Hoophouses and High Tunnels for Local Food and Farming

John A. Biernbaum, Department of Horticulture, Michigan State University

Introduction

This publication is intended to introduce farmers, market gardeners, school garden organizers and home gardeners to the principles of in ground, organic vegetable production in unheated greenhouses. For those considering greenhouse vegetables as a new opportunity, there are a wide variety of marketing, structure and crop options to consider. One purpose of this presentation is to help with those choices by providing an overview of key considerations. Many of the necessary decisions are better made with some appreciation of the bigger picture and parts that are interdependent. For those already started in greenhouse vegetable production, the purpose is to give detailed management recommendations, particularly for winter production and harvesting.

The topics presented are as follows:

Part 1: Building

1. Marketing Options and Strategies
2. Site Selection, Layout and Preparation
3. Preconstruction Weed and Soil Quality, Fertility and Biology Management
4. Structure Options and Design Principles
5. Construction Basics and Recommendations

Part 2. Growing

6. Environmental Management: Light and Temperature
7. Environmental Management: Soil Quality, Fertility, Biology and Moisture
8. Crop Selection and Production Methods
9. Weed, Insect and Disease Management
10. Post Harvest Storage and Handling

1. Marketing Options and Strategies

Reasons for Protected Cultivation. The probability is very high that an investment in structures for protected cultivation will quickly return the initial investment and provide a range of production options that will increase farm income, increase food security, or improve quality of life. The methods described here are economically feasible for commercial production, educational purposes and personal enjoyment.

From a farm perspective, a protective structure can help open new markets, can help reduce the risk of unpredictable weather impacting crop production, and can help extend the season so that the summer growing and marketing season is not so intensive. The market environment is changing towards a greater realization of the value of supporting local business, protecting farmland, and a realization of the high cost of transporting food crops on average of 1500 miles from field to fork.

From an educational perspective, a protective structure can make plant growing and harvesting feasible on a year-round basis. Students of all ages need opportunities for active learning and the chance for practical, tangible accomplishments that can bring life to the curriculum. The garden also provides an opportunity for teachers to invite members of the community to participate in school activities and student growth by providing what in most cases will be essential support for teachers not familiar with gardening.

From a personal perspective, a structure 15’ x 20’ up to 30’ x 48’ can provide a garden capable of producing much more than the needs of an average family while at the same time providing protection from garden visitors like rabbits and deer and an outdoor place for exercise and physical activity the year round. The dietary impact of fresh vegetables can have a major impact on the health of most families.

Types of Structures. There are a variety of structural options available for protected cultivation. While the concepts are not new and are widely used around the world, the current growth in interest in protected cultivation has led to multiple options and the potential for confusion until more standardization develops. Let's take a minute to differentiate if possible between cold frames, high tunnels, hoophouses and greenhouses.

What is a high tunnel or a hoop house?

In simple terms, a high tunnel or hoophouse is a greenhouse like cold frame used to extend the growing and harvest season both in the spring (starting in February) and fall (continuing though November). These are the same structures routinely used as cold frames for over wintering container-grown nursery stock. By definition, a greenhouse has heat other than solar energy. While not everyone agrees, the terms greenhouse, high tunnel, hoophouse and cold frame are sometimes used interchangeably. I think there are some differences that can be identified between the different types of structures. I am most familiar with using greenhouses and the type of production my presentation focuses on is best done in a greenhouse so I am mostly going to use the term greenhouse. But first some more explanation of the other structures.

One of the early forms of crop protection in commercial field production was the use of wire wickets or hoops to cover a single row of plants with polyethylene. Often the covering was only left on in the beginning part of the season to get an earlier start in the field in areas where the season was too short or where there was a good return for crops ready to market early. These tunnels over rows of crops were called low tunnels. Later, larger structures suitable for people to walk in were developed and these were called high tunnels.

One of the differentiating factors between the various names is whether the structure is covered with a single layer of polyethylene film (high tunnel) or two layers with an electric inflation fan keeping the two layers separate for greater insulation as well as a tighter covering less prone to move about in the wind (hoophouse or greenhouse). The term high tunnels is used for single layer structures. However, these structures can be either a single peak or multiple structures can be connected together. The multi peak structures (Haygrove Hightunnels) are not designed to support snow loads so they have limited or three season uses. In areas where wet snow is possible in mid to late April (such as Michigan), the benefit to early season extension is reduced. The structure is usually made of galvanized steel pipe structure. The polyethylene covering is usually 6 mil (0.006 inch thick) greenhouse-grade 3 to 4 year polyethylene film. Hoop houses are single structures – not multiple bays and often have a rounded roof as opposed to a more peaked or gothic roof angle.

Crops are grown directly in the soil covered by the structure. Primary protection provided is from low temperature, wind and rain (causing excessive soil moisture and/or wet foliage, flowers and fruit) with some protection from insect pests and diseases. High tunnels range in width from 14' to 34' and length of 30' to over 100' (96' is common). Usually high tunnels are in the 14' to 20' range with wider structures more likely to be called greenhouses. Summer cooling is usually achieved by rolling up the side wall plastic from the baseboard to the hipboard on a simple hand cranked pipe. Large end wall doors or vents can provide intermediate levels of cooling and equipment access. Air and soil temperatures can be elevated by trapping of solar energy and soil heat with an internal frost fabric covering the crop at night. The structure may be stationary and anchored by ground posts driven to a depth of 24 to 30" or may be constructed on a sled like base to allow dragging with a tractor and then anchored by turn buckles attached to ground anchors. High tunnels are more common for season extension then winter harvesting.

When does a high tunnel or hoop house become a greenhouse?

When winter production and harvesting of baby leaf salad greens and vegetable crops are planned for December and January in northern climates (outdoor temperatures to -20F and prolonged 2-4 week cloudy periods), the addition of a second layer of polyethylene with air inflation, and the use of 30' or wider frames are recommended. Insulation of the perimeter can increase productivity or the perimeter planting areas. For winter harvesting, an internal layer of frost fabric or greenhouse polyethylene supported above the crop by a frame or curtain system are also used within the structure. Providing minimal heat with gas fired, forced air unit heaters to maintain temperature just above freezing can increase the range of crops and eliminate the need for the internal covering which can reduce light unless removed daily on sunny days and then replaced at the end of the day. With an emphasis on heat retention, it may be possible to eliminate the roll up side walls and use only end wall ventilation through a peak vent and large end wall doors. End wall ventilation is facilitated by a 30' wide structure with a taller peak and thus more opportunity for hot air to raise and exit the structure at the ends. Summer crops are selected and managed (high soil moisture) to tolerate internal temperatures of 100+F that may occur without any shading or light reduction.

Advantages/strengths of protected cultivation:

Low cost of construction, readily available from a number of companies, relatively easy to build (but must be well built to stand up to wind). Multiple, high value crop production options with rapid payback. Allows production and sales to be more year-round, which could reduce summer work load? Early sales can develop customer loyalty at farmers markets. There are several possible options and configurations.

Disadvantages/concerns of protected cultivation:

Without heat, there is still some (but much less) susceptibility to the unpredictable nature of weather. Roll up sides are easy to put up and down, but you have to be there morning and evening or with severe weather. Heavy rainfall can lead to soil washing or splashing inside tunnel if roll up sides are up. Structures have to stand up to winds. The disadvantages are mostly management issues that can be solved.

Possible Uses and Crops:

Season extension for warm season vegetables

- Key crops: tomato, pepper, cucumber, eggplant, herbs (basil)
- Ventilation (roll up sides) and irrigation are important, high temps benefit some crops.
- Trellis, cages, staking or some form of support are necessary.

Winter harvesting for cool season vegetables

- Key crops: baby salad greens, head lettuce, steaming (Asian) greens, spinach, chard, carrot, beet, radish, turnip, leek, parsley, cilantro, Chinese cabbage, bok choi, tatsoi, etc
- Scheduling is planned so the crops are grow in the fall, prior to low temperature and light.
- The high tunnel acts as a refrigerator for winter harvest - and growth resumes in February
- Internal frost fabric layer suspended over the crop and not touching the crop is important.

