

# Season Extension Techniques for Market Gardeners

HORTICULTURE TECHNICAL NOTE

*Abstract: Market gardeners can grow crops year-round with season extension techniques. Cultural practices, plastic mulches, row covers, and low tunnels provide growers with earlier, later, and higher-quality produce that can capture more markets and demand higher prices. High tunnels or hoophouses, which are essentially unheated greenhouses, have gained increased interest around the country in the past 10 years. Many growers now consider hoophouses essential to the success of their market gardens; they are the focus of research projects, workshops, and new manuals. This publication describes these season extension techniques and provides sources for equipment, supplies, and further information.*

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January 2005  
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## Introduction

Market gardeners use a variety of techniques to extend the growing season. Since season extension has a long history, current techniques involve both rediscovery and innovation. Gardeners through the centuries have learned to use available materials to produce earlier crops in the spring, grow cool-season crops in summer, maintain production well into the fall, and even harvest crops through the winter. Time-honored methods include cold frames heated with manure, masonry walls or stone mulch as heat sinks, and cloches (glass bell jars) to protect individual plants. Improvements in glass quality were big news for season extenders of the 18th and 19th centuries. (Ashton, 1994) More recently, plasticulture (use of plastics in agriculture) has greatly extended the possibilities for year-round production. Plastic film mulches, drip irrigation, row covers, low tunnels, and high tunnels



High tunnels protect high value crops. Photo by Janet Bachmann

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or hoophouses, help to protect crops from the weather. The use of plastic in horticultural crop production has increased dramatically in the past decade. High tunnels are springing up around the country, as more and more market gardeners see them as essential to their operations.

Benefits from year-round production include year-round income, retention of old customers, gain in new customers, and higher prices at times of the year when other local growers (who have only unprotected field crops) do not have produce. Other potential benefits of season extension technologies are higher yields and better quality. In addition, with year-round production you can provide extended or year-round employment for skilled employees whom you might otherwise lose to other jobs at the end of the outdoor growing season. Disadvantages include no break in the yearly work schedule, increased management demands, higher production costs, and plastic disposal problems.

Eliot Coleman, a market gardener in Maine who uses various techniques to grow vegetables year-round, summarizes the contribution season extension makes to sustainability.

... to make a real difference in creating a local food system, local growers need to be able to continue supplying "fresh" food through the winter months . . . [and] to do that without markedly increasing our expenses or our consumption of non-renewable resources. (Coleman, 1995)

The information in this publication and in the materials listed as **Further Resources** can help you analyze the benefits and costs of season extension techniques on your farm.

## Cultural Practices

Almost all plants benefit from increased early- and late-season warmth. Many cultural techniques can modify the microclimate in which a crop is grown, without using structures or covers, though some of these techniques require long-term planning.

### Site Selection

Garden site selection is very important for extended-season crop production. Cold air, which is heavier than warm air, tends to settle into valleys on cold nights, limiting the growing season there. In areas of relatively low elevation, a

## Related ATTRA Publications

Compost Heated Greenhouses

Greenhouse and Hydroponic Vegetable Resources on the Internet

Low-cost Passive Solar Greenhouses

Root Zone Heating

Solar Greenhouse Resource List

Specialty Lettuce and Greens:  
Organic Production

Scheduling Vegetable Plantings for  
Continuous Harvest

higher-elevation site only a few miles away can easily have a 4- to 6-week longer growing season. A site on the brow of a hill, with unimpeded air drainage to the valley below, would be ideal where season extension is an important consideration. (In more mountainous areas, temperatures drop as elevation increases.)

In northern states, land with a southern aspect is the best choice for early crops, as south-facing slopes warm up sooner in the spring. Furthermore, the closer to perpendicular the southern slope is to the angle of sunlight, the more quickly it warms.

South-facing slopes may not be advantageous in the southern U.S., where soil is likely to be relatively shallow, poor in soil fertility, and low in accumulated organic matter. If there has to be a choice between a sunnier aspect and native soil quality, the latter wins out, especially in the South, where winters and early springs are not as cold as in the North.

### Soils and Moisture Content

Soils can affect temperature because their heat storage capacity and conductivity vary, depending partly on soil texture. Generally, when they are dry, sandy and peat soils do not store or conduct heat as readily as loam and clay soils. The result is that there is a greater daily temperature range at the surface for light soils than for heavier

soils, and the minimum surface temperature is lower. Darker soils often absorb more sunlight than light-colored soils and store more heat. Consequently, areas with lighter-colored soils (and no ground cover) are more prone to frost damage.(Snyder, 2000)

Bare soil absorbs and radiates more heat than soil covered with vegetation. Although the radiated heat helps protect against frost, cover crops provide many other benefits. Mowing to keep the ground cover short provides a compromise.

In addition, moist soil absorbs and radiates more heat than dry soil, because water stores considerable heat. To maximize this effect, water content in the upper one foot of soil where most of the change in temperature occurs must be kept near field capacity.(Snyder, 2000)

## Irrigation

Overhead sprinklers, furrow, and drip irrigation can be used to protect crops from frost. Sprinklers are turned on when the temperature hits 33°F. When the water comes in contact with plants, it begins to freeze and release heat. As ice forms around branches, vines, leaves, or buds, it acts as an insulator. Although the level of protection is high, and the cost is reasonable, there are several disadvantages. If the system fails in the middle of the night, the risk of damage can be quite high. Some plants are not able to support the ice loads. Large amounts of water, large pipelines, and big pumps are required. Water delivered to a field via drip and furrow irrigation, however, can keep temperatures high enough to prevent frost damage without the same risks.(Evans, 1999; Snyder, 2000)

## Smudge Pots and Wind Machines

Smudge pots that burn kerosene or other fuels are placed throughout vineyards or orchards to produce smoke. The smoke acts like a blanket to keep warm air from moving away from the ground. The smoke is also a significant source of air pollution, and smudge pots are rarely used anymore.(Atwood and Kelly, 1997) Today, using oil and gas heaters for frost control in orchards is usually in conjunction with other methods, such as wind machines, or as border heat (two or three rows on the upwind side) with undertree sprinkler systems.(Evans, 1999; Geisel and Unruh, 2003; Snyder, 2000)

Specialty cut flower growers Pamela and Frank Arnosky in Texas have a lot of experience dealing with wide fluctuations in temperature, and in a recent article they describe various methods for protecting high-value crops. They give this description of wind machines.

Cold air is heavier than warm air, and on a still night, the cold air will sink below the warm air and actually flow downhill. This is what happens when people say you have a “frost pocket.” As cold air flows downhill, it gets trapped in valleys and low spots. Even a row of trees can hold cold air in a pocket. Unless your farm is perfectly flat, you probably have a frost pocket somewhere, and you can avoid trouble by planting that spot later in the spring, or with hardy plants.

As the cool air sinks, the warm air is pushed up, and settles in a layer just above the field as an “inversion layer.” This is a pretty neat phenomenon



Orchard-Rite Ltd. wind machines protect crops from frost, and with added Agri-Cool™ System protects apple crops from hot weather. Photo courtesy of Orchard-Rite, Ltd.

that occurs on perfectly still nights. The inversion layer can be quite warm, and often is not very far off the ground. . . .

In big orchard operations, you will often see giant fans on towers among the trees. These fans are there to take advantage of the trapped inversion zone. They mix the warm air above and prevent the cold air from settling among the trees. They are super-expensive, but so is losing a crop. Fans like this only work in a still, radiational frost.(Arnosky, 2004)

More information about wind machines is available from contacts listed under **Further Resources**.

## Windbreaks

Windbreaks decrease evaporation, wind damage, and soil erosion, and provide habitat for natural enemies of crop pests. They are also an important part of season extension, helping to create protected microclimates for early crops. Windbreaks should run perpendicular to (across) the prevailing direction of early-season winds.(Hodges and Brandle, 1996) Existing stands of trees can be used, but choose trees for windbreaks carefully, so that shading, competition for water and nutrients, and refugia for plant pests do not become problems.

Fall-planted cover crops of small grains (rye, barley, winter wheat) can serve as windbreaks the following spring; at plow-down, strips are left standing every 30 to 40 feet and cut or tilled under when no longer needed. Each strip should be the width of a small-grain drill (10 to 12 feet). However, small winter-grains may be too short to constitute an effective windbreak for early spring crops. Top-dressing with compost will help ensure a good stand. Another option is to plant perennial grass windbreaks that will maintain protection through winter and early spring.

These are only general guidelines; experimentation and adaptation are necessary to find the best solution for a particular situation. Other windbreaks include snow fences, commercial windbreak materials, brush piles, stone walls, old fencerows or hedges, shrubs, berry brambles, and even overgrown ditches. In any case, windbreaks should not be allowed to interfere with down-slope air drainage and should allow for some circulation to prevent air stagnation and frost pockets.(Lamont, 1996; Hodges and Brandle, 1996)

## Cultivar Selection

Cultivar selection is important for early crop production. The number of days from planting to maturity varies from cultivar to cultivar, and some cultivars germinate better in cool soil than others. Staggered planting dates can be combined with the use of cultivars spanning a range of maturity dates to greatly extend the harvest season for any one crop. Early-maturing cultivars are very important in going for the early market, though in many cases the produce will be smaller. Some later-maturing cultivars also have better eating qualities and yields than earlier cultivars. Information on varieties adapted to your area is available from local growers, seed catalogues, trade magazines, Cooperative Extension, and resources listed at the end of this publication.

Brett Grohsgal, who co-owns Even' Star Organic Farm with his wife, Dr. Christine Bergmark, in southern Maryland, says that seed saving and genetic management are keystones of their winter cropping system. They started with purchased seed, but after several years of careful selection and seed saving, they have their own supply of seed for crops adapted to their harsh local winter weather.(Grohsgal, 2004)

## Shade

Although season extension usually brings to mind an image of protecting plants from the cold, modifying temperatures in mid-summer can also be important. Shade over a bed can create a cool microclimate that will help prevent bolting and bitterness in heat-sensitive crops such as lettuce and spinach, make it possible to grow warm-weather crops in areas with very hot summers, and hasten germination of cool-weather fall crops. Some growers provide cooling shade by growing vines such as gourds on cattle panels or similar frames placed over the beds. Shade fabrics, available from greenhouse- and garden-supply companies, can be fastened over hoops in summer to lower soil temperatures and protect crops from wind damage, sunscald, and drying. Placing plants under 30 to 50% shade in midsummer can lower the leaf temperature by 10°F or more.(Bartok, 2004)

Commercial shade fabrics are differentiated by how much sunlight they block. For vegetables like tomatoes and peppers, use 30% shade cloth in areas with very hot summers. For lettuce, spinach, and cole crops, use 47% in hot areas, 30% in northern or coastal climates. Use 63% for shade-

loving plants. (The maximum shade density – 80% – is often used over patios and decks to cool people as well as plants). (Peaceful Valley, 2004) See the ATTRA publication *Specialty Lettuce and Greens: Organic Production* for more on growing lettuce in hot weather. Shade houses can also provide frost protection for perennials and herbs during winter. Temperatures inside can be as much as 20°F higher than outdoors. (Bartok, 2004)

Silver Tufbell from Peaceful Valley Farm Supply is a specially developed alternative to woven shade fabric. It is impregnated with silver-finish aluminum for very high light as well as infra-red (heat) reflection. This, combined with a close weave, gives 45% shading during the day, but reflects heat back to the crop at night. Silver Tufbell is especially suited for sun- and heat-sensitive crops. The reflective surface also deters many pests, especially whiteflies and aphids, from approaching the crop. (Peaceful Valley, 2004)

Steve Upson, who has been working with hoop-houses at the Noble Foundation in Oklahoma, began installing Kool-Lite Plus brand poly film, in attempts to keep the houses cooler in the summer. He says this film, which blocks solar infra-red radiation, has kept temperatures up to 12°F cooler during the afternoon and evening. He says although you can expect to pay 75% more for Kool-Lite Plus, the additional cost can be justified, considering the costs associated with the use of shade fabric. (Upson, 2002)

## Transplants

Use of transplants (versus direct seeding) is another key season-extension technique. Some crops have traditionally been transplanted, and recent improvements in techniques have expanded the range of crops suited to transplant culture. Transplants provide earlier harvests by being planted in a greenhouse several weeks before it is safe to direct-seed the same crop outdoors. If a grower uses succession planting or multiple cropping (i.e., follows one crop with another in the same spot), transplants provide extra time for maturing successive crops. Transplants hit the ground running, with a 3 to 4 week head start on the season. Transplanting aids in weed control by getting a jump on the weeds and by quickly form-



Plastic mulch can increase yield and quality of potatoes. Photo courtesy Penn State Center for Plasticulture.

ing a leaf canopy to shade out germinating weed seedlings. Transplants also avoid other pests that attack germinating seeds and young seedlings, such as fungal diseases, birds, and insects.

## Multiple Cropping

Planting more than one crop on the same bed or row in one year intensifies the cropping schedule. Immediately after one crop is harvested, another is planted. Dr. Charles Marr and Dr. William Lamont (1992) list the following advantages of multiple cropping, and conclude "if you can't triple crop, then you certainly can consider double cropping."

- Cost savings. Money spent on plastic mulch, drip irrigation lines, and other equipment covers three crops instead of one.
- Higher gross per acre. In his triple cropping field trials, Lamont realized gross returns of \$13,000 to 15,000 per acre.
- Improved cash flow. Multiple harvests throughout the season can provide income at critical times and distribute returns more evenly over a longer period.
- Risk management. Multiple cropping provides a hedge against the loss of a crop to freezes, hailstorms, and other crises.
- Increased productivity. Small areas of land are thus made more productive, a great boon in areas where cropland is scarce or costly.

Table 1. Spring-Fall Planting Sequences for North Carolina

Please note that crops in the same family never follow each other in the same field or bed in the same year. The same rule applies to triple cropping sequences.

Spring	Fall
Peppers	Summer squash, cucumbers, or cole crops
Tomatoes	Summer squash, cucumbers, or cole crops
Summer squash	Tomatoes or cole crops
Eggplant	Summer squash
Cucumbers	Tomatoes
Muskmelons	Tomatoes
Watermelons	Tomatoes
Honeydews	Tomatoes
Cole crops	Summer squash, pumpkins, muskmelons, or tomatoes
Cauliflower	Summer squash, pumpkins, muskmelons, or tomatoes
Snap beans	Summer squash, pumpkins, muskmelons, or tomatoes
Southern peas	Summer squash, pumpkins, muskmelons, or tomatoes
Lettuce	Summer squash, pumpkins, muskmelons, or tomatoes
Sweet corn	Summer squash, tomatoes, or cucumbers
Strawberries	Tomatoes, summer squash, cucumbers, or pumpkins

(Sanders, 2001)

Table 1 shows examples of double cropping sequences from North Carolina. (Sanders, 2001)

Table 2 shows examples of triple cropping sequences suitable for plasticulture in Kansas. (Marr and Lamont, 1992) For related information, see the ATTRA publication *Scheduling Vegetable Plantings for Continuous Harvest*.

