June 2006 Growing for Market.)

Nitrate Uptake in Low Light Greens

It has been well documented that the ingestion of excessive nitrates from our diet and water can be detrimental to human health, especially in the very young. The European Union has set limits for nitrate levels in greens. The United States has not yet taken action. Farmers should be aware of this food safety issue and act accordingly in order to produce healthy food.

Greens grown in low light (off-season, winter production) have greater potential to accumulate unhealthy nitrate levels. Plants can take up nitrates in excess of their needs. There are a number of management strategies that can moderate nitrate uptake and improve its assimilation, giving the end result of healthy greens with low levels of nitrates.

The range of suggested practices includes:

- Harvest greens later in the day.
- Do not sell older, more mature leaves.
- Supply adequate soil moisture.
- Maintain soil pH on the high side of the normal range.
- Provide balanced soil fertility.
- Grow in warmer temperatures.
- Select cultivars that better assimilate nitrates (when this characteristic is known).
- Use legume-based compost as a source of nitrogen.

Salinization

Like irrigated lands in arid climates, high tunnels may be vulnerable to the accumulation of salts. If allowed to build up, salts may cause damage to crops. If soils within the high tunnel are well-drained, irrigation water may leach some of the salts through the soil profile, as occurs with adequate, regular precipitation outside. However, if the soil is poorly drained, accumulated salts will actually be brought up to the surface when soil moisture evaporates.

The application of synthetic fertilizers, animal manures, or manure-based compost (all with significant salts) can result in the build up of salts over time in high tunnel soil. Sodium chloride—table salt—is not the only problematic salt in soil. At excess levels, other salts also cause drought-like stress, interfere with seed germination, and inhibit plant growth. Plants with higher drought tolerance typically handle increased soil salt concentrations better than more drought susceptible plants. Nutrient uptake and other metabolic processes can also be disturbed by soil salinity.

In addition to directly affecting the plants, elevated salinity levels have been anecdotally associated with damaging outbreaks of symphylans, tiny arthropod pests (also known as garden centipedes) that feed on plant rootlets and root hairs. "The effects of high soil salts aren't pretty on plants or income," says Steve Moore, speaking from personal experience.

Salt stress can mimic the symptoms of drought stress, nutrient deficiency, and root rots caused by soil-borne pathogens. Thus, it makes sense to pursue a proper diagnosis of the problem. One way to test for salinity is with an electrical conductivity (EC) meter (available for under $100). *(See "Ben Meadows" and "Pike Agri-Lab" on page xx.)* Electrical conductivity is a measure of the ability of a solution to transmit an electrical current. The higher the salt level, the greater the current. EC readings are usually given in deciSiemens per meter (dS/m). In general, readings over 1 dS/m may indicate problems for some fruits and vegetables. When comparing your EC values to those that are published, be sure you are using equivalent sampling procedures. Otherwise, you will not be comparing "apples to apples."

Salinity Tolerance of Common Vegetables Grown in Utah

Crop	**Threshold value**	**10% yield loss**	**25% yield loss**	**50% yield loss**
	EC (dS/m)	EC (dS/m)	EC (dS/m)	EC (dS/m)
Asparagus	5.0	8.0	11.0	13.0
Beans	1.0	1.5	2.3	3.6
Beets	5.3	8.0	10.0	12.0
Broccoli	2.7	3.5	5.5	8.2
Cabbage	1.8	2.8	4.4	7.0
Cantaloupe	2.2	3.6	5.7	9.1
Carrot	1.0	1.7	2.8	4.6
Cauliflower	2.7	3.5	4.7	5.9
Celery	1.8	3.5	5.8	10.1
Corn, Sweet	1.7	2.5	4.0	6.0
Cucumber	2.5	3.3	4.4	6.3
Lettuce	1.3	2.1	3.2	5.2
Onion	1.2	1.8	2.8	4.3
Peas	0.9	2.0	3.7	6.5
Pepper, Bell	1.3	2.2	3.3	5.1
Potato	1.7	2.5	3.8	5.9
Radish	1.2	2.0	3.0	8.0
Spinach	3.7	5.5	7.0	8.0
Squash/pumpkins	3.9	4.9	5.9	7.9
Sweet Potato	1.5	2.4	3.8	6.0
Tomato	2.5	3.5	5.0	7.6
Turnips	0.9	1.9	3.1	4.9
Watermelon	2.0	2.5	3.5	4.5

(Continued on next page.)

“Salinization” continued from page 56.

EC is the electric conductivity of the extract using a water saturated paste solution. Note the reduction of yield as a function of increased salts. *From Utah State University Extension, http://extension.usu.edu/files/agpubs/salini.htm.*

The following strategies can help reduce soil salinity in high tunnels:

- Provide adequate soil drainage through natural means (locating tunnels on well-drained soils) or improve soil drainage through artificial means (drainage tiles or pipes).
- Allow the soil to dry and then scrape off a top layer of soil and salts. Add more soil as needed.
- Flush out the salts periodically. This can be done either by removing the cover or by flooding the high tunnel during the off-season. This second approach requires a great deal of irrigation water, however. When changing the poly film every four years, consider leaving the tunnel uncovered and exposed to natural precipitation for a period of time.
- Reduce the amount of salt-forming fertilizers and use vegetable-based compost containing legumes.

In caterpillar and multi-bay tunnels such as Haygroves, which are uncovered during the off-season, salt build-up is eliminated because precipitation flushes away the excess.

Adapted in part from “Salt Tolerance of Plants”, Alberta Government Agriculture, Food, and Rural Development, www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex3303.

Interior Tunnel Layout

The growing space in a high tunnel is often broken up into beds. Some farmers create raised beds slightly or substantially higher than the surrounding pathways by adding compost and/or soil. Beds can be made manually with hand tools, or mechanically with equipment such as a roto-tillers or bed shapers. A good tunnel layout optimizes crop production and accessibility. Farmers strive to maximize the growing area since space is costly and limited, while allowing ready access to all portions of the tunnel.

Longitudinal Beds

Setting up the rows or beds along the long axis of the tunnel is the most typical high tunnel layout, and is especially suited to growing tomatoes or other trellised or staked single row crops *(see Diagram 13)*. Tomatoes benefit from goods air circulation, which longitudinal rows can provide via large gable end vents and doors.

A long row configuration has other advantages. It makes it easier to utilize inner row covers on a bed-by-bed basis. Fewer connections are needed for T tape. Long rows facilitate the use of tractor-driven equipment. They can also make for a simpler system, especially if only one or very few different crops are grown in the tunnel. Long rows also allow the easier use of overhead grow troughs.

Plants grown along the perimeter of a tunnel may exhibit an “edge effect,” with poorer growth common closest to the side walls because temperatures are lower there. Wider high tunnels have less of this chillier growing space relative to their overall area than narrower high tunnels, and this should be considered when determining high tunnel size. Some farmers reserve this space for especially hardy crops. For example, the Zemelskys grow hardy pea tendrils around tunnel perimeters in winter.