High value specialty crop protection

- Small fruit like strawberries and raspberries
- Cut flowers like larkspur or snapdragon.
- Reduction of insect, disease, rain and wind damage.

Additional Background and Literature

On Farm Programs

Eliot Coleman (1995, 1998a, 1998b; : http://www.fourseasonfarm.com/) is perhaps the most visible proponent and practitioner of using unheated or minimally heated greenhouses for winter production and harvesting of vegetables. "The Four Season Harvest" was originally published in 1992 and outlined the methods for a moveable greenhouse that could be pulled just prior to snow fall or severe frost from serving as late season protection of warm season vegetables to cover winter greens already established in the field. His season extension work initially started in cold frames and then greenhouses were built over the cold frames so the cold frames could be easily accessed during heavy snow conditions.

Eventually cold frames were replaced by an internal layer of plastic film and then frost fabric to allow more ventilation.

Coleman (1998b) gives credit for early winter greenhouse vegetable research to Emery Emmert at the University of Kentucky who used polyethylene film when it was first developed to grow protected vegetables in a greenhouse in 1949. He credits Scott Nearing (1977), his neighbor in Maine, who observed weeds growing in his unheated greenhouse in the winter which lead him to investigate what other crops might survive the freezing winter conditions. He also credits the French farmers (as do others) and their use of individual class cloches over transplants set out early in the season long ago, as well as European, Asian, and Japanese (Roberts, 1996) farmers who widely used low cost, unheated protective structures for vegetable production for many decades. It is possible that international observers of Emmert's work at the University of Kentucky applied his methods much sooner than here in the United States.

Another experienced farmer and very visible proponent of the winter greenhouse is Steve Moore (Byczynski, 2003; DeVault, 2004). Steve used the winter greenhouse at Warren Wilson College and then at his own farm, both in eastern Pennsylvania and studied a variety of covering materials and carefully monitored temperature. He uses the term "passive solar greenhouse" to accurately describe his methods of both winter (cool season crops) and summer (warm season crops) crop production. Biointensive methods of maintaining soil health and fertility to allow high density plantings and multiple crop rotations provides for a very productive cropping system. Information about Steve is available at www.newfarm.org in articles by George DeVault from April 6 and 20, 2004 (see article archive).

Another proponent of season extension with hoophouses is Lynn Byczynski in Kansas. Her emphasis has been cut flowers although she has grown a wide range of crops. She has written extensively about her own and others experiences and the results as well as construction recommendations are compiled in the Hoophouse Handbook (see www.growingformarket.com)

Paul and Alison Wiediger of Au Natural Farm in Kentucky have presented a great summary of their experiences using hightunnels over many years and recommendations in their self published book *Walking to Spring – Using high tunnels to grow produce 52 weeks a year*.

Also at www.newfarm.org are a two part series on greenhouse construction (March 21 and April 9, 2003) and greenhouse growing (May 23 and June 3, 2003), as well as summer recommendations (August 17, 2004) by Don DeVault. Melanie and George DeVault provide a Greenhouse 101: Winter Survival Guide on January 12, 2004. A four part series written by Katie Olender (March 17 and 31, April 19 and May 12, 2005) is a summary of information presented by John Biernbaum of Michigan State University at a one day *Organic Univeristy* workshop in LaCrosse, Wisconsin.

Grower and other practical recommendations related to solar greenhouses, cold frames, and growing and protecting crops under cold weather conditions are presented in a number of books listed in the literature cited section below (McCullagh, 1979; Head, 1989; Poisons, 1994; Colebrook, 1988; Ashton, 2001; Handen, 2003). Useful information about salad and Asian greens is available in *The Organic Salad Garden* and *Asian Vegetables*, both by Joy Larkom (2003, 2001). She is one of the people responsible for collecting seed and helping bring a wider array of vegetables to the world.

University Based Research and Programs

Otho Wells studied the use of "hightunnels" for the extended season production of warm season vegetables for over 20 years at the University of New Hampshire (Bachman and Earls, 2000). See http://horticulture.unh.edu/topic.html for detailed PDF article and diagrams and for links to pictures see http://ceinfo.unh.edu/Common/Documents/hightunl.html.

His research was followed and continued by the plasticulture and high tunnel program at The Pennsylvania State University (Lamont, 2003) where over 30 separate structures have been built and used with a primary emphasis initially on extending the warm season for tomatoes followed by addition research related to cutflowers and small fruits. See http://plasticulture.cas.psu.edu/ for Penn State Center for Plasticulture.

Research programs have also been started at Kansas State (Ted Carey and Kim Williams), University of Missouri (Lewis Jet) and University of Nebraska (Laurie Hodges) and an extensive list of programs, personnel and results can be seen at www.hightunnels.org.

The research program at Michigan State University has investigated the production of baby leaf salad greens for two years (2001 to 2003) and then a wide range of vegetable and leafy green crops under production for a 48 week CSA farm with 50 members. The farm is managed by graduate and undergraduate students working with John Biernbaum and Laurie Thorp. For more information see www.msuorganicfarm.com. For up to date research reports see www.hoophouse.msu.edu .

Quick Summary of Winter Harvest Principles:

More information about crops and methods is presented later, but a quick summary of winter harvest principles seems relevant here. There are four key aspects to the winter harvest (Biernbaum, et al, 2004). There first is the use of cold tolerant crops that can handle repeated freezing and thawing. Examples include spinach, chard, kale and many leafy greens as well as root crops like carrot and beets. The second is that the crops must be planted and grown early enough in the fall season so that the majority of development has occurred before light and temperature conditions are too low for a reasonable rate of growth. Light available for growth and to warm the structure and soil declines dramatically at northern U.S. latitudes (40 to 45). A third important factor is the use of crops that allow for multiple harvests either by removing outer, larger leaves at regular intervals or by cutting the entire plant back to within an inch or so above the soil so the growing point still remains. These leafy crops are able to regrow during the lower light and temperature winter conditions. The fourth factor is the protection of the crop by a greenhouse and internal layers of polyethylene or fabric. The protection from wind, rain and snow, and therefore excess moisture limits damage to the foliage. The protective layers, when covered by moisture as a result of condensation and or ice under freezing conditions, trap long wave radiant energy in the greenhouse and prevent freezing of the soil and allow maintenance of temperatures in the 15F range even when temperatures outside have dropped to -20F.

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2. Site Selection and Preparation:

Many texts on farming provide information about selecting land based on water availability, natural temperature conditions (heat zone maps), frost free days, light, wind, access to market etc. For a given farm, the best place to build a greenhouse is also based on a number of factors. Some serious thought about the location of the greenhouse can help minimize costs, maximize efficiency, and in the case of light – maximize productivity. Ready access in all types of weather can help keep things simple.

Roads

Our first greenhouses for the salad greens research were built on the Horticulture Teaching and Research Center (HTRC) and only a few feet from a road. I did not anticipate what the roads would be like with the increased traffic and under wet conditions, particularly during the spring thaw. Several hundred dollars of gravel and spreading costs were not in the budget. On sandier soils, there likely will be no issue of wet roads. The ability to plow and move snow out of the way also needs to be considered.

Access to Utilities – Water and Electric

Irrigation water is needed year-round which in the northern U.S. means lines buried 40" to 48" and a frost free hydrant. Trenching and installation of water lines can be done well in advance of construction once the site is identified. If additional greenhouses may be added in the future, consider not putting the end of the water line at a hydrant that will be in a greenhouse. Extend the line and place the end of the line at a hydrant outside – where it could be dug up if the line needed to be extended for more greenhouses. Remember to put several cubic feet of gravel around the drain at the base of the hydrant so that it can quickly drain.

With double layer film and air inflation, electricity is necessary for the blower. Power lines can be placed in the same trench as the water line. I have heard of people using a solar powered blower, but it is rare at this point in time. I read that the annual cost of running the inflation blower for one greenhouse is only about $5.