Table 2. Examples of triple cropping sequences

Spring	Summer	Fall
Cole crops	Summer squash	Tomatoes
Lettuce	Cucumbers	Tomatoes
Sweet corn	Cucumbers	Tomatoes

(Marr and Lamont, 1992)

## Plasticulture for Season Extension

During the past 10 years there has been an explosion in the use of plastics in agriculture. The term “plasticulture” is used to describe an integrated system that includes – but is not limited to – plastic film mulches, drip irrigation tape, row covers, low tunnels, and high tunnels. Some benefits of a comprehensive plasticulture system include:

- Earlier crop production (7 to 21 days earlier)
- Higher yields per acre (2 to 3 times higher)

- Cleaner, higher-quality produce
- More efficient use of water resources
- More efficient use of fertilizers
- Reduced soil and wind erosion (though erosion may increase in un-mulched paths between rows)
- Potential decrease in disease
- Better management of certain insect pests
- Fewer weeds
- Reduced soil compaction and elimination of root pruning
- The opportunity for efficient double or triple cropping (Lamont, 1996)

## Disadvantages of Plasticulture: The Disposal Dilemma

Costs and management time will both increase with the use of plasticulture, but if it's done well, the higher productivity and profit should more than compensate. The most serious problems associated with plasticulture have to do with removal from the field and disposal. Machines are commercially available to remove plastic mulch from the field (Zimmerman, 2004; Holland, 2004) and to roll and pack it into bales, but for smaller-scale growers this is probably not an option. Other obstacles to recycling include dirt on the plastic, UV degradation, the high cost of collecting and sorting, and a lack of reliable end-use markets. But recycling technologies and initiatives are evolving. Dr. William Lamont, an advocate of plasticulture, envisions a future when growers will remove, chop, and pelletize field plastics for use as a fuel. Lamont and others at The Penn State Center for Plasticulture are currently testing a heater manufactured in Korea that burns plastic pellets made from waste plastics of all types. Dennis DeMatte, Jr., who as manager of the Cumberland County (New Jersey) Improvement Authority works with New Jersey's greenhouse plastic film recycling program, stated that since the program was initiated in 1997, the CCIA has recycled approximately 80 percent of the film collected. From 1997 through 2002, the state collected about 1,120 tons of film. (Kuack, 2003) Web sites for more information about recycling agricultural or greenhouse-related plastic products include:

The Penn State Center for Plasticulture  
[www.plasticulture.org/newsletters/ASP\\_April04.pdf](http://www.plasticulture.org/newsletters/ASP_April04.pdf)

Cumberland County Improvement Authority  
[www.ccia-net.com](http://www.ccia-net.com)

Agriculture Container Recycling Council  
[www.acrecycle.org](http://www.acrecycle.org)

USAg Recycling Inc.  
[www.usagrecycling.com](http://www.usagrecycling.com)

Cornell University Environmental Risk Analysis Program  
<http://environmentalrisk.cornell.edu/C&ER/PlasticsDisposal/AgPlasticsRecycling/>

## Plastic Mulches

Plastic mulches have been used commercially on vegetables since the early 1960s. Muskmelons, tomatoes, peppers, cucumbers, squash, eggplant, watermelons, sweet corn, snap beans, southern peas, pumpkins, and okra will all ripen earlier and produce better yields and fruit quality when grown on plastic mulch.

Plastic mulches have helped growers in extreme northern and high-altitude climates harvest heat-loving crops that were previously impossible for them to grow. In the northeastern U.S. small acreages of sweet corn are established by transplanting into plastic mulch for an early crop. Broccoli, cauliflower, pumpkin, and winter

squash can also be established as transplants into plastic, if earliness and reduced environmental stress are required. In the Southwest, spring melons are direct seeded then covered with plastic strips to accelerate germination and development. At the three to four leaf stage, the plastic is removed. (Guerena, 2004)

Small-scale market gardeners will probably lay down plastic mulch by hand. Tim King, market gardener near Long Prairie, Minnesota, has been using a system of raised beds, drip irrigation, plastic mulch, and fabric row-cover tunnels since 1986. He says that although doing everything by hand is very labor intensive, they are very pleased with the flexibility this gives them to "hybridize" the parts of the system in various ways. It also al-

lows them to reuse much of the material a second and even a third season.(King, 2002)

Mechanical application can save time. Many growers have found that a simple tractor-pulled mulch layer will reduce overall costs and help ensure a uniform installation that will resist wind damage. Plans are available for a mulch layer that can be built in a farm shop (Thompson et al., 2004), and the machines are also commercially available. They can also be designed to install a drip irrigation line at the same time.(Zimmerman, 2004; Holland, 2004) Plants or seeds can be set through slits or holes in the plastic by hand or with a mechanical transplanter. Labor savings from mechanical transplanters are significant, even on limited acreages.

For successful plant establishment with plastic mulch, it is important that beds be level, the plastic is tightly laid, drip irrigation tape is placed in a straight line in the center of the bed, and water is applied through the irrigation system immediately after transplanting. Never use plastic mulch without irrigation.

Certified organic producers should be aware that organic standards place certain restrictions on the use of plastic mulches. For example, PVC plastics may not be used as mulches or row covers. Also, plastic mulches must be removed from the field before they begin decomposing—which would seem to eliminate photodegradable films from organic production.

Plastic mulches are available in a number of colors, weights, and sizes for various needs. Many come as 3- to 5-foot wide rolls that can be laid over soil beds with a tractor and mechanical mulch layer. Extensive research with colored mulches has been conducted at the Horticulture Research Farm, Rock Springs, Pennsylvania, by staff of The Pennsylvania State University Center for Plasticulture. (See **Further Resources** for contact information.)

*Black plastic mulch* is the most commonly used. It suppresses weed growth, reduces soil water loss, increases soil temperature, and can improve vegetable yield. Soil temperatures under black plastic mulch during the day are generally 5°F higher at a depth of 2 inches and 3°F higher at a depth of 4 inches compared with bare soil.(Sanders, 2001) Black plastic embossed film has a diamond-shaped pattern. It has the

same advantages as smooth black plastic. The pattern helps to keep the mulch fitted tightly to the bed. For plastic mulch to be most effective, it is important that it be in contact with the soil that it covers. Air pockets act as insulation that reduces heat transfer.

*Clear plastic mulch* will allow for greater soil warming than colored plastic. It is generally used in the cooler regions of the United States, such as New England. Clear plastic increases soil temperatures by 8 to 14°F at a depth of 2 inches, and by 6 to 9°F at a depth of 4 inches.(Orzolek and Lamont, no date) A disadvantage is that weeds can grow under the clear mulch, while black mulch shades them out. Therefore, clear plastic is generally used in conjunction with herbicides, fumigants, or soil solarization. Organic growers may want to experiment with clear plastic to find out whether weeds become a real problem. The mulch's benefit to the crop may outweigh the competition from weeds.(Coleman, 1995)

*White, coextruded white-on-black, or silver reflecting mulches* can result in a slight decrease in soil temperature. They can be used to establish a crop when soil temperatures are high and any reduction in soil temperatures is beneficial.

*Infrared-transmitting (IRT) mulches* provide the weed control properties of black mulch, but they are intermediate between black and clear mulch in warming the soil. IRT mulch is available in brown or blue-green.

*Red mulch* performs like black mulch, warming the soil, controlling weeds, and conserving moisture, with one important difference. In Pennsylvania experiments, tomato crops responded with an average 12% increase in marketable fruit yield over a 3-year period. There appears to be a reduction in the incidence of early blight in plants grown on red mulch, compared with plants grown on black mulch. When environmental conditions for plant growth are ideal, tomato response to red mulch is minimal. Other crops that may respond with higher yields include eggplant, peppers, melons, and strawberries.(Bergholtz, 2004) (Red mulch also suppresses nematodes. See the ATTRA publication *Alternative Nematode Control*.)

*Additional colors* that have been investigated include blue, yellow, silver, and orange. Each reflects different radiation patterns into the canopy of a crop, thereby affecting plant growth and development. Increased yield was recorded for peppers grown on silver mulch, cantaloupe on green IRT or dark blue mulch, and cucumbers and summer squash on dark blue mulch,

compared with black. Insect activity can also be affected: yellow, red, and blue mulches increase peach aphid populations; silver repels certain aphid species and whiteflies and reduces or delays the incidence of aphid-borne viruses in crops.(Orzolek and Lamont, no date)

*Photodegradable film* has much the same qualities as other black or clear plastic film, but is formulated to break down after a certain number of days of exposure to sunlight. The actual rate of breakdown depends on temperature, the amount of shading from the crop, and the amount of sunlight received during the growing season. Buried edges of the film must be uncovered and exposed to sunlight. Use of photodegradable film eliminates some of the disposal problems associated with regular plastic, but is not without problems, and its availability has decreased rather than expanded during the past five years. A representative of one company that no longer offers photodegradable mulch says they discontinued the product because the breakdown was not consistent. Photodegradable mulch is not allowed for use in organic production.

## Biodegradable Mulches

Biodegradable plastics are made with starches from plants such as corn, wheat, and potatoes. They are broken down by microbes. Biodegradable plastics currently on the market are more expensive than traditional plastics, but the lower price of traditional plastics does not reflect their true environmental cost. Field trials in Australia using biodegradable mulch on tomato and pepper crops have shown it performs just as well as polyethylene film, and it can simply be plowed into the ground after harvest.(Anon, 2002) Researchers with Cornell University also found that biodegradable mulches supported good yields, but the films they used are not yet commercially available in the U.S.(Rangarajan et al, 2003) Bio-Film is the first gardening film for the U.S. market. Made from cornstarch and other renewable resources, it is 100% biodegradable. Bio-Film is certified for use in organic agriculture by DEBIO, the Norwegian control and certification body for organic and biodynamic agricultural production, and is available from Dirt Works in Vermont. (See **Further Resources.**)

Paper mulch can provide benefits similar to plastic and is also biodegradable. An innovative group in Virginia carried out

on-farm experiments to explore alternatives to plastic. They compared soil temperatures and tomato growth using various mulches, including black plastic, Planters Paper, and recycled kraft paper. Plastic, paper, and organic mulches all improved total yields of tomatoes grown in the trials, when compared with tomatoes grown on bare soil.(Schonbeck, 1995; Anderson, 1995)

Recycled kraft paper is available in large rolls at low cost. Participants in the experiment were concerned that it would break down too quickly. To retard degradation, they oiled the paper. This resulted in rather transparent mulch and, as with clear plastic, soil temperatures were higher than under black plastic. Weeds also grew well under the transparent mulch. To reduce weed growth and to keep the soil from becoming too hot, the experimenters put hay over the oiled paper several weeks after it was laid.

Planters Paper is a commercially available paper mulch designed as an alternative to plastic. It comprises most of the benefits of black plastic film and has other advantages. It is porous to water. Left in the soil, or tilled in after the growing season, it will degrade. Tomatoes grown with this mulch showed yields and earliness similar to tomatoes grown in black polyethylene mulch, even though the latter resulted in slightly higher soil temperatures. Planters Paper, however, is considerably more expensive than black plastic. It does not have the stretchability of plastic, and it tends to degrade prematurely along the edges where it is secured with a layer of soil. The paper is then subject to being lifted by the wind. Rebar, old pipe, or stones – rather than soil – can be used to secure the edges.(Bergholtz, 2004)



Penn State Center for Plasticulture trial of potatoes grown with colored plastic mulch, drip irrigation, and floating row covers. Photo courtesy Penn State Center for Plasticulture.

## Melons, more and earlier

One study, based on three years of field trials in Utah, found that clear plastic mulch increased watermelon yield by 20%, while using the mulch and a row cover increased the yield by 44%, in comparison with melons raised without plasticulture. The mulch also allows for earlier planting. Dr. Alvin Hamson, the primary author of the study, recommends covering the cultivated beds with clear plastic a week or two before transplanting. Then set the transplants into slits cut into the plastic. The mulch will trap enough heat to protect the melon plants down to an air temperature of 27°F. Some further tips from Dr. Hamson: Transplant three-week-old seedlings into the field (harden them off first) about the same time apple blossoms open in your area. If you plan to use a floating row cover in addition to the mulch, you can set out transplants a week before apple bloom. Be sure to remove the row cover a week before the melons begin to flower, so that bees can pollinate them, and remove it gradually—leave the cover off for a few more hours each day for a week. Dr. Hamson recommends the same early planting technique for summer squash. (Long, 1996)

Another study, done at an experiment station in Connecticut, involved multiple cropping of specialty melon transplants using black plastic mulch and floating row covers. Yields from these beds were up to three times higher than yields from beds planted in plastic mulch without the row cover. The earliest-yielding cultivars in this study were Passport (galia) and Acor (charentais), both developed with shorter days to maturity for use in northern climates. These specialty melons are larger than cantaloupe and fetch a higher price. Accounting for the added expense of row covers, the researchers concluded that “row covers not only increased early fruit and total fruit, but profitability is about 6-fold greater when melons are grown for retail or wholesale.” (Hill, 1997)

## Floating Row Covers

Floating row covers are made of spun-bonded polyester and spun-bonded polypropylene and are so lightweight that they “float” over most

crops without support. (Crops with tender, exposed growing points, such as tomatoes and peppers, are exceptions. To prevent damage from wind abrasion, the cover should be supported with wire hoops.) The spun-bonded fabric is permeable to sunlight, water, and air, and provides a microclimate similar to the interior of a greenhouse. Plants are protected from drying winds by what amounts to a horizontal windbreak, and the covers give 2 to 8°F of frost protection. In addition to season extension, advantages include greater yields, higher-quality produce, and exclusion of insect pests.

Floating row covers are available in various weights ranging from 0.3 to 2 ounces per square yard. The heavier the cover, the more degrees of frost protection it affords. Sizes range from widths of 3 to 60 feet and lengths of 20 to 2,550 feet. Wider covers are more labor-efficient, as there is less edge to bury per covered area. Durability is related to weight, type of material, and the additives used.

The lightest covers are used primarily as insect barriers. They can protect crops such as cabbage and broccoli from loopers and cabbage worms by excluding the egg-laying moths. Eggplant, radishes, and other favorites of the flea beetle are easily protected by floating row covers. Be sure to rotate crops in fields or beds planted under row covers, since overwintering insects from a previous crop can emerge under the cover. (Hazzard, 1999) Various diseases spread by insect vectors such as aphids and leaf hoppers are prevented as long as the cover remains in place. Disadvantages to the lighter covers are that they are easily damaged by animals and are seldom reusable. The lightest covers have a negligible effect on temperature and light transmission.

Medium-weight covers are the most commonly available. They are used to enhance early maturity, increase early yields and total yields, improve quality, and extend the season or make possible the production of crops in areas where they could not otherwise be grown. They also serve as insect barriers. Crops commonly grown with protection of medium-weight covers include melons, cucumbers, squash, lettuce, edible-pod peas, carrots, radishes, potatoes, sweet corn, strawberries, raspberries, and cut flowers.

Heavier covers, those exceeding 1 ounce per square yard, are used primarily for frost and freeze protection and where extra mechanical strength and durability are required for extended-season use. The microclimate created by heavier covers is similar to that created by



Floating row covers are available in various weights and sizes. Photo courtesy of Ken-Bar.

medium-weight covers, but they can be reused for three to four seasons or more.

Floating row covers can be installed manually or mechanically. Immediately after transplanting or direct seeding, lay the covers over the area and weigh down or bury the edges. Small-diameter concrete reinforcing bar (rebar), cut to manageable lengths, is excellent for weighting the edges. Enough slack should be left in the cover to allow the crop to grow. Row covers placed over crops growing on bare soil create a favorable environment for weed germination and growth. Periodic removal of the cover for hand cultivation is not practical. Weed control can be a significant problem under row covers, unless they are used in combination with plastic or other mulches.

In self-pollinated crops, or leafy vegetables such as lettuce or cabbage, the covers can be left on for most of the production period. One caution when growing tomatoes or peppers under covers is in regard to heat – temperatures that rise above 86°F for more than a few hours may cause blossom drop.(Wells, 1992) With insect-pollinated crops, such as melons, squash, or cucumbers, the covers must be removed at flowering to allow for insect pollination. The covers may, however, be replaced after the crop has been pollinated. Removing the covers should be considered a hardening-off procedure. Over the course of a few days, keep the covers off for longer and longer periods. Final removal is best done on a cloudy day, preferably just before a rain. Plants will suffer more transition shock if exposed to sun and wind.