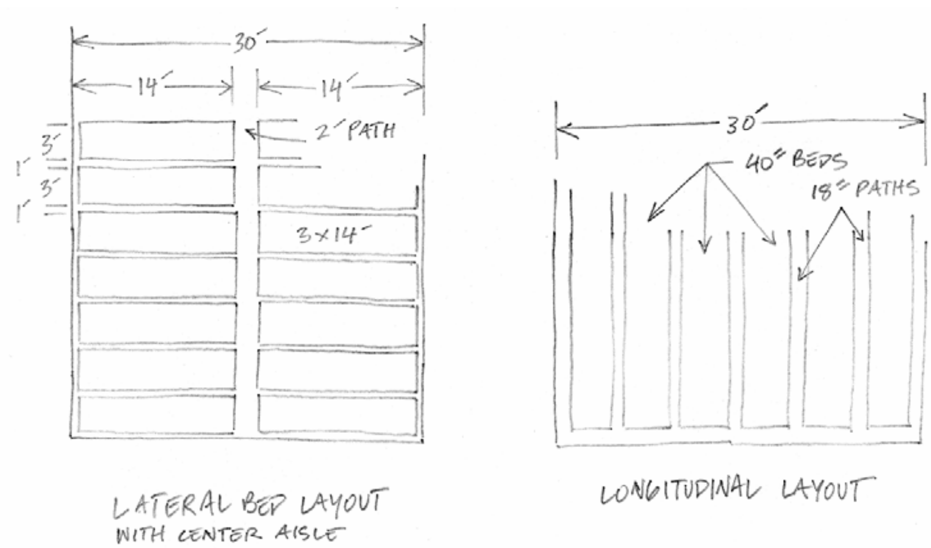


DIAGRAM 13. BED LAYOUTS

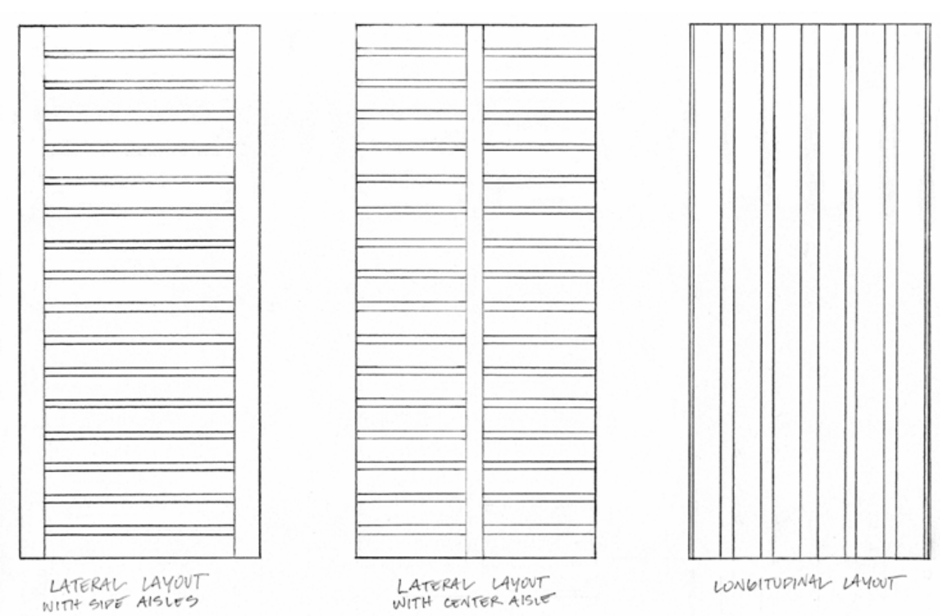
Lateral Beds

Orienting beds laterally across the width of a high tunnel is another solution to the twin challenges of access and crop optimization *(see diagram below).* This layout utilizes a center aisle, with beds running perpendicular to the aisle. Even in a 30' wide tunnel, a worker never has more than 14' to go from the aisle to the far end of a bed. For harvesting as well as for transplanting, this kind of accessibility means a lot. Using this configuration, the farmer can afford to make the single, center aisle generously wide without worrying about squandering prime growing space. In fact, this layout provides slightly more growing space than one divided into longitudinal beds.

The central aisle makes it easier to move materials in and product out. Worker movement is also more efficient. Flats for transplanting and harvest lugs can be put in the lateral pathways so that workers don’t have to walk over them when coming and going. A monorail or overhead tram can even be installed to mechanically move materials down the center. The central aisle layout simplifies the use of hoses. A drawback for those using drip irrigation is that many more drip starts are required because there are so many more short beds. A 30' x 144' high tunnel with a center aisle and beds spaced 4 feet apart has as many as 70 individual beds.

For tunnels with an East-West orientation (which is best for winter growing), configuring lateral North-South beds will result in less shading of crops. When using interior covers, the lateral bed layout enables the farmer to cover the entire tunnel with just two pieces of row cover, one to the right of the central aisle, and one to the left. Steve Moore has designed a simple rail system that supports the row cover over each half of the tunnel’s beds, making covering and uncovering a relatively quick process *(see page 52 for the “tunnel within a tunnel” discussion).* This approach saves labor and retains heat better.

Lateral beds can also be laid out across the entire structure, with aisles situated along the long sides of the tunnel. This layout makes sense under cold growing conditions, as the edges offer the least protected microclimate, but has a drawback in that it situates aisles where there is the least amount of headroom in a high tunnel. Slack Hollow Farm is currently using a variation on this layout.



Crop Establishment

Seedbed Preparation

High tunnel growers use both flat and raised beds, and some use both in different situations. Raised beds are especially beneficial to spring crops because they improve soil aeration and facilitate water drainage, resulting in warmer soils, increased microbial activity and nutrient availability, and enhanced root development.

There are many ways to prepare the seedbed within a high tunnel. The spectrum of possibilities ranges from hand tools to small-scale, tractor-powered field equipment. Self-propelled roto-tillers are an intermediate option between tractors and hand tools. As long as a tractor can be found that fits inside the structure, equipment such as chisel plows, spaders, tillers, bed shapers, and mulch layers can be used in high tunnels. Equipment manufacturers have begun to make specialized tunnel-scale equipment. Ample ventilation will make the use of diesel and gasoline engines in high tunnels a safer and more tolerable task.

Winter growing pioneer Eliot Coleman has devised a market garden production system relying solely on hand tools, some of which he designed. After adding soil amendments, he loosens the soil with a broad fork (a 24" wide fork that harnesses body weight rather than muscle power to loosen soil without inverting it). Next, the beds are leveled, and debris, roots and rocks are removed using an extra-wide bed preparation rake. Short tubular fingers (which can be purchased with the rake) can be placed over selected rake tines to individually mark rows or a grid pattern for seeding or transplanting. *(See “Johnny’s Selected Seeds” on page 69.)*

Seeding and transplanting

Because of the tight spacing in a high tunnel, seeding and transplanting is usually done manually. Northern producers use transplants for long-lived, warm weather vegetables and for most cut flower species (other than those grown from vegetative structures like bulbs or corms). In contrast, direct seeding is the popular method for starting short season, more closely spaced crops like salad greens and spinach.

There are a variety of push seeders on the market costing between $100 and $500 and up. Earthway Company manufactures one of the least expensive one-row seeders on the market. Several of these light-weight plastic seeders can be attached in a gang and pushed by hand. The more durable old Planet Junior seeders are still available from used equipment dealers *(see "Tools" on page 70)* and on eBay. In addition, Planet Junior production has resumed. Johnny's sells a European push seeder modeled after the Planet Junior (though welded rather than cast) for half the price of the new $500-plus version. One-, four-, and six-row pin-point seeders are another mainstay of tunnel growers. Designed for seeding salad crops in close-row spacing, they create uniform plantings that do not need to be thinned.

Crops that are transplanted in the field are also usually transplanted in the high tunnel, including tomatoes, peppers, eggplants, cucumbers, summer squashes, melons, basil, and other herbs. Early season transplants are usually started in a heated greenhouse (or in compost-heated hot beds within the high tunnels), and transplanted into the unheated high tunnel when the climate becomes conducive to their growth.

Most cut flowers are also transplanted. For some slow-growing or hard-to-germinate species, purchasing plugs from a nursery can save on labor and fuel costs. However, plugs bring the risk of thrips and other pest outbreaks that can cause difficulties in the entire house or, worse, the multiple houses into which the starts from the greenhouse are transplanted.

Direct seeding is not the only way to start salad and braising mix crops like Asian greens, lettuces, chards, bok choys, and other relatively quick-growing greens. For greens following tomatoes, Ted Blomgren finds that transplanting allows him to keep the tomatoes in the ground three weeks longer. Then, within days of removing a tomato planting in the fall, the newly transplanted winter crops are well-established for his winter CSA.

Additional tomato yields, in his view, more than offset the cost of soil mix and labor for tending flats of seedlings in the greenhouse. This approach also reduces the risk of germination failure and gives him the plant stands for which he is looking.

For these mid-fall plantings, Ted sows up to five seeds per cell in 98-cell trays. This seeding yields clumps of plants that are set six inches apart within and between rows in 3' wide high tunnel beds. Arugula, kales, Asian brassica greens, chard, and Red Salad Bowl (his favorite lettuce cultivar for winter growing) are among the crops he grows this way.

As a rule, the way to boost the economic return from the high tunnel investment is to keep its growing space well utilized. Intercropping and succession cropping are strategies for making optimal use of space. Interplanting scallions or fast-growing greens with slow-growing tomatoes, for example, are ways to boost economic returns from a high tunnel.

Watering

Careful attention should be paid to irrigation in high tunnels. The plant canopy in a high tunnel is usually greater than it is in the field, and water needs are correspondingly greater. During the spring and summer, when high tunnel crops are growing especially fast, their demand for water is quite high. It is not uncommon for high tunnel tomato and cucumber growers to irrigate every day during the height of summer. Water needs shrink as the days become shorter and colder. By winter, very little irrigation is required. Over the course of the year, and depending upon the growth stage of a crop, growers will adjust the amount of water provided.

Drip irrigation is a common method for providing water to plants in high tunnels. High tunnel systems are identical to those used in the field. Drip tape delivers water without wetting foliage. Preventing prolonged leaf wetness, which contributes to crop disease, is especially important in warm season crops. Drip systems are often automated with a timer to ensure regular watering. Using multiple drip lines on a bed will also provide for the water needs of multiple rows of crops. Drawbacks to drip irrigation include the cost and amount of plastic involved and the fact that drip tape interferes with crop cultivation.

Direct seeded plantings, especially the greens and root crops that are closely spaced, may be less suited to drip irrigation. For these applications, overhead sprinklers have a place in high tunnels. To break the disease cycle, watering should be done in the morning to allow plants to dry before evening.

An irrigation system can be devised that uses either drip tape or overhead sprinklers, depending on the crop rotation in the high tunnel. Low pressure, small volume micro sprinklers are available that can run off the same main trunk as drip tape, making the conversion of an irrigation system simple. New irrigation technology and products are becoming available all the time.