Light

Since we are in the business of harvesting light, maximizing exposure to the sun is very important. Start with an awareness of the path of the sun over the day and the seasons and if there are buildings or trees that cast shadows. The length of the shadow is longest in late December and can reach over twice the height of the object making a shadow. A building 15 feet tall can cast over a 30 foot shadow in December but perhaps less than a 5 foot shadow in June. If the soil slopes to the south or towards the sun, it may be a few degrees warmer than level ground, which is good, but it may make building the greenhouse more difficult.

To maximize light in greenhouses, an east-west orientation is preferred at northern latitudes for maximum light during the winter. This means that the ends of the greenhouse fast east and west and during the day the sun enters mostly from the side of the greenhouse. With multiple structures, consider shadows of one structure on the next. Our 20' structures are 11' tall at the ridge and we left 20' between. In December, the shadow of one touches the next structure.

Wind

It helps to know the direction of the prevailing wind. Some wind can help with ventilation and cooling. Excessive wind can possibly damage the structure. With heated greenhouses, 15 to 20 mph winds can double heat loss. If blowing snow is a major factor, the orientation can be selected to help remove snow so it blows between the greenhouses and out rather than up against the walls of the greenhouse. Weather information including wind direction is available from the National Oceanic and Atmospheric Administration (www.noaa.org) or local airports.

Temperature

If you are not already familiar with the temperature conditions of your sight, a heat zone climate map is a good place to start when identifying normal length of the growing season and winter minimums. When selecting a sight for a tree fruit orchard, farmers may look for areas near large bodies of water, or sloping land, or south facing slopes – looking for conditions that influence the formation of frost and the drainage of cold air – resulting in warmer temperatures on average. Occasionally geographic conditions can create a type of bowl that traps cold air and can run as much as 5 to 10 degrees F colder than surrounding areas. These same considerations should be taken into account when selecting the site for the greenhouse and the warmest possible site selected.

Drainage of Rain Water

A half inch of rain displaced from the roof of a 30' x 96' greenhouse is approximately 900 gallons of water. If all the water is absorbed along the sides of the greenhouse, the soil inside the greenhouse wall can become very wet, particularly in the winter and after the spring thaw. This may not be a problem on sandy, well drained soil, but for our houses, we experienced flooding inside the greenhouse. We had to add drainage pipe (4" round plastic) in trenches along the walls and cover them with gravel. If the greenhouse is built on a slightly raised area, so water moves away from the structure, additional drainage is probably not required. You may also be able to use the natural slope of the land to drain rainwater away.

Moveable or Stationary House?

It is possible to build the greenhouse so it is moveable. This is usually done by using a base that acts like a sled. Another option is to build on a pipe rail or a track like used for a train. Once the structure is moved, it must be attached to ground anchors so it is not lifted by strong winds. The decision of wheter to build a moveable greenhouse is influenced by soil quality and fertility management and production rotations. Moveable tunnels allow rotation with green manures and resting the soil with exposure to rainfall during part of the year. It also allows starting a fall cool season crop outside while the greenhouse is used to protect warm season crops, until low temperature, frost or snowfall lead to covering the winter crop. Most greenhouse construction for vegetables is currently using stationary structures.

Level ground makes construction easier, but is not essential. Leveling side to side more important that end to end. A transit or laser level can help evaluate the site but are not commonly available. A garden hose full of water can be used to compare the height of posts or locations separated by the distance of a 50' hose.

Soil Quality and Preparation

Part of the planning process includes preparing the soil (cultivated, free of weeds, organic matter added) in advance of building. Because there are a number of options, we will cover that topic in a separate section. The type of soil in the chosen location, as with any type of farming or gardening, will impact nutrient and water retention as well as the ease of cultivating, planting and sowing seed. While a nice sandy loam would likely be the choice for vegetables, soils from sands to clays can produce good crops with the right management.

In the planning process, please consider future access for adding fairly large amounts of organic matter to the soil (quantity likely depends on the type of soil). In year 3 we recognized that soil organic matter and our initial applications of compost were not so evident and the soil was becoming more difficult to work and water. In year four we opened the ends of the greenhouses and backed in a large manure spreader full of decomposed leaves and wood shavings. It would be important to consider access in the planning stage – ie room to turn a tractor and spreader. An alternative low tech approach would be pulling in a pickup truck and unloading it in the greenhouse – or unloading into a cart or wheelbarrow for spreading if time and human labor are available. We added the equivalent of six heaped pick-up truck beds of material to a 20'x96' house – which would take a long time one cart at a time.

3. Preconstruction Weed and Soil Quality, Fertility and Biology Management

One option is to build a structure where crop production is already in progress and the soil is relatively fertile and weed populations are reduced. With protected cultivation, production is more intensive from a space use perspective and a time perspective and it is important that the soil quality and organic matter be protected. The program at Penn State uses a plasticulture program with plastic covered beds with drip tape fertigation (frequent or constant application of water soluble fertilizer in the irrigation water) and application of fungicides, insecticides or soil fumigants as necessary. We are recommending management suitable for organic certification based on building soil organic matter with compost and green manure /cover crops and the development of active soil biology. Additional information is available in a separate publication – Principles and Practices of Organic Farming – also by John Biernbaum. There is a wealth of information available at the ATTRA web site, www.attra.org .

If the ground is currently in sod, it is highly recommended that soil preparation begin a year in advance if possible (although this is not essential). The sod could be inverted with a plow or broken with a rotary spade or rototiller. Multiple cultivations will likely be necessary to remove perennial weeks and quack grass. After each cultivation, a cover crop such as rye, oats or buckwheat can be planted and then incorporated at the next cultivation.

An alternative to preparing the soil by frequent cultivation is sheet composting. Thick layers (several inches) of straw, hay, leaves, or wood shavings – or better yet a combination of all - can be used to stop the growth of all current vegetation. A total of from 6 to 12 inches of loose mulch can be applied. The mulch will help maintain moisture and promote biological degradation of the sod. The mulch can be continuous if transplants are used and planted through the mulch with roots into the soil. After several months the mulch and the dead and decaying underlying sod can be broken up with a chisel plow and then mixed and shallowly incorporated with a disc. Once decayed, and if the soil and mulch are not too wet, the mulch can be incorporated to allow development of a seed bed for direct seeding.

If the ground is currently being cultivated, organic matter can be increased by addition of straw, hay, leaves or wood shavings; the production of cover crops, such as winter rye or wheat, oats, or in the warm season, sorghumxsudan or buckwheat. Compost is another good option. It has been recommended by Steve Moore and Eliot Coleman that animal manure based compost is not necessary and not recommended due to the higher nitrogen content.

In other publications I have outlined a recipe for plant based compost that includes proportions of 1 bale straw, 1 bale wood shavings like those used for animal bedding, 1 bale peat, 1 bale grass hay (first cutting), 1 bale alfalfa hay (second cutting), 1 bale fresh cut green plants (we use cut comfrey or grass clippings), and the equivalent of a bale of soil. If we don't count the soil, we have a ratio of 3 bales of "browns" or carbon to 3 bales of "greens" or nitrogen. A common recommendation is for 3 browns to 1 green. The mixture outlined will heat easily. The amount of carbon could be increased with up to 3 bales of moist or partially decayed leaves or plant material with "woody" stems.

With regards to organic matter, it is important to understand that the soil in the greenhouse will be intensively cultivated throughout the year. The soil temperature in the greenhouse will be elevated and most likely the soil moisture level will be maintained at levels that favor plant growth as well as biological activity. With the likely greater decay rate, additions are necessary for soil health.

As with any crop production system, it is helpful to have the soil analyzed for macronutrient content (nitrogen, phosphorus, potassium, calcium and magnesium). Minerals such as lime to adjust pH and add calcium or magnesium, rock-phosphate to add calcium and phosphorus, gypsum for calcium and sulfur, and potassium sulfate can be added prior to construction of the greenhouse.

