

MINNESOTA HIGH TUNNEL PRODUCTION MANUAL FOR COMMERCIAL GROWERS

Second Edition

Reviewed and Updated 2012



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Dedication to Dr. David Wildung



For 35 years, Dr. David Wildung has been the inspiration and leader of the horticulture program at the University of Minnesota North Central Research and Outreach Center (NCROC). In 1970, when Dave arrived, the horticulture program at NCROC was in its infancy, and now it has grown to encompass 16 acres of fruit, flower, and woody ornamental plantings. Dave's enthusiasm for the horticulture program and love for his work is always apparent. No matter how busy he may be, he finds the time to answer a question or offer advice. His many awards and his service to the horticultural community illustrate this enthusiasm. Most afternoons Dave can be found out in the field, noting the quality of the strawberries, tasting the first blueberry fruit of the season, looking for disease in the mums, counting the ripening apples in the orchard, and recently doing intensive research in his two new high tunnels. He has commented many times that the NCROC apple orchard is one of his favorite places on earth! Dave's vision for the horticulture program at NCROC and the University of Minnesota leaves a legacy that will benefit all of us, not only in northern Minnesota but in the larger horticultural community.



A great big thanks, Dave, from all your University of Minnesota colleagues, producers, Master Gardeners and friends!



Introduction to High Tunnel Production in Minnesota

Terrance T. Nennich, University of Minnesota

This edition of the Minnesota High Tunnel Production Manual reflects what we have learned in the five years since the first edition. Research in high tunnel crop production continues at the North Central Research and Outreach Center in Grand Rapids. New high tunnel research projects have been initiated in SWROC Lamberton, Crookston, WCROC Morris, Waseca, and on the St. Paul Campus.

Growers have continued to experiment and refine their methods, as well. The ongoing sharing of experiences and research among growers and researchers in Minnesota has long been a source of satisfaction to all of us in the horticultural community. High tunnels are a new, exciting venture for continued cooperation and outreach. The state high tunnel conferences and the U of M high tunnel website <http://hightunnels.cfans.umn.edu/> are important ways of forging new relationships and building on the great community we already have.

Two other excellent high tunnel resources are the Penn State Center for Plasticulture High Tunnel Manual, available for purchase at <http://plasticulture.psu.edu/node/115> and the Cornell University High Tunnel website <http://www.hort.cornell.edu/hightunnel/>. While our climate is more extreme than that of either of Pennsylvania or New York, most of the basics of high tunnel crop production are similar, making research and recommendations from these states relevant for growers in the Upper Midwest, too. Researchers in these states have been very generous in sharing their expertise with us, and we gratefully acknowledge their assistance.

What's New in the Second Edition?

New chapters in the second edition are raspberry and garlic production, ventilation, and pollination. The chapters on fertility and fertigation, irrigation, organic production, internal and external environment, diseases, tomatoes, cucumbers, and marketing and economics have been substantially updated and revised. New information can also be found in the chapters on site selection, construction, tomatoes, cucumbers, and onions.

What is a High Tunnel?

At its simplest, a high tunnel is a non-permanent structure with no electrical service and no heating. A single layer of greenhouse plastic covers the frame, is left on year-round, and lasts two or three years. Vents are opened and sides rolled up manually. Plants in the tunnel are protected from frost by mulch or row covers.

More complex high tunnels have begun to find favor in Minnesota. These structures may have electricity and thermostatically-controlled ventilation, along with heaters to protect plants from freezing. Electrical service also makes it possible to install a fertigation system with a small pump to pull the fertilizer solution into the drip irrigation tubing.

More sophisticated tunnels may have a lot in common with greenhouses, but the structures are still only semi-permanent, supplemental light is not used, and plants are nearly always grown in the soil, rather than in containers, on benches, or hydroponically.

High tunnels require a substantial capital investment up front, but sometimes can pay for themselves in the first year and even return a profit, if managed properly. Before getting

started in high tunnel production, growers are encouraged to learn all they can about the technology and to develop a sound marketing plan.

Benefits and Risks of High Tunnel Production

High tunnel technology is well-suited for production of horticultural crops in Minnesota.

- Not only can the growing season be lengthened and extreme low temperatures be moderated, but also the quality of many crops is greatly improved.
- Fruit and foliage that stays dry inside a high tunnel is less prone to diseases, and pressure from many insect and vertebrate pests is lower in a tunnel.
- Growers using high tunnels can plant superior varieties that do not ripen early enough or produce high enough yields when field grown.
- In some parts of the state, perennial crops such as garlic and raspberry can *only* be profitably produced in tunnels.

While the potential for early production, high yields, superior quality, and very profitable crops from high tunnels is great, this method of production also demands more intensive management. Growers should start small and learn as they go, taking the recommendations from this manual and refining their production practices to optimize their use of the tunnels.

Some of the ways high tunnel management can be more demanding than field production:

- Native soil must be amended with large amounts of compost and often sand, too, to make it suitable.
- Because natural rainfall is excluded from the tunnel, and plants are growing fast, keeping a close watch on irrigation is essential.
- Temperatures inside the tunnel, even on relatively cool days, can rise quickly when the sun is bright, so adequate, timely ventilation is also essential.
- Plants grow fast and big in tunnels, making sturdy stakes, well-constructed trellises, and proper pruning of many crops very important.
- Plants started early inside a high tunnel will flower early, often before insect pollinators are available, so growers have to manage pollination.
- With fast growth and high yields comes a demand for nutrients much greater than that of field-grown plants.
- While many insect pest pose less of a problem in high tunnels, others can be particularly damaging, and mites can flare almost instantly, so pest monitoring is another essential.

High Tunnels in Minnesota

David Wildung and Pat Johnson North Central Research and Outreach Center, University of Minnesota

It has been said that Minnesota has no spring. Weather in April and May can be very unpredictable with the potential for frost that can damage tender vegetable transplants always present. Typically vegetable growers and home gardeners must wait until mid-to late-May to plant warm season vegetable crops for fear of frost injury. Indeed, frost can occur in northern Minnesota well into June. Growers who take a chance and plant in May often need to take special precautions or use frost protection systems to keep the young transplants from suffering damage. When successful, growers are rewarded with earlier production and better market prices. When unsuccessful, extra time, labor, and other expenses greatly reduce profits. Producers want that early market, and any growing system that will help produce an earlier crop is desirable.

At the same time that the frost danger is so great in April and May, the day length is increasing and the sun angle is at its highest, making conditions optimum for plant growth and development. High tunnels offer a way for Minnesota growers and gardeners to capture some of the light and heat from these long days. At the same time, high tunnels enable growers to start the tender warm season crops in an environment that is less threatening and easier to protect from frost. It is not uncommon during a sunny early May day when the air temperature is in the 50's to have the temperature inside the high tunnel be well over 80 degrees -optimum for plant growth and establishment.

By definition, a high tunnel is a non-permanent structure that has no electrical service, no automated ventilation and no heating system. High tunnels typically are ventilated by manually rolling the sides up or down as needed using a roll bar. They are covered with a single layer of 6-mil greenhouse plastic that is left on the structure year around and normally will last two to three years. Frost protection in the spring and fall should be available and typically can be provided by heavy row covers or, more reliably, by standby portable propane heaters.

The Minnesota High Tunnel Project started in 2003. During the 2003 and 2004 growing seasons great contrasts were seen in growth and production both within and between the high tunnels and the field. The 2003 season was early, had no major frost events in May, had much-above-average temperatures during the entire season, and resulted in outstanding production both in the high tunnels and in field-grown plants. By contrast, the 2004 season was very late, had as many as 13 frost events in May, had frost on June 16, had another on August 20, and was much cooler than average all season. Field production was delayed and poor at best. If it had not been for the much-above-average temperatures in September, no field tomato production would have occurred at all in 2004. High tunnel production was again early, dependable, and prolific. The benefits of high tunnels in Minnesota were never more evident than during the 2004-growing season. High tunnel production in both seasons was significantly earlier, greater, and resulted in fruit that was larger and of better quality than that produced under field conditions.

In addition to the yield factors listed above, high tunnel production has some other noticeable benefits over field production. Because of the earlier planting date and better growing environment in the high tunnels, it is possible for the grower to provide a steady amount of

good quality product to the market for a longer period of time. High tunnel production also seems to be more predictable and dependable than field production, making market planning easier. These factors are good for both the grower and customer. For example, during the 2004 season, customers frequently asked when the tomatoes would be available. High tunnel tomatoes were available much earlier than field ripened tomatoes and at a time that was very close to when ripe fruit had been available during the 2003 season. Another very noticeable factor in high tunnel production was the much-reduced occurrence of insect and disease damage. Tomatoes were grown in both seasons without septoria or early blight symptoms in the high tunnels, whereas, by late August these diseases had killed nearly all of the field-grown plants. Aster yellows, which infects many of the carrots grown in the field, was not a problem in carrots grown in the high tunnels. Radishes grown in the field are usually infested with root maggots, and they were not bothered by maggots in the high tunnels. Reducing these insect and disease factors led to less pesticide use as well as better, more dependable production. A third noticeable advantage in high tunnel production was cultivar selection. Often in Minnesota, a grower may have to select a cultivar for field production because it matures earlier than others, though it may not have the yield potential of cultivars developed for regions with longer growing seasons. High tunnels allow growers to not only grow these earlier-maturing cultivars for their early crop, but also allow growers the opportunity to maximize production by choosing longer-maturing, full-season cultivars. For example, the tomato cultivar Cobra produces very little ripe fruit in the field under northern Minnesota conditions; however, under high tunnel production it is capable of producing up to 20 pounds of fruit per plant.

High tunnel production is very different from field production in that the grower has much more control over the environment. In high tunnel production, the grower can control water, fertility, and temperature. The grower needs to monitor and select the best levels of these factors and to choose which cultural practices to implement. There are different levels of management and culture within the high tunnel. For example, one grower may choose to let the tomato plants grow on the ground in a matted row system where another grower may choose to tie the plants to stakes or to trellis the plants and prune them as they develop during the season. Whichever the growing system or environmental factors used, careful and more-detailed management is necessary. This manual contains many suggestions you will need to get started in high tunnel production. It is hoped that this manual will assist growers in their quest for success.

World wide, the greatest success with high tunnels has been in regions where growing seasons are somewhat marginal either being too cool or too short. In Minnesota, the growing seasons are both too cool and too short, making the potential value of high tunnel production unlimited for Minnesota producers and gardeners.

Managing Risk with High Tunnels

Terrance T. Nennich, University of Minnesota

Managing risk in agriculture production has been a major concern to growers for many decades. While the modern trend is to manage risk with tools such as crop insurance and guaranteed income insurance, these tools do not address issues such as enhancing marketplace demand and building a consumer base with buying power. There are no better risk management tools than those that help produce a consistent, high-quality crop for the marketplace while using low-cost inputs. High tunnels are one of the most effective risk management tools that have recently been developed for specialty crop producers in Minnesota. While much development and research needs to be done in the near future in Minnesota with high tunnels, this manual will serve as a guide to minimizing risk with the use of high tunnel technology.

In order to be successful, specialty crop producers must be able to manage six major types of risk that high tunnel production addresses.

- Production Risk
- Marketing Risk
- Crop Mix Risk
- Consumer Judgment Risk
- Consumer Maintenance Risk
- Financial Risk

Production Risk

Production risk includes the effects of natural occurrences, such as limited heating units, frosts, hail, excessive moisture, drought, untimely rains, insects and diseases. High tunnel production addresses all of the above problems at a very inexpensive cost. For example, the growing season of 2004 was one of the coolest in history for many areas in Minnesota. On August 20, areas of northern Minnesota were as much as 600 growing-degree-days below normal. This translated to growing conditions approximately three to four weeks behind average. Then, on the night of August 20, 2004, much of central and northern Minnesota received an unusual killing frost, with temperatures falling below freezing for as long as four hours and lows reaching down into the lower 20-degree range. The combination of reduced growing-degree-days and the unusual devastating frost left nearly all vegetable producers in the area with a crop of poor quality or with little to no crop at all. High tunnel production in 2004, however, produced excellent crops as much as three weeks earlier than the average for field crops. In addition, these crops were of a very high quality, with production continuing until late fall.