Pest Management

Weed Management

No farmer wants to spend precious time combating weeds. Besides competing with crop plants for light, nutrients and water, weeds may serve as reservoirs for plant pathogens and arthropod pests such as thrips, aphids and spider mites. These pests may also find crop plants attractive. They often act as plant disease vectors, too. Weeds can also turn harvesting and processing of certain crops like salad greens into an aggravating task. For these reasons, and because weeds that produce seeds will cause trouble later, allowing weeds to grow is not a good idea.

Weed problems are compounded by the enhanced microclimate of a high tunnel. Its longer season and more moderate cold season conditions provide a perfect habitat for many weeds. For instance, chickweed, a winter annual that flourishes under the mild winter conditions present inside a greenhouse, can cause serious difficulties for winter salad greens growers.

Whether inside a high tunnel or in the field, reducing the weed seedbank in the soil is a key principle in weed management. Unless preventative measures are taken, high levels of weed seeds are likely to translate into high weed pressure. The good news is that within the finite boundaries of a high tunnel, farmers have found it possible with vigilance and timeliness to regain the upper hand on weeds, even after they have raged out of control.

High tunnel growers use hand hoes, stale seedbed techniques, and plastic and organic mulches to manage their weeds. Hand hoes are particularly well suited to the intimate environment of a high tunnel. If used when weeds are very small, hand hoes provide fast and effective weed control. Often, a single well-timed hoeing will produce a weed-free salad or cut flower crop. If given a weed-free start and good growing conditions, these fast-growing crops should out-compete weeds. Hand hoes are available in several configurations (e.g., oscillating stirrup hoes, push-pull hoes and collinear hoes), and in sizes ranging from 3" to 12" wide. *(See "Tools" section on page 70.)*

Stale Seed Bedding

Stale seed bedding is a versatile approach that allows the grower to nip weed pressure in the bud. The idea is to encourage weed seeds to germinate and then to kill the emerging weed seedlings before they can take hold. This process is repeated up to several times in rapid succession typically before the crop itself is planted.

As a new grower, David Zemelsky at Star Light Gardens in Connecticut experienced an incremental build up of the weed seedbank in his high tunnel beds. Weediness ultimately impacted yields in his greens. As a result of his struggle with weeds, he has become a believer in the value of stale seed bedding.

As an example, consider stale seed bedding for a winter crop of baby brassica greens following tomatoes. First rip out the tomato vines, add soil amendments, and renovate the bed. To avoid bringing up new weed seeds, do not invert the soil! Instead, loosen the bed with a broad fork as one of several ways to achieve this end. After the bed is readied for planting, firm it and, if necessary, irrigate to encourage weed seeds to sprout. When the new weed seedlings are still in the white thread stage, use a propane flamer or very shallow tillage with a stirrup hoe to destroy them. Take care not to bring up more weed seeds from lower in the soil profile when tilling.

Carrying out stale seed bedding requires a several week break in the cropping cycle. Because high tunnels are an expensive horticultural environment compared to open fields, it is worth making this sacrifice to optimize growing conditions before weed pressure gets out of hand. The farmer must be an effective manager to take advantage of the narrow window available in the crop sequence for stale seed bedding.

Another weed problem that growers may face is the encroachment of perimeter vegetation, including quack grass, into a tunnel. If regular mowing is not sufficient, try landscape fabric as a weed barrier. It should be well secured on bare ground along the outside perimeter of the tunnel. Mow right up to it. A foot wide barrier of landscape fabric on a tunnel's inner perimeter is also an option.

Mulching

Mulching with organic materials such as rye or oat straw is an option for weed prevention in crop beds for tomatoes and the like, especially if additional soil warming is not essential. Straw retains soil moisture and eventually breaks down into soil organic matter, with no disposal needed.

However, straw left in place indefinitely can attract mice and other unwanted rodents. Organic mulches can exacerbate slug infestations. Straw mulch may also interfere with the functioning of precision seeders. Andy Jones of Intervale Community Farm experienced this problem when he direct seeded greens after a straw-mulched tomato crop. He warns, “Even a fine toothed landscape rake leaves behind enough bits to give the planter (and me) conniptions.”

Straw has another role between beds. Ted and Jan Blomgren at Windflower Farm use straw to prevent weeds between beds, whether they are mulched with plastic or left bare.

For long-lived crops such as tomatoes, peppers, melons, and cucumbers, many farmers opt for synthetic mulches to stymie weeds and heat the soil. Their use in tunnels is no different from field situations. Black (or other colored) plastic can be applied with a mulch layer or laid down by hand. U-shaped ground staples—6" galvanized steel or plastic staples—are one way to pin down this plastic film.

After amending the soil in preparation for planting, Tim and Janet Taylor, at Crossroads Farm in Vermont, cover the ground in their high tunnels from wall to wall with a solid sheet of heavy black plastic mulch. Steve Groff, at Cedar Grove Farm in Pennsylvania, plants tomatoes into heavy-duty landscape fabric. At Cramer’s Posie Patch, white plastic mulch does double duty—it suppresses weeds and cools the soil for cool season cut flowers.

One way to make planting holes in landscape fabric is to use a propane torch. Minor (or major) mishaps can occur, as the material is flammable, and care should be used. Cutting an “X” in the fabric is another method. Both approaches have their proponents and detractors.

Plastic mulch can harbor plant pathogens, some of which may overwinter in folds of the material so its reuse can be risky. The bacterium that causes Bacterial Canker in tomatoes, for example, is thought to overwinter on tomato stakes and mulches. Where possible, rotate landscape fabric for use with other crops that do not host the same diseases.

Chris Lincoln at New Minglewood Farm used 6' wide pieces of landscape fabric to cover the ground in and between four 10' x 100' walk-in tomato tunnels. With 2' between each tunnel and two rows within each tunnel spaced 6' apart, he was able to plant the tomato transplants at the intersection where one piece of fabric ended and the next started.

Managing Diseases in High Tunnels

Many growers have chosen high tunnels, in part, because they offer protection against the diseases their field crops encounter. Septoria leaf blight, (one of the most troublesome diseases of tomatoes in New York State), for example, is virtually unheard of in high tunnels. Crops inside high tunnels usually experience much shorter periods of leaf wetness than crops in the field. Diseases will not occur in the absence of the environmental conditions necessary for the existence of the pathogen that causes them.

Nevertheless, disease is not eliminated in high tunnels. Leaf mold (*Fulvia fulva*) on tomatoes, for example, has become increasingly commonplace. The danger of an infestation is highest when airflow inside the tunnel is low and relative humidity is high. Selecting resistant varieties, reducing plant populations, increasing tunnel ventilation (by adding gable-end vents, etc.) and promoting improved air circulation inside the tunnel (e.g., adding fans) are each parts of a potential solution to the problem.

Growers have reported other disease problems as well. These include bacterial canker and Verticillium wilt in tomatoes; powdery mildew in tomatoes, cucumbers, squashes, late season lettuces, and flowers; Alternaria leaf spot in brassicas; Fusarium root rot in lisianthus; and leaf spot in Bells of Ireland, among others.

Tomato growers should pay careful attention to variety selection. Disease-resistant varieties with good yields and eating qualities are increasingly available. Where the incidence of soil-borne diseases has been high, some growers have turned to grafting. Mike Collins, who grows greenhouse tomatoes in southern Vermont, grafts ‘Buffalo’ scions onto a vigorous and disease-resistant rootstock. The practice increases his cost of production but it also provides him with superior yields of excellent tasting fruit.

A preventative approach to disease management is the best strategy. In general, it is best to take steps to enhance air movement and reduce relative humidity. The following tactics are also recommended:

- Provide adequate plant-to-plant spacing to avoid excessive shading and enhance air circulation.
- Select disease-resistant varieties.
- Maintain a pest-free environment. Keep high tunnels free of the weeds that harbor diseases and the insects that transmit them.
- Practice good sanitation. Remove diseased crop residues, and sanitize mulches and trellises.
- Provide the nutrients and water necessary for optimal crop growth.
- Utilize a good crop rotation.
- In the absence of a winter crop, open the tunnel so that disease spores can be killed by winter temperatures.

Ecological Insect Management in High Tunnels

By Steve Moore

Insect pests generally cause less damage in high tunnels than they do in the field, in part, because the crops inside are growing at a time when pests are less active. The tunnel itself functions as a barrier to insect pests, at least until temperatures warm to the point that the tunnel sides are open much of the time. Nevertheless, insects in high tunnels can cause economic losses. Aphids and thrips, both of which have fairly broad host ranges, can be particularly troublesome in high tunnels. And high tunnels can also harbor pests and allow them to hatch earlier than outside.

Years of experience have proven the effectiveness and shortcomings of a biologically-based high tunnel pest control program. Here are some important considerations to achieve good control of potential "pests."

Develop Healthy Soil

Healthy, balanced soil is the single most important factor in attaining healthy plants. Our most important amendment is well-made biologically active compost. We also use this medium for our flats and transplants. We avoid excess nitrogen as it compounds pest and disease problems and it makes the food less nutritious.