These elements can also be added through the addition of compost or animal manures. Because we had access to nutrient rich animal manure based compost that included wood shavings and straw from animal bedding, we used the compost and not mineral sources of fertilizer. Depending on the diet of the animal and the mixtures used for composting, finished compost can be high in nutrients. The rates to use can vary widely.

When preparing soil prior to construction, it is important to recognize that irrigation may be necessary to keep the process on schedule. To get the necessary growth, cover crops need to be irrigated when rainfall is limiting. Cover crops are also useful to help move nutrients in less soluble mineral forms to biological forms that are released as the plant material is degraded by soil microorganisms.

Reducing the weed seed levels in the surface layers of soil may also depend on irrigation. Once we had our plots prepared with cover crops and compost incorporated, be began a program of watering to stimulate weed seed germination followed by shallow cultivation. During warm conditions, (greater than 70F average daily temperature, this process can take about 2 weeks and could be done from 2 to 4 times. This process is also know as stale bed preparation.

4. Structure Options and Design Principles

There are at least 20 plus greenhouse manufactures that can provide structures in the Midwest United States. At this point in time, there is no one clear favorite when a variety of factors including design, quality, options, costs and transportation costs are take into consideration so selecting which one will take a little time and priority setting. If low cost is most important, then the Clearspan structures from FarmTek are probably an easy choice. If the strongest, longest lasting structure is most important, the there are other choices. Following is a list of some key considerations.

1. Frame Width, Steel Strength and Design

Width ranges from 14 to 34 feet wide, lengths up to 100 to 200 feet.
Four foot bow spacing most common in North, some companies may offer 5' or 6' spacing.
Steele thickness or gauge – most commercial houses are 13 gauge for strength, galvanized steel
For wider houses – 30' – 1.9" or 2" diameter pipes are common
For narrower – 18'-24' – 1 5/8 or 1.66" diameter pipes are common
Is there a reduction in cross ventilation with roll up sides as width increases? Originally 20' or less width was recommended, now some say 30' is ok in Northern latitudes (above 40^o)
We like the 30' wide houses for winter production
With a limited budget, a wide greenhouse can be extended in length when funding allows.

Purlins and cross bracing important for snow and wind strength – many variations.
Gothic (more peaked, sheds snow better) is preferred over Quonset (rounded and flatter)
Lets in more light in winter, easier to ventilate out heat.
Side wall height can influence access and ventilation. Higher sides are an advantage.
Higher sides also allow pathways along the colder, wetter outside edges.
Snow and wind loads can vary dramatically by geographic location - important considerations
Need enough space between houses for snow to slide off and to prevent shadows.

2. Covering Type and Layers

The most common film used for greenhouses is polyethylene. Other types of film are available but rarely used. Greenhouse film is different than hardware type polyethylene because it has additives to keep it from breaking down due to the ultraviolet (UV) radiation in sunlight. The standard film thickness is 6 mil (0.006 inch) and the most common types last for 3 to 4 years.

Greenhouses are normally covered with two layers which are inflated with air to provide more structure and an insulating layer. With heated greenhouse, the second inflated layer is generally reported to decrease heating requirement by 40%. If any heating at all will be used in the structure, even if only minimal heat on very cold nights, a double inflated layer is necessary. A single layer will provide significant crop protection and is what is most common in hightunnel or hoophouse production. Are first greenhouses have been covered with just one layer for the last four years. Where we have such a large emphasis on winter production, we have decided to go with the second layer in most cases. We have two greenhouses with the double layer. The plastic does not blow and flap under windy conditions and there is an approximately 4F advantage or increase on average under cold and freezing conditions.

Greenhouse films can be purchased with a variety of additives. Standard film is transparent to long wave or thermal radiation that is radiated by the soil or objects in the greenhouse – similar to the earth cooling on a clear night with no clouds. Just as clouds can help trap or reflect thermal radiation back to the earth and increase night time temperatures, an additive can be placed in the plastic to help trap thermal radiation in the greenhouse. There are studies showing how these infarred or “IR” additives can improve energy efficiency in heated greenhouses. To my knowledge there are not controlled studies of how much this helps under unheated greenhouse conditions. Our experience has been that there is normally condensation or moisture on the plastic under cold conditions, or ice under freezing condition. The moisture or ice helps to trap the heat energy. However, perhaps with the IR additive, more moisture could be ventilated from the greenhouse and the plastic kept dryer, which would increase light transmission. My current recommendation would be to use an IR film if it is available. The added cost is usually small (what % of the film?).

Another common additive can help prevent the formation of condensation into water droplets on the plastic. Drips falling on the crops below can lead to wet foliage and disease development. With condensation additives, the moisture spreads into a film rather than droplets. It is not clear how much this helps in an unheated greenhouse relative to dripping, temperature, and increased light transmission.

A more recently available additive to greenhouse film can “diffuse” the light coming through the film so it is more uniform and there are less shadows. We have one house covered with this film. Although we cannot make careful comparisons between the plastic types, it does appear that diffusion of the light and increased light uniformity has some advantages, one of which may be temperature uniformity.

3. Baseboards, Hipboards and Endwalls

Most treated wood not allowed in contact with soil for organic certification. The baseboards can be up off the ground if something else is used to go into or contact the ground – such as plastic film or rigid plastics. Endwalls add to strength of structure in heavy snow and wind areas. Endwall ventilation at top and though doors important of winter ventilation. Access of cultivation equipment through end walls or end doors can be helpful. In protected areas where wind pressure on endwalls is not great, very minimal end wall support has been used. Structures without endwalls will not be able to support as much snow load.

Purchased end wall kits from manufactures can add significantly to the structure cost. For this reason, all early houses were built with wooden end walls that we made. The last few Farmtek structures were built with 1.5" square tubular steel, their connectors, and welded steel frame doors. These will clearly last much longer and at this point are recommended if funds for capital invest are available.

4. Roll up sides and ventilation

There are some conflicting ventilation design considerations for winter and summer greenhouse growing. In the winter, while an air tight or draft free greenhouse does not appear to be essential for crop survival, a few degrees increase in temperature can make a difference on those few critically cold nights (air temperatures below 0F to -20F or below) and for some of the less cold tolerant crops (like lettuce). In these cases, fewer openings or air leaks around vents and roll-up sides can be an advantage.

While some sources state that roll up sides are essential, there are successful greenhouse grows in southeastern Pennsylvania (Steve Moore) and Kentucky (The W????) that are not using roll up sides and still doing summer production of warm season vegetables. Without rollup sides, large enwall doors and vents – particularly if placed to take advantage of natural winds – can keep temperatures down to the high 90's or low 100's. While it is not a pleasant work environment for humans (get in there early in the morning while it is still cool), the warm season vegetables such as tomatoes, peppers, eggplants, cucumbers, summer squash, melons and beans all seem to grow well. A key issue is pollination for fruit set. There have not been careful studies that I am aware of, but grower experience indicates that fruit set is adequate despite the high temperatures and possible effects of the temperature on pollinators.

With roll up sides, summer temperatures can be maintained close to outside temperatures. For anyone with prior greenhouse experience, there is a tendency to shade the greenhouse roof to reduce temperature. Based on experience of other growers and personal experience, shading the roof is not recommended for warm season fruiting crops. Shading can be helpful for cool season leafy greens.

(More details provided in the temperature and light section.)

5. Structure Economic Considerations:

Construction costs per square foot are in the $1.50 to $2.00 range for materials (plus labor) if endwalls and roll ups are made with locally available materials. Manufactured end walls and rollup sides are very easy to assemble, but add significantly to the cost. The cost of labor is an important consideration here. Without construction experience, it may be cheaper to buy the kit. End walls can be $200 to $400, with doors adding to costs. Roll ups can also be $200 to $400 with crank mechanisms adding significantly to the cost. The cranks are easy, but not essential. A simple T or L handle works great, even over a 100' to 200' distance. Shipping/transportation costs can be in the $250 to $500 range for a 96' tunnel and plastic.

Production capacity or growing space can be near 55% up to 80% and will influence profitability. Reductions in aisle and access space increase production but may limit access for some employees.