Marketing Risk

Marketing risk is a key concern in specialty crop production. Unlike commodity grains, which can be stored for long periods of time to be sold and consumed as needed, most fresh fruits and vegetables have very short shelf lives. Modern consumers of fruits and vegetables are demanding that their produce be harvested just hours before the point of sale. This consumer trend is creating a challenge for fresh-market producers. In order for fresh-market producers to be successful with many commodities, they must concentrate on managing marketing risk in the following areas: providing a long-term supply, providing a uniform supply distribution, providing consistent high quality, and supplying seasonal niches. High tunnel production in Minnesota, with proper management, can address the marketing

challenges of fresh fruit and vegetable producers as shown in the research done in Minnesota over the last few years.

Crop Mix Risk

While there have been several studies done concerning the number of items that fresh market producers need to sell at their stand to become profitable, two indicators of success have emerged. The first is to be diversified, growing a mix of vegetables and fruits while having at least 8-12 different products on the stand at one time. The other is to become specialized in one item and become the "king" of that item. In the short growing season of Minnesota, high tunnel production is a very economical way of meeting these goals.

Consumer Judgment Risk

The consumer's evaluation of a producer is a major concern. Studies have shown that a producer is often judged by the lowest quality product on display. Even if other products that the producer has are of the highest quality, a low quality product that is sold among high quality products will reduce sales of all products. Crops from high tunnels are of very high quality. High tunnel producers have reported that when they switch production from high tunnels to the field, the crop quality often goes down and so do their sales.

Consumer Maintenance Risk

Maintaining a steady stream of loyal customers is extremely important to profitability. In order to maintain a steady stream of customers, a producer must have a continuous supply of high quality products. Far less effort is needed to maintain an existing customer than to develop a new one. High tunnel production is a tool that can be used to maintain a continuous supply of high quality produce.

Financial Risk

Financial risk management takes on many forms, as pointed out in the economic section of this manual. The authors of this manual agree that financial risk management should start with excellent production and marketing tools since the growth of an operation will depend on them. With the harsh climate of Minnesota, especially in central and northern Minnesota, producers must look at unique ways to ensure success with low-cost, economical investments. High tunnel production can provide an effective way to manage financial risk.

Managing Risk:

Production Comparisons Between High Tunnels And The Field

David Wildung and Pat Johnson, North Central Research and Outreach Center

As the previous section states, the use of high tunnel growing systems in Minnesota greatly assists growers in reducing their production risk. In order to evaluate differences between high tunnel and field production, comparisons were made between the same cultivars planted in the high tunnels and in the field at their normal planting times for both the 2003 and 2004 growing seasons. An additional comparison was made between high tunnel and field plantings planted on the same date. Comparisons were made with tomatoes, peppers, and cucumbers.

The following factors were evaluated: the date of the first ripe fruit, pounds of early production, the % early fruit production, the amount of ripe and total fruit produced, % of good (marketable) fruit, the number of ripe fruit produced per plant, the average fruit size (lbs/fruit), and the amount of ripe fruit per unit area (Ripe-LBS/square foot). All fruit harvested by August 1 each season was considered early (LBSIPLT) fruit. The planting dates were 5/7/03 in the high tunnel and 6/13/03 in the field. A second high tunnel planting was also made on 6/13/03. The 2004 planting dates were within one day of the 2003 planting dates. The high tunnel and field planting dates were 37 days apart and, in themselves, represent a very significant advantage for the high tunnel system. These planting dates pose much less risk for high tunnel situations than for field production systems. A grower in northern Minnesota would never plant tomatoes in the field as early as 5/7, even with frost protection. However, this date is very realistic in the high tunnel if frost protection can be provided. The results are summarized in six tables below.

TOMATOES

In 2003 there was a difference of 41 days between the first ripe fruit in the high tunnel and that in the field. In 2004 the difference was even greater --50 days. In 2004, with the high tunnel and field plantings both planted on 6/14/04, the first ripe fruit in the high tunnel matured 41 days earlier than in the field. In the high tunnel, fruit ripened 9 days later in 2004 than in 2003. This difference was most likely due to the slightly cooler high tunnel temperatures during fruit set in 2004. However, the difference in the field was even greater (18 days). Actual early production again favored high tunnel production. High tunnels produced 5.1 pounds of ripe fruit by August 1, 2003, compared to no fruit produced in the field on the same date. In 2004 the difference was not as great (0.9 compared to 0.0). This early production represented 43% and 12% of the total crop for 2003 and 2004, respectively. For both seasons, no early production occurred in the field crop. Any production before August 1 should provide a great marketing advantage. Fruit size in 2003, was 0.473 pound in the high tunnel compared to 0.326 pound in the field.

Table 1. Sunshine tomato planting comparison (Determinate)

	High Tunnel	Field	High Tunnel	High Tunnel	Field
Planting Date	5/7/03	6/13/03	5/6/04	6/14/04	6/14/04
First Ripe	7/17	8/27	7/26	8/4	9/14
Early (LBS/PLT)	5.1	0	0.9	0	0
Ripe (LBS/PLT)	11.8	10.4	7.5	9.0	13.6
Total (LBS/PLT)	18.6	16.1	11.1	10.1	24.7
% Early (LBS)	43%	0%	12%	0%	0%
% Good (LBS)	64%	65%	68%	89%	55%
Fruit/PLT	25.0	32.0	16.0	16.0	26.4
LBS/Fruit	0.473	0.326	0.472	0.560	0.516
Ripe-LBS/square foot	1.87	0.58	1.19	1.43	0.76

Field production in 2003 was badly damaged by foliar disease, which was not a problem in the high tunnel. During the 2004 season, the size of fruit produced in the field was actually larger than that produced in the high tunnel (0.472 pound compared to 0.516 pound). Fruit size was virtually the same both years in the high tunnel, while it was extremely variable in the field. The more uniform fruit size in the high tunnel is much better for marketing. Fruit set appeared to be better in the field for both years, with field plants setting more fruit per plant.

In 2003, this advantage did not translate into more total production because fruit size was so much smaller in the field than in the high tunnel. In 2004, total production per plant in the field was greater, but it was later to ripen. Finally, ripe fruit per square foot produced with the Sunshine cultivar was much greater both years in the high tunnel compared to field production. This difference was over three times as much in 2003 (1.87 pounds per square foot compared to 0.58 pounds per square foot). In 2004 the difference was 1.19 pounds per square foot compared to 0.76 pounds per square foot in the field.

In summary, the cultivar Sunshine matured earlier fruit, produced more early fruit, produced larger fruit, and yielded more fruit per square foot in high tunnels than in field production. In addition, there was less year-to-year variation in all characteristics with high tunnel production. For Cobra plants planted at their normal planting times, the first mature fruit was 38 days earlier in the high tunnel than the field in 2003 and 52 days earlier in 2004. For plants planted on the same planting date, high tunnel production was 14 days earlier than field production in 2003 and 15 days earlier in 2004.

Table 2. Cobra tomato planting comparison (Indeterminate)

	High Tunnel	High Tunnel	Field	High Tunnel	High Tunnel	Field
Planting Date	5/7/03	6/13/03	6/13/03	5/6/04	6/14/04	6/14/04
First Ripe	8/1	8/25	9/8	8/9	9/16	10/1
Early (LBS/PLT)	0.6	0	0	0	0	0
Ripe (LBS/PLT)	12.1	6.0	8.6	15.7	5.9	0.2
Total (LBS/PLT)	19.0	10.9	13.5	18.2	10.3	17.8
% Early (LBS)	5%	0%	0%	0%	0%	0%
% Good (LBS)	64%	56%	63%	87%	57%	1%
Fruit/PLT	33.2	8.0	21.0	35.8	11.2	0.8
LBS/Fruit	0.364	0.601	0.408	0.439	0.523	0.196
Ripe-LBS/square foot	1.91	0.95	0.48	2.48	0.94	0.01

Since Cobra is a late maturing cultivar, it did not produce much of its crop by August 1, even in the high tunnel. In 2003, early production was only 5% of the total ripe fruit produced for the season in the high tunnel. In the field, no fruit was produced in the early season. During the 2004 season, no early fruit was produced even in the high tunnel. Ripe fruit for the entire season was much greater in the high tunnels than in the field for both years. In 2003, production in the high tunnel was 12.1 pounds per plant compared to 8.6 pounds per plant in the field. In 2004, the difference was even greater (15.7 pounds per plant in the high tunnel compared to 0.2 pounds per plant in the field). Fruit set was considerably better both years in the high tunnel than in the field. In the high tunnel, fruit set was 33.2 fruit per plant for 2003 and 35.8 fruit per plant for 2004, compared to 21.0 and 0.8 fruit set in the field for 2003 and 2004, respectively. Fruit size was slightly better in the field during the 2003 season (0.408 pounds in the field compared to 0.364 pounds in the high tunnel). However, during the 2004 season, fruit size was much better in the high tunnel (0.439 pounds per fruit in the high tunnel compared to 0.196 pounds per fruit in the field). The late high tunnel planting had larger fruit size than the field plots both years. Comparisons of the total fruit produced per square foot showed a decided advantage for the high tunnel. High tunnel production was almost four times greater than in the field during the 2003 season (1.91 pounds per square foot compared to 0.48 pounds per square foot). The difference was even greater in 2004 (2.48 pounds per square foot compared to 0.01 pounds per square foot). Cobra is a late maturing cultivar that would not be suggested for field production in northern Minnesota. Indeed, during the 2004 season it produced less than one ripe fruit per plant in field production at Grand Rapids. However, Cobra is a terrific cultivar for high tunnel production if trellis systems are used. It produces a heavy crop of good-sized, uniform tomatoes. In summary, the cultivar Cobra matured earlier fruit and produced more ripe fruit, more fruit per plant, and more fruit per square foot in high tunnels than in field production. Moreover, it produced a very good crop during the 2004 season in high tunnels when no crop at all was produced in the field.

Table 3. Ultra Sweet Tomato Planting Comparison (Indeterminate)

	High Tunnel	High Tunnel	Field
Planting Date	5/6/04	6/14/04	6/14/04
First Ripe	7/26	9/8	9/24
Early (LBS/PLT)	1.2	0.0	0.0
Ripe ((LBSIPLT)	14.9	8.9	0.9
Total (LBSIPLT)	19.0	12.3	25.0
% Early (LBS)	8%	0%	0%
% Good (LBS)	78%	73%	4%
FruitIPLT	33.2	16.0	2.2
LBSIFruit	0.447	0.558	0.422
Ripe-LBS/square foot	2.36	1.41	0.05

Comparisons with Ultra Sweet were made only during the 2004 season. The first ripe fruit occurred 60 days earlier in the high tunnel than in the field. Even when planted on the same day, the high tunnel first ripe fruit date was 16 days earlier than in the field.

Every parameter evaluated showed a decided advantage for high tunnel production during the 2004-growing season. This fact was true even when comparing the crops planted on the same date in the high tunnel and in the field. Even though Ultra Sweet produced a heavy crop of fruit in the field (25.0 pounds per plant), 96% of it was immature and never ripened. Much of this immaturity was due to the late 2004 field season, but a lot of the immaturity would occur in the field every season in northern Minnesota because of the mid-season

maturity of the cultivar itself. Ultra Sweet produced 2.36 pounds per square foot of ripe fruit in the early high tunnel planting, 1.41 pounds per square foot in the late high tunnel planting, and 0.05 pounds per square foot in the field. High tunnel production with Ultra Sweet was much more dependable than field production, from earlier maturity to greater yield per square foot of growing area.