A research project reinforced my intuition that healthy soil leads to healthy plants. As part of a three-year beneficial insect project, we reared beneficials in our own greenhouse. We acquired aphid-infested tomato plants, re-potted several of them, and placed them in insect cages. A colleague who was counting the insects remarked that only certain plants had any aphid egg deposition. After a few weeks, we took a minute together to look at the plants. We found that only the plants in prepared, sterilized media were hosting the aphids while those in our compost were free of aphids.

Encourage Beneficial Insects and Other Arthropods

According to the old adage, "diversity leads to stability," we are aiming for a balance between the "good" and "bad" organisms. Eliminating all of the bad (pest) organisms invites trouble, and in the absence of beneficial insects, pests can quickly become a problem.

Avoid synthetic pesticides and use natural and botanical pesticides sparingly. As a general rule, beneficial insects are more sensitive to pesticides than pests. Synthetic chemicals often have long residual effects. You will be amazed at the number of beneficial insects indigenous to your greenhouse when you don't suppress them.

Don't bring in plants that may have pests or pesticide residues. We learned this the hard way by accidentally bringing in tomato plants sprayed with the insecticide, Lannate (active ingredient methomyl). The long-lasting residues of this insecticide are lethal to most beneficial insects for 8 to 12 weeks. Because the Lannate-treated tomatoes wiped out beneficial populations that came in contact with them, we were unable to introduce beneficial insects in a timely fashion. Although we applied other strategies, the aphids almost got ahead of us. *(See "Koppert Side Effect Database" on page 74.)*

Another high tunnel grower reports that pests come along with every shipment of plugs. For example, fungus gnats arrived with lisianthus plugs almost every time they order them.

Remove weak and injured plants. Just as wolves following deer herds will cull the weak and old, insect pests and plant disease organisms will hone-in on those plants that are best not left in the gene pool. As farmers, we select for traits such as yield, climatic adaptability, or taste. Yet we often ignore pest susceptibility traits by substituting chemical controls instead.

Know, Scout, and Monitor

Know your insect neighbors at all stages of their life cycles. If you have ever looked at the larval stage of a ladybug, you will agree that they look anything but helpful. Yet even in this stage, they are aggressive pest controllers. A good insect identification book *(see page 74)* that shows the various insect life stages and lists their primary food sources is indispensable.

Careful scouting will enable you to discover insects and diseases (and estimate their incidence) before it is too late to manage them. In scouting, typically 2% of the plants should be observed. Over time, you will become familiar with which insects like which plants and where to look for them. For example, whiteflies "like" the third set of leaves down on tomato plants.

Sticky cards are a well-accepted and inexpensive monitoring tool. Yellow cards attract most insect pests, including whiteflies and aphids, while blue cards attract thrips. Attach these cards to posts or strings with clothespins. Write the date on the card so it serves as a record of pest activity. Each card can be used for an entire month. For the first week, remove the protective paper from one half of one side of the card. The next week, place clear plastic wrap over the used section and remove the protective cover from another half of the card. The next week, continue on the back of the sticky card. At the end of the four-week period, the card provides a snapshot of weekly changes in the populations of certain pests.

In addition to scouting and sticky cards, there are other monitoring practices. Index plants attract specific pests. For example, to determine if thrips are present, use New Guinea Impatiens, a plant they favour. Plants like these can also function as a trap crop that will be destroyed in order to reduce the specific insects. Exercise caution when using this approach. Early in our greenhouse experience, we grew Impatiens transplants for sale in part of a tomato greenhouse. This was a big mistake, as we invited every thrips in the county to infest our tomatoes.

Pest Control Options

Sometimes an insect pest population exceeds the level at which beneficial insects can provide adequate or timely control. Faced with this situation, I might turn to a biorational insecticide, such as a fatty acid like Safer's Soap. A soap application can knock down localized outbreaks of certain pests (e.g., aphids and whitefly), allowing beneficial populations to gain an advantage.

A drawback of this strategy is the potential harm to beneficial insects populations, for even these soaps have a lethal effect on some beneficials. Restrict the use of botanical pesticides such as rotenone and pyrethrum. Though natural, these pesticides can devastate beneficial insects as well.

Beneficial insects can be purchased to help bring particular pests under control. It is absolutely critical to introduce beneficial insects before the pest population can no longer be controlled by beneficials. Therefore regular monitoring is an essential component of any biological control program.

In my climate and growing conditions, I have introduced parasitic wasps such as *Aphidius colemani* to control aphids and *Encarsia formosa* to control whitefly. Beneficial insect suppliers can help you determine what species of parasitoid or predator will be most appropriate and effective for your situation. These suppliers provide basic directions on how to use them and often will help with troubleshooting as it is in their interest for you to be successful with your beneficial introductions. *(See "Beneficial Insects" on page 69.)*

Provide Food and Habitat for Beneficials

Growing in the soil (as opposed to hydroponically) allows many beneficial insects to complete their life cycles and hence respond to pest pressures. For example, *Amblyseius cucumeris,* a predator mite that relishes thrips, needs the soil for part of its life cycle. Additionally, undisturbed soil will encourage ground and rove beetles, generalist insect predators.

Some beneficials cannot fly. These beneficials are easily stranded on a plant "island" after they have eaten all the pests within their reach. When the canopy of plants inside a high tunnel touches, it provides a concourse for wingless beneficials such as predatory mites and midge larvae. This allows them to walk between plants so they can access and attack their pest prey. If your plants don't touch, you need a different beneficial.

Feed beneficial insects. One study documented a 600% increase in beneficial insects where they were fed. One nectar substitute is 3 to 6 ounces of powdered sugar dissolved in a gallon of water. A pollen substitute is a half-pound nutritional yeast dissolved in water. Spray these solutions every week to 10 days when you see pests. When using these nectar and pollen substitutes, exercise caution about foliar diseases.

Insectary Crops

We establish insectary crops for food and habitat. These are plants that flower rapidly and are good nectar sources, providing high-energy food for beneficial insects. Excellent insectary plants include dill, cilantro, and others in the *Umbelliferae* family; yarrow; sea holly; and crimson clover. In a 30' x 96' hoop house, we often plant 10 to 12 square feet of permanent insectary plants throughout the high tunnel.

"Banker plants" are host plants grown to rear pest species that are not harmful to the cash crop. Banker plants can be grown in the high tunnel. The pseudo-pests raised on the banker plants attract and increase the population of beneficial insects that can control the "real" pests on cash crops. A classic example is using barley or other small grains to raise grain-specific aphids. These aphids, in turn, attract beneficial insects which can control populations of other types of "pest" aphids within the tunnel.

Cherish Your Spiders

Spiders consume twice their body weight every day. While spiders are indiscriminate eaters, investigators have found that at least 80% of their diet consists of pest insects. *(See "LeSar and Unzicker" article referenced on page 74.)* Spiders eat aphids, leafhoppers, whiteflies, and cucumber beetles, as well as many other pests, and their pheromones also scare off a lot of insects.

Habitat is important to spider survival. They need a hiding place during the day and in the winter, though they may overwinter in the soil. Easy-to-make spider condos consist four or five 6" long bamboo sections bundled together. To make a section, cut the bamboo so that it includes a node near one end. It should look like an upside down test tube or a pipe with a cork in it at the top. Wrap four or five of these together and place them near problem pest areas as needed. These can be suspended a couple inches off the ground attached to the inner cover support structure.

Glossary

Come-along. A hand operated geared rachetting device to pull heavy objects.

Drift punch. A tapered metal pin used to align holes, knock out bolts or other debris from holes.

Ground pipe, post, or pin. A pipe buried in the ground and attached to the bow to support the structure. It functions as an anchoring foundation member.

Haygrove. A company, based in the United Kingdom, that manufactures field scale tunnels, mobile livestock buildings and specialist horticultural machinery. They manufacture multi-bay high tunnels.

PEX. Cross-linked high-density polyethylene used as tubing in radiant heating systems.

Pike pole. A pole that has a natural or designed hook on one end that catches the bow and assists in pushing the bow, especially above one's reach.

Plumb. To make something perpendicular to the earth's surface using gravity (typically a string and heavy weight).

Purlin. Typically a horizontal length of swedged pipe attached at the ridge and points along the bow to add structural integrity and strength.

Spline. In high tunnel/greenhouse construction a spline is a short (approx. 12" to 18”) pipe used to join two similar diameter pipes, usually the bow and ground pin/pipe. The spline has a smaller outside diameter (O.D.) than the inside diameter (I.D.) of the two pipes it is joining. These pipes are commonly joined by tek screws or bolts.

Swedged pipe. 4" or 5” of one end of a pipe is rolled to a smaller diameter, allowing it to be inserted into the end of another pipe.

Truss. A structural member (pipe in high tunnels) connecting the bows and often the ridge purlin. It adds structural strength.

Resources

This list is not intended to be complete and does not comprise an endorsement of the companies listed. There are many other reputable manufacturers and distributors besides those listed below.