Baby salad greens can generate $0.50 to $1.00/sq ft per harvest with 2 to 4 harvest possible over the winter for payback in one season. Similar data exists for tomatoes (ATTRA Season Extension). A conservative investment to start is recommended.

Possible Sources: (Widely available, transportation cost can be significant - buy local if possible.)
Rimol – New Hampshire www.rimol.com
Nifty Hoops - www.niftyhoops.com
Atlas Greenhouse Company www.atlasgreenhouse.com
BFG (bfgsupply.com); Broker for DeCloet Greenhouse
Keeler-Glasgow (Southwest Michigan Area); made to order. (keeler-glasgow.com)
Ledgewood Farms (Ed Person, New Hampshire farmer; 603-476-8829); high quality, made to order.

Clearspan/ FarmTek; (East Coast or Iowa?, farmtek.com).
Harnois (www.harnois.com , Canadian); used by growers in northeast for moveable structures on sleds.
Haygrove Tunnels (Imported from England); suitable for connecting; haygrove.co.uk/tunnels.php - these are not the same as regular high tunnels and are not intended for winter coverage.
Zone 3Gardening, Jack Middleton, Gaylord Michigan, 231-546-3554 (Focus on Northern Michigan)
See www.hightunnels.org for a more complete listing with contact information.

Sources from the southern or western United States where snow loads are not as great may not provide as strong a structure. East coast companies can have good houses, but high transportation costs. It is also possible to build your own using local materials.

5. Construction Basics and Recommendations

If you have already built your first greenhouse, you can probably skip this section. There is a good chance you went through the process from "How am I going to do this?" to "That was not so hard!" or in some cases, "Look at that – and I built it!!". One key part of this entire process is that the structures are not only affordable; they do not require a skilled construction crew. Having built or helped build 12 structures from 6 manufactures over the last four years, there are a few generalizations that I can offer.

While the structures from different manufactures are similar, they are not the same. It is surprising to me the number of variations for how to do essentially the same thing. One key difference is the directions provided. In some cases I had no directions, in other cases there were good, step by step details. If you have no prior greenhouse building experience, a good set of directions will make life much easier and you should inquire about their availability, or even ask to see them before you make a purchase. Some manufactures normally sell to bedding plant producers who already know how to build. These companies are not used to giving much customer support. Part of the process of choosing the structure should include evaluating the sales and customer support if you think you will need it.

Following is a list of 10 steps in the order they usually occur. My personal experience has been that once the ground posts are in correctly, it is all down hill from there.

1. Square the Foundation (Check three times; plan for any slope; think water drainage)
2. Pound the Ground Posts (Spacing, vertical (plum) and level side to side are important.)
3: Assemble the Rafters and Put in Place (Requires a large flat surface.)
4. Attach the Purlins (Make sure rafters are equally spaced.)
5. Plum the Structure and Ends (To make sure that the end walls will be plum/vertical.)
6. Attach the Baseboards (Good time to think about drainage and rodents.)
7. Attach the Hipboards (If used for roll-up sides.)
8. Build the Endwalls, Doors and Vents (Many variations possible.)
9. Install wire lock or lath for holding plastic (Important for strength in wind.)
10. Cover with Plastic (Install inflation fan if using double layer film.)

One good source of construction recommendations and pictures is the *HoopHouse Handbook* available from Growing for Market (www.growingformarket.com). We normally provide examples of directions from specific manufactures in our workshop notebooks.

Part 2: Growing

6. Environmental Management: Light and Temperature

As we look at some of the details of light and temperature management, we will see that in the summer there is generally an excess of light for adequate plant growth and yield as long as plant spacing is adequate, and that keeping temperatures in the greenhouse cool will be a key management strategy. For winter production and harvesting for latitudes above 40^{o} latitude, maximizing light is going to be important. Without clouds, there generally is enough light for plant growth, but light also is a primary factor influencing both day and night temperature in the greenhouse.

Light Management:

At our latitude in Michigan (about 41^{o}N) the day length ranges from about 9 hrs on Dec 21 to around 16 hours on June 21. Does this mean there is about half the light in December that there is in June? No, because in addition to decreasing day length, during the winter the intensity of light is also decreasing dramatically. How much does the light change seasonally?

To answer this question, we need to first understand that the amount of light available for plant growth is a result of the day length and the light intensity. For example, if we have plants in a room and turn on a light for 12 hrs at 250 footcandles (intensity), we could get similar plant growth if the light was on for only 6 hours at 500 footcandles or 24 hrs at 125 footcandles.

In our greenhouse, light intensity of course changes from sunrise to sunset. If we measure how much light there is each second and add it up all day, we get a unit of measure that includes both time and intensity. For plant growth in greenhouses, this unit is called the daily light integral (DLI) and has units of sunlight energy per unit of area and day or unit time - mols per square meter per day (or per second). The DLI can range from as low as 2.5 mol/day to as much as 50 moles/day – a factor of 20. That means there might only be 5% of the light on a cloudy December day that there is on a sunny day in late June. We can easily say the difference is at least 10 times the amount and not one half or one quarter. Battery operated equipment to measure the DLI is available for about $450 (www.spectrum.com) but is not necessary. We use one in our research to help identify differences.

From greenhouse flower production research, we know that when the DLI drops below 10 for the day, that plant growth slows considerably. We also know that the outside light level drops to this point or lower in December and January in Michigan. When we take into account that the greenhouse covering can reduce the light by 60 to 70%, we begin to understand why plants do not grow much in December and January.

Before we switch to talking about temperature, we should not that based on our previous discussion, there is plenty of extra light for plant growth in the summer. This extra light tends to heat up the greenhouse but obviously does not hurt the plant. For most crops, except cool climate leafy green crops like lettuce, we do not need to provide any shade in the summer.

Temperature Management:

Just as the total amount of light over the day or DLI is a good predictor of the amount of plant growth, the *average daily temperature* or ADT is also a good predictor of the amount of plant growth. However, we also need to take into account that most warm season plants like tomatoes or melons do not grow very much at all if the temperature get down to 50 or 55F. We call the temperature where growth is minimal or stopped the *base temperature.* For cool season crops like spinach, the base temperature, where there is little or no growth, is in the range of 32 to 35F. As the average daily temperature increases above the base temperature, in general plants grow proportionally more until the temperature optimum, which is around 75-77F is reached. For example, if the range from base temperature to optimum temperature is 50F to 75F (25 degrees difference), for each 5degree F increase in ADT, the plants would grow about 20% (5 divided by 25 = 0.20 or 20%) faster.

Soil temperature can also influence plant growth. For plants growing in containers in heated greenhouses, soil temperature usually follows air temperature in a predictable fashion. When growing in unheated greenhouses in the native soil, soil temperature will be influenced by the amount of sunlight, the amount of soil moisture, and the air temperature. If the soil does freeze, it is difficult for plants to take up water when the sun comes out bright and the soil has not thawed. For winter growing, soil temperature is one indicator of the energy or temperature in the greenhouse.

Interior row covers with frost protection fabric increase temperatures significantly. In the greenhouse, there usually are not problems related to wind blowing and moving the covers. When the air temperature decreases, moisture from the air condenses on the fabric. As explained previously, the moisture helps to trap long wave radiant energy emitted by the soil or plants. Ice forming on the covers and the plastic helps trap heat. We call this the cloud or igloo effect. We have examples of temperature outside being from 0 to -20F while temperatures under the cover inside the greenhouse have rarely gone below 15F. Most of what we grow survives at this temperature. Lettuce will survive but top growth is damaged, usually once air temperature under the cover goes below 20 to 25F.

Opening the covers in the morning on sunny days to allow the sun to warm the soil can help increase temperatures under the fabric when it is pulled over the crops at the end of the day. Following warm days, it is important that fabric covers are pulled back into place before air temperature approach freezing or the damp fabric will freeze together and tear when pulled apart. Under very cold conditions, some growers will apply a second layer of fabric at night.