PEPPERS

For Aristotle pepper, the first ripe fruit was 40 days earlier in 2003 and 32 days earlier in 2004 in the high tunnel than in the field. High tunnels also provided an advantage in terms of the percentage of early production, with 27% of the fruit in high tunnels ripened by August 1 both years compared to 0% in the field.

Table 4. Aristotle Pepper Planting Comparison

	High Tunnel	High Tunnel	Field	High Tunnel	Field
Planting Date	5/7/03	6/13/03	6/13/03	5/6/04	6/14/04
First Ripe	7/24	8/28	9/2	7/26	8/27
Early (LBS)/PLT)	1.1	0.0	0.0	0.8	0.0
Ripe (LBS/PLT)	4.1	1.6	2.3	3.0	2.5
Total (LBS/PLT)	4.8	2.0	2.7	3.2	3.1
% Early (LBS)	27%	0%	0%	27%	0%
% Good (LBS)	84%	78%	84%	94%	79%
Fruit/PLT	11.2	4.2	6.2	8.4	7.9
LBS/Fruit	0.364	0.365	0.369	0.356	0.320
Ripe-LBS/square foot	1.08	0.42	0.38	0.79	0.42

For crops planted on the same date in 2003, fruit matured 5 days earlier in the high tunnel than in the field. Total ripe fruit produced for the season was better for both years in the high tunnels. In 2003, total ripe fruit produced was 4.1 pounds per plant in the high tunnel compared to 2.3 pounds in the field. In 2004, the difference was smaller, 3.0 pounds in the high tunnel compared to 2.5 pounds in the field. The percentage of marketable fruit (% Good) was the same in 2003; but during the 2004 season, the percentage of marketable fruit from the high tunnel was better (94% compared to 79%). Fruit set (Fruit/PLT) in the high tunnels was better both years, especially in 2003 when 11.2 fruit per plant were produced compared to 6.2 fruit per plant in the field. Fruit size (LBS/Fruit) was fairly equal; but during the 2004 season, fruit size was slightly larger in the high tunnels (0.356 pounds per fruit compared to 0.320 pounds per fruit). High tunnel systems yielded much higher production per square foot for both years. In 2003, production was 1.08 pounds per square foot compared to 0.38 pounds per square foot. In 2004, the difference in the high tunnel was still greater than in the in the field, but somewhat less pronounced (0.79 pounds per square foot in the tunnel compared to 0.42 pounds per square foot in the field).

In summary, the pepper cultivar Aristotle, matured fruit earlier, produced 27% of its total crop before August 1, produced more fruit per plant, produced more total ripe fruit for the season, and produced more ripe fruit per square foot of area in high tunnel production compared to field production.

Like the Ultra Sweet tomato, Vivaldi peppers were only compared during the 2004 season. The first ripe fruit for the pepper cultivar Vivaldi was mature 43 days earlier in the high tunnel

than in the field. Even for plants planted on the same planting date, the high tunnel plants produced fruit 22 days earlier than the field planting.

Table 5. Vivaldi Pepper Planting Comparison

First Ripe	7/19	8/9	8/31
Early (LBS/PLT)	1.4	0.0	0.0
Ripe ((LBS/PLT)	5.4	3.6	2.2
Total (LBS/PLT)	5.6	4.0	3.7
% Early (LBS)	26%	0%	0%
% Good (LBS)	97%	90%	61%
Fruit/PLT	16.8	10.2	7.5
LBS/Fruit	0.324	0.348	0.300
Ripe-LBS/square foot	1.42	0.95	0.37

In the high tunnel, 26% of the fruit were ripened by August 1 compared to no ripe fruit by that date in the field planting. In every comparison, the early high tunnel planting had a decided advantage over the field planting. For plants planted on the same date, the high tunnel planting was intermediate but better than the field planting in every characteristic evaluated. With the Vivaldi cultivar, production was earlier, larger, and of better quality in the high tunnel. Additionally, the high tunnel crop set more fruit per plant, had larger fruit size, and produced more fruit per square foot of area compared to the field crop.

CUCUMBERS

High tunnel yield for cucumbers is extremely heavy and relatively early compared to tomatoes and peppers. Sweet Success produced its first ripe fruit in June both years in the high tunnels.

Table 6. Sweet Success Cucumber Planting Comparison

	High Tunnel	High Tunnel	Field	High Tunnel	High Tunnel	Field
Planting Date	5/7/03	6/13/03	6/13/03	5/6/04	6/14/04	6/14/04
First Ripe	6/30	7/29	7/25	6/11	7/15	7/29
Ripe ((LBS/PLT)	20.7	9.1	24.7	22.9	10.9	22.7
Total (LBS/PLT)	21.0	9.2	24.7	23.0	11.3	25.3
% Good (LBS)	99%	98%	100%	99%	96%	89%
Fruit/PLT	22.2	12.2	37.0	31.2	17.2	29.0
LBS/Fruit	0.933	0.740	0.668	0.735	0.634	0.780
Ripe-LBS/square foot	3.28	1.44	1.37	3.63	1.73	1.26

The first ripe fruit was harvested 25 days earlier in 2003 and 48 days earlier in 2004 in the high tunnels compared to in the field. Regardless of location, most of the harvested crop was of good quality. In both years, the percentage of good fruit ranged from 89% to 100%. In 2003, fruit size was considerably larger in the high tunnels than in the field. The time between harvests should have been less, particularly in 2003 when the fruit size averaged 0.933 pounds per fruit. Cucumber growth and development can be very fast in the high tunnels, and an every-other-day harvest certainly would not be too frequent. Production per square foot was very large in the high tunnels, with 3.28 pounds of ripe fruit per square foot or more produced both years compared to 1.37 pounds per square foot or less in both years with field production. Even in the late year of 2004, field production was good. In summary, the cucumber cultivar Sweet Success produced very heavy crops both in the field and in the

high tunnel. High tunnel production was much earlier to mature and produced more fruit per square foot than in the field. Other than more production per square foot, there did not seem to be any advantage to the high tunnel plantings over the field plantings planted on the same date.

The six warm season cultivar comparisons above illustrate the decided advantage of high tunnel production compared to field production in northern Minnesota. Besides being able to plant earlier in the high tunnels than in the field, with a safer environment, production is significantly earlier (in these typical examples from 25 to 60 days earlier). In most cases, a real marketing bonus results from production before August 1 in northern Minnesota. In almost every example, the yield of total ripe fruit is significantly greater with high tunnel production than with field production. The percentage of marketable fruit, fruit set, and fruit size all are at least as good and, in most cases, much better with high tunnel production than with field production. With high tunnel production, more dependable harvests occur, and the risk of yearly variability of product is reduced compared to field production. High tunnel production makes possible the growing of some late season cultivars like Cobra tomato, which would not be able to mature in the field during northern Minnesota's short growing season. High tunnels enable the production of such higher yielding cultivars that can contribute to more uniform fruiting and the production of more high quality fruit, all of which are of great value to improved marketing success. Finally, with the intense management systems used in high tunnels, the productivity per square foot is from two to five times greater than with field production systems.

Site Selection

David Wildung and Pat Johnson, University of Minnesota

Since a grower will be producing a high quality product and using a high level of management, the site and soil should be considered with great care. Even though, by definition, a high tunnel is not a permanent structure and should not be considered such, site selection is important in the success of the high tunnel. What often is not considered permanent becomes so after a few years.

The most important aspect of site selection should be good soil drainage and an elevation above the surrounding area. The location should be slightly higher than the surrounding area so water will not drain into the high tunnel or flow through it if heavy rains occur. The site should be level so that tillage such as bed making is easier. In addition, a level site is important for irrigation so more uniform water distribution can occur. Problems with elevation should be corrected before any construction occurs. At Grand Rapids, the location we chose to put our high tunnels was slightly lower than the surrounding area.



Figure 1. Sand added to site

We removed the top 12 inches of soil, backfilled with 8 inches of washed sand, and then put the original soil back. As each layer was put back it was incorporated and mixed by tilling with the layer below it. In all operations, care was taken to minimize compaction of the soil. The result was an elevation that was several inches above the surrounding area and a site that was level for the high tunnel frame. While this preparation took considerable time initially, it has provided a location that has produced good crops with no drainage problems.



Figure 2. Preparing the planting bed



Figure 3. Subsoiling the planting bed

Soil type is limited to the soil type on your farm. Internal soil water drainage should be a consideration; but since all of the water will have to be provided by irrigation, the grower can control the water needs of the plants for the most part. Lighter textured soils like sandy loams or loamy sands are most desirable because they will warm up more quickly in the spring, are easily worked, provide a good media for root development and respond more readily to irrigation and fertilizer applications. Returning organic matter to the soil should be an important consideration when long-term use in the same location occurs. With the intense management and heavy crop nutrient use in high tunnels, soil organic matter can be depleted more quickly than under traditional field production systems. Because of the potential of diseases and insects, crop residue from high tunnel crops should not be incorporated back into the soil.

Orientation of high tunnels is often a matter of personal preference. Successful production has been obtained with east-west or north-south orientation. Everything else being equal, a north-south orientation is probably best for optimum sun exposure and less shading, particularly with close row spacing and the use of a trellis system that results in tall plants. A north-south orientation will warm up more quickly on a sunny morning, but typically by 9:00 AM high tunnels have to be opened because they are too hot anyway.

While high tunnels can be shut down during strong winds, a windbreak on the windward side of the tunnel may be helpful in reducing the effect of strong winds. Since most of our strong winds come from the southwest or northwest, a windbreak on the west side of the tunnel may be beneficial. A deciduous windbreak on the west side of a high tunnel will provide wind protection and slight shade from hot afternoon sun during the summer. In the fall, the deciduous windbreak will lose its leaves to create less shade when the sun angle is lower and more heat is needed in the tunnel. Since some light air movement is advantageous in the high tunnel to assist in pollination, a deciduous windbreak, which allows more wind through than an evergreen windbreak, is more desirable.

Construction Aspects

David Wildung, Pat Johnson, and Keith Mann, University of Minnesota

The Penn State University 2003 High tunnel Production Manual is an excellent reference for all aspects of high tunnel production (The Center for Plasticulture: <http://plasticulture.cas.psu.edu>). It is particularly good for high tunnel construction and maintenance. The aspects discussed below are a few hints that we have found useful during the two years that we have used our high tunnels at NCROC.

Upon completion of the high tunnels, particularly when there needs to be any soil preparation work done, the area surrounding the high tunnel can be muddy. Sand spread on the ground at both gable ends can help reduce mud being carried in and out of the tunnel or into vehicles during rainy periods. Over time, sanding any roadways near the high tunnels helps keep the area cleaner until more permanent grass can become established.

After applying the plastic to the high tunnel frame, a small piece of duct tape was applied wherever there was a connection or wherever an exposed screw from the frame was in contact with the plastic. This practice has reduced plastic damage from rubbing and should allow for the longer use of plastic on the tunnel.

Shortly after construction, it was noticed that when even a slight wind would blow through the corners of the roll-up sides of the high tunnel the plastic would stretch and eventually create an open area that never was fully closed. This opening allowed cold air into the tunnel at night. While visiting the Penn State High Tunnel Facility, it was found that their solution to the problem was to put a second sheet of plastic over each corner on the inside for a distance of five to eight feet. This completely eliminated the problem and made the roll-up sides more airtight (see Figures 1 and 2 before and after plastic was attached).



Figure 1. Before corner plastic was attached.



Figure 2. Plastic corner attached, Lamberton, MN (K. Bellina, University of Minnesota)

During the first few months of use with a hook and latch door device, it became apparent that some other system was needed. Slight door warping sometimes prevented easy latching. Hooks were sometimes latched from the outside, and this required having to walk to the other end of the tunnel to get out. A better system needed be found. Devising a

simple door latch system that worked from either side and yet kept the doors from opening on their own was very helpful in getting in and out of the high tunnels without a lot of difficulty. Penn State has a good system, and NCROC adapted an easy solution for this purpose too (see Figures 3 and 4 door latch systems).