Greenhouse Structures

Also see "Multi-Bay Structures"

Ledgewood Farm Greenhouse Frames
Ed Person, owner
132 Old Mountain Rd.
Moultonborough, NH 03254
603/476-8829
ed@ledgewoodfarm.com
www.ledgewoodfarm.com
Manufactures pipe frame greenhouses and high tunnels. Ledgewood frames are used in all areas of agriculture for plant protection, livestock housing, and storage. Why not buy from a fellow farmer who grows in the structures he sells!

Rimol Greenhouse Systems, Inc.
Bob Rimol
Northpoint Industrial Park
40 Londonderry Turnpike
Hooksett, NH 03106
877/746-6544, 603/629-9004
www.rimol.com/agricultural.asp
A newer manufacturer of greenhouses; shade structures and related systems, serving primarily small and medium-size businesses. Many different options available for heating, cooling. environmental control, irrigation, and crop support systems. Strong customer support includes prompt delivery, outstanding directions, and availability of experienced staff to answer questions. All greenhouses are designed for heavy snow and wind loads.

Harnois Industries
1044 Principale C.P. 150
St-Thomas (Joliette)
Quebec, Canada, JOK 3LO
888/427-6647
www.harnois.com
A leading greenhouse structures and equipment manufacturer, their extensive line of greenhouses includes gutter connects and a unique vent ridge system. Their freestanding 40' OIvaltech has 10' high roll-up sides for maximum ventilation and natural light.

Atlas Greenhouse Systems
9596 US Hwy 82 East, P.O. Box 558
Alapaha, GA 31622
800/346-9902, 229/532-2905
Fax 229/532-4600
service@atlasgreenhouse.com
www.atlasgreenhouse.com/cf.html
Manufacturer of agricultural, educational and hobby greenhouses and a large supplier of greenhouse equipment for the commercial greenhouse grower. Freestanding and gutter connected greenhouses as well as cold frames and shade structures to small or large size growers around the world. Atlas inventories a comprehensive selection of heaters, fans, coverings, ground fabrics, shade cloth, doors, and many other specialized items in our own warehouse ready for immediate shipping.

Griffin Greenhouse & Nursery Supply
1619 Main Street, P.O. Box 36
Tewksbury, MA 01876 (corporate office)
978/851-4346
www.griffins.com
Regional offices:
Auburn, NY 315/255-1450
Brookhaven, NY 631/286-8200
Bridgeton, NJ 856/451-5170
Cheshire, CT 203/699-0919
Ewing, NJ 609/530-9120
Latham, NY 518/786-3500
Morgantown, PA 610/286-0046
Gray, ME 207/657-5442
Founded in 1947 by Charles J. Griffin. A major greenhouse and nursery supplier in the Northeast and Mid-Atlantic with a broad line of products. Online catalog.

Growell Greenhouses
Mike Tripedino, owner
791 Coleman Rd.
Cheshire, CT
203/272-8147
Greenhouse and solarium builders and distributor of greenhouses equipment and supplies. Mike is helpful and willing to walk you through putting up your own house. He will also send crews to erect houses and re-cover them.

Nexus Corporation
10983 Leroy Drive
Northglenn, CO 80233
800/228-9639, 303/457-9199
Fax 303/457-2801
www.nexuscorp.com
Serving commercial greenhouse growers for over 35 years with a broad range of greenhouse structures and excellent customer service. All their structures can be customized for the size, covering, heating, cooling, and controls.

XS Smith
Corporate Headquarters
932 Page Rd.
Washington, NC 27889
800/631-2226
Also 1602 Lawrence Ave., Suite 103
Ocean, NJ 07712
732/643-0433
Fax 732/643-0699
info@xssmith.com
sales@xssmith.com
Manufacturer of greenhouse structures and horticultural products since 1946. Wide line of greenhouses from small ground-to-ground Quonset structures to multi-span gutter-connected complexes.

W. H. Milikowski, Inc.
10 Middle River Drive
Stafford Springs, CT 06076
860/684-1595, 800/243-7170

Fax 860/684-3022
Full-line greenhouse and nursery supplier, including a range of structures made by Star Steel, an affiliate. Serves New England and adjacent region with warehouses in CT, NJ, and Syracuse, NY.

CropKing Inc.
230 Quadral Dr.
Wadsworth, OH 44281
330/335-1687, Fax 330/335-1689
techsupport@cropking.com
www.cropking.com
A 23-year-old company specializing in controlled environment agriculture and hydroponics, CropKing is a manufacturer, importer, and distributor of commercial facility structures, hydroponic growing systems, supplies, and equipment, in North America and the Caribbean.

Multi-Bay Tunnels

Haygrove Tunnels
Ralph Cramer (East Coast Contact)
116 Trail Road North
Elizabethtown, PA 17022
866-HAYGROVE
ralph.cramer@haygrove.com
www.haygrove.com
Also see www.haygrove.co.uk
World leaders in the design and manufacture of field scale tunnels, mobile livestock buildings and specialist horticultural machinery. Haygrove are growers based in Herefordshire in the United Kingdom.

Greenhouse Supplies and Plastic Disposal

(Plastic film, row cover, plastic disposal, greenhouse supplies, irrigation supplies)

Plastic Film

Farm Tek
1440 Field of Dreams Way
Dyersville, IA 52040
800/327-6835, Fax 800/457-8887
www.farmtek.com
Commercial greenhouses and supplies, tension fabric buildings, range farm products, etc.

Green.Tek, Inc.
417 East Fulton Street
Edgerton, WI 53534
800/747-6440, Fax 608/884-9459
info@green-tek.com
www.green-tek.com
Green-Tek is a leading converter and fabricator of plastic coverings for the greenhouse and architectural glazing industries. Products include polycarbonate multiwall and corrugated sheeting, poly films, and shade cloth.

Klerks Plastics Products
546 L&C Distribution Park
Richburg, S.C. 29729
888/255-3757, Fax 803/789-4001
www.klerksusa.com/products
Klerks is a global supplier of high quality plastic products for horticulture and agriculture. Some of its breakthroughs in greenhouse films are KoolLite 380 and advanced long-lasting anti-condensation films. KoolLite 380 selectively filters the light spectrum, giving growers the highest quality of PAR light available.

Northern Greenhouse Sales
Box 42, Neche, ND 58265
204/327-5540
www.northerngreenhouse.com
Various thicknesses of CLEAR (and colored) Superstrong Woven Poly for greenhouses, barn curtains, etc.

Recoltech
519 Notre-dame St
Rémi, Québec, Canada J0L 2L0
450/454-6996, 877/254-6996
Fax 450/454-7167
info@recoltech.com
www.recoltech.com
Plastic mulches, floating row covers, drip and other irrigation equipment. Primarily a French speaking company.

Row Cover

American AgriFabrics
1282 Old Alpharetta Rd.
Alpharetta, GA 30005
800/565-5151, 770/663-7600
Retailer and wholesaler of AgroFabric Reemay, landscape fabric, netting.

Dubois Agrinovation Inc.
478, Notre-Dame
Saint-Remi, Quebec, Canada J0L 2L0
450/454-3961, 800/667-6279
www.DuboisAg.com
Row cover, irrigation supplies, plastic mulch, bird netting, etc. Formerly "Plastitech."

Ken-Bar, Inc.
Summit Industrial Park
147 Summit St., Building 3D, Suite 3
Peabody, MA 01960
800/336-8882, 781/944-0003
Fax: 781/944-1055
info@ken-bar.com
www.ken-bar.com
A pioneer in developing and providing new and innovative products to the grower since 1972. Products include SRM-Red reflective plastic, floating row covers such as Dupont 5131(formerly "Typar 518") and Dupont Ag-06 (formerly "Remay"), Agritape root zone heaters, and convection tubing. Also makes a high tunnel ridgevent distributed Farm Tek.

Peaceful Valley Farm & Garden Supply
P.O. Box 2209
Grass Valley, CA 95945
888/784-1722
helpdesk@groworganic.com
www.groworganic.com
Row covers, pest management, tools, propagation supplies, etc. Distributes Tufbell, a hard-to-find, expensive but extremely durable row cover made of polyvinyl alcohol. Online catalog.

Polymer Group Inc.
800/631-5594, Fax 919/207-3140
www.agribon.com
www.polymergroupinc.com
PGI is a global leader of engineered fabrics, manufacturing and distributing more than 150 products including Agribon and Agriforce. Purchase from a grower supply company.

Suntex CP, Inc.
P.O. Box 21633
Sarasota, FL 34276 (Sales)
888/786-8391, Fax 941/847-0600
Order fax 888/786-8394
info@suntexcp.com
www.suntexcp.com
The Suntex agricultural line includes Covertan Pro non-woven row covers & Agro Poly Embossed Mulch Films. Covertan Pro is transparent, and air and water permeable, assuring unifiorm heat and moisture exchange.

Plastic Disposal

Daniel Zook
Zook Plastic Recovery
183 South Farmersville Rd.
Leola, PA 17540
717/656-4422
Call for collection schedule. Mr. Zook is now paying up to $80 - $100 for clean greenhouse film. Highest prices are during his seasonal drives.