In the summer, temperatures can reach 100+F. Usually temperatures are reduced by ventilation (roll up sides) rather than shading. For summer lettuce production, the tunnel could be used as a shade structure. There is some question about just how limiting the high temperatures are to warm season crops. High temperatures may not be limiting if soil moisture is maintained at high levels.

7. Environmental Management: Soil Quality, Fertility, Biology and Moisture

We still have a lot to learn about caring for the soil under long term greenhouse conditions. In this section I will share what we have learned so far and provide our current recommendations. Covering the soil with a greenhouse prevents natural rainfall (30" on average in Michigan) which can wash or leach nutrients and soluble salts from the soil (can be both desired and undesired), can lead to very dry soil if irrigation is not adequate, elevates soil temperature and prevents soil freezing which increases the activity of the soil microorganisms. We know that building soil organic matter without providing an excess of nutrients, protecting soil structure, rotating crops to prevent development of soil born plant pathogens and maintaining soil moisture are four important parts of greenhouse vegetable soil mangement.

Soil Quality and Physical Properties

In order to have good production over the long term, we need the soil to have good water absorption (soak up water easily) and good water retention (hold water and release it to plants). We also need for there to be adequate air spaces in the soil and exchange of air so there is oxygen for the roots. These characteristics are referred to as the *soil physical properties*. Soil texture (particle size – sand, silt, clay) and structure (how the particles are glued or held together), including the amount of organic matter determine the soil physical properties.

With the warmer temperature and likely ideal moisture, soil microorganisms will likely be active and therefore breaking down organic matter faster than in out door conditions. A good question is what type of organic matter to add. In general, nutrients are not leaching, although crop removal might be high. Carbon / organic matter like straw, leaves and wood shavings will provide an energy source without adding excess nutrients like nitrogen, phosphorus and potassium. However, particle size needs to be such that it does not interfere with planting and seeding. Larger particle material can be used as mulch on the surface, which allows initial breakdown prior to shallow incorporation, or it can be composted first. Manure based compost will add more nutrients and current recommendations are to use it sparingly if at all.

In general, there is not a need to turn the soil or deep cultivate, particularly if the soil was well prepared prior to building the greenhouse. Deep cultivation will likely bring more weed seed to the surface where they will germinate in response to the light. Organic matter and amendments can be shallow incorporated with the understanding that plant roots, soil biology – particularly earth worms if present and irrigation water will carry the nutrients deeper. If deep cultivation or soil management are needed, or the use of a tractor in the greenhouse is anticipated, end walls can be built with large doors to allow access. After four years in our first houses, this summer we add over an inch of leaves and aged wood shaving bedding and tilled the entire house with a rototiller. We moved the leaves and bedding in with a pto driven manure spreader followed by spreading out the material evenly with rakes.

New Hampshire and Penn State research has emphasized plastic covered beds and drip irrigation fertigation on sandy to light textured soils. More work on warm season crops but expanding. Emphasis at Michigan State on organic production methods, winter harvesting, compost incorporation and use of hand tools only in tunnel including broadfork. High organic matter from compost and cash crop root residuals can increase water absorption and retention and potentially increase carbon dioxide concentration of the greenhouse atmosphere under cool weather conditions when the greenhouse is not ventilated.

Nutrients

The six macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulfur) and the seven micronutrients (iron, manganese, zinc, copper, boron, molybdenum and choride) need to be present and in the proper balance for plant growth. One good indicator of nutrient availability is how well the plants are growing and how the yield compares to other farmers. A standard field or garden soil test will give a reasonable indication of what nutrients are present or limiting for usually under $20 to $25. The soil pH (acidic, neutral, alkaline) will provide an indication of the availability of nutrients and whether lime is necessary.

Included in the power point course material are graphs of the pH and nutrient levels in our greenhouses over the past four years.

Tools and Soil Preparation

For routine working of the soil between crops, we use a four step process. Step 1 is to use a broad fork (Johnny's Selected Seeds) or a spading fork to lift up the soil and provide aeration without inverting the soil. This lifting process also allows compost or organic matter that has accumulated in the surface soil layer to drop down to deeper levels. Our soil has a significant clay component and is primarily worked by hand so it usually fractures in larger clumps. Step 2 is using the 3-tined cultivator (Johnny's Selected Seeds – not always pictured in the catalog) and breaking up any large clods or clumps of soil. This also helps to mix the soil. Step 3 is adding compost or Bradfield Alfalfa (see next section for rates). Step 4 is using the 30" hay rake to mix the compost or alfalfa into the top 1-2 inches of soil and to level the bed. The rake will help break up remaining large chunks of soil. If we are transplanting, a less prepared surface is needed than if we are seeding with the pinpoint seeder. A uniform, flat seedbed is important for uniform depth of seeding, uniform seed germination and ease of harvesting.

Recommendations for Compost

It is often 8 to 16 weeks (or more) between crops and the average time might be 12 weeks (3 months). With some down time, we may be preparing beds 2 to 4 times per year. For the first four years, we have averaged compost addition two to three times per year if crops are doing well. As mentioned above, the compost is added after broadforking and raking out the bed to keep it more in the surface layers of soil. Having the compost towards the surface helps with water absorption and seed germination.

The rate of compost to apply is dependent on the type of compost, with particular emphasis on the nitrogen content. Eliot Coleman makes a plant and seaweed based compost that he applies at a rate of 5 gallons per 12 square feet of bed space. Steve Moore recommends from 1.6 to 3.6 cu feet of compost per 100 square feet of bed space. At MSU, we have average a 5 gallon bucket per 20 square feet of bed.

To standardize these recommendations, we need to know that 1 cubic foot (12"x12"x12") of volume equals 7.5 gallons of volume. Therefore, a 5 gallon bucket is 0.67 or 2/3 cubic foot. A standard rate recommendation is to add a given weight or volume per 100 square feet of bed space. If the three rates above are converted to cubic feet per 100 square feet, we get a range of from 1.6-3.6 for Steve Moore, 3.3 for MSU, and 5.5 for Eliot Coleman. If we convert that to gallons per 100 square feet, we get 12 to 27 for Steve Moore, 25 for MSU, and 41 for Eliot Coleman. The difference from low to high is a factor of about three. The more frequent the application and the better the soil and crop growth, the lower the rate necessary. Compost nitrogen content can range from 1 to 3% and needs to be considered.

Recommendations for Bradfield Alfalfa

What if you do not have compost available? For the first four years, we added nothing but Bradfield alfalfa based 3-1-5 fertilizer to some of our plots and growth was as good as the compost treatment. The heavier soil was more difficult to work, planting and watering were more difficult, and we had to add lime to raise the pH (compost treatments did not need lime). Recommended rates on the bag are 25 lbs per 1000 square feet or 2.5 lbs per 100 square feet. A gallon weights about 5 lbs so that would be about 0.5 gallon per 100 square feet. This is much lower than the compost rate above. The fertilizer is OMRI approved so it is suitable for organic production. It is made up of about 50% alfalfa with poultry protein, potassium sulfate, molasses and micronutrients added. It is available in a granular form that is made so it looks similar to pet food. This product will soon be carried by suppliers of Purina and Land of Lakes products. When we first started the greenhouse, we made one application at the recommended rate and then two weeks later made a second application.

Water and Soil Moisture Management

Careful irrigation and lack of heavy rainfall can reduce soil compaction which can improve plant growth. However, soil moisture can become limiting as soil drys at deeper depths after being covered for several months. While we originally thought that maintaining drier soil in the winter helped with winter growth and production, we are now concerned that we have allowed the soil to become too dry for the summer. Frequent watering during the summer is time consuming and can compact the soil.

Some method of deep soaking irrigation is necessary to maintain soil moisture at deeper (> 8") depths during the warm sunny seasons. With our high number of small beds and wide crop diversity, drip irrigation does not seem like a good option in our greenhouses. With our water quality (high calcium and iron), overhead spray irrigation is challenging, so we tried subirrigation. We dug a 15" deep trench the length of one greenhouse, about 1/3 in from the side and placed a perforated 4" plastic drain tile with sock covering in the trench and then covered it. We inserted a ¾ " water line with holes drilled about every 18 inches so the water would be distributed evenly over 50 feet. Our greenhouse soil slopes so we could not go the entire 96' and stay level. Perhaps a better alternative would have been to bury drip tape either alone or in the subirrigation drain pipe.