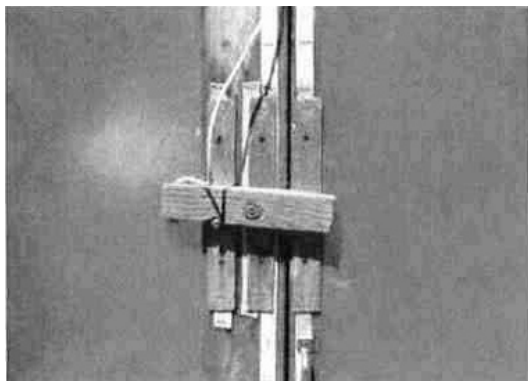


Figure 3. Minnesota Door Latch.



Figure 4. Penn State Door Latch.

For the two high tunnels that NCROC built in 2003, the end wall construction suggestions provided in the Penn State high tunnel manual were used. We also used overhead trellis wires that were fastened into these end walls. By mid-August of 2003, the end walls of both tunnels were being pulled inward by the heavy plant load on the trellis wires. While this problem should have been anticipated, it was not noticed until it was almost too late. Before the 2004 growing season, a 2x6 board and angle iron reinforcing were added above the doors at each end of the tunnel (see Figures 5 and 6 for end wall before and after reinforcement).



Figure 5. End wall before reinforcement.



Figure 6. End wall after reinforcement.

This additional reinforcement solved the problem and allowed our trellis system to resist sagging from the additional weight of the plants on the end walls.

Over the years we have made vast improvements to our high tunnels, in turn making the construction of new high tunnels much easier.

Figures 7-16. The images below show a step-by-step construction of a high tunnel in Lamberton, MN (photos courtesy of K. Belina, University of Minnesota).





The High Tunnel Environment - Light

David Wildung and Pat Johnson, University of Minnesota

The success of horticultural crop production depends upon the environment in which the crop grows. Anything a grower can do to improve the environment will also improve their chance of success. The use of high tunnels in Minnesota can greatly improve that chance of success. Environmental factors include light, wind, temperature, water and nutrition. This section will cover light, wind, and temperature factors in the high tunnel. Water (irrigation) and nutrition will be covered in other sections of the manual.

Light is necessary to manufacture the photosynthates needed for the plant growth that will ultimately produce and ripen a crop. Light and temperature are considered the master environmental factors, and together they affect worldwide plant distribution. While little can be done beyond applying shade cloth to reduce the amount of light in the high tunnel, examining day length and the amount of sunlight available during the growing season can provide insight into when the potential for crop success will be greatest. In Minnesota, the day length and light intensity vary greatly from month to month during the spring, summer and fall. If the longer periods of light during the season can be coupled with better growing temperatures produced inside the high tunnel, greater production should be realized.

Table 1 gives the approximate day length and the percentage of possible sunshine in Grand Rapids, MN, between March and November. As can be seen from the table, by March 15 day length is about 12 hours. The potential for good plant growth at this time is somewhat limited.

Table 1. Approximate Day Length and Sunshine: March through November at Grand Rapids, MN*				
	Day Length Sunrise to Sunset			
Date	Hours	Minutes	Month	% Possible Sunshine
March 15	11	54	March	55
April 15	13	39	April	56
May 15	15	7	May	57
June 15	15	55	June	58
July 15	15	32	July	65
August 15	14	14	August	61
September 15	12	33	September	52
October 15	10	53	October	46
November 15	9	19	November	35
*Adapted from US Naval Observatory Weather statistics. http://www.usno.navy.mil/USNO/astronomical-applications/data-services				

Day length increases during April to 13 hours 39 minutes by April 15. While the day length is increasing, the angle of the sun is also increasing, creating more potential growing degree-days inside the high tunnel. During this time, temperatures in the high tunnels may be warm enough during the day for good plant growth to occur (Table 5). Through May, June, July and August, day length is at its longest and is optimum for plant growth and development.

In the fall, by September 15, day length already has shortened to about 12.5 hours and is decreasing rapidly. After October 1, day length is less than 12 hours, definitely limiting plant

growth. Day length is not only decreasing rapidly in September and October, but the angle of the sun is also decreasing, limiting plant growth and slowing the ripening of immature fruit. A third factor also affects fruit ripening in September and October. It is the amount of sunshine that occurs. As Table 1 shows, there is a rapid drop in the percentage of possible sunshine from 61% in August to 52% and 46%, respectively, in September and October. Altogether, the reduced day length, a lower sun angle, and a lower percentage of possible sunshine diminish the potential success for high tunnels in late September and October in northern Minnesota. This reduced plant development even if good growing temperatures and growing degree-day accumulations can be obtained inside the high tunnel.

During both the 2003 and 2004 growing seasons at Grand Rapids, September had 500 or more growing degree days and October 1-16 had over 200 growing degree days in the high tunnels (Tables 3 and 4). With minimal frost protection, the plants were kept alive until October 16, 2003 and November 8, 2004. Due to the reduced light conditions, however, fruit ripening was relatively poor after mid-September, even though fruit set on some of the indeterminate tomato cultivars was still heavy. Evaluation of the results from the 2003 and 2004 growing seasons in relation to sunlight patterns indicates that the optimum growing period for high tunnel production in northern Minnesota is from early April to mid September.

The High Tunnel Environment – Temperature

David Wildung and Pat Johnson, University of Minnesota

The environmental factor that restricts plant growth and development the most is temperature, especially during spring in Minnesota. It is also the factor where high tunnel systems can provide the most positive impact.

Every crop has specific cardinal temperatures at which growth and development are best. There are three cardinal temperatures for every crop. The minimum cardinal temperature is the lowest temperature at which crop growth can occur. The optimum cardinal temperature is the temperature when crop growth is at its greatest. Finally, the maximum cardinal temperature is the highest temperature at which crop growth can occur. Plants can tolerate temperatures above or below these cardinal temperatures, but growth and development processes are best when within the minimum and maximum range and close to the optimum cardinal temperature. Specific crops vary in their cardinal temperatures. Table 2, adapted from Knott's Handbook for Vegetable Growers, gives the approximate temperatures for the best growth and quality development of those vegetable crops that are suited for high tunnel production.

Evaluation of this table shows that the vegetable crops do vary greatly in their temperature tolerance, and the best success with high tunnel production will occur when crops requiring similar temperature ranges are grown together. For example, tomatoes and peppers grown together in the same tunnel will certainly do better than if tomatoes and broccoli are grown together.

Table 2. Approximate Temperatures for Best Growth and Quality of Selected Vegetable Crops.*			
Temperature (°F)			Crop
Maximum	Optimum	Minimum	
85	55-75	45	Onion, Garlic
75	60-65	40	Beet, Broccoli, Cabbage, Chard, Radish
75	60-65	45	Carrot, Lettuce, Pea, Potato
80	60-70	50	Snap Bean, Lima Bean
90	65-75	60	Cucumber
80	70-75	65	Tomato, Sweet Pepper
95	70-85	65	Eggplant, Hot Pepper, Okra
*Adapted from Knott's Handbook for Vegetable Growers. Lorenz and Maynard. 1988. P 70.			

While the optimum cardinal temperature is an important factor to consider for optimum crop performance, temperature fluctuations are also significant. The best growth and development rates occur for all vegetable crops when temperature fluctuations remain within their cardinal temperature range. With tomatoes, for example, fluctuating daily temperatures between 70°F and 75°F are optimum for good plant growth, fruit set, and red color development. Fluctuating temperatures are most critical during blossoming. Temperatures below 60°F or above 80°F for any length of time during bloom can cause flowers to abort or drop even if they are pollinated. Once fruit set has occurred, higher temperatures are not as harmful.

High tunnel growers should try to maintain tunnel temperatures as close to the cardinal maximum and minimum as possible but realize that it may not always happen. During warm days, temperatures can rise well over 90°F during the late morning or early afternoon in the high tunnels. Ideally, night temperatures should not drop below 60°F but many Minnesota nights are not that warm. Fluctuating temperatures are not a problem during Minnesota summers. The biggest concern will be to maintain the temperatures above the minimum cardinal temperature, especially during blossoming and fruit set.

Tables 3 and 4 compare the average monthly maximums and minimums both inside and outside of the high tunnels during the 2003 and 2004 growing seasons at NCROC. Appendix 1 provides the daily temperatures inside and outside of the high tunnels for the 2003 and 2004 growing seasons.

The 2003 field-growing season (Table 3) averaged 61.0°F compared to 57.3° F (3.7°F greater) for the 2004 growing season. The maximum temperatures averaged 4.4°F greater in 2003 than in 2004, and the minimum temperatures averaged 3.0° F greater.

Table 3. 2003 Temperature and Growing Degree Day Comparisons – Grand Rapids, MN								
Date	High Tunnel				Outside Air			
	Max	Min	Avg	GDD	Max	Min	Avg	GDD
May 4-31	94.9	41.7	68.3	453	68.5	41.0	54.7	260
June	92.1	55.4	73.8	615	76.9	50.2	63.5	436
July	88.6	55.6	72.1	630	82.1	56.2	69.1	584
August	88.0	57.1	72.5	651	84.1	58.0	71.0	634
September	86.6	47.1	66.9	500	69.4	45.1	57.2	316
October 1-16	83.1	39.0	61.0	246	63.1	37.6	50.3	118
Average	88.9	49.3	69.1	3095	74.0	48.0	61.0	2348

Table 4. 2004 Temperature and Growing Degree Day Comparisons – Grand Rapids, MN								
Date	High Tunnel				Outside Air			
	Max	Min	Avg	GDD	Max	Min	Avg	GDD
May	88.2	43.3	65.8	502	61.4	36.4	48.9	184
June	90.0	51.4	70.7	568	73.4	46.9	60.2	366
July	90.4	57.1	73.7	624	78.4	53.9	66.2	505
August	86.3	52.3	69.3	544	72.1	48.4	60.2	374
September	89.1	53.6	71.3	570	73.4	49.4	61.4	396
October 1-16	77.0	41.1	59.0	207	59.1	34.7	46.9	83
Average	86.8	49.8	68.3	3015	69.6	45.0	57.3	1908

Using tomatoes as an example, field production with tomatoes was above average in 2003 and much below average during the 2004-growing season. During the months of June, July and August when most of the growth occurs with tomatoes in the field, the 2003 growing season had average temperatures closer to the cardinal optimum temperatures than those occurring during the 2004 growing season. What about in the high tunnels? The 2003 growing-season average temperature was slightly warmer than the 2004 growing-season (0.8°F), with the average maximum temperature 2.1° F higher in 2003 and the average minimum temperature of 5°F lower in 2003. The average temperatures both years in the high tunnels during June, July, and August were optimum for tomato growth and development (72.8°F in 2003 and 71.2°F in 2004). The only way to improve the high tunnel temperature environment, at least for tomato production, would be to raise the minimum temperature averages to the minimum cardinal temperature for tomatoes.

The crucial question is how much warmer is the high tunnel environment compared to the outside field environment. For the 2003 growing season (Table 3), high tunnel temperatures averaged 8.1° F warmer than the outside air temperatures, with the maximum averaging 14.9°F warmer and the minimum averaging 1.3°F warmer. During the 2004 growing season, the high tunnel temperatures averaged 11.0° F warmer than the outside air, with the maximum averaging 17.2°F warmer and the minimum averaging 4.8°F warmer. The high tunnel temperature environment was dramatically better for warm season crop production both growing seasons; but in 2004 when field conditions were less than ideal, the high tunnel temperature environment created the difference between a good crop in the high tunnels and a poor crop in the field (Section 3 - Risk Management).