Karen Kritz
Agricultural Economic Development
Division of Marketing & Development
NJ Department of Agriculture
PO Box 330, Trenton, NJ 08625-0330
609/984-2506, Fax 609/341-3212
karen.kritz@ag.state.nj.us
www.nj.gov/agriculture/divisions/md/prog/recycling.html
Ms. Kritz is the recycling maven who initiated NJ's horticultural film recycling programs.

Cumberland County Improvement Authority
Dennis DeMatte, Recycling Coordinator
2 North High St.
Millville, NJ 08332
856/825-3700
ccia@ccia-net.com
www.ccia-net.com
A recycling collection and marketing program for horticultural film and other materials in southern NJ. Procedures for preparing plastic film for recycling downloadable from website. Out of state materials accepted.

Trex Company
Andrea Dahl
160 Exeter Dr., Winchester, VA 22603
800/289-8739, 540/542-6300,
adahl@trex.com
Ms. Dahl can assist entrepreneurs in creating collection programs for agricultural plastic films. Clear, clean plastic films are preferred.

For more background and resources on agricultural plastic recycling, visit: environmentalrisk.cornell.edu/AgPlastics

Greenhouse Supplies

Hydro-Gardens, Inc.
P.O. Box 25845
Colorado Springs CO 80936
800/634-6362
hgi@hydro-gardens.com
www.hydro-gardens.com
Since 1968, a specialist in hydroponics. Greenhouse supplies, organic fertilizers, pest management supplies, beneficial insects, books, seeds, irrigation equipment, general supplies.

International Technology Services
P.O. Box 75
Lafayette, CO 80026
800/375-1684
rghome@ intertechserv.com
www.greenhouseinfo.com
Serving conventional and organic growers for over 20 years. Beneficial insects, pest trapping and monitoring supplies, pest identification guides, bumblebees form pollination, fertilizers and fertilizer injection systems, biological and botanical pesticides, polypropylene ground covers, etc.

K.C. Schaefer Supply Co. Inc
2655 Springwood Rd.
York, PA 17402
717/741-5088, Fax 717/741-5089
www.schaefer-hort.com
Wholesales farm supplies.

Nolts Produce Supply
152 N. Hersey Ave.
Leola, PA 17540
717/656-9764
Very good, reliable source of agricultural supplies.

Silver Creek Supply
5656 S. Susquehanna Trail
Port Trevorton, PA 17864
570/374-8010, Fax 570/374-8071
silcreek@mail.uplink.net
www.silvercreeksupply.net
Greenhouse, lawn and garden, and nursery supplies, including seeds, irrigation products, fertilizers, and mulch plastics.

Wetsel Growers Supply
P.O. Box 791
961 North Liberty Street
Harrisonburg, VA 22801
540/434-6753, 800/572-4018
Fax 540/434-4894
wetsel@shentel.net
www.wetsel.com
Wetsel's commercial grower department supplies greenhouse frames and skins, environmental

systems, watering and irrigation systems, and other items.

Irrigation

Also see "Nolts Produce Supply" under "Greenhouse Supplies."

Charles W. Harris Company, Inc.
Jim Peeler, owner
New address: 72 Tower Hill Rd.
Brimfield, MA 01010
888/928-3731
Full line of agricultural irrigation equipment and supplies.

DripWorks, Inc.
190 Sanhedrin Circle
Willits, CA 95490
800/522-3747
Design & Tech Support 707/459-6323
Fax: 707/459-9645
sales@dripworksusa.com
design@dripworksusa.com
www.dripworksusa.com
Quality drip irrigation and micro irrigation supplies for home owners, landscapers, farmers and greenhouse owners. Drip emitters, micro sprayers, emitter tubing, T-Tape® drip tape, misters, timers, filters, etc. Their on-line store has complete product line with product descriptions.

International Irrigation Systems - Irrigro
P.O. Box 163, 1755 Factory Outlet Blvd.
Niagara Falls, NY 14304-0163
877/477-4476 (IRRIGRO)
905/688-4090
Fax 905/688-4093
sales@irrigro.com
www.irrigro.com
Equipment and supplies for the watering needs of commercial growers and home gardeners worldwide. With over 20 years of manufacturing and field experience, Irrigro has made significant technological breakthroughs (such as super-strength seals, pressure compensating flow controllers, and subsurface conduit).

Netafim USA
Drip Irrigation Solutions
5470 E. Home Ave.
Fresno, CA 93727
888/NETAFIM, 559/453-6800
Fax 800-695-4753
www.netafimusa.com
Full range of drip and micro-irrigation products and technical support. Since 1965.

Rain-Flo Irrigation
884 Center Church Rd.
East Earl, PA 17519
717/445-6976
Leading manufacturers of plastic laying and removing machinery, water-wheel transplanters and suppliers of plastic mulches, irrigation equipment including drip, overhead pipes, and pumps and floating row covers.

Trickle-eez Company
Sales Offices:
4266 Hollywood Rd.
St. Joseph, Michigan 49085
800/874-2553, 269/429-8200
Fax 269/429-6669
3550 Chambersburg Rd.
Biglerville, PA 17307
800/672-4700, 717/337-3030
Fax 717/337-1785
info@trickl-eez.com
www.trickl-eez.com
A leading dealer in drip irrigation, and other types of irrigation systems for over 25 years.

Monitoring and Testing Equipment

Gempler's
P.O. Box 44993
Madison, WI 53744-4993
800/382-8473
customerservice@gemplers.com
www.gemplers.com
Gempler's carries many soil sampling supplies including pH kits, nitrate testing kits, soil sampling devices including soil probes and soil compaction testers, and many other sampling tools. Also suppliers of protective equipment and supplies for agricultural production, maintenance, etc.

Timberleaf Soil Testing
39648 Old Spring Rd.
Murrieta, CA 92563-5566
951/677-7510
tmbrlfsoiltest@verizon.net
The Timberleaf soil test was developed especially for market gardeners who practice the biointensive approach. The basic soil test includes base saturation/CEC, estimated nitrogen release, available nutrients, pH, and soluble salts. Optional tests exist for organic matter, trace minerals, and composts/ greenhouse media. The detailed soil test report contains the test results and explanations, and organic fertilization recommendations.

Also for General Agriculture:

Ben Meadows Company
P.O. Box 5277
Janesville WI 53547-5277
800/241-6401, Fax 800/628-2068
www.benmeadows.com
An extensive line of soil testing supplies includes electrical conductivity meters (starting at $100), penetrometers, shear tester, soil charts, soil educational kits, soil testing meters, tensiometers and irrometers, test kits and strips, tile probes, auger kits, rotary hammer kits, sieves, and accessories.

More Scientific:

Cole-Parmer
625 Bunker Court
Vernnon Hills, IL 60061
800/323-4340, Fax 847/247-2929
info@Coleparmer.com
www.coleparmer.com
Specialized equipment for monitoring plant nutrition and soil nutrient levels. Extensive list at their website.

Pike Agri-Lab Supplies
154 Claybrook Rd.
Jay, ME 04239

207/897-9267, Fax 207/897-9268
info@pikeagri.com
www.pikeagri.com
This family-run business provides test kits and monitoring instruments to assist farmers and composters and promote biological agriculture. Pike Agri-Lab also develops and manufactures tools in Maine and can help farmers set up their own test labs, for performing quick, simple tests in the field. Operating since 1977. Pike Agri-Lab sells a combination pH and soil salts (electrical conductivity) meter for $144.

Beneficial Insects (Suppliers)

IPM Labs. Inc.
P.O. Box 300
Locke, NY 13092-0300
315/497-2063
ipmlabs@baldcom.net
www.ipmlabs.com
IPM Labs supplies beneficial organisms for the biological control of pests and provides support to facilitate their successful use. They produce 7 species of beneficial organisms and distribute more than 45 other species.

Great Lakes IPM
10220 Church Rd., NE
Vestaburg, MI 48891
989/268-5693, 989/268-5911, or 800/235-0285, Fax 989/268-5311
glipm@nethawk.com
www.greatlakesipm.com
Insect monitoring systems for the professional grower. Suppliers of pheromone lures, insect traps, visual traps, insect sweep nets, ground cloths, bird netting, trapping adhesives, soil probes, grain probes and thermometers, beneficial insects and other insect supplies.

Rincon-Vitova Insectaries Inc.
P.O. Box 95
Oak View, CA 93022
800/248-2847
www.rinconvitova.com
RVI produces and distributes insects and other organisms, supplies and tools for biological control of pests. Safe alternatives to microbes "from insects to microbes." Biological control programs use predators, parasites, pathogens and antagonists and build on active beneficial microbes in soil. Sole distributor for D-Vac vacuum insect sampling equipment.

The Green Spot Ltd.
93 Priest Rd.
Nottingham, NH 03290-6204
603/942-8925,
www.greenmethods.com
Suppliers of biological control organisms and excellent information on individual bio control agents.

Beneficial Insects (Organizations)

Pennsylvania Integrated Pest Management Program
Cathy Thomas, Coordinator
PA Dept. of Agriculture
Bureau of Plant Industry
2301 North Cameron Street
Harrisburg, PA 17110-9408
717/772-5204
caththomas@state.pa.us
paipm.cas.psu.edu/green/greenhouse.html
A highly recommended resource.