We have also used an overhead oscillating sprinkler in the greenhouse. The back and forth motion can go side to side with the sprinkler located in the center aisle. This method washes the foliage and leaches nutrients down into the root zone. When in production, it is important to let the crop foliage dry before evening. We will often use this method after the houses have been cleaned out and we are bringing up soil moisture prior to replanting.

Crop Rotations

Soil health is dependent on not growing the same crop over and over again in the same location (same soil). It is important to have a planting plan and planting records so crops from different families or different types are rotated around the greenhouse.

There are many detailed papers on organic soil management at www.attra.org and by SARE.

8. Crop Selection, Production Methods and Gross Income Comparisons

As we learn more about each crop and have more information to share, this section could develop into a book on it own. The purpose here is to introduce the range of greenhouse crops already being grown by farmers and to categorize them into groups for which I will provide recommendations. The groupings that seem obvious at this point in time are:

- Warm season vegetables
- Baby leaf salad greens
- Cool season leafy vegetables
- Cool season heading vegetables
- Cool season root vegetables
- Culinary herbs
- Cut flowers
- Small fruit

Warm season vegetables

Key crops: tomato, pepper, cucumber, eggplant, summer squash

Planting Methods: transplants

Goals: season extension – as much as 4-6 weeks earlier in the spring and later in the fall; additional yield and production possible during cool or rainy seasons; reduction of insect and foliar disease pressure

Key Concerns: summer ventilation of structures – excessive temperatures may reduce fruit set

Pollination necessary for fruit set - With roll up sides, bees and other insects will enter the houses for pollination. Mechanical agitation of the plants by shaking or blowing may be necessary for some crops at some times of the year. One example that was given was blowing the plants with a leaf blower.

Support necessary – trellis, cages, staking

Regular/daily harvesting important

Baby leaf salad greens (BLSG)

Key Crops: lettuce (several types and colors), spinach, kale, chard, mizuna, arugula, beet greens, Chinese cabbage (Tokyo bekana like lettuce in winter), tatsoi, pac choi,

Planting Method: direct seed – seeding density is important; pin point seeder makes uniformity easier.

Goals: regular harvests of high value, high flavor, diverse color and flavor, tender salad greens

Key Concerns: Scheduling for consistent harvest; coordinating planting of crops with faster or slower germination and growth rates for harvest on same day;

See separate report on salad greens selection and yields.

Cool season leafy vegetables

Key Crops: spinach (S), chard (T), kale (T), beets (S), komatsuna (T)

Planting Method: direct seed (S) and transplant (T); can provide BLSG and then larger leafy crops.

Goals: regular supply of dark green leafy vegetables suitable for steaming or stir fry; high in flavor, vitamin and mineral content; multiple harvests are possible, usually by hand removing the mature leaves and bunching them;

Key Concerns: few; these crops provide multiple harvests even under low temperature conditions; some consumers may need help with preparation tips and developing the habit of eating steamed greens regularly; don’t over do the kale.

Cool season heading vegetables

Key Crops: lettuce, tatsoi, Chinese cabbage, pacchoi, meiquing choi

Planting Method: transplants

Goals: Scheduling is planned so the crops are grown in the fall, prior to low temperature and light.

The high tunnel acts as a refrigerator for winter harvest - and growth resumes in February

Internal frost fabric layer suspended over the crop and not touching the crop is important.
Key Concerns: crops need to be planted early enough in the fall to insure head development, although most crops can be harvested small; cold hardiness of the larger heads probably is not as great as smaller or less mature crops like BLSG or leafy green crops; low calcium may show up as poor quality leaves or marginal necrosis; high greenhouse humidity may reduce quality or lead to foliar disease infection.

Cool season root vegetables
Key Crops: potatoes, carrots, turnip, radish, beet,
Planting Method: direct seed
Goals: Mostly variety in winter CSA shares; flavor is best during the cool growing condtions
Key Concerns: damage by rodents; most of these crops can be easily produced in the field over a fairly long season; economic return likely not as high as for BLSG, leafy greens and heading greens; carrots need to be planted by the first week of August at our farm to develop to full size; carrots can be sown in again in late January or early February; potatoes are best sprouted first under warm (70F) moist conditions and then carefully planted in early March;

Culinary herbs
Key Crops: Parsley (T), cilantro (S), basil (T)
Planting Method: Seeding (S) or Transplant (T)
Goals: regular harvests for restaurants or for CSA distribution
Key Concerns: beds of parsley can produce over many (6-9) months- outer mature leafs are individually harvested; beds of cilantro are cut and need replanting after several (2-3) harvests;
Other herbs that may require some heat: Rosemary, Greek oregano

Cut flowers
Key Crops: snapdragons, larkspur, lilies, daffodils, many others possible
Planting Methods: primarily transplants, some direct seed, some bulbs or corms
Goals: Season extension; protection from wind and rain to increase quality; protection from four legged predators (deer); greater stem length with reduction in wind, regulated irrigation and greater temperature difference between day and night temperature.
Key Concerns:

Small fruit
Key Crops: strawberries, raspberries
Planting methods: transplants
Goals: Season extension – fruit to market earlier; For raspberries in Northern latitudes cover may be necessary to get any crop at all; Maximize harvestable fruit – reduced rain and insect damage;
Key Concerns: Profitability / economics still under study; profitable in specialty or high value markets or when used as a customer attractant to facilitate sales of other crops.

Comparing crops and cropping methods

If you wanted to know whether tomatoes or potatoes were more profitable in the greenhouse, how would you go about making the comparison? Tomatoes start as transplants and take many weeks before any harvest, but then they can provide a harvest over an extended period of time. Potatoes are planted from seed potatoes and also take several weeks before being ready to harvest, and then are usually harvested all at once.

We make comparisons based on the amount (lbs) of yield per unit area, the value of the crop per unit weight ($/lb) and the amount of time it was in the greenhouse (weeks). For example, tomatoes planted on 2'centers and 4' between rows have about 2'x4' or 8 sq ft per plant. If we harvest 4 lbs of fruit on average from each plant over a time period of 24 wks, we harvested about 4lbs per 8 sqft or 0.5 lbs/sqft. If we sell the tomatoes at $4.00 per pound, the gross income (before subtracting costs) is 0.5 lb/sqft times $4 per pound or $2 per square foot. To compare to a crop that takes less time, we have to express the income on a common unit of time, like weeks or days. So if the crop was in the greenhouse for 24 wks, we would take the $2/sq ft and divide by 24 wks and get a gross income of $0.083 per sq ft and week.

Lets do an example with BLSGs. Under ideal growing conditions, we can harvest about 1 pound of salad greens from 6 sq ft over a period of about 4 weeks when it is warm (>70F) or up to 8 wks or more when cold (<55F). That 1lb of BLSG might sell for $6 per lb. What we have then is 1lb / 6 sq ft or 0.167 lb per sqft. At 0.167 lb/sqft time $6 per lb gives us $1 per sqft. If it took only 4 weeks to grow, we would divide $1/sq ft by 4 weeks and get $0.25 per sqft wk. This would indicate that under these conditions, the BLSG generated 3 times more gross income per unit time and area then tomatoes. The next step would be to consider how much it cost in labor and crop related materials to grow each crop so we could then determine how much of the gross income was actual profit.

Using these methods we could also calculate the income from strawberries or cutflowers. Farmer experience to date suggests that the income for strawberries would likely be on the low side and the gross income from flowers would be on the high side. Crops like leafy greens would be somewhere in between. Crops like spinach that are ready to harvest fairly quickly and can be harvested over long periods of time, tend to generate more gross income per unit area and time. We can also see that keeping the greenhouse space full of plants as much of the time as possible will increase income from the greenhouse.