Floating row covers can be used again in the fall. This sometimes involves modifying the technology. When floating row covers are used for spring crops, the covers are removed before the crops mature, while with fall crops the covers remain on the mature plants. In windy conditions this sometimes results in abrasion of the plant leaves, which can mar the appearance of a leafy crop. In that case, the cover could be supported

on wire hoops or bowed fiberglass rods, so it no longer rubs against the vegetable crop.(Coleman, 1995)

Row covers should be stored away from sunlight as soon as they are removed from the field. Many have been treated to resist degradation by UV light; whether or not that is the case, they will last longer if stored carefully in a dark, dry place. Fold or roll the covers in a systematic way to make them easy to unfurl for the next season's use.(Hazzard, 1999)

### **Hoop-Supported Row Covers (Low Tunnels)**

Row covers made of clear or white polyethylene are too heavy to float above the crop, so they are supported by hoops. Dimensions vary, but a typical structure is 14 to 18 inches high at the apex and wide enough to cover one bed. They are commonly used in combination with black plastic mulch for weed control. Hoop-supported row covers are often called low tunnels. They offer many of the same benefits as floating row covers, but are not permeable to air or water and are more labor-intensive. There are several types of low tunnels.

Slitted row covers have pre-cut slits that provide a way for excessive hot air to escape. At night the slits remain closed, reducing the rate of convective heat loss and helping to maintain higher temperatures inside the tunnel.

Punched row covers have small holes punched



Slitted row covers have pre-cut slits that provide a way for excessive hot air to escape. Photo courtesy of Ken-Bar.

about 4 inches apart to ventilate hot air. The punched covers trap more heat than the slitted tunnels. They are best for northern areas and must be managed carefully to avoid overheating crops on bright days. They are useful for peppers, tomatoes, eggplant, most cucurbits, and other warm-season crops that grow upright.

Tunnels that use two 3-foot wide plastic sheets stapled together at the top are commonly used by farmers growing trellised crops such as cherry tomatoes, long beans, and bitter melons. These tunnels are more expensive to put up, but they require little equipment investment. Most of the work to put them up is done by hand.(Ilic, 2004)

Hoops for supporting slitted or punched row covers are often made from 10-gauge galvanized wire. The pieces are cut to 65 to 75 inches long. Each end is inserted about 6 to 12 inches deep on each side of a row or bed to form a hoop over it. Hoops are spaced 5 to 8 feet apart – or less. Tim King, a market gardener in Minnesota, cuts hoops 3 to 4 feet long and spaces them 2 feet apart in the beds.(King, 2002) The covers are anchored on each edge with soil. Tunnels can be set by hand or with machines that resemble plastic mulch layers.

## Cold Frames

Traditional low structures such as cold frames and cloches are continually being modified by innovative gardeners and garden supply manufacturers. Although cold frames work well in protecting crops in cold weather, construction costs are high compared to plasticulture systems. For special situations, many publications contain plans for cold frames, solar pods, and other small portable structures. *Solar Gardening*, by Leandre and Gretchen

Poisson, listed under **Further Resources**, is one such publication. A more recent article on cold frames can be found in the November 2004 issue of *Fine Gardening* magazine.(Vargo, 2004)

## High Tunnels

High tunnels, also called hoop houses, have been attracting a lot of attention in the past few years, as more and more market gardeners have come to consider high tunnels essential tools in their operations. A high tunnel is basically an arched or hoop-shaped frame covered with clear plastic and high enough to stand in or drive a tractor through. Traditional high tunnels are completely solar heated, without electricity for automated ventilation or heating systems. Crops are grown in the ground, usually with drip irrigation. Compared to greenhouses, high tunnels are relatively inexpensive, ranging in price from \$1.50 to \$3.00 per square foot – and even less for the Haygrove multibay tunnels discussed below.

High tunnels are used extensively in Europe, Asia, and the Middle East. Although high tunnels are not used as much in the United States as in other parts of the world, interest here is growing rapidly. Universities and agricultural organizations around the country are conducting high-tunnel research, market growers are hosting workshops on their farms and at conferences, and more articles are appearing in trade journals and newsletters.



Right: The most critical components of hoop house strength are the end walls. Below: At the Noble Foundation, wood end-posts fabricated from two 2- by 6-inch boards, corrugated fiberglass. Photos courtesy of Noble Foundation.



Universities and Foundations Conducting High Tunnel Research			(Lamont, 2003)
University or Foundation	Contact	Phone	E-mail
Pennsylvania State University Center for Plasticulture	Bill Lamont	814-865-7118	wlamont@psu.edu <a href="http://plasticulture.cas.psu.edu">http://plasticulture.cas.psu.edu</a>
Ohio State University	Matt Kleinhenz	330-263-3810	kleinhenz1@osu.edu
University of New Hampshire	Brent Loy	603-862-3216	jbloym@christa.unh.edu
Rutgers University	A.J. Both	732-392-9534	both@aesop.rutgers.edu
University of Maryland Cooperative Extension	Bryan Butler		bb113@umail.umd.edu
University of Missouri-Columbia	Louis Jett	573-884-3287	jettl@missouri.edu
Kansas State University	Ted Carey	913-438-8762	tcarey@oznet.ksu.edu
University of Nebraska	Laurie Hodges	402-472-1639	lhodges@unl.edu
University of Minnesota	Terrance Nennich	218-694-2934	nenni001@umn.edu
Michigan State University	John Biernbaum	517-353-7728	biernbau@msu.edu
Noble Foundation, Oklahoma	Steve Upson	580-223-5810	sdupson@noble.org
Healthy Farmers Healthy Profits Project, University of Wisconsin	Astrid Newenhouse	608-262-1054	astridn@facstaff.wisc.edu
University of Kentucky	Brent Rowell	859-257-3374	browell@ca.uky.edu



Haygrove Tunnel with Cherries. Photo courtesy of Haygrove Tunnels.

Several manuals on hoophouses have been published recently. They give details on construction, crop production, economics, and sources for supplies, equipment, and additional information. Some of these were written by market gardeners who have built and are using hoophouses. Others were published as a result of research done at

The High Tunnels Web site, [www.hightunnels.org](http://www.hightunnels.org), is another valuable resource. At this site, researchers, Extension specialists, professors, students, technicians, and growers are collaborating to share their experience and knowledge about the use of high tunnels in the Midwest.

universities and private foundations. Titles and ordering information for these are provided under **Further Resources**.

High tunnels have had a tremendous impact on season extension. Market gardeners say the structures pay for themselves in one season.

- Crops grown in hoophouses have higher quality and are larger than those grown in the field.
- Crops grown in hoophouses can hit the market early when prices are high and help to capture loyal customers for the entire season.
- Hoophouses allow certain crops to be grown throughout the winter, providing a continuous supply to markets (and tables) the entire year.

Crops that have been grown in high tunnels include specialty cut flowers, lettuce and other greens, carrots, tomatoes, peppers, squash, melons, raspberries, strawberries, blueberries, and cherries. Although high tunnels provide a measure of protection from low temperatures, they are not frost protection systems in the same sense that greenhouses are. On average, tunnels permit planting about three weeks earlier than outdoor planting of warm season crops. They also can extend the season for about a month in the fall. Earlier plantings and later harvests would require a supplemental heating system.

## Location and Site Preparation

Alison and Paul Wiediger of Au Naturel Farm in south-central Kentucky grow winter vegetables in 8,500 square feet of high tunnels. In regard to locating a hoophouse, they advise other growers to put it close to the house. Especially on cold days, the shorter the walk from the house to the hoophouse, the more pleasant the trip will be — and the more likely you will be to make it. The Wiedigers advise other growers to prepare the site so that the ground is level from side to side, and has no more than 3% slope from end to end. Avoid wet or shady areas and obstructions to ventilation. Make sure drainage around the site is good. You don't want water running through the house every time it rains. (Wiediger, 2003)

## Orientation

Dan Nagengast of Wild Onion Farm in eastern Kansas says the orientation (east-west or north-south) depends on your location. Manufacturers recommend orienting the house to capture the most light in winter. For locations north of 40° latitude, the ridge should run east to west. For locations south of 40° latitude, the ridge should run north to south. At any latitude, gutter-connected or closely spaced multiple greenhouses will get more light if they are aligned north-south because they avoid the shadow cast by structures to the south.(Byczynski, 2003) Dr. Lewis Jett, in Columbia, Missouri, says that a high tunnel should be oriented perpendicular to prevailing winds: in regard to orientation of a high tunnel, sunlight is less important than ventilation.(Jett, 2004)

## Design and construction

A high tunnel is not difficult to build. The most common design uses galvanized metal bows attached to metal posts driven into the ground 4 feet apart—a traditional quonset style structure. Carol A. Miles and Pat Labine in Washington offer construction details for a 10-foot by 42-foot structure that can be built for \$350.(Miles and Labine, 1997) See Appendix I.

The *High Tunnel Production Manual*, published by The Pennsylvania State University Center for Plasticulture, details the construction and use of 17- by 36-foot tunnels using a gothic arch design developed by Penn State. (They chose this smaller size for research purposes.) The center section of the end walls can be opened up for easy access by machinery.(Lamont, 2003) Construction details only are shown in Appendix II, Design and Construction of the Penn State High Tunnel.

The *Hoop House Construction Guide*, by Steve Upson of the Noble Foundation, provides details for three designs: quonset, straight wall, and triple side-vent. Upson says the quonset structure is generally the least expensive to purchase. While satisfactory for producing low growing crops, trellised crops can't be grown close to the sides. Straight wall designs provide unhindered internal access along the sides of the house, while permitting plenty of vertical growing space, but because of the additional pipe required, expect to pay more for materials and to spend more time on construction. The triple side-vent has vents on both ends of the tunnel; one side of the house

is taller than the other, and the third vent is at the top of the tall side. This is the most expensive of these three designs. See **Further Resources** for information.

Strength is important. Heavy-gauge galvanized steel pipe is best for hoops. Setting the hoops four feet rather than any further apart is also recommended. Growers in snowy climates might choose a peaked-roof structure instead of the quonset style.(Bartok, 2002) The most critical components of a hoop house for strength are the end walls.(Upson, 2004) At the Noble Foundation, wood end-posts fabricated from two 2- by 6-inch boards, corrugated fiberglass panels for end-wall glazing, and industrial steel frame doors with heavy-duty latches, provide long-lasting end walls.

The most economical covering is 6-mil greenhouse grade, UV-treated polyethylene, which should last three to five years. Do not use plastic that is not UV-treated — “It will fall apart after half a season.”(Mattern, 1994)

Roll-up sides used on many high tunnels provide a simple and effective way to manage ventilation and control temperature. The edge of the plastic is taped to a one-inch pipe that runs the length of the tunnel. A sliding “T” handle is attached to the end of the pipe so that the plastic can be rolled up as high as the hip board. Ventilation is controlled by rolling up the sides to dispel the heat. Depending on temperature and wind factors, the two sides may be rolled up to different heights.

Coleman (1995) gives the following advice for dealing with wind.

Wind whipping and abrasion can be a serious problem. No matter how carefully the cover is tightened when it is first put on, it always seems to loosen. There are two ways to deal with this. The simplest is to run stretch cord over the top of the plastic from one side to the other.... One cord between every fourth rib is usually sufficient. The tension of the stretch cord will compensate for the expansion and contraction of the plastic due to temperature change and will keep the cover taut at all times. The second solution is to cover the tunnel with two layers of plastic and inflate the space between them with a small squirrel cage fan. This creates a taut outer surface that resists wind and helps shed snow.

## Missouri cut flower grower builds a solar-powered hoophouse

When Bryan Boeckmann of Westphalia, Missouri, decided to start cultivating cut flowers, a high tunnel seemed like the natural choice. But he had a problem: He couldn't always be in Westphalia to make the required adjustments. Temperatures in such a structure can easily get too high on a sunny day, and the grower must be on hand to open the vents.

"I work full time for the fire department in Jefferson City, and the temperature in a high tunnel can change a lot in a 24-hour period," he said. "I had to have something I could rely on. Fortunately, necessity is where most good ideas come from." Boeckmann's good idea was to use solar power to automatically raise and lower the side curtains on his tunnel. His project was funded by a grant from the Missouri Department of Agriculture.

Jim Quinn, the MU extension researcher who helped with the project, said Boeckmann was inspired by existing technology in poultry barns. "He had seen how poultry curtains work, and he thought, 'Why can't I do the same thing with a high tunnel and use solar power?'" The curtains are made of white, woven, tarp-like material. They are pulled up to close the sides and lowered to open the sides of the tunnel. Quinn said the innovation "is really a nice fit. The times when you need to adjust the curtains are when there's a lot of sunny weather, and that's also when the solar power is available."

Boeckmann initially hoped to drive the side curtains with conventional electric power, but hooking into the grid was "cost-prohibitive," he said. He called on Missouri Valley Renewable Energy (MOVRE), a firm in Hermann, Missouri, to design and build a solar unit. Using mostly used parts, MOVRE owner Henry Rentz constructed a small building with two solar panels on the roof and an inverter, batteries, and control panel within.

"I found some used stuff for Bryan because I wanted him to succeed in what he was doing," said Rentz. "Those batteries alone would have cost \$1,600 new. I basically did it to show people something that already works."

The system succeeded beyond their expectations. "In June, when we had that extended period of rain, that system ran for 11 days without sun," Rentz said.

"It's fairly simple," Boeckmann said. "Once you've initially set it up, typically you don't have to mess with it. You just have to set the thermostat." The thermostat in the hoop house senses temperature and, at a set point, triggers a mechanism that very slowly raises or lowers the plastic side curtains. "The reason it moves so slowly is to give the temperature in the building a chance to adjust," he said. "It takes it 15 minutes to go all the way up. You can do it manually really fast, if a storm is coming."

Boeckmann also uses solar power to drive his irrigation pump—"a little bitty pond pump that doesn't eat up a lot of juice."

He believes his innovations could boost the already growing interest in high tunnel construction. "There's good reason for the interest," he said. "The difference they make is phenomenal, considering it's just a sheet of plastic stretched over a frame. They just keep improving them."

For more information, contact Jim Quinn at 573-882-7514 or by e-mail at [quinnja@missouri.edu](mailto:quinnja@missouri.edu). (Rose, 2004)

Irrigation is essential for adequate and timely watering. Watering can be done by hand, through a trickle or drip system, or by overhead emitters. The Pennsylvania State Center for Plasticulture *High Tunnel Production Manual* discusses the advantages of drip irrigation from water being delivered directly to the soil around the crops.

- Efficient water and fertilizer use
- Reduced weed competition in areas outside the beds
- Ability to simultaneously irrigate and work inside tunnels
- Reduction in disease potential because water doesn't get on the leaves

If you choose trickle irrigation, use one line per row, or depending on the crop, one line per double row. If the soil is adequately fortified with nutrients, supplemental feeding might not be necessary; however, nitrogen can be applied through the trickle system.

The manual also discusses overhead irrigation and provides details on how to construct an overhead system. This allows irrigation water to be applied evenly to the entire soil surface. It can be used to leach salts from tunnel soils or to establish and grow cover crops within the tunnel.

A floor covering of a single sheet of 6-mil black plastic or landscape fabric provides several advantages. It warms the soil, controls weeds, greatly reduces evaporation of soil moisture, and serves as a barrier against diseases in the soil that could infect plant parts above ground. Secure the edges (sides and ends) of the plastic to prevent wind from blowing the plastic over the plants.