IPM Program—NYS Agricultural Experiment Station
P.O. Box 462
Geneva, NY 14456
315/787-2432, 800/635-8356
Fax 315/787-2360
www.nysipm.cornell.edu
www.nysaes.cornell.edu/recommends
The New York State Integrated Pest Management Program develops sustainable ways to manage pests and helps people to use methods that minimize environmental, health, and economic risks.

Biointensive Agriculture

Ecology Action
5798 Ridgewood Rd
Willits, CA 95490
707/459-0150
www.growbiointensive.org
For the past 31 years, Ecology Action has been researching, developing and sharing millennial-old techniques for growing more food in a small area, using simple tools and seeds, while maintaining or increasing the health and productivity of the soil.

Seeds and General Farm Supplies

Johnny's Selected Seeds
955 Benton Ave.
Winslow, ME 04901
877/564-6697, Fax 800/738-6314
rstore@johnnyseeds.com
www.johnnyseeds.com
Quality vegetable, herb, and flower seeds and tools, equipment, and supplies to critical home gardeners and small commercial growers. An independent company since 1973 and employee owned since 2006. All of Johnny's seeds and accessories are tested at the company's certified organic farm in Albion, ME.

Fedco Seeds
P.O. Box 520
Waterville, ME 04903-0520
207/873-7333
www.fedcoseeds.com
A source for cold-hardy selections (seeds, tubers, trees, and bulbs) adapted to the Northeast climate as well as a large selection of certified organic cultivars and regional heirloom varieties. Fedco's product lines (including organic growers supply) and cultural hints encourage sustainable growing methods. Three free catalogs annually. Mail order, fax and internet orders only except during designated pickup. No phone orders.

Germania Seed Company
5978 North Northwest Hwy.
P.O. Box 31787, Chicago, IL 60631
800/380-4721, 773/621-6631
Fax 800-410-4721
www.germaniaseed.com
Since 1932. Specialist in flowers. Distributes annual, perennial and vegetable seeds, plants, and plugs.

High Mowing Seeds
76 Quarry Rd.
Wolcott, VT 05680
802/472-6174, Fax 802/472-3201
www.highmowingseeds.com
This small, family-owned, certified organic seed company located in Northern Vermont ships across the U.S. to customers who value organic seeds, sustainable agriculture, and good service.

Wild Garden Seed
P.O. Box 1509
Philomath. OR 97370
541/929-4068
www.wildgardenseed.com
This organic seed and vegetable farm in the Pacific Northwest produces farm-original varieties of many salad greens, vegetables, herbs and a few flowers. All seed is open pollinated, untreated, germ and vigor tested in living soil mix, and well cleaned.

Bountiful Gardens
18001 Shafer Ranch Rd .
Willits CA 95490
707/459 6410, Fax 707/459 1925
bountiful@sonic.net
www.bountifulgardens.org
Untreated open-pollinated seed of heirloom quality for vegetables, herbs, flowers, grains, green manures, compost and carbon crops. Rare and unusual varieties, medicinal herbs, super-nutrition varieties. Also biointensive books/videos for growing soil sustainably using mini-farming techniques such as double-digging, intensive spacing, and companion planting. Fine tools, basic organic gardening supplies, and non-toxic insect controls.

Peaceful Valley Farm Supply
(See Row Cover listing)

Miscellaneous Supplies

Surplus Center
P.O. Box 82209
Lincoln, NE 68501
800/488-3407, Fax 402/474-5198
customerservice1@surpluscenter.com
www.surpluscenter.com
Surplus Center is a warehouse distributor for many name brand manufacturers, such as Parker Hydraulics, Hypro Pumps, Chief Hydraulics, and Prince Hydraulics. It also offers low wattage 12 volt DC blowers for inflating high tunnel plastic using solar power. Many other products.

Tools

CSA Works
Michael Docter
Hadley, MA
foodbankfarm@yahoo.com
Parts and planting guide for Planet Jr. seeders.

Johnny's Selected Seeds
(See Seed listing)
Carries hard-to-find market gardener tools that are useful for intensive cultivation in high tunnels. Precision seeders (pinpoint and other models), collinear hoes, broadfork, bed preparation rake, etc.

Peter B. Johnson
7967 Ft. Loudon Rd.
Mercersburg, PA 17236
717/328-4857
lpjohnson@innernet.net
U-bar for bio-intensive agriculture handmade by a family business.

Market Farm Implement
257 Fawn Hollow Rd.
Friedens, PA 15541
814/443-1931
www.marketfarm.com
Vegetable crop machinery from tillage to harvest. Sells Cole Planet Jr. (over $500 per row).

Roeters Farm Equipment
565 120th St.
Grant, MI 49327
231/834-7888
www.roetersfarmequipment.com
New and used vegetable equipment, including vintage Planet Jr. seeders.

Further Information and References

These references and resources are intended as a starting point for further reading. This list is by no means exhaustive or definitive. We acknowledge that some items may be outdated or difficult to find.

Agriculture Information Services

Appropriate Technology Transfer to Rural Areas (ATTRA)
P.O. Box 3657
Fayetteville. AR 72702
800/346-9140
www.attra.org
Free publications, information packets, and other technical assistance from the National Sustainable Agriculture Information Service. For farmers, extension personnel, educators, and others involved in sustainable agriculture. Created and managed by the National Center for Appropriate Technology (NCAT). Relevant publications include:

- *Greenhouse IPM: Sustainable Aphid Control*
- *Greenhouse IPM: Sustainable Thrips Control*
- *Greenhouse IPM: Sustainable Whitefly Control*
- *Root Zone Heating for Greenhouse Crops*
- *Season Extension Techniques for Market Gardeners*
- *Solar Greenhouses Resource List*

Organic Agriculture Information
www.organicaginfo.org
Frequently updated website with production information, economic data, research results, farmer anecdotes, certification information, transition strategies, and other subjects related to organic agriculture. Offered by the Organic Agriculture Consortium (OAC)/Scientific Congress on Organic Agricultural Research (SCOAR) and funded by a USDA grant.

National Agricultural Library
US Dept of Agriculture
10301 Baltimore Ave. Room 304
Beltsville MD 20705-2351
301/504 6559, Fax 301/504-6409
afsic@nal.usda.gov
www.nal.usda.gov
Two resources: AGRICOLA database and the Alternative Farming Systems Information Center, (www.nal.usda.gov/afsic)
AGRICOLA, one of the largest databases in the world, is a tremendous resource for academic information. NAL has one of the world's largest and most accessible agricultural information collections.

Periodicals

Growing for Market
PO Box 3747
Lawrence, KS 66046. 800/307-8949
growing4market@earthlink.net
www.growingformarket.com
(Monthly, $33) An informative, thoughtful magazine mostly written by farmers. Often has useful articles about growing winter greens. Supportive of organic, sustainable agriculture.

HortIdeas
750 Black Lick Rd.
Gravel Switch, KY 40328.
gwill@mis.net
users.mikrotec.com/~gwill/index.html
(Monthly, $25) Independent advertising-free gardening newsletter that abstracts new information from a wide range of sources relevant to horticulture. For over two decades.

Acres: A Voice for Eco-Agriculture
P.O. Box 91299
Austin, TX 78709
518/892-4400
info@acresusa.com
www.acresusa.com

The New Farm: Farmer-To-Farmer Know-How from the Rodale Institute
www.newfarm.org
A free electronic newsletter with searchable database.

Cold Stress Physiology

Levitt, J. Responses of Plants to Environmental Stress. Orlando, FL: Academic Press. 1980.

Environment

Thorton, PhD, Joe. *Environmental Impacts of Polyvinyl Chloride Building Materials*. A Healthy Building Network Report. 2002. 110 pp. (From the Institute for Local Self-Reliance, 202/232-4108, www.healthybuilding.net).

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Whitehead, William. Grow Fruit in Your Greenhouse. London, UK: Faber and Faber. 1970. 163 pp.

Gardening

Jeavons, John. How to Grow More Vegetables. 6th ed. Berkeley, CA: Ten Speed Press, 2002, 240 pp.

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General Greenhouse

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Edey, Anna. Solviva: How to Grow $500,000 on One Acre and Peace on Earth. Martha's Vineyard, MA.: Trailblazer Press, 1998. 221 pp.

Grotzke, Hienz. Biodynamic Greenhouse Management. Biodynamic Farming and Gardening Association. 1998. 112 pp. $12. (25844 Butler Road, Junction City, OR 97448, 888/516-7797, www.biodynamics.com).

Mazria, Edward. The Passive Solar Energy Book. Emmaus, PA: Rodale Press. 1979. 435 pp.

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Salt, Bernard. Gardening Under Plastic: How to Use Fleece, Films, Cloches and Polytunnels. London, UK: B.T. Batsford Ltd. 127 pp.

Smith, Shane. The Bountiful Solar Greenhouse; A Guide to Year-Round Food Production. Santa Fe, NM: John Muir Publications Inc. 1982. 221 pp.