9. Weed, Insect, Disease and Rodent Management

The defined and confined space of the greenhouse, the potential to prevent soil moisture extremes and keep plant foliage dry, and the potential to exclude wildlife would all seem to help reduce weed, insect and disease pressure. There is still much work to be done to minimize crop losses due to weed competition, insect infestations and disease infections.

Weeds. The basics of preparing the soil and allowing weed seed to germinate was previously discussed in section 2. When starting with a clean greenhouse, the strategies are similar to working in the garden. At the top of the list is not letting current weeds go to seed. It is also important to observe what weed seeds may be blowing in from out side. At each opportunity, fallow ground should be watered and maintained to allow weeds to germinate, and then quickly and shallowly cultivated to clean up the space. Since weeds will typically only germinate from the top two inches of soil, cultivation methods that avoid exposing the seed in deeper soil will usually reduce the amount of seed germinating.

Insects. Over the first four years of growing in the high tunnels, we have experienced very limited damage due to insects. The most common heated greenhouse pests, whitefly, thrips and fungus gnats have not been visible at all. Managing these pests during transplant production is a key to keeping them out of the greenhouse. The one pest we have had to manage is aphids.

Temperature is a key factor influencing the development of insect pests. With freezing temperatures during the winter, there are essentially not insect pests. As temperatures increase in February and March, while the greenhouse is still mostly closed and there are no natural predators, aphid populations can begin to develop. The warmer the temperature, the more likely a population will grow to damaging proportions. It is true for most all greenhouse insect pests that temperatures above 60-65F will lead to much faster insect growth.

The other factor for aphids appears to be soil nitrogen availability. With increasing nitrogen availability or more correctly nitrogen excess, the probability of seeing aphid populations increase to damaging proportions is much greater. We have learned not to use excess compost or organic nitrogen fertilizer, particularly as the soil is warming and biological nitrogen is naturally increasing.

If we cannot reduce aphid populations by spraying water, we will spray soap solutions. We just target the affected plants.

There is extensive information about greenhouse insect management at www.attra.org . Over the years we have experimented with purchasing and releasing biological predators or parasites. While effective, the cost of overnight shipping often doubles the cost of the small quantity needed for a greenhouse. If only one release is made and predator populations can be maintained, the cost is likely reasonable. It is not likely cost effective to make multiple releases over time.

In general, we assume that predators are present in the greenhouse since we do not see damaging levels of insects. We do see lots of spiders in the greenhouses, unlike heated greenhouses where pesticides are sprayed, and based on observations and comments from other organic farmers, it is likely the spiders have some effect on balancing insect populations.

Diseases. We have seen very limited soil born (root rot) or foliar fungal damage to date. The first winter season we lost some lettuce plots to rot. We believe the cause was to high a plant density and too much soil moisture – and perhaps wet foliage from watering. The availability of water droplets or free moisture on plant foliage for 3 to 4 hours or longer increases the probability of foliar diseases. This does not mean that getting irrigation water on the foliage is always a bad thing. There is little anticipated problem when foliage is wetted from irrigation, as long as the foliage has a chance to dry in a few hours. Infection develops when foliage is wet for longer periods of time.

Soil born root rot pathogens are also favored by excessive soil moisture or conditions that damage plant roots, such as wilting or excess fertilizer. Healthy soils, maintained with organic matter, biological activity and proper watering, leads to health plant roots. Another key is the rotation of plant species so the same crops are not growing in the same soil for multiple crop rotations.

Rodents, Moles and Voles. Rodents can be a serious problem in vegetable greenhouses. As previously mentioned, the first step is to consider exclusion during construction by using methods to exclude them around the perimieter. The next step for us is trapping. We have used standard mouse traps but the maintenance and routine checking can be time consuming. Idea of water trap? Use of mulches can also provide a place for rodents to bed.

10. Post Harvest Storage and Handling

No matter how well grown, how local, and how short the time since harvest, the quality of fresh vegetables will quickly deteriorate if water content is not maintained and temperature is not lowered. One advantage of cool and winter season production is that it is much easier to keep crops hydrated and cool then during the heat of summer. Refrigeration is often a large expense for small scale farm operations, and perhaps can be avoided with winter harvesting (more on refrigeration below).

The method of marketing will also determine how much handling and storage is necessary. Washing produce, packaging, and refrigerating can all add significantly to the handling time and cost. Washing salad greens prior to marketing probably reduces quality and storage time compared to holding in plastic bags and washing at the time of consumption.

Time of Day and Moisture. Leafy green, head, and root vegetables are often better tasting if harvested early in the morning. Lettuce is perhaps the most likely to loose flavor and develops bitterness as the day progresses – usually due to higher light intensity and increasing temperature. Early in the morning, crops will be full of water or "turgid", therefore less likely to wilt. With air temperature less than 60F, greens can be placed in food grade five gallon buckets, plastic containers with lids, or waxed cardboard boxes and then moved directly to a cool location (<50F) or a cooler (usually set at about 40F).

In some cases there may be heavy dew or excess moisture that may require waiting until some drying has occurred. Handling certain crops – like cucurbits (cucumbers, squash, melons) or tomatoes - while the foliage is wet might increase the probability of spreading foliar diseases.

Temperature and Cooling. Cold water is often used for cooling. Large containers to hold water – cleanliness. Water purity. – Importance of removing soil?

Refrigeration. Marketing options – how long product can be held. Temperature 50 or 40 – but can be too low for warm season crops. Insulated building or space in another building. Using an air conditioner for short term cooling. Good publications available. In ground?

Regulations. Safe and legal handling of food products is a separate topic that all food producers should become familiar with and the topic is only introduced here with some key points. In general, marketing of fresh, unpackaged or minimally packaged produce is less regulated than packaged or processed food. Key topics to be familiar with include:

1. avoiding any contact with animal manure, including pet or bird droppings
2. any water used to wash vegetables must be water safe enough to drink and free from possible human pathogens.
3. Containers used for washing and storage must be clean and free of pathogens
4. Plastic containers or bags are to be "food" grade plastic

Summary. We started with marketing options as a key consideration that influences many production choices and now we see that it also influences handling and storage choices. Each level of processing or packaging usually adds labor cost but also usually increases the selling price and potential profit. A key is to keep enough records and to do enough calculations to insure that the investment in time or resources is indeed increasing the profit or net return.

Overall Summary and Additional Information:

Take a look again at the list of topics presented at the start – the purpose is to help you reflect on the big picture. I have attempted to divide the many topics into pieces that can be considered individually as well as weave the topics together to demonstrate how they are best integrated to create a successful greenhouse plan. I can only present what I have experienced, read about, or observed and learned from other farmers. There clearly are many other possibilities already out there and not yet tried. Remember that there are successful greenhouse farmers who had nothing to read, study or consider in advance, so it is not as complicated as all these words might make it sound. But hopefully the suggestions here will help make your experience a little easier and increase your probability of success.

Please review the literature recommended earlier in this article and the articles and information provided in the workshop notebook. There are many resources available for answers. One of those resources is the hightunnel listserve. Signup is available at www.hightunnels.org .

Check out www.hoophouse.msu.edu for possible updates and new information.

John Biernbaum
biernbau@msu.edu
http://www.hrt.msu.edu/john-biernbaum
Department of Horticulture, Michigan State University, East Lansing, MI 48824-1325
517-355-5191 x 1419

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The Hoophouse Handbook book. Read reviews from worldâ€™s largest community for readers. A hoophouse is a low-cost, low-tech greenhouse structure that is er...Â A hoophouse is a low-cost, low-tech greenhouse structure that is erected right in the field so plants can be grown in the ground but with some protection from the elements. Hoophouses rely on the sun for heat and natural ventilation for cooling. Hoophouses have been widely used in Europe for decades. Now growers everywhere are discovering the many benefits of growing in a A hoophouse is a low-cost, low-tech greenhouse structure that is erected right in the field so plants can be grown in the ground but with some protection from the elements.