Temperature management using the roll-up sides is critical. On sunny mornings, the sides must be rolled up to prevent a rapid rise in temperature. Tomato blossoms, as mentioned earlier, will be damaged when temperatures go above 86°F for a few hours. Even on cloudy days, rolling up the sides provides ventilation to help reduce humidity that could lead to disease problems. The sides should be rolled down in the evening until night temperatures reach

65°F. A maximum/minimum thermometer is a great aid in keeping tabs on temperature.

Twenty feet by 96 feet is a size commonly used by market growers. This size allows efficient heating and cooling, efficient growing space, and adequate natural ventilation. Lynn Byczynski and Dan Nagengast who grow specialty cut flowers and vegetables in Zone 5 near Lawrence, Kansas, have five hoophouses, each 20 by 96 feet. They purchased Polar Cub cold frames from Stuppy Greenhouse Company. They chose Stuppy not because it was the only greenhouse manufacturer, but because it was the closest, so shipping costs were least expensive. The cost for two houses was \$3,250, including the metal frames, four-year poly covering, wiggle wire to attach the poly to the frames, and shipping. Lumber to install the roll-up sides and poly-covered endwalls cost an additional \$1,600. They also paid a neighbor \$300 to prepare the site with a bulldozer and laser leveling device. In their first year, the hoophouses produced more than twice what they cost. The record of crops grown, planting and harvest dates, and revenue per square foot is shown in Table 3. (Byczynski, 2003) Additional details, including photos that show the construction of a Stuppy's Polar Cub cold frame at Wild Onion Farm, can be found in *The Hoophouse Manual: Growing Produce and Flowers in Hoophouses and High Tunnels*. See **Further Resources**.

Alison and Paul Wiediger also use a commercially available 20- by 96-foot high tunnel, in



Hoophouses at Wild Onion Farm. Photo courtesy of Wild Onion Farm.

Hoophouse production at Wild Onion Farm			
Crop	Date planted	Dates of harvest	Revenue per square foot
<b>Fall-planted flowers</b>			
Delphinium 'Clear Springs' and "Bellamosum"	9/28/00	4/26/01-7/26/01	\$2.67
Dianthus (Sweet William)	9/25/00	4/24/01-6/1/01	\$5.05
Larkspur 'Giant Imperial'	10/7/00	5/2/01 - 6/10/01	\$3.25
<b>Spring-planted flowers</b>			
Stock 'Cheerful'	3/21/00	5/18/00-5/30/00	\$1.92
Campanul 'Champion'	4/1/01	6/3/01-6/30/01	\$3.62
Lisianthus	4/12/00	6/26/00-10/8/00	\$3.32
<b>Fall-planted vegetables</b>			
Arugula	9/27/00	fall, spring	\$1.31
Cilantro	9/27/00	fall, spring	\$0.95
Chinese cabbage	9/27/00	fall	\$1.11
Green onions	9/27/00	fall	\$0.61
Leeks	9/27/00	spring	\$1.10
Lettuce	9/27/00	fall, spring	\$0.40
Mizuna	9/27/00	fall	\$0.69
<b>Spring-planted vegetables</b>			
Cucumbers	4/12/00	summer	\$1.34
Tomatoes	4/12/00	summer, fall	\$3.55
Byczynski, 2003			

addition to two 21- by 60-foot tunnels. They think there is value in building as large a structure as is practical. (Wiediger, 2003)

Most of the growing in this tunnel will be in spring, fall, and winter when outside temperatures are cooler/colder. We believe that both the earth and the air within the tunnel act as heat sinks when the sun shines. At night, they give up that heat, and keep the plants safe. The smaller the structure, the smaller that temperature "flywheel" is, and the cooler the inside temperatures will be.

They also find that plants close to the walls do not grow as well as the plants further from them. The larger the frame, the larger the percentage of effective growing area. And most growers want more, rather than less, space at the end of one growing season.

Twenty feet wide, however, may be as wide as you can get with the inexpensive cold frame type hoophouses without interior bracing. Longer

than 100 feet or so may be too long for effective natural ventilation.

The Wiedigers use a double layer of 6-mil, 4-year poly to cover their tunnels. A small fan blows air between the two layers to create an insulating barrier against the cold. Construction and management details can be found in their manual, *Walking to Spring: Using High Tunnels to Grow Produce 52 Weeks a Year*. See **Further Resources** for ordering information.

### Haygrove Multibay Tunnel Systems

With Haygrove tunnels, innovative growers are literally covering their fields to protect high-value crops from early and late frost, heavy rain, wind, hail, and disease. The frames also provide support for shade cloth and bird netting. (DeVault, 2004) The British company Haygrove was started in 1988 with a little more than two acres of strawberries in hoophouses. By 2002, Haygrove had expanded to nearly 250 acres of soft fruits, includ-



Full production in early March at Au Naturel Farm, lettuces and spinach. Photo courtesy of Au Naturel Farm.

ing strawberries, blackberries, red currants, and cherries, grown under plastic in England and eastern Europe. They also came up with a new design for multibay tunnels and sold 3,000 acres of tunnels throughout Europe. Haygrove tunnels are now being distributed and used in the U.S. Haygrove sells tunnels from 18 to 28 feet wide per bay, with a three bay minimum. There are no walls between bays. The total length and width can be whatever the grower desires. Company representative Ralph Cramer in Lancaster County, Pennsylvania, says he has seen tunnels as short as 65 feet and as long as 1,100 feet. They have been used to cover from 1/3 acre to 100 acres (of blueberries in California). Unlike greenhouses, Haygrove tunnels don't need to be built on flat ground, but can be built on slopes. Cramer says advantages of the systems include lower cost and better ventilation. (Cramer, 2004) One acre of Haygrove tunnels costs about 55 cents per square foot, or about \$24,000. (Byczynski, 2002)

North Carolina market gardeners Alex and Betsy Hitt covered two quarter-acre blocks with Haygroves in 2004. One block was planted to specialty cut flowers, the other to organically grown heirloom tomatoes. Heirlooms have not been bred to resist foliar diseases, and growing organically limits fungicide options. Alex was pleased with the resulting decrease in plant disease: "We have very severe foliar disease



Haygrove tunnels covering large area. Photo courtesy of Haygrove Tunnels.



Haygrove tunnel with tomatoes. Photo courtesy Haygrove Tunnels.

problems on our tomatoes in the field and traditionally would pick a crop for about five weeks, and then it would be dead. With the Haygroves, we picked from the same number of plants for almost 10 weeks and picked and sold 35% more fruit than last year.” (Hitt, 2004) Hitt also noticed less disease in the Haygroves, compared with single bay tunnels with roll-up sides. He attributes the difference to better ventilation in the Haygroves, since they vent so high, resulting in less humidity. (Cramer, 2004)

Pennsylvania grower Steve Groff of Cedar Meadow Farm agrees. In 2004, despite the early arrival of late blight in the eastern United States and Canada, Groff’s six inter-connected bays yielded more than 3,000 25-pound boxes of tomatoes (by October 11), with seventy percent of them grading out at No. 1. His unprotected fields yielded only about 25 to 60 percent percent No. 1s. Groff says 2004 was an extremely unusual year, with a lot of wet weather. Tunnels allowed him to reduce fungicide use by more than 50 percent and allowed tomato harvest to begin two to three weeks earlier. They also extended the season: On October 11, Groff was still picking from tomatoes planted in April, and expected to harvest 100 to 200 more 25-pound boxes. (DeVault, 2004, Groff, 2004)

Leitz Farms in Sodus, Michigan, covered 10 acres of tomatoes this year to help control growing conditions. Fred Leitz, one of four brothers who run the family farm, said the plants look healthier than the ones outside and show no sign of disease. Their operation was featured on the front page of *Vegetable Growers News*. (Morris, 2004)

Haygrove tunnels, unlike single bay hoophouses, are not designed to carry a snow load, so they cannot be covered with poly during the winter in areas that have snow. John Berry, director of Haygrove, says “Haygrove tunnels are designed to be temporary low-cost structures that can be moved with the crop. The key management task is venting. Unlike conventional single hoop houses, multibay tunnels can be completely opened to ensure the crop is not stressed by heat or humidity.” Strawberries grown with this system can be picked two to three weeks earlier in the spring; yields of raspberries, blueberries, and strawberries have consistently been 30 percent higher in tunnels, compared with field grown berries; and the grade-out percentage for soft fruit under the tunnels runs about 90:10 Class A to B, compared with 75:25 for conventional outdoor production. (Otten, 2003)

## The mobile high tunnel

The “salad days” of season extension were arguably in the second half of the 19th century, on the outskirts of Paris, where 2,000 or so market gardens employed cloches and cold frames to produce 100,000 tons of out-of-season produce per year. Many of these growers built small trackways on which to move the heavy glass cloches and frames to different parts of the garden. (Poisson, 1994) For the past century, European horticulturists have put railcar wheels on greenhouses and rolled them on iron rails. The rails extend two or more times the length of the greenhouse, making multiple sites available for one house. Eliot Coleman describes a sample cropping sequence for a mobile greenhouse or high tunnel.

An early crop of lettuce is started in the greenhouse on Site 1. When the spring climate is warm enough for the lettuce to finish its growth out-of-doors, the ends are raised and the house is wheeled to Site 2. Early tomato transplants, which need protection at that time of the year, are set out in the greenhouse on Site 2. When summer comes and the tomatoes are safe out-of-doors, the house is rolled to Site 3 to provide tropical conditions during the summer for transplants of exotic melons or greenhouse cucumbers.

At the end of the summer, the sequence is reversed. Following the melon and cucumber harvest, the house is returned to Site 2 to protect the tomatoes against fall frosts. Later on, it is moved to Site 1 to cover a late celery crop that was planted after the early lettuce was harvested. Then Site 1 is planted to early lettuce again, and the year begins anew. (Coleman, 1992)

Coleman has adapted these practices to his own garden, replacing the heavy and costly iron with more practical wooden rails. He provides plans for his mobile high tunnel, and year-round cropping plans, in his book *Four-Season Harvest*. See **Further Resources**.

## Economics of Season Extension

One method for determining whether season extension techniques can be a profitable addition to a farming operation is called partial budgeting. (Ilic, 2004) A partial budget requires assessment of changes in income and expenses that would result from changing to a different

practice. It is called a partial budget because it is not necessary to calculate the expenses that would be the same for either practice. Steps to follow in the analysis include:

- Decide what crop will be grown using a season extension technique.
- Decide what season extension technique will be used.
- Calculate costs of the new technique, including supplies, rent or purchase of specialized equipment, labor, water, pest management. Allow for extra hours of labor due to inexperience in the first year.
- Calculate the added gross income from the new technique. Gross income is simply the price per unit of produce sold multiplied by the number of units sold. Income changes as a result of a change in the price received per unit, a change in the number of units sold, or both.
- Calculate any reduced expenses associated with the change. For example, use of black plastic or paper mulch will reduce the need for cultivation or herbicides. Use of floating row covers will reduce the need for other insect pest management operations.
- Add up all the increases and decreases of expense and income and calculate the total change in profit.

Specific information on costs of materials and supplies is available from the companies and in the manuals listed under **Further Resources**. The *High Tunnel Production Manual*, *High-Tunnel Tomato Production*, *The Hoophouse Handbook* and several Noble Foundation bulletins contain sample budgets for a number of fruits, vegetables, and cut flowers.

It must be remembered that any sample budget is just that—a sample. All market gardeners bring their own mix of skills, values, and resources together to build a unique system. According to Coleman(1992):

The secret to success in lengthening the season without problems or failures is to find the point at which the extent of climate modification is in balance with the extra amount of time, money, and management skill involved in attaining it. When planning for a longer season, remember the farmer’s need for a vacation period during the year. The dark days of December and January, being the most difficult

months in which to produce crops, are probably worth designating for rest, reorganization, and planning for the new season to come.

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## Further Resources

### Publications

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Low-cost Passive Solar Greenhouses. 1980. By Ron Alward and Andy Shapiro. NCAT, Butte, MT. 174 p.

Root Zone Heating. ATTRA Publication. 2002. By Steve Diver. NCAT, Fayetteville, AR. 40 p.

Solar Greenhouse Resource List. ATTRA Publication. 2003. By Barbara Bellows. NCAT, Fayetteville, AR. 35 p.

Specialty Lettuce and Greens: Organic Production. ATTRA Publication. 2002. By George Kuepper and Janet Bachmann. NCAT, Fayetteville, AR. 26 p.

Scheduling Vegetable Plantings for Continuous Harvest. ATTRA Publication. 2002. By Janet Bachmann. NCAT, Fayetteville, AR. 27 p.

The Hoophouse Handbook: Growing Produce and Flowers in Hoophouses and High Tunnels. 2003. By Lynn Byczynski (ed.). Fairplain Publications, Inc. 60 p.  
*Includes information on construction and management, including crops to grow and sources of supplies. To order, send \$15 plus \$4 shipping to:*

GFM  
P.O. Box 3747  
Lawrence, KS 66046  
800-307-8949 (toll-free)

Extending the Season: Six Strategies for Improving Cash Flow Year-Round on the Market Farm. 2004. Edited by Lynn Byczynski, Fairplain Publications. 60 p.  
*Includes articles about protected early and late crops; winter crops in the field and unheated hoophouse; high-dollar crops for the heated greenhouse; storage crops to sell months after harvest; value-added products to sell year-round; creating year-round markets. \$15 plus \$4 shipping from GFM.*

Walking to Spring. 2003. By Paul and Alison Wiediger. Au Naturel Farm. 94 p.  
*The Wiedigers tell how they use high tunnels to grow produce 52 weeks a year. Includes information on construction, crops grown, record-keeping, and additional resources. The price is \$15 plus \$3.50 shipping and handling. Order from:*

Au Naturel Farm  
3298 Fairview Church Road  
Smiths Grove, KY 42171  
270-748-4600  
[wiediger@msn.com](mailto:wiediger@msn.com)  
<http://aunaturelfarm.homestead.com/>

High Tunnel Production Manual. 2003. By William J. Lamont et al. The Pennsylvania State University. 164 p.  
*Covers construction, production, and economics for vegetables, berries, sweet cherries, and flowers. Includes additional resources. To order, send a \$25 check made out to The Pennsylvania State University to:*

Dr. Bill Lamont  
Department of Horticulture  
206 Tyson Building  
The Pennsylvania State University  
University Park, PA 16802

High-Tunnel Tomato Production. 2004. By Lewis Jett. University of Missouri Extension. 28 p.  
*The book covers everything from building high tunnels to selecting varieties, fertilization, caging and staking, pest management, and intercropping. The intercropping section tells how you can grow 12 different vegetables in a 12-month period. Available for \$10 from:*  
Extension Publications  
University of Missouri  
2800 Maguire Blvd.  
Columbia, MO 65211  
573-882-7216  
800-292-0969 (toll-free)

Hoop House Construction Guide. 2004. By Steve Upson. Samuel Roberts Noble Foundation Agricultural Division. 46 p.  
*Excellent photos show all construction details from preparing the site to attaching the poly covering. The resulting hoophouse is sturdy enough to withstand the extremes of Oklahoma weather. Contact:*  
Steve Upson  
The Samuel Roberts Noble Foundation, Inc.  
P.O. Box 2180  
Ardmore, OK 73402  
580-223-5810  
[sdupson@noble.org](mailto:sdupson@noble.org)