Another method of evaluating the effect of temperatures on growth is by using growing-degree-day (GDD) calculations. GDD calculations are used by the canning industry to determine optimum harvest times. They are also used by the Minnesota Department of Agriculture (MDA) to measure temperature variation from year to year and to compare different locations around the state in the same year. For example, during the 2003 growing season at Grand Rapids, MN, between May 1 and October 19, the MDA calculated there were 2441 GDD - 413 above average. For the 2004 growing season during the same time, the MDA GDD total was 1957 - 75 GDD below average.

For this project, the 50-86 method was used, the same one used for determining corn GDD calculations. In this system, if the actual minimum temperature for the day is below 50° F, it is listed as 50° F, the assumption being that no growth occurs at less than 50° F. If the actual maximum temperature for the day is above 86°F it is listed as 86°F, again assuming that no growth occurs at greater than 86°F. The individual GDD for each day is then calculated using the following formula:

$$\frac{[\text{Maximum (or 86 if over 86)} + \text{Minimum (or 50 if under 50)}]}{2} - 50 = \text{GDD}$$

The daily GDD were calculated and compared for both inside the high tunnel and for outside air during the 2003 and 2004 growing seasons. These daily calculations appear in Appendix 1. The monthly average accumulated GDD for each environment appears in Tables 3 and 4.

The average GDD for Grand Rapids, MN is about 2030 per season, which is comparatively low for Minnesota. During the 2003 growing season, 2348 GDD accumulated (Table 3), with well-above average GDD's occurring in June, July, and August. Field production of warm season crops was better than average. In contrast, the 2004 growing season accumulated 1908 GDD (Table 4), with July being the warmest month accumulating 505 GDD. During May, frost occurred on 13 different days. While NCROC escaped frost on August 20, much of the region suffered extensive frost damage. Field production of warm season crops was poor. If it had not been for the warmest September on record, field production would have been nearly zero. Market gardeners depending upon field production of warm season crops during the 2004 growing season had a disastrous year.

In contrast, the GDD accumulations in the high tunnels were much better both years than occurred in the field (Tables 3 and 4). A total accumulation of 500 GDD or more occurred during every month for both years between May and September (except May, 2003, when 453 GDD occurred). During the 2003 high tunnel growing season (Table 3), June, July, and August enjoyed 600-plus GDD accumulations, which enabled the plants to get off to a fast

start with excellent fruit set and early fruit harvest. While the 2004 high tunnel-growing season had 500 plus GDD accumulations from May through September, early fruit set, especially on tomatoes, may have been slightly reduced from the 2003 season. Based on evaluations for just these two seasons, it would appear that GDD accumulations of over 600 in June may enable the plants to get off to their best start as well as allow them to obtain optimum fruit set. Warm nights are most important in this regard.

Near the end of the growing season, good GDD accumulation occurred both years. In September, adequate heat units should have been available in the high tunnels to ripen developing fruit (over 500). Despite this fact, fruit ripening slowed, especially during the last half of September. Lower light levels are believed to be the main reason for the reduced ripening that occurred.

Comparing the high tunnel environment with the outside air, two favorable factors of the high tunnel temperature environment are very apparent (Tables 3 and 4). First, the high tunnel GDD accumulations are much higher both years, averaging 3055 GDD for the 2003 and 2004 seasons. GDD accumulations in the field averaged 2128 GDD for the two summers. On average, that is 927 GDD or 43% more heat units in the high tunnel than in the field. The second dramatic difference is that, when comparing the two seasons, there was a 440 GDD or a 23% difference in the outside air GDD between the 2003 and 2004 growing seasons. This difference to a grower was the difference between a better-than-average crop in 2003 and near crop failure in 2004. In contrast, the difference in GDD accumulation in the high tunnels between 2003 and 2004 was 80 GDD or less than 3%. Good crop production was obtained both years in the high tunnels. The uniformity of temperature in the high tunnels means that a grower can expect a good crop. At the very least, the prospects for obtaining a good crop are much better than under field conditions. For both seasons in the high tunnels, the GDD was 43% higher than the outside environment and the variation was less than 3%. These two factors alone show the very dramatic advantage of the high tunnel temperature environment. Since day length is rapidly increasing in April, when can a grower plant in the high tunnel environment? Table 5 compares temperatures and GDD accumulation during the first half and last half of April 2004, at Grand Rapids, MN.

Table 5. April 2004 Temperature and growing Degree Day Comparisons – Grand Rapids, MN								
	High Tunnel				Outside Air			
	Max	Min	Avg	GDD	Max	Min	Avg	GDD
April 1-15	78.2	30.9	54.5	200	52.3	25.5	38.9	41
April 16-30	89.4	37.5	63.4	236	57.1	30.8	44.0	58
April Average	83.8	34.2	59.0	436	54.7	28.1	41.4	99
*Frost protection heat turned on in high tunnel 4/26/04.								

As Table 5 shows, the high tunnel environment averages 17.6°F warmer than the outside air (59.0°F compared to 41.4°F). The minimum temperature average was 6.1 of warmer in the high tunnel than the outside air (34.2°F compared to 28.1°F). The average maximum temperature (83.8°F) in the high tunnel is warm enough to support warm season crop growth, but the average minimum temperature is still cool (34.2°F). The average minimum temperatures did increase dramatically during the last half of April (30.9°F compared to 37.5°F). Based on this experience in northern Minnesota, high tunnel planting in early April should be limited to cool season crops that can withstand some frost. Warm season crops should not be planted before mid-April and then only if there is good frost protection available.

Even though, by definition, a high tunnel has no heat, under Minnesota conditions, growers need to have some means of frost protection in the early spring and fall, especially in northern Minnesota. In May of 2003 at NCROC, no frost events occurred after May 3; however, in May 2004, 13 frost events occurred during the month with the last one on May 28 (see Appendix 1). In the spring of 2003, freeze covers provided frost protection in one of our tunnels. In 2004, a portable propane heater was used. These heaters can be thermostatically controlled, are easy to use, and, most importantly they are dependable and effective. Figures 1 and 2 show both methods of frost protection.



Figure 1. Propane heater



Figure 2. Frost covers over strawberries

2003 was the first experience using freeze covers in high tunnels for frost protection. The differences that occurred outside and inside the tunnel as well as under freeze covers were evaluated. Table 6 shows the maximum and minimum average and range of temperatures that occurred under each condition between May 4 and May 25, 2003. The biggest difference was in the maximum temperature range among the three environments. The critical difference for frost protection was in the minimum (range) temperature column.

Table 6. Temperature Comparisons May 4-25, 2003 – Grand Rapids, MN		
Location	Maximum (Range)	Minimum (Range)
Outside Air	66.4 (79-45)	40.9 (50-33)
In High Tunnel	93.1 (120-55)	41.3 (51-33)
Under Freeze Cover	100.8 (128-64)	48.0 (59-39)

There was very little difference between the outside and high tunnel minimum temperatures (40.9°F outside compared to 41.3°F in the high tunnel). The freeze cover averaged 48.0°F, offering 7.1 of temperature protection over the outside air temperature and a 6.7°F advantage in the high tunnel with and without the cover. In Table 7 the value of freeze covers was evaluated on specific nights when the temperatures were coolest. Even though no frost occurred during these nights, the dramatic effect of the freeze covers can be seen.

Table 7. Value of Freeze Cover (Minimum Temperature °F)			
Date	Under Freeze Cover	In High Tunnel	Outside Air
5/8/03	49	45	43
5/15/03	46	38	37
5/21/03	46	38	36
5/23/03	45	36	35
5/24/03	47	40	38
Average	47	39	38

Freeze covers offered 8°F to 9°F of protection over outside air and the hightunnel minimum temperatures. The high tunnel environment itself surprisingly only provided a 1°F advantage over the outside air. This means that growers should not depend on the high tunnel alone to provide much frost protection advantage over outside air temperatures. High tunnels will need to have some frost protection system available in the spring. In some respects, it is surprising that the high tunnels do not provide more protection. The large quantity of incoming heat absorbed by the soil during a sunny day should allow the soil to act as a heat reservoir at night. It does not seem to do that. On the other hand, use of the freeze cover probably holds that soil heat in and prevents its escape to the air, accounting for the 8°F higher temperatures that occurred under the covers. This difference is dramatic. The downside of using freeze covers is that they have to be put on and removed each day, and some type of framework may have to be built for them. This framework can interfere with other operations in the high tunnel itself.

This chapter has covered several aspects of the high tunnel environment and compared the tunnel environment with the outside air. The advantages of high tunnels in terms of modified temperatures accounts for their dramatic advantage in the production of warm season crops in Minnesota.

The High Tunnel Environment - Wind

David Wildung and Pat Johnson, University of Minnesota

High tunnels provide excellent protection from winds and storms. These conditions often create driving rain and hail, which can seriously damage similar crops growing in the field. This protection alone will increase the potential for greater crop production in high tunnels. Because high tunnels can be easily opened or closed, a grower can decide how much wind goes through the tunnel. Tunnels definitely should be shut down during strong storms. With the cultural systems used in a high tunnel, such as raised beds and trellising, even moderate winds can damage plants by blowing them over or snapping them off at the base. At NCROC pepper plants without support have been blown over and should have been staked shortly after transplanting.

Light air or wind movement through the high tunnel is desirable. It will help remove humidity and cool the high tunnel, especially on hot sunny mornings in the summer when temperatures rise rapidly after sunrise. The ventilation provided by a light gentle wind through the tunnel will help dry foliage, reducing the potential for disease infection. Light wind is also important in the high tunnel to assist in pollination. Gentle movement of the plants by the wind moving through the tunnel will improve pollination, especially with tomatoes and cucumbers. Trellised plants react especially well to this movement by the wind.

The High Tunnel Environment - Ventilation

Larry Jacobson, Department of Bioproducts and Biosystems Engineering, University of Minnesota

Ventilation is essential to success with high tunnel production. Air in unventilated tunnels will be too hot, too moist, too still, and too low in carbon dioxide for good plant growth.

Temperature Management

During the growing season, temperatures inside a high tunnel are nearly always warmer than outside. On warm bright days, inside temperatures may be too high for optimal plant growth. In extreme circumstances, outright plant death can occur. Temperature management is the primary goal of all ventilation systems.

Temperature (°F)			Crop
Maximum	Optimum	Minimum	
85	55-75	45	Onion, Garlic
75	60-65	40	Beet, Broccoli, Cabbage, Chard, Radish
75	60-65	45	Carrot, Lettuce, Pea, Potato Snap Bean, Lima Bean
80	60-70	50	
90	65-75	60	Cucumber
80	70-75	65	Tomato, Sweet Pepper
95	70-85	65	Eggplant, Hot Pepper, Okra

*Adapted from Knott's Handbook for Vegetable Growers. Lorenz and Maynard. 1988. P 70.

Moisture Management

As air is heated, it expands, increasing its capacity to hold moisture. Every 18 degree (Fahrenheit) temperature increase *doubles* the moisture-holding capacity of air. The humidity level inside a tunnel is typically significantly higher than outside.

Many plant diseases thrive in warm, moist, still air, making ventilation very important for plant health. Fresh air, cooler and dryer than the air in tunnel, must be brought in to keep plant pathogens from flourishing.