Story, David. Plastic and Vegetables: A Guide to Organic Growing in Polytunnels. Dublin, Ireland: IOFGA (Irish Organic Farmers and Growers Association). 1993, 54 pp.

Stinson, Richard F. Greenhouse Crop Production, Student Manual. University Park, PA: PSU. 1983. 223 pp.

Taylor, T.M. Secrets to a Successful Greenhouse and Business. Melbourne, FL: Green Earth Publishing Co., Inc. 1999. 279 pp.

Greenhouse Design

Aldrich, Robert A. and Bartok, John W., Jr. Greenhouse Engineering. Ithaca, NY: Northeast Regional Agricultural Engineering Service (NRAES, Cooperative Extension, PO Box 4557, Ithaca, NY 14852-4557, 607/255-7654, nraes@cornell.edu, www.nraes.org). Revised ed. NRAES-133. 212 pp. $30.

Bartok, John W., Jr. Energy Conservation for Commercial Greenhouses. Ithaca, NY: NRAES. Revised ed. 2001. NRAES-3. 84 pp. $17.

Bartok, John W., Jr. Greenhouses for Homeowners and Gardeners. Ithaca, NY: NRAES. 2000. NRAES-137. 200 pp. $30.

Bartok, John W., Jr. Retractable Roof Greenhouses and Shadehouses. Factsheet. Available at: www.hort.uconn.edu/Ipm/greenhs/bartok/htms/retractableroofgreenhouses.htm.

Mazria, Edward. The Passive Solar Energy Book. Emmaus, PA: Rodale Press. 1979. 435 pp.

Greenhouse Plans

Sunspace & Solar Greenhouse Plan
Brace Research Institute
Publication Dept., Faculty of Engineering, P.O. Box 900
MacDonald College of McGill University
Ste. Anne de Bellevue, Quebec, H9X 3V9, Canada
514/398-7833, Fax 514/398-7767
ae12000@musica.mcgill.ca

Solstice Publications/Domestic Technologies Inc.
P.O. Box 2043
Evergreen, CO 80439
303/674-7700, Fax 303/674-7772
dri@domtech.com
A source for finding and purchasing articles, books, and reports on sunspaces and solar greenhouses.

Also see:
www.healthgoods.com/education/healthy_home_information/Building_Design_and_Construction/reading_sunspaces_greenhouses.htm

High Tunnel & Season Extension Publications

Coleman, Eliot. The New Organic Grower's Four-Season Harvest. White River Junction, VT: Chelsea Green Publishing Co. 1992. 212 pp.

Coleman, Eliot. The Winter Harvest Manual: Farming the Backside of the Calendar. Four Season Farm, 609 Weir Cove Rd., Harborside, ME 04642. 1998. 57 pp. Order from Fedco, *Growing for Market*, or directly from Eliot at above address.

Dreer, Henry A. Vegetables Under Glass. Henry A. Dreer, 714 Chestnut St., Philadelphia, PA. 2nd ed. 1896. 105pp.

Gerst, Jean-Jacques. Growing Vegetable Crops Under Direct Covers. Paris, France: Centre Technique Interprofessionnel des Fruits and Legumes. 1987. 165 pp.

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Jett, Lewis. High Tunnel Tomato Production Guide (Publication M170). University of Missouri. Details about building a hoop house, with many photos, plus tomato production

information including color photos of insects, disease, and physiological disorders. 28 pp. $10. From MU Ext. Publications, 800/292-0969, muextension.missouri.edu/explore/manuals/m170.htm

Janick, Jules and Swaim, David. Development of an Innovative Production and Marketing System for Specialty Vegetables. Final Report. No date. Purdue University. www.hort.purdue.edu/newcrop/hfresh/finalreport.pdf

Lamont, Bill and Orzolek, Mike. High Tunnel Production Manual 2003. Over 150 pp. $26.50 payable to Penn State University. Mail payment to Dr. Bill Lamont, Dept. of Horticulture, 206 Tyson Building, Penn State University, University Park, PA 16802.

Poisson, Leandre and Gretchen. Solar Gardening. White River Junction, VT: Chelsea Green Publishing Co. 1994. 267 pp.

Wiediger, Alison and Paul. Walking to Spring: Using High Tunnels to Grow Produce 52 Weeks a Year. From Au Naturel Farm, 3298 Fairview Church Road, Smiths Grove, KY 42171. $15 plus $3.50 S/H or from *Growing for Market*.

High Tunnel Research, Education and Websites

Connecticut
Martin Gent
Dept. of Forestry and Horticulture
Connecticut Agricultural Experiment Station
203/974-8489,
Martin.Gent@po.state.ct.us
Physiology of high tunnel crops – growth, yield, nutrients, environment

Kansas, Missouri, and Nebraska
www.hightunnels.org
High Tunnel Team of Central Great Plains

Michigan
John Biernbaum
Michigan State University Dept of Horticulture
517/355-5191 x419
biernbau@msu.edu
Winter growing in unheated tunnel research since 2001. Also 48-week CSA at student organic farm
New interactive online course in 2007: Passive Solar Greenhouses for Protected Cultivation (credit and non-credit enrollment options). Future courses on compost and organic transplants.

Maine
Barbara Murphy
University of Maine Cooperative Extension, Oxford County
207/743-6329
bmurphy@umext.maine.edu
Comparison of cut flower production in field and in high tunnel, including season extension.

Gleason Gray
University of Maine Cooperative Extension, Penobscot County
207/942-7396
ggray@umext.maine.edu
Active solar heating in a high tunnel for spring and fall season extension. Experimental design includes black tubing containing circulating water mounted on bows, flexible tubing buried 6" deep, and a buried 5,000 gallon storage tank.

New Jersey
Rutgers University High Tunnel Project. See archived reports at: aesop.rutgers.edu/~horteng/HighTunnels/HighTunnels2005.pdf

New York
Marvin Pritts
Cornell Dept. of Horticulture
607/255-1778
mpp3@cornell.edu
Small fruit in high tunnels – raspberries, strawberries, etc.

Reid, Judson
Cornell Vegetable Program
315/536-5123
jer11@cornell.edu
Tomato, cucumbers, peppers and cover crops variety trials in high tunnels.

Stephen Reiners
Dept. of Horticultural Sciences, NYS Ag Experiment Station
315/787-2311
sr43@cornell.edu
General vegetable culture, soil fertility.

Chris Wien
Dept. of Horticulture, Cornell University
607/255-4570
hcw2@cornell.edu
Season extension in cut flowers, day length considerations in manipulating time of bloom.

Ohio
Ron Becker
Ag & IPM, Ohio State University Extension, Wayne County
330/264-8722
becker.4@cfaes.osu.edu
Implementation of Integrated Pest Management practices in high tunnels.

Brad Bergefurd
Ohio State University South Centers
740/289-2071 x136
bergefurd.1@osu.edu
http://southcenters.osu.edu/hort/
High tunnel strawberries, tomatoes, and moveable tunnel structures – research, extension, on-farm demonstrations.

Matt Kleinhenz
Dept. of Horticulture and Crop Science, Ohio Agricultural Research and Development Center
330/263-3810
kleinhenz.1@osu.edu
High tunnel design, use in conventional and organic systems, cultural practices and product quality.

Pennsylvania
Center for Plasticulture, Penn State University
http://plasticulture.cas.psu.edu
Research, events, experimental results, etc.

Insects (Beneficial and Pest)

Carr, Anna. Rodale's Color Handbook of Garden Insects. Emmaus, PA: Rodale Press. 1979, 241 pp.

Casey, Christine, ed. Integrated Pest Management for Bedding Plants. Ithaca, NY: Cornell University Press. 1999. 117 pp. $14.50

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Howard, R.J., Garland, J.A., and Seaman, W.L. Diseases and Pests of Vegetable Crops in Canada. Societe d'entomologie du Canada, 393 Winston Avenue, Ottawa, ONT, Canada K2A lY8. (613/725-2519) ISBN 0-9691627-3-1 (soft and hard cover, English and French).

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Thomas, Cathy and the Pennsylvania IPM Program. Greenhouse IPM with an Emphasis on Biocontrols. Penn State University. Based on Bug vs. Bug article series. 108 pp. Over 90 full-color images.
Download free PDF file from http://paipm.cas.psu.edu/ghmanual.htm
Or send check or money order for hard copy ($12 plus $5 S/H per order) to Publications Distribution Center, PSU, College of Ag. Sci., 112 Ag.Admin. Building, University Park, PA 16802-2602. Credit card orders, 877/345-0691.

Nitrates

Affleck, Elisabeth A. Nitrate Levels in Greenhouse Grown Salad Mix: A Case Study of Three Sisters Bioshelter, (unpublished). Dept. of Parks and Recreation, Slippery Rock University, Slippery Rock, PA. May 1998. 48 pp.

Sideman, Eric PhD. Nitrate Accumulation In Winter-Harvested Crops: A Growers' Guide. Maine Organic Farmer and Gardener. June-August 1999. 40-41 pp.

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