Four-Season Harvest: Organic Vegetables from Your Home Garden All Year Long. 1999. By Eliot Coleman. Chelsea Green Publishing. 234 p.  
*Inspired by Scott and Helen Nearing's garden in the late '60s and based on the author's success with harvesting fresh vegetables year-round in New England, this book contains details on design, construction, and management of the outdoor garden, cold frames, mobile high tunnels, and root cellars. Also includes growing tips for 50 vegetable crops, a planting schedule for extended harvests for all locations in the U.S., and sources of tools and supplies. Written primarily with the home gardener in mind, but much of the material can be applied to a commercial operation. Available from bookstores, on-line booksellers, or directly from the publisher:*  
Chelsea Green Publishing  
P.O. Box 428  
Gates-Briggs Building #205  
White River Junction, VT 05001  
800-639-4099 (toll-free)  
[www.chelseagreen.com](http://www.chelseagreen.com)

The New Organic Grower (Revised edition). By Eliot Coleman. 1995. Chelsea Green Publishing Company. 340 p.  
*The New Organic Grower has become a classic for small-scale market gardening. This revised edition includes chapters on season extension, including plans for constructing moveable hoophouses. It provides background information for his 1998 publication, below. Eliot Coleman and Barbara Damrosch grow and market from October through May in Maine.*

The Winter-Harvest Manual: Farming the Back Side of the Calendar. 1998. By Eliot Coleman. Four Season Farm. 62 p.  
*This manual describes what Coleman and his wife Barbara Damrosch have learned since the above book was written. It includes their reasons for "farming the back side of the calendar" and details about how they do it, as well as a list of seed, tool, and supply companies. Available for \$15 including postage from:*  
Four Season Farm  
609 Weir Cove Road  
Harborside, ME 04642

Use of Plastic Mulch and Row Covers in Vegetable Production. 2003. By Dean McCraw and James E. Motes. Oklahoma Cooperative Extension Fact Sheet F-6034. 8 p.  
[www.osuextra.com](http://www.osuextra.com)

The Gandhi of greenhouses, Part I & Part II. 2004. By George DeVault. The New Farm. April 6, April 20.  
[www.newfarm.org/features/](http://www.newfarm.org/features/)  
*Two articles describe the passive solar production system used by Steve and Carol Moore in Spring Grove, Pennsylvania.*

Waste oil heater. 1980. Anon. Mother Earth News. 11 p.  
[www.bagelhole.org/](http://www.bagelhole.org/)  
*The article provides instructions for making your own waste oil heater from an old water heater tank. It is said to burn used crankcase oil both cleanly and without any detectable odor, and put out a lot of heat. The heater is designed for use in a shop or garage rather than in an open field.*

## Organizations

American Society for Plasticscience

526 Brittany Drive  
State College, PA 16803-1420  
814-238-7045  
[www.plasticulture.org](http://www.plasticulture.org)

**National Greenhouse Manufacturers Association**

20 W. Dry Creek Circle, Suite 110  
Littleton, CO 80120  
800-92-NGMA  
303-798-1338  
[ngma@ngma.com](mailto:ngma@ngma.com)  
[www.ngma.com/](http://www.ngma.com/)

## Recycling Contacts

**American Plastics Council**

1300 Wilson Blvd.  
Arlington, VA 22209  
800-243-5790 (toll-free)  
703-741-5000

[www.americanplasticscouncil.org/](http://www.americanplasticscouncil.org/)

*Since 1990, the plastics industry, as individual companies and through organizations such as APC, has invested more than \$1 billion to support increased recycling and educate communities in the United States. The Association of Postconsumer Plastic Recyclers hosts a Website as a service to the plastic packaging industry to promote the most efficient use of the nation's plastics recycling infrastructure and to enhance the quality and quantity of recycled post-consumer plastics.*

## Manufacturers and Suppliers

NOTE: This list is intended to be neither comprehensive nor exclusive. Endorsement of any particular product or company is not implied. Additional suppliers, both wholesale and retail, are listed in the manuals and on the High Tunnel Web site described above. Many resources are also listed in the *American Vegetable Grower* magazine's annual Source Book (July issue) and the *Greenhouse Grower*. Contact:

Meister Publishing Co.  
37733 Euclid Ave.  
Willoughby, OH 44094  
440-942-2000

*Good Fruit Grower* is another trade magazine that lists suppliers. Contact:

Good Fruit Grower  
105 South 18th Street, Suite 217

Yakima, WA 98901  
509-575-2315  
[www.goodfruit.com/buyers/](http://www.goodfruit.com/buyers/)

**A.M. Leonard**

P.O. Box 816  
Piqua, OH 45356  
800-543-8955 (toll-free)  
[www.amleo.com](http://www.amleo.com)

*General tools, also landscape fabric, plastic film, shade cloth.*

**American Plant Products & Supplies**

9200 N.W. 10th  
Oklahoma City, OK 73127  
405-787-4833  
800-522-3376 (toll-free)  
[www.americanplant.com](http://www.americanplant.com)

*Source of greenhouse frames, films and glazing, shade cloth, row covers, mulch film.*

**Atlas Greenhouse Systems, Inc.**

P.O. Box 558  
Alapaha, GA 31622  
800-346-9902 (toll-free)  
[service@atlasgreenhouse.com](mailto:service@atlasgreenhouse.com)  
[www.AtlasGreenhouse.com](http://www.AtlasGreenhouse.com)

*Structures. Highly recommended by growers in the South and Midwest.*

**CropKing, Inc.**

5050 Greenwich Rd.  
Seville, OH 44273  
330-769-2002  
[cropking@cropking.com](mailto:cropking@cropking.com)  
[www.cropking.com](http://www.cropking.com)

*Offers grower-training workshops in hydroponic production.*

**Dirt Works**

6 Dog Team Rd.  
New Haven, VT 05472-4000  
800-769-3856 (toll-free)  
[admin@dirtworks.net](mailto:admin@dirtworks.net)  
[www.dirtworks.net/](http://www.dirtworks.net/)

*Source of Bio-Film 100 biodegradable mulch.*

**FEDCO Seeds**

P.O. Box 520A  
Waterville, ME 04903  
207-426-9005  
[www.fedcoseeds.com](http://www.fedcoseeds.com)

*Floating row covers, plastic film mulches.*

**Frost Boss Wind Machine**

Hawkes Bay Wind Machines, Ltd.

Hastings, New Zealand  
[www.frostboss.com.nz/](http://www.frostboss.com.nz/)  
*Source of wind machines for frost protection.*

Griffin Greenhouse & Nursery Supplies  
1619 Main Street  
P.O. Box 36  
Tewksbury, MA 01876  
978-851-4346  
[www.griffins.com](http://www.griffins.com)  
*Wholesale distributor of a range of plasticulture products.*

Harmony Farm Supply & Nursery  
3244 Hwy. 116 North  
Sebastopol, CA 95472  
707-823-9125  
[info@harmonyfarm.com](mailto:info@harmonyfarm.com)  
[www.harmonyfarm.com](http://www.harmonyfarm.com)  
*Floating row covers, frost blankets, landscape fabric, cold frames, greenhouse poly.*

Haygrove Tunnels  
Ralph Cramer  
116 Trail Road North  
Elizabethtown, PA 17022  
866-HAYGROVE (toll-free)  
[Ralph.cramer@haygrove.com](mailto:Ralph.cramer@haygrove.com)  
[www.haygrove.co.uk](http://www.haygrove.co.uk)

Holland Transplanter Co.  
P.O. Box 1527  
Holland, MI 49422-1527  
800-275-4482 (toll-free)  
[www.transplanter.com](http://www.transplanter.com)  
*Manufacturer of mechanical transplanters, bed shapers, mulch layers, mulch lifters, and related equipment.*

Hummert International  
4500 Earth City Expressway  
Earth City, MO 63045  
800-325-3055 (toll-free)  
[www.hummert.com](http://www.hummert.com)  
*Drip irrigation, landscape fabric, greenhouse frames, poly covering, floating row cover, other supplies.*

Jaderloon  
P.O. Box 685  
Irmo, SC 29063  
800-258-7171 (toll-free)  
[jaderloon@jaderloon.com](mailto:jaderloon@jaderloon.com)  
[www.jaderloon.com](http://www.jaderloon.com)  
*Offers a complete line of structures and wide selection of accessories including film*

*fastening systems, inflation blowers, polycarbonate sheets, and poly patch.*

Johnny's Selected Seeds  
955 Benton Ave.  
Winslow, ME 04901  
207-861-3900  
[www.johnnyseeds.com](http://www.johnnyseeds.com)  
*Floating row covers, slitted row covers, black poly mulch, IRT-100 green poly mulch, landscape fabric, tacks and staples, cold frames, seeds for hoophouse/greenhouse production and for hot weather lettuces.*

KEN-BAR, Inc.  
25 Walkers Brook Drive  
Reading, MA 01867-0704  
800-336-8882 (toll-free)  
[info@ken-bar.com](mailto:info@ken-bar.com)  
[www.ken-bar.com](http://www.ken-bar.com)  
*Suppliers of Dupont AG-06, Typar, Custom-Cover 5131, clear polyethylene slitted and punched row covers, Insolar slitted/punched row covers or tunnels, wire for hoops, embossed and smooth black plastic mulch, Planters Paper mulch, SRM-Red plastic mulch, IRT plastic mulch, and clear polyethylene tubes.*

Ledgewood Farm Greenhouse Frames  
Route 171  
Moultonboro, NH 03254  
603-476-8829  
*Manufacturere of Penn State type Gothic-arch design frames.*

Mechanical Transplanter Co.  
1150 Central Ave.  
Holland, MI 49423  
800-757-5268 (toll-free)  
[mtc@mechanicaltransplanter.com](mailto:mtc@mechanicaltransplanter.com)  
[www.mechanicaltransplanter.com](http://www.mechanicaltransplanter.com)  
*Mechanical transplanters, bed shapers, mulch layers, mulch lifters, low tunnel layers, floating row covers, colored film mulches, and photodegradable mulch.*

Orchard-Rite, Ltd.  
P.O. Box 9308  
Yakima, WA 98909  
509-457-9196  
[www.orchard-rite.com](http://www.orchard-rite.com)  
*Source of wind machines and orchard heaters.*

Peaceful Valley Farm Supply  
P.O. Box 2209

Grass Valley, CA 95945  
888-784-1722 (toll-free)

[www.groworganic.com](http://www.groworganic.com)

*Agribon and Tufbell floating row covers, slitted row covers, shade cloth, IRT mulch, Planters Paper, black embossed polyethylene mulch film, repair tape, clips, hoops, Wall-O'-Water.*

Plastitech, Inc.

478 Notre Dame

St. Remi, Quebec

Canada J0L 2L0

450-454-3961

800-667-6279 (toll-free)

[info@plastitech.com](mailto:info@plastitech.com)

[www.plastitech.com](http://www.plastitech.com)

*Plastic mulch, floating row covers, tunnels, irrigation, artificial windbreak material, mechanical mulch layers.*

Rain-Flo Irrigation

884 Center Church Rd.

East Earl, PA 17519

717-445-6976

*On-farm family-owned and -operated business. Manufactures vegetable growing machinery and supplies and carries almost all brands of irrigation equipment, specializing in drip irrigation. Floating row covers, plastic film mulches, mulch layers, transplanters, mulch lifters.*

ReflecTek Foils, Inc.

P.O. Box 310

Lake Zurich, IL 60047

888-439-6121 (toll-free)

[www.repelgro.com](http://www.repelgro.com)

*Metalized UV reflective and other plastic film mulches.*

Stuppy Greenhouse Mfg.

1212 Clay

North Kansas City, MO 64116

800-733-5025 (toll-free)

[greenhouse@stuppy.com](mailto:greenhouse@stuppy.com)

[www.stuppy.com](http://www.stuppy.com)

*Offers a variety of both coldframes and greenhouses.*

Special thanks for their contributions to Dr. William J. Lamont, Dr. Carol Miles, Lynn Byczynski and Dan Nagengast, Alison and Paul Wiediger, Ralph Cramer, Steve Groff, Alex Hitt, Bryan Boeckmann, and Steve Upson.

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**EB1825**


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## PORTABLE FIELD HOOPHOUSE



By

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Area Agricultural Systems Agent, Lewis County

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The Evergreen State College, Olympia, WA

When constructing a greenhouse would be unwieldy and too expensive, a plastic-enclosed house—the hoophouse—fulfills most of a small farmer's or home gardener's needs. So named because of the arched or "hoop" structure that supports the plastic "skin," hoophouses are available in many lengths.

If you have a small farm business and are looking for ways to increase crop diversity or earliness, this portable field hoophouse may help. Some crops that are well suited to this type of hoophouse include tomatoes, peppers, eggplants, and melons—crops that need to be planted after danger of frost and that generally mature late in the season west of the Cascade Mountains. The hoophouse effectively allows a grower to produce early yields of crops that require more heat units than the environment may otherwise provide.

The hoophouse rests directly over the soil in the field, using no benches or special growing media. Two people can easily dismantle and reassemble the lightweight structure in a different section of the field each year or within a growing season. An advantage to moving the hoophouse around the field is crop rotation, which avoids pest buildup. Another is the low cost, approximately \$350 for a 10' X 42' hoophouse.

The following hoophouse design will result in a structure approximately 10' wide at the base, 6 1/2' high at the center, and 42' long (Figure 1). Growers can easily adjust the length by adding or taking away support hoops and altering the length of the polyethylene plastic appropriately. The maximum length of polyethylene plastic available on the market is 100', which governs the maximum length for constructing a hoophouse. While initial construction of the hoophouse will take a day, two people can later put it up and take it down in only 2 hours. Storing the hoophouse out of the field during the winter months spares it from some of the worst weather and makes it last many years. Using wood treated with water-based preservatives also increases the longevity of the structure.



FIGURE 1.

Portable field hoophouse, 10' wide by 42' long, resting directly on soil surface in the field.

## Selecting Materials

Polyethylene plastic is available in many grades. A 6 mil weight is recommended for greenhouses. Selecting a lighter weight (4 mil) is not recommended. Untreated polyethylene will cost less initially; however, the lifespan of the material is significantly less, and the material will likely degrade after one year of use. When treated with a UV inhibitor, 6 mil plastic generally is guaranteed for 3 years.

Gases that escape from the PVC (polyvinyl chloride) pipes contribute to the deterioration of the polyethylene plastic. To prevent "off-gasing," paint the PVC pipes with white latex paint. Use wood treated with water-based preservatives for the base of the door frame, where the wood comes into contact with the soil. Untreated wood used for the remainder of the frame will not severely affect its longevity. Choose a mid-weight (4 oz to 5 oz) corrugated plastic for the ends. A clear plastic generally will darken over the years, whereas a colored plastic will lighten with time. The color of the plastic will not affect the usability of the hoophouse. Most light will enter through the polyethylene sides.

The choice of nylon twine for tying the hoops in place is broad. Twisted twine is susceptible to unraveling, while braided twine is more durable. Natural fiber twine (jute or cotton) is not recommended due to the stretching these materials experience. Baling twine is inexpensive and durable.

## Materials

- 9 ea. 2" X 4" X 12' boards, treated with water-based preservatives
- 4 ea. 2' X 8' sheets of 4 oz greenhouse-grade corrugated plastic
- 30 ea. 1/2" X 18" lengths of reinforcing rod (rebar)
- 17 ea. 18' lengths of 1" rigid white schedule 40 PVC (20' lengths cut down)
- 430' good quality nylon twine (minimum tensile strength 210 lbs.)
- 1 piece of 6mil polyethylene plastic sheeting, 50' long x 20' wide
- 38 ea. 3" galvanized self-tapping screws with rubber washers
- 30 ea. 1" galvanized self-tapping screws with rubber washers
- 10 ea. 1/4" X 4" bolts and matching wing nuts

- battery powered drill

## Building the Ends

Two of the two-by-four boards will become the bottoms of the door frames. Construct both door ends in the same fashion. For each door frame, place an 11-foot length of two-by-four down with a 4-inch side facing up. Mark the center of the 11-foot board, then mark  $14\frac{1}{2}$ " on each side of the center. These marks frame a 29" length in the middle of the board, which will become the bottom of the doorway. At each end of the framing board, measure 6" and drill two 1-inch holes next to each other into the bottom piece, placing the holes as close together as possible (Figure 2).