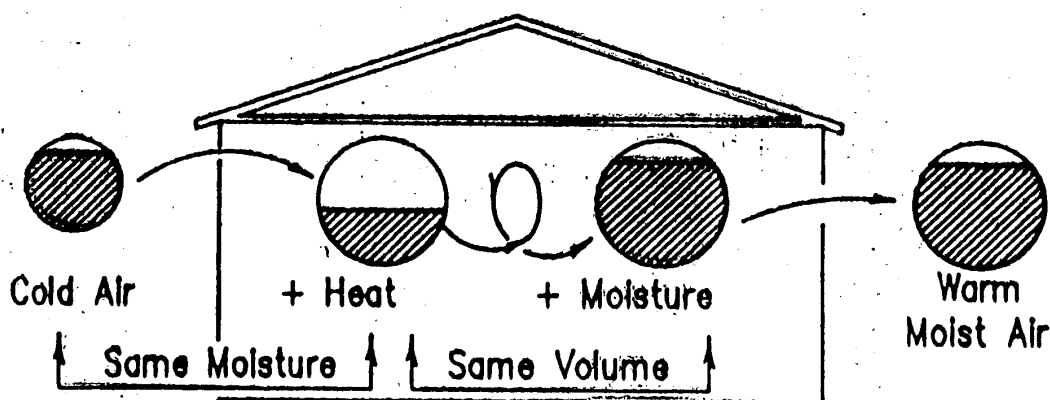


Figure 1. Air expands as it is heated and can absorb more moisture.

Air Movement

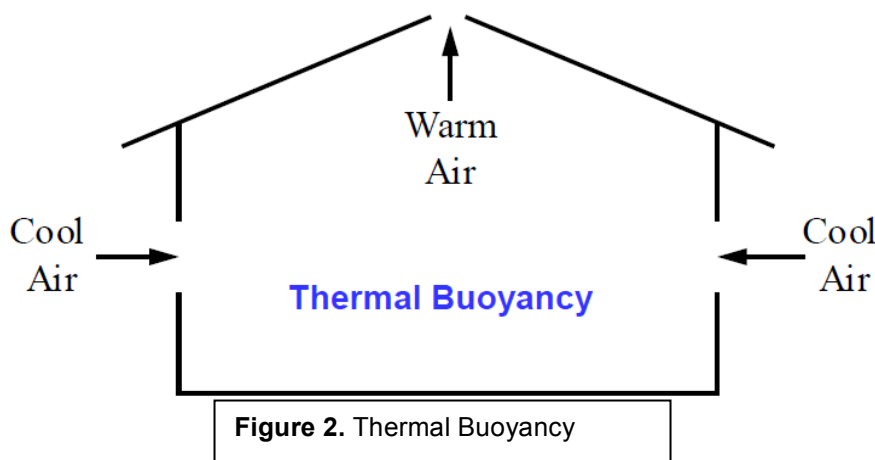
Even if air inside a high tunnel could be kept at an ideal temperature and humidity level without ventilation, plants perform better when air moves across their leaves. Stems are stronger and stouter. Photosynthesis is optimized as oxygen is carried away from leaves and carbon dioxide is made available. Transpiration from leaves is increased, moving water and nutrients through the plant.

Carbon Dioxide Levels

In warm, bright conditions, tomato plants, as an example, are limited in growth by the amount of available carbon dioxide in the air. While supplementing carbon dioxide in a high tunnel is not economically feasible, one of the goals of a ventilation regime must be to keep fresh, carbon dioxide-rich air moving into the tunnel.

NATURAL VENTILATION

Natural ventilation will occur if the tunnel has well-placed air inlets and outlets. Warm air is lighter than cold air, so it will rise towards the roof of the tunnel. This phenomenon is called “thermal buoyancy.” If there are vents close to the high points of the end walls, warm air will naturally flow out. Vents may also be placed on the roof of the tunnel.



Cool, fresh air must be able to enter the tunnel. Usually air inlets are at the sides of the tunnel. When sides are rolled up even slightly, cool air close to the ground will flow into the tunnel to replace the warm air exiting at the high vents.

Wind is abundant in most of Minnesota, most of the year. Wind will assist in pulling the warm air out of the tunnel and driving the cooler air in.

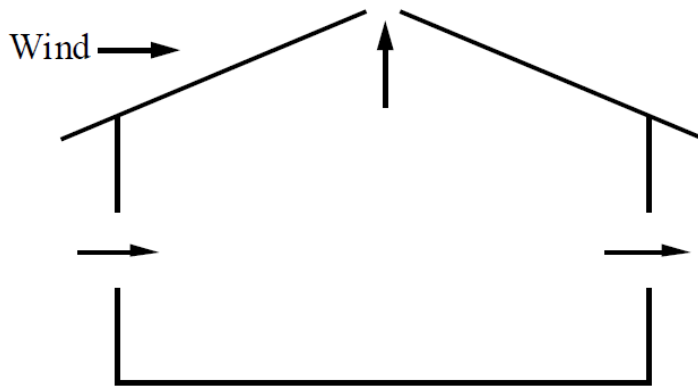


Figure 3. Natural Ventilation – Wind Driven

When using natural ventilation, it's important to monitor the temperature in the tunnel, opening the vents and inlets as the temperature rises, and closing them as the temperature falls.

On hot, humid, still days in summer, natural ventilation may not be adequate for optimal growth.



Figure 4. Natural Ventilation – Inlets and Outlets



Figure 5. Inlet



Figure 7. Ridge type outlet



Figure 6. Outlet

MECHANICAL VENTILATION

Many high tunnel systems use no electricity. For these systems, natural ventilation is the only option, and it is certainly the less expensive option.

Some growers choose to install electricity so that they can use fans. The fans should be set up to exhaust warm, moist air from the tunnel, producing negative pressure within the tunnel, and drawing fresh air in.

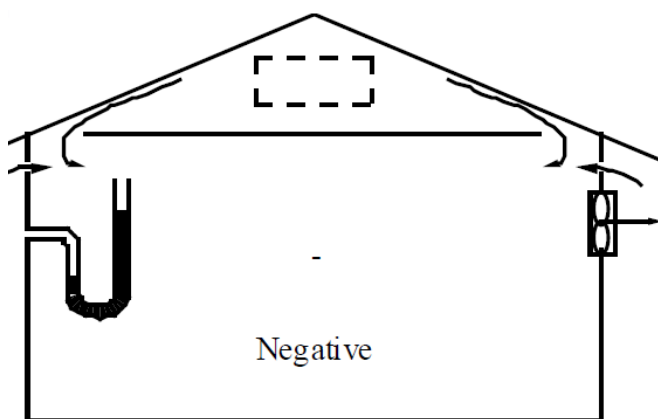


Figure 8. Mechanical Ventilation – Negative Pressure

The simplest fan systems are manually operated. Growers monitor temperatures and turn the system on when necessary. More complex systems use remote-read thermometers and thermostatically-controlled vents. These systems will be most appropriate for high-value crops, and for growers with more area under tunnels, so that the initial cost of the system can be spread over a larger operation.



Figure 9. Manual roll up of sidewalls



Figure 10. Automated temperature sensor and inlet controller

For any mechanically-vented systems to work properly, the tunnel must be fairly “tight.” Seal up corners where sidewalls meet end walls. This will prevent air leaks, so that the fan can produce the negative pressure necessary to pull a steady flow of air through the tunnel. Sealing these corners will also prevent the wind from grabbing and tearing the plastic, and will make it easier for humans or mechanisms to roll up the sidewalls.



Figure 11. Before plastic was attached



Figure 12. After plastic was attached

Crop Layout & Planting Methods

David Wildung and Pat Johnson, University of Minnesota



Figure 1. Multiple crops in one high tunnel

The layout and planting methods used in high tunnels are more critical than in the field because the smaller area of the high tunnel is so much more intensely managed. The plants are spaced more closely and maintained more highly than in the field. The expectations for higher productivity are greater. Adapting layout and planting methods to accommodate these differences is important to success. At the same time, the principles of high tunnel layout are similar to those used in the field.

Tunnel layout really begins when a crop is removed in the fall. All old plant debris should be removed from the tunnel. Old plants can harbor insects and disease and should be removed and discarded. All trellis posts, wire, string, plant clasps, and hooks should be removed and discarded or, alternatively, should be sterilized with disinfectant if they will be used again. If ground-cover plastic and trickle irrigation tube were used, they too should be pulled up and discarded. Before the ground freezes in the fall, the area in the high tunnel should be worked up and any desired organic matter should be added. Finally, soil tests should be taken so that the nutrient status can be monitored and corrected, if necessary, early the following spring.

Pre-irrigation is the next step in the layout process. In the spring of 2004, it was surprising how dry the soil inside the high tunnel had become over the winter. Because the covering plastic was left on our high tunnels, the soil received no water from snowmelt, rain, or irrigation since the previous fall. The soil needed a heavy irrigation to bring it up to field capacity. This was done as soon as the soil had thawed and would absorb irrigation water. Sprinklers were used, but solid set irrigation is another good alternative.

Once the soil is at field capacity, it can be worked again to incorporate organic matter. At that time, all necessary solid fertilizer and lime should be added to the soil. One thing to remember when working with high tunnels is that they will warm up much more quickly than field plots. Even in northern Minnesota, some operations can be done in the high tunnels in late March. This would be unheard of in the field!

After the soil preparation process is completed, row spacing should be determined. The row spacing used depends on the management of the crop, the crop grown, and the width of the tunnel. Small seeded vegetables, like carrots, beets, or radishes, don't need much room and can be grown in multiple rows to use space more efficiently. Larger seeded vegetables, such as snap beans or sugar snap peas, may need to be trellised. These crops can be planted in double rows with a trellis wire in between for the plants to climb on. The row spacing for transplanted warm-season crops, like tomatoes, cucumbers or peppers, depends on several factors. These include whether or not trellising will be done, how much trellising and pruning will be done, and whether determinate or indeterminate cultivars will

be grown. Certainly, tomatoes can be grown in traditional ground beds with no pruning or trellising, and several high tunnel growers in Minnesota have been successful with this system. If a ground bed system is chosen, ample spacing between rows is necessary to allow ease of work and movement. Because of favorable growing conditions, growth and row closure will occur faster in a high tunnel than in the field; therefore, high tunnel row spacing should be at least as great as, and perhaps greater than, traditional field row spacing. If intense management with trellising and pruning is planned, the row spacing can be closer. For example, 4.0 to 4.5 feet between trellised tomato, cucumber or pepper rows has been found to be enough space for good production. At NCROC, pruning and trellising have been used extensively. The high tunnels are 21 feet wide with five rows spaced 4.2 feet apart. This spacing was most efficient in terms of the area used, while still providing sufficient room for crop growth, maintenance, and harvest.



Figure 2. Measuring planting bed



Figure 3. Smoothing planting surface

With the row spacing determined, the next decisions are whether or not to use raised beds and whether or not the beds should be covered. The soil can be left as it was tilled with no beds formed or it can be formed into raised beds with or without plastic. The decisions to use beds or plastic are often personal preference.



Figure 4. Direct seeded crop with trickle irrigation

At NCROC, neither beds nor plastic for direct seeded vegetables were used. Not creating beds for these crops was done because the water distribution and growth patterns were more uniform when using multiple rows and trickle irrigation without beds. Water from trickle irrigation tubing on raised beds had a tendency to run off the sides of the beds making the wetting pattern less uniform with multiple rows. In addition, with multiple rows root growth and development were more uniform without the rounded shape of the beds.

Plastic was not used with direct-seeded crops because most are cool-season crops and are used as filler crops before the main crop is planted. With warm-season transplants, raised beds, trickle irrigation, and black plastic were used. For these long-season crops, the raised

beds and trickle irrigation provided more uniform water and fertilizer distribution, leading to better root growth. The black plastic helped hold in moisture, warmed the soil, and enhanced weed control in and around the growing plant. While other systems certainly can be used, the results from this approach in our tunnels have worked well.

The height and width of the beds are another important consideration. Beds do not have to be more than two to three inches high and no more than 14 to 18 inches wide at the base. Larger beds can interfere with water distribution or with foot traffic while working inside the tunnel. Placement of the irrigation tubing in the beds is important for uniform water distribution. In 2003, we laid the trickle tube in the middle, on the top of the bed. In some cases, the tubing moved slightly. When the water distribution pattern was checked in the fall, we found that the water pattern was not always in the center of the bed. During the 2004 season, this was corrected by creating a shallow furrow less than one-inch square down the center of the bed. The trickle tube was laid in the furrow. This furrow was easy to make and stabilized the placement of the trickle tube, allowing for more uniform water distribution.