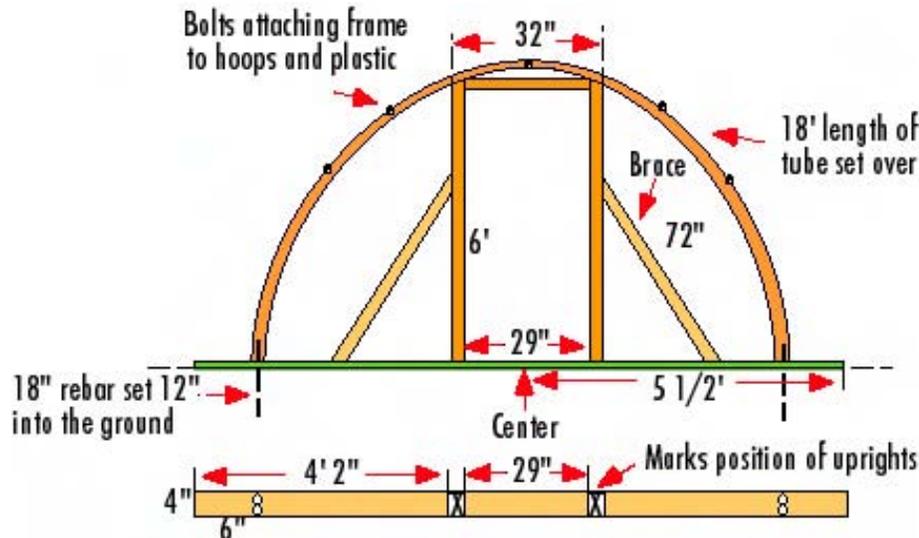


FIGURE 2.

Top view of bottom piece with two holes drilled 6" from each end and door uprights marked, and front view of the hoophouse end frame.

Turn the bottom piece on its side and insert a PVC length into holes at opposite ends, to form a hoop. This will be the outermost hoop. The corrugated plastic and door frame will attach to it. Cut two 6-foot lengths of two-by-four for the door uprights, along with one 32-inch piece for the top (header) of the door. Screw the header into the uprights, using the 3-inch self-tapping screws, so that the door frame is 2" wide and 4" deep. The door frame is then screwed to the bottom piece at the marked position using 3-inch self-tapping screws. Brace each side of the doorway with a two-by-four cut 72" long with the ends appropriately angled. Screw braces in place with 3-inch self-tapping screws.

Cut the corrugated plastic, lining up the ridges horizontally, to fit the ends of the hoophouse. Fitting the corrugated plastic horizontally gives added strength to the ends. Overlap the top piece of corrugated plastic a few inches over the bottom piece to keep the ends weatherproof. Use 1-inch self-tapping screws with rubber washers to attach the corrugated plastic to the door frame and the hoop. The rubber washer is helpful to keep the corrugated plastic from cracking.

Attaching the ends to the hoop structure with bolts makes the hoophouse quite easy to take apart and reassemble.

## Forming the Hoop Structure

In the field, mark an area 10' wide by 42' long for the hoophouse site. At each of the four corners hammer an 18-inch piece of reinforcing bar (rebar) 12" into the ground, leaving 6" above the surface. The aboveground portion of the rebar will hold the PVC hoops of the hoophouse in place. Place a door frame upright at one end, inserting the PVC hoop onto the rebar. In what will be the inside of the hoophouse, attach a support leg to each door upright (Figure 3). Using 3-inch self-tapping screws, attach the support legs to the side of each door frame that will face the polyethylene plastic. Attach a support "foot" to the end of each leg and pound them into the ground. The support legs will keep the hoophouse frame from shifting, losing its shape, or straining the plastic. Place the second door frame at the opposite end of the area marked for the hoophouse. Insert the PVC hoop over the rebar and secure with support legs in the same fashion.

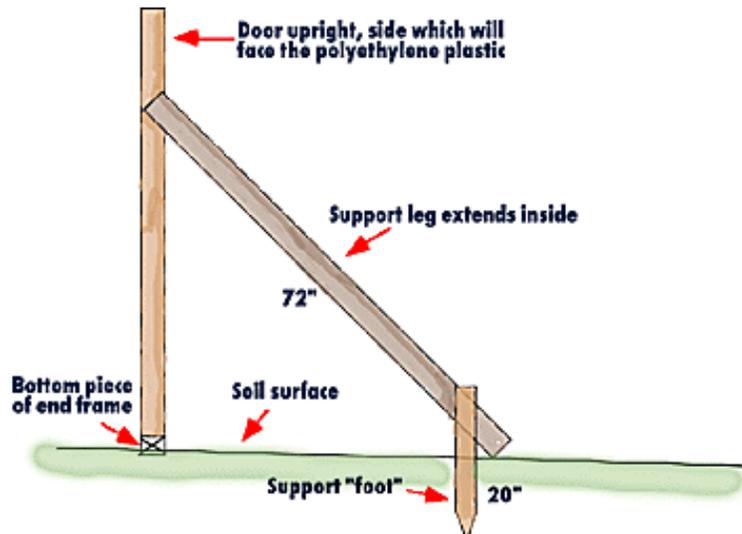


FIGURE 3.

Support leg and "foot," attached to the side of door upright which will face the polyethylene plastic, on what will be the inside of the hoophouse.

At 3-foot intervals along each of the 42-foot sides, hammer rebar into the ground, always leaving 6" above the surface. Gently bend an 18-foot length of PVC, positioning each end directly above the rebar, and carefully slide the PVC ends onto the rebar to form an arch (Figure 4). Repeat this procedure until you have formed 13 PVC hoops. It is not necessary to insert rebar into the two remaining holes in the bottom of each of the door frames. Simply insert the PVC into the holes, forming a double hoop at each end. When the polyethylene plastic is in place, bolt the double hoops together.

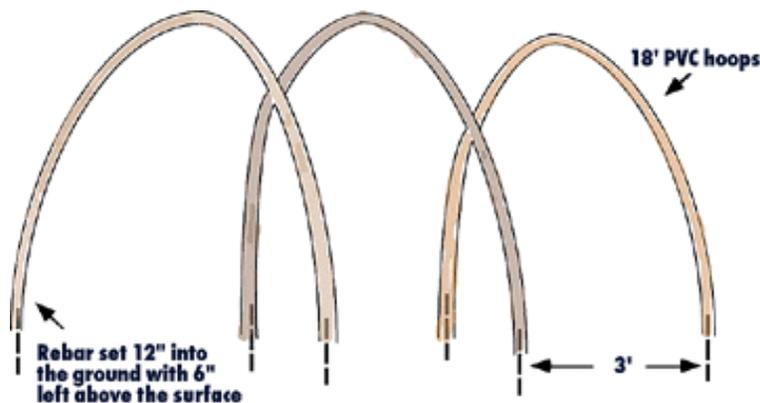


FIGURE 4.

View of the PVC hoops outlining the sides of the hoophouse.

Starting at one end of the hoophouse, attach one end of the twine to the top center of the second hoop—the hoop immediately next to the door frame end. Pass the twine over to the next hoop, pulling it tight and looping it around the hoop. Continue on to each successive hoop until all hoops are attached together. When you reach the last hoop, reverse the process until you are back where you started. Connecting the hoops with twine helps to stabilize the hoop frame and will support the polyethylene plastic that will lie on top of it. It is important to keep the twine tight to prevent the plastic from sagging and collecting water when it rains. This would cause stress on the plastic and on the PVC framework.

Measure and cut a 5-foot strip off the 50-foot length of polyethylene plastic. This will leave a piece 45' long by 20' wide to be used for the hoophouse body. Use the piece 5' long by 20' wide for the doors. Spread the 45-foot length of polyethylene plastic across the hoop structure, pulling it tight, and insert the ends of the plastic between the double-hoops at each end. Bolt the corrugated plastic to the double-hoop ends, keeping the polyethylene plastic sandwiched between. To bolt the ends together, drill five holes through the corrugated plastic, the double-hoop ends, and the polyethylene plastic. Space the bolts so that one is at the top center, and two are on each side spaced 2' apart (Figure 2). Place a rubber washer over the hole on the corrugated plastic side, insert the bolt, and secure the wing nut on the inside of the hoophouse.

Secure the polyethylene plastic in place with twine tied over every hoop except the double hoop ends. To attach the twine to the hoops, lift the PVC hoop up slightly, tie a 20-foot length of twine to the rebar, and slip the PVC hoop back in place. Throw the twine over the hoophouse to the other side and tie it in the same fashion to the rebar supporting the other end of the PVC hoop. The twine should be just loose enough to allow slipping the polyethylene plastic up when raising the sides of the hoophouse for ventilation. Tying the plastic down at each hoop prevents the plastic from blowing out due to wind pressure.

## Finishing Touches

The doors are simply polyethylene plastic sheeting, weighted on the bottom and hung on hooks at the top of the doorways. Cut the remaining piece of 5' X 20' polyethylene plastic to form two pieces 5' wide and 6' long. Attach a narrow piece of scrap wood at each end of the 6-foot length of polyethylene plastic. You can roll the plastic doors up on warm days to allow a breeze through the hoophouse, lowering the temperature. The polyethylene plastic along the 42-foot sides of the hoophouse also can be rolled up and attached with twine to the hoops (Figure 5). This additional ventilation is necessary during the hot summer months in most climates. To use the hoophouse, form two soil beds, one running down each side of the hoophouse, and install drip tape in each bed for easy watering (Figure 6). Transplant or direct seed crops into the soil.



FIGURE 5

View of the side of the hoophouse, showing polyethylene plastic secured by twine. A side of the hoophouse has been raised for ventilation and tied in place with twine.



FIGURE 6.

Transplant crops into the soil inside the hoophouse. Lay drip tape down the center of each bed.

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# Design and Construction of the Penn State High Tunnel

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**ADDITIONAL INDEX WORDS.** season extending technology, plasticulture, plastic mulch, drip irrigation, fertigation

**SUMMARY.** Plasticulture technology, especially high tunnels for extending the production period of a wide variety of horticultural crops, is an accepted production practice worldwide. In particular, high tunnels offer a production system that minimizes the effect of the environment on crop production and allows growers to continue to farm in densely populated areas. Only recently has the use of high tunnels in the U.S. been investigated and this research has been centered in the northeastern U.S. In 1999 the High Tunnel Research and Education Facility was established at Pennsylvania State University that resulted in the development of a unique high tunnel design. A detailed description of the new design and construction is presented in this report.

The High Tunnel Research and Education Facility (HTREF) was established at the Pennsylvania State University as part of the Penn State Center for Plasticulture. The center is a clearinghouse for research and educational efforts in the field of plasticulture, which is the use of plastics in any phase of agricul-

tural production. The HTREF consists of 28 high tunnel research units that have dimensions of 17 ft wide × 36 ft long × 9 ft high (5.2 × 11 × 2.7 m) and a support building located at the Horticulture Research Farm, Russell E. Larson Research Center, Rock Springs, Pa. Here research is being conducted to evaluate new designs for high tunnels and plastic coverings, cropping options, sequencing of vegetables and other horticultural crops, as well as production recommendations and budgets for crops grown in high tunnels.

The first eight tunnels were constructed using the design and system of crop production developed by Otho Wells and colleagues from the University of New Hampshire (Sciabarrasi and Wells, 1999; Wells, 1991, 1996, 2000; Wells and Loy, 1993). The New Hampshire design (Fig. 1) consisted of wood-framed end walls that were covered either with clear plastic film or exterior grade plywood. A door was framed into the end wall for general access in and out of the tunnel. To accomplish tillage operations in the tunnel, the end walls had to be removed. This required detaching the plastic and removing a series of screws. In addition, a continuous sheet of 4-year, greenhouse grade, clear plastic film was used to cover the entire tunnel, both the top and roll-up sides. The plastic was attached to a 1 × 6-inch (2.5 × 15.2-cm) hipboard, using two 1 × 3-inch (2.5 × 7.6-cm) boards that were attached to the hipboard.

If a problem developed with the top covering or the roll-up sidewalls, or the covering needed to be replaced, all the screws fastening the 1 × 3-inch board had to be removed. This caused problems with the integrity of the screws and weathering of the boards due to a buildup of moisture under the plastic.

The objectives for developing a new high tunnel design were 1) to developed end walls that would afford quicker and more convenient access into the tunnels for performance of

tillage and other operations associated with plasticulture systems and 2) to allow separate sheets of plastic to be used for the covering the top and sides of the high tunnel that would facilitate a quicker means of recovering a tunnel if a problem developed with either the plastic covering on the top or sidewalls.

## Details of construction using the Penn State high-tunnel design

The pipe framing and assembly is the same for either the New Hampshire or the Penn State design. A general view of the Penn State high tunnel is presented in Fig. 2. A detailed list of components and prices used in construction of a 17 × 36-ft high tunnel using the Penn State design can be found in the



**Fig. 1. High tunnel constructed using the New Hampshire design developed by Otho Wells, University of New Hampshire.**



**Fig. 2. High tunnel constructed using the Penn State design developed by researchers and extension specialists at the Penn State High Tunnel Research and Education Facility.**

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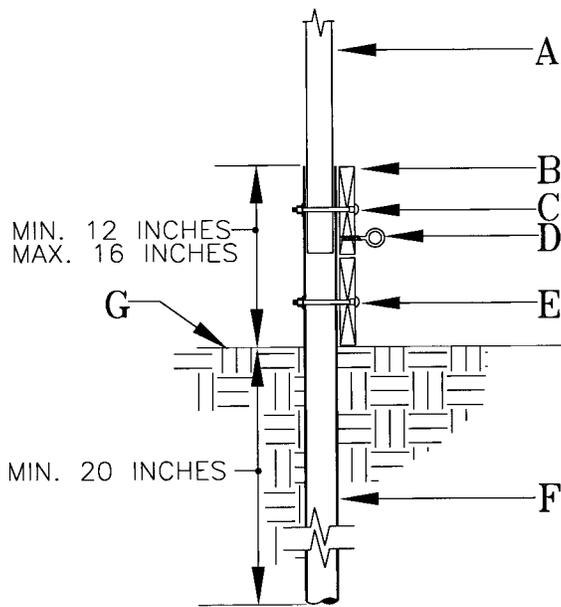
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**Fig. 3. Installation of the ground post and baseboard.** (A) Hollow galvanized-steel bow. (B) Two pressure-treated wooden baseboards (reference Fig. 15G). (C) One 4.5 × 0.25-inch (11.4 × 0.6-cm) galvanized carriage bolt installed through pre-drilled holes in the ground post and bow. Materials are lined up with pre-drilled holes in the bow and ground post as supplied by the manufacturer before insertion of the bolt. (D) Galvanized eye screw for use in connection of the Arbor-Tie line. (E) One 4.5 × 0.25-inch galvanized carriage bolt installed through pre-drilled holes in the ground post and the baseboard. Pre-drilled holes supplied by the manufacturer are the only holes used when attaching the baseboards. (F) The manufacturer-supplied ground post should be installed to a recommended minimum depth of 20 inches (50.8 cm) below finished grade. There should be a minimum of 12 inches (30.5 cm) and a maximum of 16 inches (40.7 cm) remaining above finished grade for installation of the bow and baseboard. (G) Ground level or finished grade.

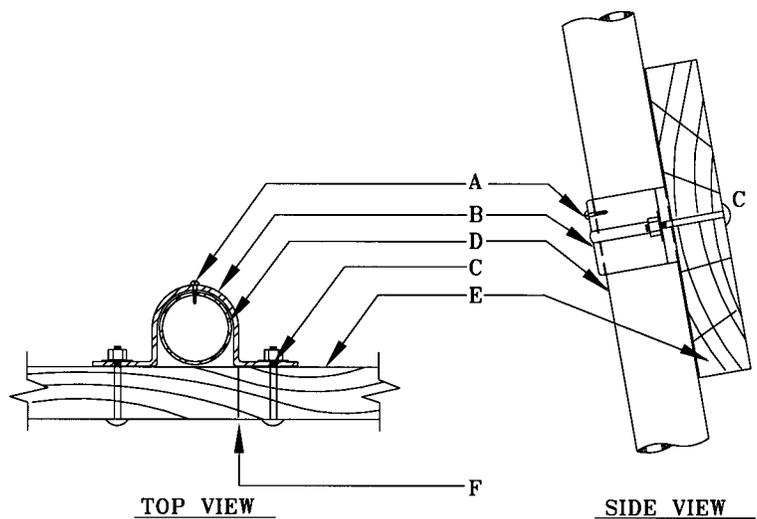
*Penn State High Tunnel Manual* (Lamont et al., 2001) available from the senior author. The manual also includes extensive environmental data as well as information on production of a wide variety of horticultural crops in the high tunnels. The price for the 17 × 36-ft high tunnel is about \$1,900.00, depending on prices of locally purchased materials.

### Construction steps

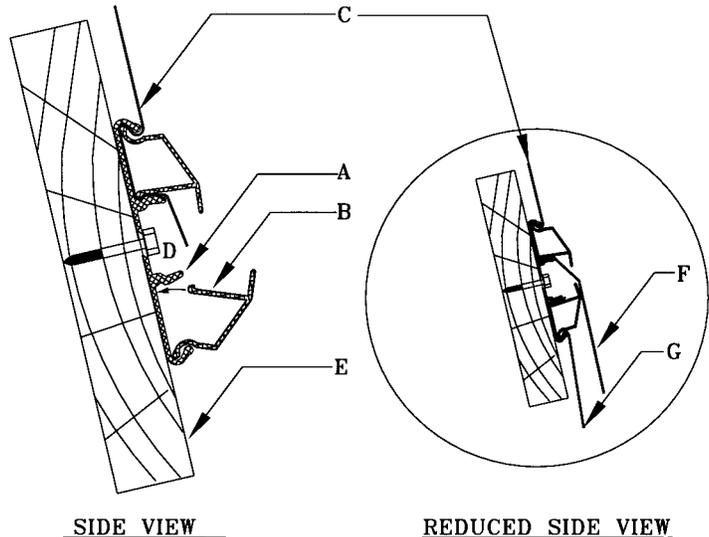
The pipe frame kits were purchased from Ledgewood Farms (Moultonboro, N.H.). The high tunnel pipe frame kit (17 × 36 ft) consisted of ground posts, bows, purlins, roll-up sides kit, and nuts and bolts. The pipes used in the kit are made of galvanized steel tubing. The

ground posts are 13-gauge pipe with a 1.9-inch (4.83-cm) outside diameter (OD), the bows are 14-gauge pipe with a 1.66-inch (4.2-cm) OD and the purlins and roll-up pipes are 15-gauge pipe with 1.32-inch (3.25-cm) OD. It is recommended that high tunnel kits with extended sides be purchased that allow the hipboard to be positioned higher on the bows and the roll-up sides to be raised higher for more efficient ventilation.

The ground posts are driven into the ground to a minimum depth of 20 inches (50.8 cm), and allowing suffi-



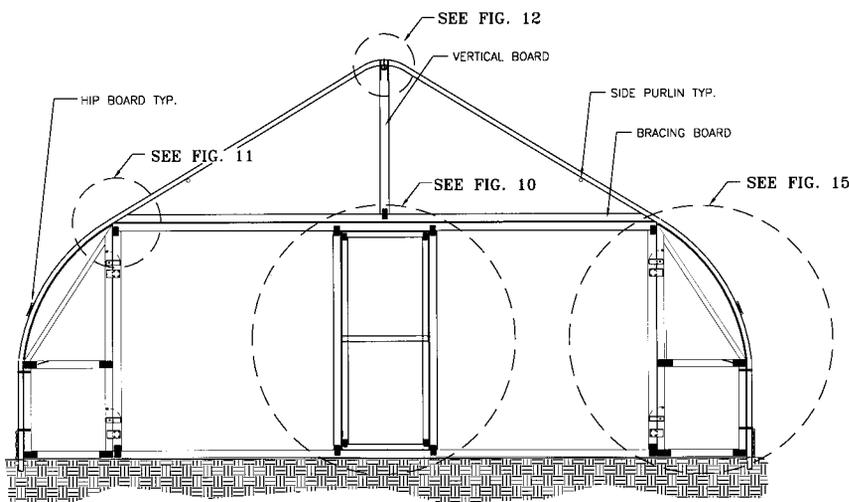
**Fig. 4. Connection of the hip board to the steel bow.** (A) Galvanized pan-head self-tapping set screw to keep the hip board in alignment on the bow. (B) Two-hole, standard-duty galvanized 1.25-inch (3.2-cm) pipe-strap hanger. (C) Two 1.25 × 0.375-inch (3.2 × 1.0-cm) galvanized steel carriage bolts, nuts, and washers to connect the strap hanger to the hip board. (D) Hollow galvanized steel bow. (E) A 1.0 × 4.0-inch (10.2 × 2.54-cm) pressure-treated wooden hip board. (F) Hip boards are cut flush with the bows at the north and south ends of the greenhouse. A one-hole, standard-duty 1.25-inch galvanized pipe strap is used to connect the hip board to the bow.



**Fig. 5. Installation of the double-rail track to the hip board.** (A) Surelock aluminum double-rail track. (B) Surelock preformed aluminum cap. (C) Plastic covering placed between the track and clamp. (D) A no. 10 × 1-inch (2.5-cm) galvanized hex-head wood screws are used every 2 ft (0.6 m), on center, to hold the rail to the hip board. (E) Hip board. (F) Plastic covering of the greenhouse trimmed so that a flap, even with the lower edge of the hip board, remains. (G) Plastic for the side panel roll-up wall locked in place with the lower clamp on the double aluminum track.



**Fig. 6. Surelock aluminum double-rail track attached to the hipboard used to attach the plastic covering to the top and side of the high tunnel. Clip is being fastened to the lower track.**



**Fig. 7. The interior view of the front section or south end of the high tunnel.**

cient length above the ground for attachment of the baseboard. Ground posts are placed on 4-ft (1.2-m) centers. The bows are then assembled and the ends inserted into the ground post and secured using the appropriate hardware. The purlins (ridgepole and two side purlins) are then assembled and attached to the bows. The corner braces are attached to keep the tunnel from shifting out of upright position. The additional construction steps after the erection of the pipe frame are described below.

**STEP 1.** Attach the baseboards (Fig. 3). The baseboards are pressure-treated 2 × 6-inch × 12-ft (5 × 15.2-cm × 3.65-m) or 2 × 12-inch × 12-ft (5 ×

30.5-cm × 3.65-m) boards. A single 2 × 12-inch × 12-ft board eliminates the potential gap that may occur when two 2 × 6-inch boards are used for the baseboard. The boards should meet at a bow and are attached using a carriage bolt with a large 5/16-inch (0.79-cm) washer that overlaps both boards.

**STEP 2.** Attach the hipboard. The hipboard is a pressure-treated 1 × 4-inch (2.5 × 10.2-cm) board that is held in place with a 1.25-inch (3.2-cm) pipe strap hanger (Fig. 4). Secure the pipe strap hanger to the bow with a small sheet metal screw to prevent the strap from moving up the bow in high winds. The other option is to drill a hole through

the bow and attach the hipboard with a 3 3/8-inch (8.6-cm) bolt.

**STEP 3.** Using screws, attach 3.25-inch (9.5-cm) Surelock aluminum double rail track (Keeler-Glasgow Company, Hartford, Mich.) to the hipboard for securing the plastic cover and plastic for the sides (Fig. 5 and Fig. 6).

**STEP 4.** Construct the upper endwalls with a bracing and a vertical board (Figs. 7, 8, and 9). Use a 2 × 4-inch × 12-ft (5 × 10.2-cm × 3.6-m) board and taper the ends so that it will fit securely between the end bows as a bracing board, temporarily attaching it to the end bow to facilitate measurement of the vertical board. Take another 2 × 4-inch board (flat side out) and place it in the center of the bracing board. Measure and cut the vertical board so that it fits snug between the bracing board and center ridgepole purlin. This will require that the vertical board be notched to fit around the center ridgepole purlin. Secure the vertical board to bracing board with mending plates front and back (Fig. 10A, B, and D). Place this frame (bracing and vertical board) in place and drill a hole on an angle up through the ends of the bracing board into the metal bow, securing it with a large self-tapping metal screw (Fig. 11E). Next take galvanized pipe strap and bring it over the top of the end bow and down to the bracing board using pan-head wood screws to secure the strapping tightly on both sides of the board (Fig. 11D). Next, take the galvanized pipe strap over the end bow and secure it to both sides of the vertical board, using pan-head wood screws (Fig. 12). The triangle section at the top of the endwalls can be covered with a variety of materials but in the Penn State design reported here it is covered with 3/8-inch (0.95-cm) exterior plywood (Figs. 7 and 8).

**STEP 5.** Attach the aluminum single-track nursery lock (Keeler-Glasgow Co.) over the end bows down to the hipboards (Fig. 12E). This is best accomplished by two people, one person holding the track on the bow while the second person drills holes through the track and the bow and fastens the track to the bow using self-taping screws.

**STEP 6.** The next step is to build the lower end walls. The Penn State design allows for the center section of the end walls to be lifted up (Fig. 13) to accommodate the accessibility of a small four-wheel-drive, 21-horsepower tractor with equipment. Equipment

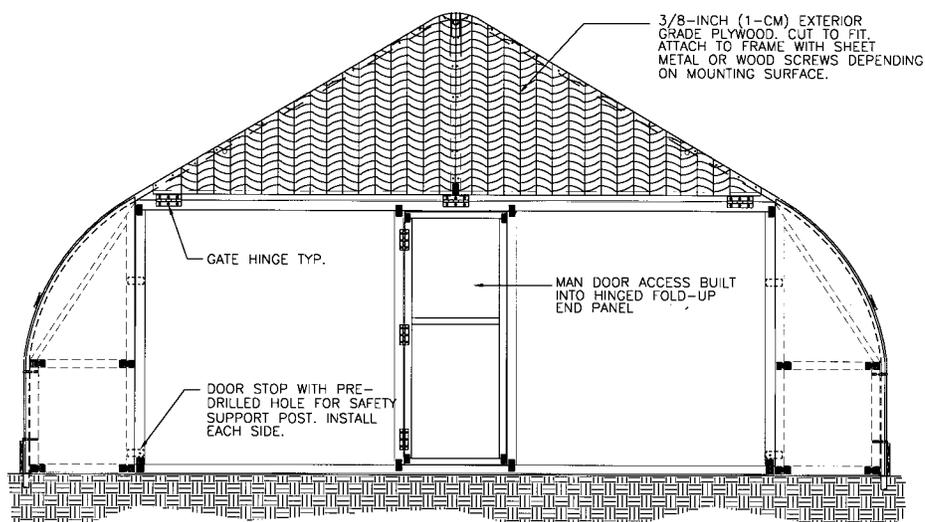


Fig. 8. The exterior view of the front section or south end of the high tunnel.

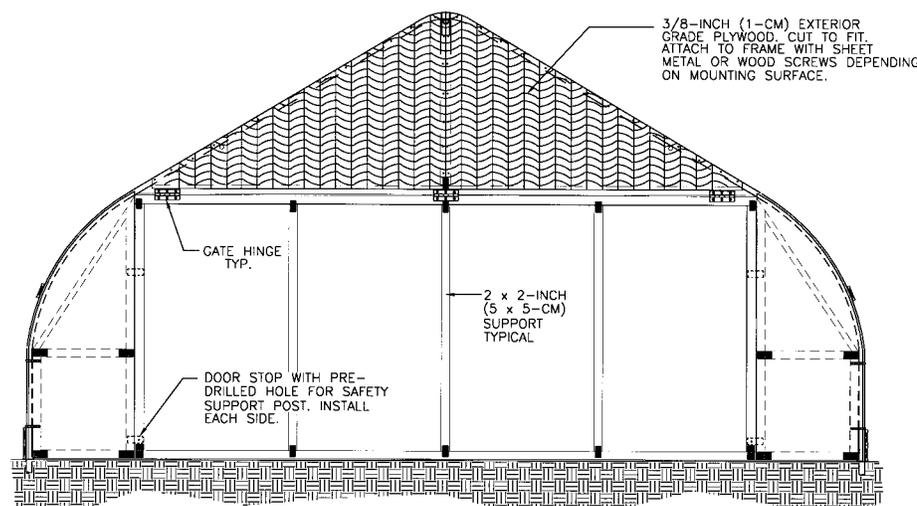


Fig. 9. The exterior view of the rear section or north end of the high tunnel.

includes a three-point hitch-mounted rototiller, that is used to prepare the soil and a small plastic mulch-drip irrigation tape applicator that is used to make raised plastic-mulch-covered beds with drip irrigation. The dimensions of the center section of lower end walls are 12 ft wide by 8 ft high (3.6 × 2.4 m). The exterior frame of both sections is constructed of 2 × 4-inch lumber with all bottom boards pressure treated because of contact with soil and water. On the 17 × 36-ft research units there is an entrance door framed on the south end wall (Fig. 8). The north end wall uses 2 × 2-inch (5-cm) lumber for internal support (Fig. 9). All the wood for the end walls is secured using mending plates on both sides. The end walls are best assembled on a firm, flat surface. It is recom-

mended to attach the plastic on the end walls using batten tape and staples while they are flat on the ground. The end walls are attached to the overhead bracing board with three strong 3.5-inch (8.9-cm) galvanized gate hinges (Figs. 8 and 9). Details of the service door are presented in Fig. 10. In a commercial size high tunnel [17 × 96 ft (5 × 29 m)] that a grower would purchase there would be a service door at each end. The center section of the lower endwall should be securely fastened when in the open position. The authors use 2 × 2-inch posts with metal dowels at each end. One end of the post is placed in the soil and the upper dowel is placed through a pre-drilled hole in the door stop (Fig. 8). The upper metal dowel should extend above the doorstop by several inches.