Figure 5. Creating furrow for irrigation tube



Figure 6. Burying irrigation tube



Figure 7. Planting beds covered in black plastic

Once the trickle tube is laid, the plastic can be tightly stretched across the bed and the edges buried. For beds of this size, three-foot wide plastic is adequate to cover the beds. These operations can all be done as soon as the ground is workable and all necessary soil preparation has been done. Then the beds can be left until planting time.

Plant placement is the next aspect of tunnel layout that affects both plant development and crop management. Transplants used in high tunnels should be large, vigorous, actively growing, and of top quality. When planted, the transplants should be very slightly offset from the trickle tube but as close as possible to it. This will enable the developing root system to receive the maximum amount of water. Alternating the plants on either side of the trickle tube, planting one on one side and the next one on the other side of the tube, allows the best use of space.

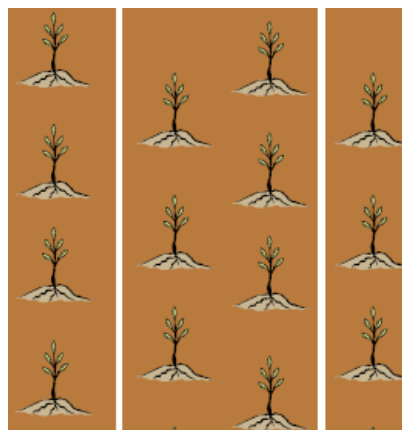


Figure 8. Graphic showing alternate plant spacing



Figure 9. Transplants in plastic

The spacing within the row can vary with the crop. Plants also need to be placed so that workers can move easily in and out of the high tunnel to maintain the crop and to harvest it once it is ripe. Outside rows of the tunnel usually can be planted from gable end to gable end; however, a minimum of two feet of space should remain unplanted at the gable ends of inside rows, especially in front of the doors. This allows room for the more vigorous plant growth in the tunnel and permits easier movement in, out and around the tunnel.

High Tunnel Trellising

Jerry Wright, Terry Nennich, Dave Wildung, and Larry Zilliox University of Minnesota, and Norm Krause, Central Lakes College



Figure 1. Plants tied to a trellis

One of the goals of high tunnel fruit and vegetable production is maximizing production space in the tunnel. Trellising allows you to grow plants vertically producing more fruit or vegetables per square foot. Another advantage is keeping the fruit off the ground reducing chances of soil born diseases, damage by ground dwelling pest and allowing for clean fruit. A final advantage is harvest is easier requiring less bending to harvest the crop.

There are many options for supporting plants. There are advantages and disadvantages of each type of support and for each crop. As an example, raspberries usually are trellised on double-armed T's with a twine or light wire strung between the posts providing adequate support for the canes.

Tomatoes or cucumbers have a number of options for keeping the plants off the ground. The tomato cage, a very common method for the home gardener, becomes too expensive and time consuming in the high tunnel. In addition cages normally are spaced three feet apart limiting the number of plants in the hoop house.



Figure 2. Staked tomato plants

Tomato plants are either a determinate and indeterminate variety based on their growth habit. Determinate varieties grow to a determined height and are heavily branched producing flower clusters at the end of the branch. Generally very little pruning is done on the plant. They are often short season varieties and have a concentrated production season. Determinate varieties are very suitable for staking but the labor of tying stems can be a challenge. Use stakes that are 4-5 feet long and are at least 1 inch square.

Drive the stake a foot deep into the ground to support the plant. Plants are generally set two feet apart in the row with this system. A disadvantage of this system is the labor to place all of the stakes in the ground and to remove them after the crop is harvested.

Indeterminate tomato varieties continue to grow though out the season and are very suited to trellising. Trellised tomatoes can be heavily pruned and planted about 2 feet apart, but the

weight of the plant and fruit can be a problem without special support. One should never hang a trellis system from the roof truss of the high tunnel as the weight can easily bend the high tunnel frame and end walls.



Figure 3. Florida weave used with tomato transplants

One trellising method uses a similar wooden or steel post sunk into the ground, with several strings strung at six to twelve inch spacing. This system known as the “Florida weave” is a compromise between staking and caging being less time consuming than staking and less expensive than the cage system. This system is commonly used with less vigorous growing plants or determinate tomato varieties. As the plant grows, it is pulled up through the twine and allowed to hang there.

Again, it can be a problem in tilling the ground especially with larger equipment. Some individuals raise the bottom wire so that a roto-tiller can till the soil under the trellis for the following year. Again, labor of installing and removing post can be a time consuming and labor intensive.



Figure 4. Sagging Wire

Another method of trellising is to place a 9 foot post about 2 feet in the ground every 6-8 feet. Wire is strung between the posts and a heavy twine is tied above each plant. As the plant grows, it is tied to the twine for support. The problem with this single wire system is that the top wire sags from the weight of the plants as they grow. Some people have used barbwire to prevent the twine from sliding towards the sag on the wire. Other problems occur as the end posts need to be anchored well and the posts need to be removed before tilling the soil in the high tunnel.



Figure 5. Framed trellis system

A framed trellis system was developed at the Staples Ag Center and has been used successfully for three seasons. Once constructed it can be used for many years and is easily assembled or taken apart when working the soil in the high tunnel. This wood trellis can be made in any dimension to meet the needs in your high tunnel. The dimensions given in our example are for a trellis that fits in a twenty one foot wide high tunnel to support 3 rows of crops.

Cost estimates shown in the example at the end of this article are based on known prices in late 2007. In all of our high tunnels, we have used non-treated wood. This design is strong enough to support 4-7 tomato or cucumber plants per 8 foot section while allowing room to move around the plants. This system will maximize the growing area in the high tunnel and with optional side extensions allow two more rows of high value crop to be grown.

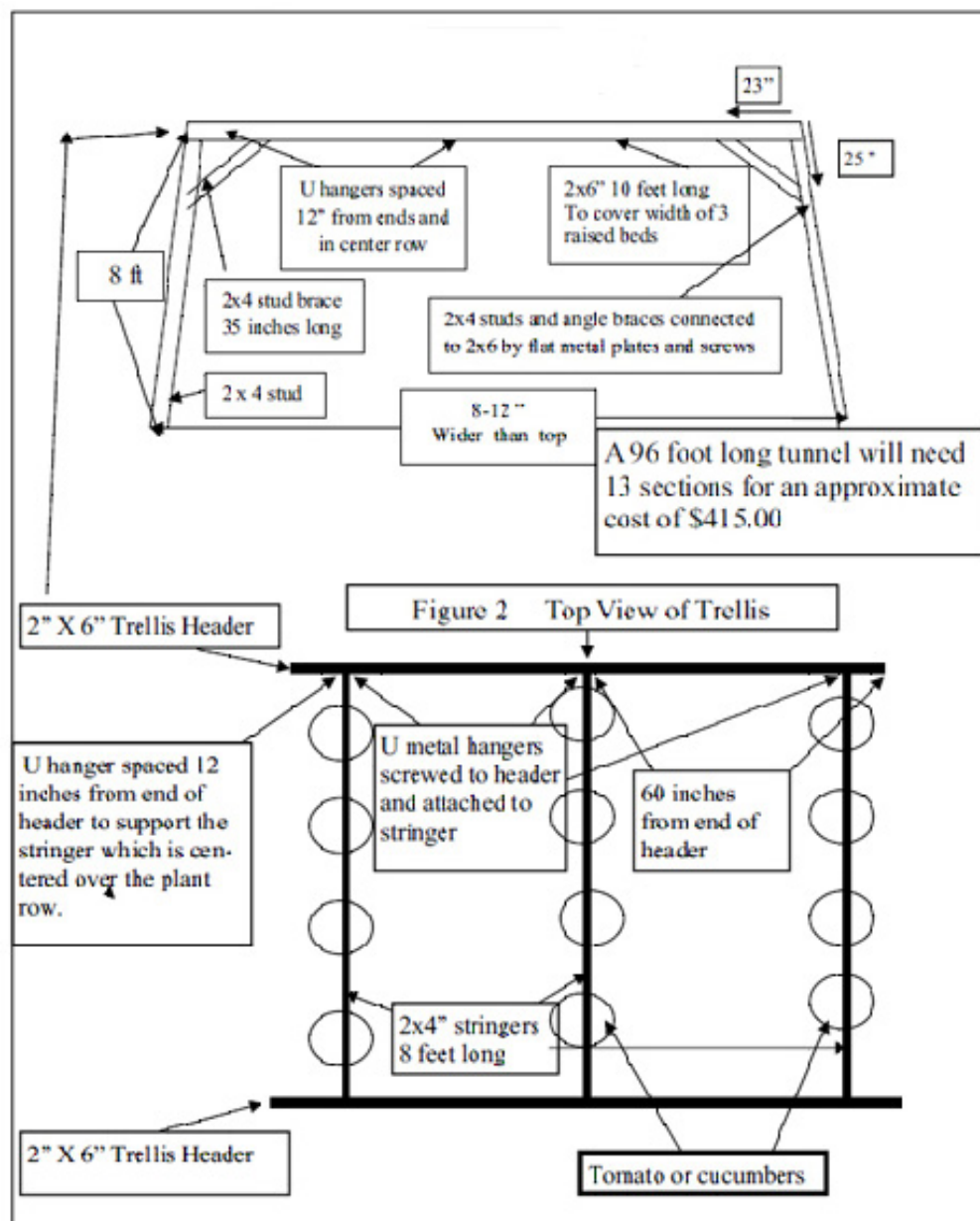


Figure 6. Front view of trellis



Figure 7. Joist U hanger using square headed screws for easy removal in fall. Mark 2X4 if you use a pin system so that stringer is used in same spot



Figure 8. Bed formation and drip tape are easily laid prior to erection of trellis



Figure 9. Ready for planting –note the string holder at the top clipped onto a screw that can be easily unwound to the lower plant 6-12" to maintain workable harvesting height.



Figure 10. Crop tied to twine using plastic ties



Figure 11. Optional extension adds an additional row to each side of mainframe



Figure 12. In full production with each plant holding 20-30 fruit in various stages

Material List Per Trellis Section

6- 2 x 4 x 8 @ \$3.30 =	\$19.80
1-2 x 6 x 10 @ \$7.00 =	\$7.00
6 U hangers @ \$0.80 =	\$4.80
12- 3 x 7 face plates @ \$0.75 =	\$9.00
Screws	\$1.50
Total	\$42.10

Materials for Optional Side Row Extensions

2- 2 x 8' @ 3.30 =	\$6.60
Screws	\$0.50
Total	\$7.10

Irrigation Considerations and Soil Moisture Monitoring Tools

Jerry Wright, Dave Wildung, and Terry Nennich, University of Minnesota Extension Service



Soil moisture is generally the most limiting element in maintaining uniform plant growth and high quality produce within a high tunnel system. A full-season crop like tomatoes, peppers or cucumbers may require 15 or more inches of drip irrigation water to meet the crop's daily water usage requirements throughout the season. To operate a drip irrigation system effectively and achieve high quality yield within a high tunnel system, a daily assessment of the soil moisture within the root zone is needed.

Irrigation systems should be designed and managed to assist a producer from planting through harvest. Too much water can reduce soil aeration and cause as much trouble as not having enough water, especially during critical growth periods like pollination and fruit development. An Extension Horticulturalist from Texas A&M University points out that even small amounts of water deficiency during certain stages can be

detrimental to the plants. This deficiency can occur even before visible wilting occurs. He also mentions that even slight water deficiencies can cause slowed growth rate, lighter weight fruit and, in tomato, blossom end rot. Sanders from North Carolina likewise states that when soil moisture is allowed to drop below the proper level, the fruit does not expand to produce maximum size before it ripens, thus reducing yield and, if moisture is allowed to fluctuate too much, blossom end rot can occur and fruit is no longer useable.