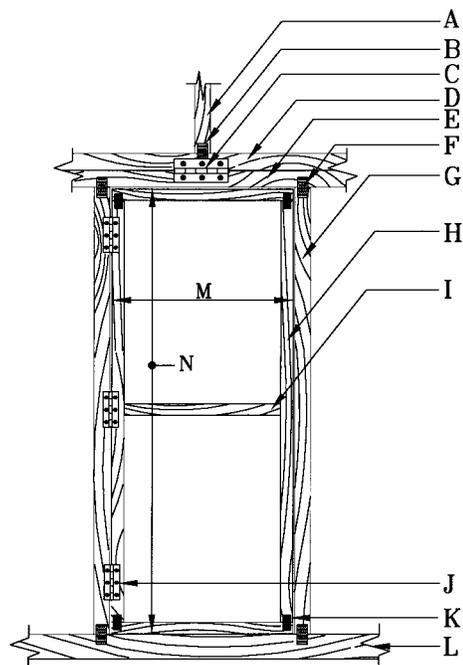
**STEP 7.** On either side of the center section are two hinged end panels (Figs. 14 and 15). These are constructed of 2 × 4-inch lumber frames that have a pressure-treated base piece and are attached to the side bows by heavy metal pallet strapping. They can be covered with a variety of materials. In the original stages of development aluminum-covered Styrofoam insulating material was used but now 3/8-inch exterior plywood is being used. Whatever material is chosen, it is cut to the outline of the bow and overlaps the edge of the center section (Fig. 14). It is held against the edge of the center section by a small piece of wood that rotates on the inside of the end panel (Fig. 15J).

**STEP 8.** The next step is to cover the top of the high tunnel. The plastic used for covering the high tunnels is 3- or 4-year life, greenhouse-grade 6-mil [0.006-inch (144-μm)] plastic. It helps to have a crew of six people and a day with wind less than 5 miles/h (8.0 km·h<sup>-1</sup>) to facilitate covering the tunnel. Snap-on clips attach the top piece of plastic to the single aluminum rail on the end bows. The top track of the double aluminum track attached to the hipboard makes the covering or recovering of the tunnels easier than the New Hampshire design. The roll-up sidepieces of plastic are 6.5-ft (2.0-m) wide and are clipped into place on the lower track of the double track (Fig. 5B). The lower end of the roll-up side is then attached to the roll-up pipe by plastic clips at every bow, while the pipe is lying on the ground. Trim excess plastic [suggest 8-inch (20.3-cm) overhang] for sidewalls (Fig. 5). The plastic can then be rolled up on the pipe (Fig. 16). Where the sections of roll-up pipe slide in to one another it is recommended to put two small machine screws, one on each side, so the pipes cannot rotate.

**STEP 9.** The next step is to attach four eyescrews on upper portion of the baseboard; one at each end and two spaced equally apart between the ends (Fig. 3D). AbortTie, a soft polypropylene material, (Ben Meadows Company, Janesville, Wis.) is placed over the tunnel and attach at the eight eyescrews. This will prevent the top cover and sides from flapping in the wind.

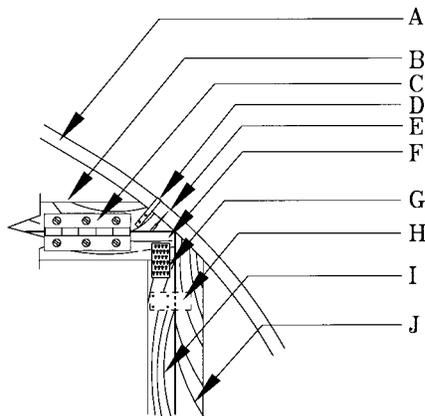
**STEP 10.** Each tunnel will need its own water supply and fertilizer injection unit. Any piping to service the units should be in a location where tilling operations will not damage the lines.

There are different options on constructing a fertilizer injection system (fertigation) and water supply system to the tunnels. The one used in the Penn State High Tunnels consists of an 11-gal/min ( $41.6\text{-L}\cdot\text{min}^{-1}$ ) Dosatron (Dosatron International, Clearwater, Fla.) unit for fertigation, a preset pressure regulator and a screen filter. It is convenient to have a spigot in each



**Fig. 10 Construction of the main entrance door.** (A) A  $2 \times 4$ -inch ( $5 \times 10.2$ -cm) vertical support from the bow to the bracing board. (B) A  $3 \times 5$ -inch ( $7.6 \times 12.7$ -cm) galvanized mending plate, both front and back. (C) A 3.5-inch (8.9-cm) galvanized gate hinge installed on the bracing board and upper support for the flip-up door. (D) A  $2 \times 4$ -inch  $\times$  12-ft ( $5 \times 10.2$ -cm  $\times$  3.6-m) bracing board. (E)  $2 \times 4$ -inch  $\times$  12-ft upper support for flip-up door. (F) A  $3 \times 5$ -inch galvanized mending plate located at top and bottom of vertical door supports, both front and back. (G) A  $2 \times 4 \times 77$ -inch ( $5 \times 10.2 \times 195.6$ -cm) vertical door support. (H) A  $2 \times 2$ -inch (5-cm) door framing. (I) A  $2 \times 2$ -inch cross support for door frame. (J) A  $2 \times 3$ -inch ( $5 \times 7.6$ -cm) galvanized entrance door hinge, three per door equally spaced. (K) A  $2 \times 4$ -inch galvanized mending plate located at each doorframe corner, both front and back. (L) A  $2 \times 4$ -inch  $\times$  12-ft lower support for flip-up door, pressure-treated lumber. (M) Suggested dimension 28 inches (71.1 cm). (N) Suggested dimension 77 inches (195.6 cm).

tunnel for water to fill the stock fertilizer containers (Fig. 17). This allows for the precise watering of crops using drip irrigation and the ability to add additional fertilizer as needed to crops especially, in double cropping situations on plastic mulch.



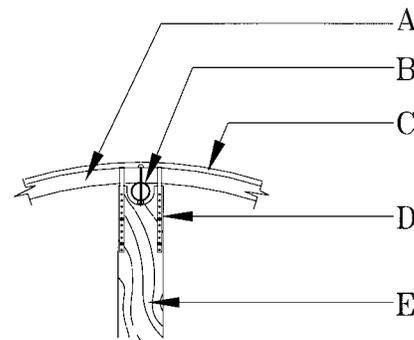
**Fig. 11. Connection of the upper end wall to the end bow.** (A) Hollow galvanized steel end bow. (B) A  $2 \times 4$ -inch  $\times$  12-ft ( $5 \times 10.2$ -cm  $\times$  3.6-m) bracing board of finished lumber is used as a fixed support for the flip-up end panel. Both ends taper cut so that the board will fit snugly against the bow and parallel to the ground. Bottom dimension on the board should be 12 ft (3.6 m). (C) A 3.5-inch (8.9-cm) galvanized gate hinge installed on bracing board and upper support for flip-up end panel. (D) Steel pipe hanger strapping used to secure the wooden support to the end bow. Galvanized pan-head wood screws with washers used to secure the strap to the wood. (E) Wooden support is also attached to the bow with a self-tapping sheet-metal screw countersunk 0.5 inches (1.3 cm) below the surface of the wooden support. Screw hole is located no closer than 2.5 inches (6.4 cm) to either end of the board. (F) Upper support of  $2 \times 4$ -inch  $\times$  12-ft finished lumber. (G) A  $3 \times 5$ -inch ( $7.6 \times 12.7$ -cm) galvanized mending plates used front and back to secure corners of panel. (H) Panel stop constructed of  $1 \times 4 \times 7$ -inch ( $2.5 \times 10.2 \times 17.8$ -cm) finished lumber and attached to the inside of the panel with 4 #8  $\times$  2.5-inch (6.3-cm) flat-head galvanized wood screws. Two stops, one top and one bottom, mounted on each side of the panel. (I) A  $2 \times 4 \times 77$ -inch ( $5 \times 10.2 \times 195.6$ -cm) side support made of finished lumber for flip-up panel. (J) A  $2 \times 4$ -inch ( $5 \times 10.2$ -cm) side support of finished lumber for the hinged side panel.

## Conclusions

The Penn State high tunnel design demonstrates that the improvements described allow for greater ease of access for equipment operations and periodic replacement of plastic than previously designed systems.

The Penn State high tunnel design of the end walls allows easy access for small power tillage equipment to the inside of the high tunnel for preparation of the soil and other operations associated with the use of plasticulture. It is a very quick operation to open the hinged end panels and lift up the center section of the end walls.

The change made to the way the plastic is attached to the hipboard allows for easy removal of either the plastic covering the top or the side walls, if a problem develops, or the covering needs to be changed due to age or a grower wishes to use different covering or materials such as insect screen on the side walls. The aluminum track system with clips is more convenient to work with



**Fig. 12. Attachment of the upper end-panel wall to the center ridge pole purlin/end bow.** (A) Hollow galvanized steel end bow. (B) Center ridge pole purlin attached to bow with hardware kit supplied by manufacturer. (C) Single-track aluminum nursery lock channel mounted on the crest of the bow with sheet-metal screws. (D) Galvanized pipe strap used to attach the vertical support to the end bow with no. 8  $\times$  1.25-inch (3.2-cm) galvanized pan-head screws and washers. One strap mounted on each side of the center purlin and fastened both front and back Straps installed before the lock channel. (E) A  $2 \times 4$ -inch ( $5 \times 10.2$ -cm) vertical support for the lower bracing board. The center of the board is custom cut to accommodate the ridge purlin before installation. The upper end of the board should rest snugly against the under side of the bow.



Fig. 13. Center section of lower portion of the end walls used in the Penn State high tunnel design opened up to allow easy entrance and exit of machinery.



Fig. 14. Side panel opened up before raising the center section in the Penn State high tunnel design.

and offers a more permanent system unlike the wood attachment system that may warp or degrade due to moisture buildup under the plastic.

For more information on high tunnels and plasticulture there are two web sites of interest: the Penn State Center for Plasticulture at <<http://plasticulture.cas.psu.edu>> (Wodecki et al., 2001) and the American Society for Plasticulture at <<http://www.plasticulture.org>> (American Society for Plasticulture, 1999).

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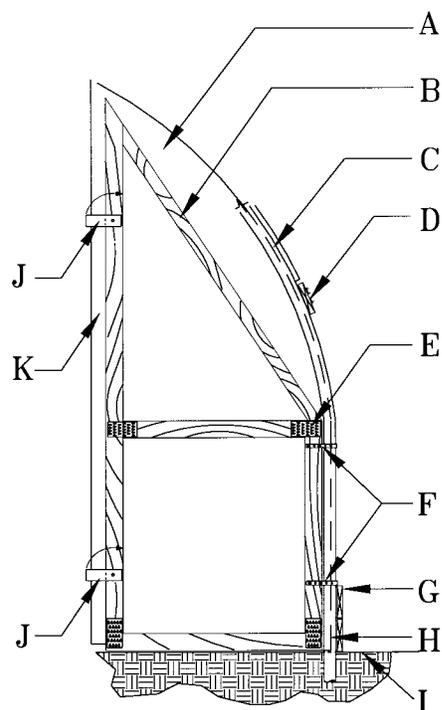
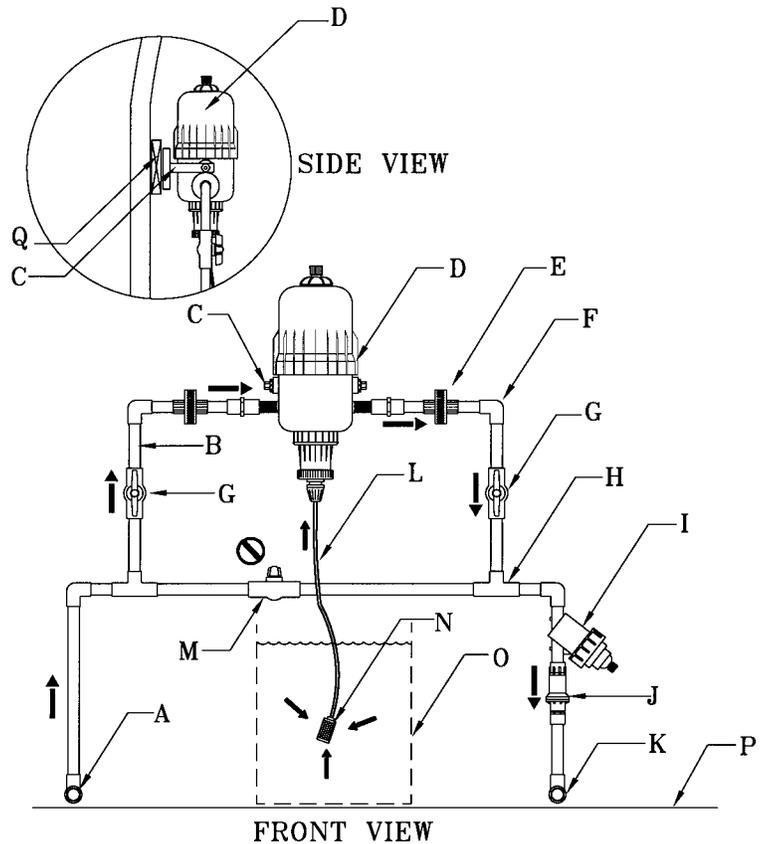


Fig. 15. Detail of the hinged end panel as seen from the interior of the high tunnel. (A) A 0.375-inch (1-cm) exterior-grade plywood panel cut to the curvature of the bow and then attached to the panel frame. (B) A 2 × 2-inch (5-cm) wooden bracing attached to the panel frame with galvanized wood screws. (C) Galvanized steel end bow with single track aluminum nursery lock channel. The nursery lock channel is mounted on the crest of the bow with sheet metal screws. (D) Pressure treated 1 × 4-inch (2.5 × 10.2-cm) wooden hip board with double rail track (reference Fig. 4). (E) A 3 × 5-inch (7.6 × 12.7-cm) galvanized mending plate mounted both front and back. (F) A 0.75-inch (1.9-cm) wide, heavy-duty pallet strap attached to wooden frame with galvanized wood screws. Two screws used per side to attach the strap to the wood. (G) Pressure-treated wooden baseboard (reference Fig. 3). (H) Metal galvanized ground post (reference Fig. 3). (I) Finished ground level. (J) Rotating wooden stop constructed of 1 × 4 × 7-inch (2.5 × 10.2 × 17.8-cm) finished lumber. Stop attached to panel frame with one wood screw to allow stop to rotate to upright position and allow panel to swing out. (K) A 2-inch (5-cm) overlap between edge of plywood facing and end panel wooden bracing.



**Fig. 17. Configuration of the fertilizer injector.** (A) Water inlet connection point using a quick-connect adaptor or regular female hose connection. (B) A 0.75-inch (1.9-cm) interior diameter (ID) schedule-40 polyvinyl chloride (PVC) pipe, typical. (C) Mounting bracket as provided by the manufacturer for the fertilizer injector. (D) Fertilizer injector (FI). (E) Threaded pipe union located on each side of the FI to facilitate installation and removal of the injector. (F) A 0.75-inch ID 90° PVC pipe elbow. (G) Straight PVC ball valve located on each side of the FI. During normal operations the valve position is open. (H) A 0.75-inch ID PVC tee. (I) In-line screen filter unit with minimum 150 mesh. (J) Pressure regulator with adjustments from 0.5 to 5 gal/min (18.9 L·min<sup>-1</sup>) with water pressure of 10 lb/inch<sup>2</sup> (69 kPa). (K) Water outlet connection point using a quick-connect adaptor or male hose connection. (L) Vacuum feed line from fertilizer tank to FI. (M) A 0.75-inch-ID straight PVC ball valve for use in bypassing FI. During normal operations the valve position is closed. (N) Inlet fitting with fine screen cover connected to feed line. (O) Liquid fertilizer mixed in movable container. (P) Ground level or finished grade. (Q) Pressure-treated 1 × 4-inch (2.5 × 10.2-cm) board mounted between two bows.



**Fig. 16. Plastic sides are rolled up to provide ventilation of the high tunnel.**

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**Season Extension Techniques for  
Market Gardeners  
By Janet Bachmann  
NCAT Agriculture Specialist  
January 2005  
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**Edited by Paul Williams  
Formatted by Ashley Rieske**

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