The frequency of irrigation depends on many factors and can vary from once every five to ten days during the early weeks of growth to every day or two during fruit sizing and ripening. Soil water can be taken up by a plant and evaporated into the tunnel atmosphere at a rate of 0.05 inches to over 0.30 inches per day. This process is called evapotranspiration and is the combination of soil surface evaporation and water loss from the plant leaves by transpiration. The water evaporated in this process is often referred to as daily ET or crop water use.

The actual amount of water evaporated each day by a plant is very dependent on the plant's canopy size, stage of growth, tunnel air temperature and intensity of sunlight (solar radiation). Hence, daily ET variation prohibits irrigating on a set frequency and supports the need for regular in-field soil water monitoring for effective water management. Granberry from the University of Georgia Extension Service states that proper irrigation scheduling is absolutely necessary if quality, yields and profitability are to be optimized and that irrigation scheduling becomes even more critical when drip irrigation is used in conjunction with plastic mulch and fertigation.

Establishing a water management plan for each crop is essential for maintaining a regular, consistent supply of soil water to 1) optimize an irrigated crop's growth, 2) enhance and protect the produce quality; 3) reduce seasonal growth and yield variability and 4) increase the chance for sustained profitability.

The intent of this chapter is to highlight the basic irrigation water management factors and tools that an operator should understand and implement during set-up of the irrigation systems as well as throughout the growing season. Also, we highly recommend that a new operator review as many as possible of the excellent web based publications from other states on how to manage an irrigation system for vegetable crops. Many of these are listed in the reference section at the end of this chapter.

IRRIGATION WATERING STRATEGIES

Deciding when to irrigate in a tunnel system is a daily decision that requires consideration of several factors by the operator. During the initial set-up, one should become very familiar with the soil profile and the drip irrigation system's average water application rate (inches per hour). In the soil profile, one should learn about the soil texture within the tunnel rows, the soil's available water holding capacity (AWC) in the top 12 to 18 inches, any potential root restricting layers, any soil drainage limitations and the optimum soil moisture levels for each crop.

During the growing season the operator needs to understand and assess the current soil moisture status in each plant row and how the different stages of plant growth, plant size and daily weather conditions, especially temperature and intensity of sunlight (solar radiation), affect the plant's daily crop water usage (ET).

Regular in-field assessment and past experience must both be used to make timely irrigation decisions. Most horticultural crops respond best to a uniformly moist soil profile. Wide fluctuations from wet to dry soil conditions generally will cause yield loss as well as reduced quality of the produce. Especially important is maintaining adequate soil water content during pollination and fruit development right up to harvest.

Sanders from North Carolina State University points out that with tomatoes, if soil moisture is allowed to fluctuate too much, blossom end rot can occur and fruit is no longer useable and that during fruit expansion stage, fruit cracking can occur if too much soil moisture fluctuation is allowed to occur.

The amount of soil water available to a plant and capable of being held within the soil profile is a function of both plant's potential rooting zone and the soil texture and organic content within the profile. Table 1 lists the typical soil water holding capacity ranges for several soil texture series (usually expressed in inches of water per inch of soil). For a typical sandy loam soil found in central Minnesota, the top foot of the soil profile might expect the soil profile to hold between 1.0 and 1.8 inches of water. These values are greatly affected by the actual organic matter content. Using data from the published county soil survey report or contacting your local SWCD office may help to identify a more accurate estimate of the soil texture and water capacity in the profile.

Most irrigated vegetable crops develop a relatively shallow rooting depth compared to dryland plants. Likewise for most vegetable crops the majority of the roots will be generally

found no deeper than 10 to 12 inches and, for some crops like onions, the depth might only be six inches. These depths are normally achieved within 30 to 40 days from planting.



To verify the actual rooting potential, a good practice especially during the first year or two of operation would be to investigate the actual rooting depth 30 to 50 days after planting. This can be done rather quickly by digging alongside one or two plants to physically observe where the majority of the roots are located in the soil profile. This type of investigation can also very quickly identify if there is also some type of rooting restriction that has been caused by the selected tillage action. It can also identify any natural barriers, such as layers of very coarse sand and gravel, which will prevent future root penetration. If the rooting depth is much shallower than anticipated, the amount of water being applied per irrigation should be adjusted to avoid over irrigating.

Table 1. Ranges in Available Water Capacity for Soil Textures		
Soil Texture	Inches of water/inch of soil	In. water/ ft of soil
Coarse Sand	0.02-0.04	0.24-0.48
Fine Sand	0.05-0.08	0.60-0.96
Loamy Sand	0.07-0.12	0.84-1.44
Sandy Loam	0.08-0.15	0.96-1.80
Loam-Clay	0.14-0.20	1.68-2.40

Research literature is limited in identifying optimum soil moisture levels for most horticultural crops. Minnesota experiences and review of other states' Extension bulletins suggest that soil moisture in the top foot should be maintained during the plant's critical periods especially at between 60 and 100% of the soil's available water holding capacity. This is especially critical during pollination and fruit development in order to achieve optimum growth. (Sanders. 1997. Vegetable Crop Irrigation – North Carolina State University and Kemble, 2000. Basics of Vegetable Crop Irrigation. Alabama Cooperative Extension Service).

This soil moisture operating range is also commonly expressed as either a percentage of soil water depletion (0 to 40%) or as a range of soil water tension values (such as 10 to 35 centibars (cbs.)). This range provides a very workable soil moisture level for maintaining most drip irrigated vegetable crops on soils with fine sandy loam to a sandy loam texture.

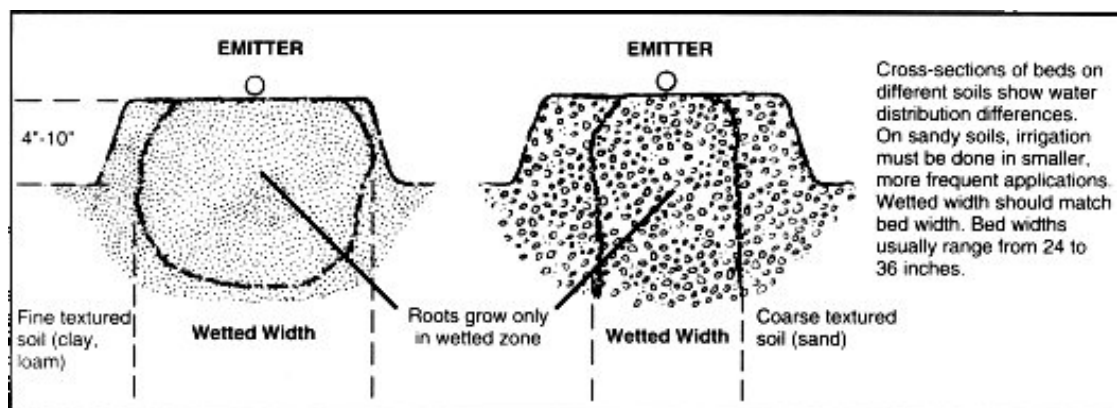
Table 2 lists soil water deficit estimates for several soil textures at different soil tensions based on actual Minnesota soil evaluations. For example, if a sensor positioned at the six-inch depth in a sandy loam soil reads 50 cbs, the table suggests that the soil is 0.7 inches depleted in the one-foot soil profile. This means that this site can hold 0.7" of additional water to return the tension back to 10 centibars or less, which is called at field capacity or full. If the reading was at only 30 cbs, the soil could only hold around 0.5 inches of additional water. The 0.5-inch deficit for the sandy loam soil could also be referred to as being 30% depleted ($0.5/1.7 \times 100\%$) and likewise the 0.7-inch deficit reading would be equivalent to around 40% depletion ($0.7/1.7 \times 100$) assuming 1.7 inches is the AWC of one-foot of soil.

Table 2. Soil Tension Versus Soil Water Deficity – Inches Per Foot						
	Soil Tension - Centibars					
Soil Texture	10	30	50	70	100	1500*
Coarse	0.0	0.1	0.2	0.3	0.4	0.7
Fine Sand	0.0	0.3	0.4	0.6	0.7	1.1
Loamy Sand	0.0	0.4	0.5	0.8	0.9	1.4
Sandy Loam	0.0	0.5	0.7	0.9	1.0	1.7
Loam – Clay	0.0	0.2	0.5	0.8	1.0	2.4

**1500 centibars is permanent wilting point and this deficity value is equal to the soil's total available water holding capacity as represented in Table 2.*

The frequency of irrigation events is very dependent on the size of the plants, the sunlight intensity (solar radiation) and the ET rate at which soil water is removed by the plant. For the first few weeks after transplanting, the frequency of irrigation generally might only be once every 5 to 10 days.

Sanders from North Carolina points out that it is important for that the soil profile to be refilled with water at each irrigation. Frequent light irrigations during early growth may result in shallow root systems. Then, as the plants start to develop a larger canopy, the irrigation frequency may increase to once every day or every other day depending especially on the amount of sun intensity. This rate of irrigation may continue until late August and then be reduced as the day length decreases and the plant's leaves start to age.



Soil water can be taken up by a plant and evaporated into the tunnel atmosphere at ET rates of 0.05 inches to over 0.30 inches per day. The actual amount of water evaporated or ET each day by a plant is very dependent on the plant's canopy size, stage of plant growth, tunnel air temperature and intensity of sunlight (solar radiation). Hence, daily ET variation prohibits irrigating on a set frequency and supports the need for regular in-field soil water monitoring for effective water management.

For a full canopy row crop like tomatoes or peppers, daily water usage (ET) might be sustained for several days at 0.25 to 0.30 inches per day or even higher on very clear days. This is especially true during the long daylight hours in June and July (0.30" is *approximately equivalent to 5 - 40 gallons of water per 100 foot of plant row per day, dependent on the plant canopy width and density*).

Table 3 shows the range of water replacement needs for several different plant canopy widths and various ET rates. Scientists from Oregon State University suggest that during

peak: water use times in a greenhouse setting cucumbers and tomatoes may require 1 to 3 quarts of water per day depending on the plant size and daily weather conditions (Hemphill, 2004. Commercial Vegetable Production Guide for Field and Greenhouse Crops).

Table 3. Estimated Amount of Irrigation Water Needed (Gallons Needed per Day/100 feet of row) for Different Plant Canopy Widths and Daily ET Rates.

Plant Canopy Width	Daily Irrigation Needs in Gallons/Plant					
	Estimated Daily Plant ET Rates					
Feet	0.05	0.10	0.15	0.20	0.25	0.30
1	3	6	9	12	16	19
1.5	5	9	14	19	23	28
2	6	12	19	25	31	37
2.5	8	16	23	31	39	47

During the crop's critical growth periods, an irrigation event it should re-wet the upper rooting depth up to 90 to 100 percent of soil's water holding capacity. The actual amount of irrigation needed to return the soil to full (also called field capacity) is difficult to determine but can be estimated by using Table 3 and then refined as the season goes along. For example, if the deeper soil profile does not show a change within 24 hours after irrigation or, in fact becomes drier, the application depth or pumping time should be increased slightly during the next irrigation. On the other hand, if the deeper soil becomes too moist after irrigation, consider reducing the application amount by shortening the operating time a little. Applying too much water in the soil can be detrimental to plant growth and will increase the risks for leaching of some of the nitrogen from the rooting zone.

The frequency of irrigation applications can differ for each crop during the growing season and should be managed differently it at all possible. Every soil profile also acts differently; therefore continuous monitoring of the soil moisture response is needed. An operator needs to be open to readjusting the irrigation time and or frequency as necessary to meet the crop's water needs and to maintain soil water levels within the optimum range.

Several soil water-monitoring tools are available to assist an operator in irrigation scheduling. Soil moisture sensors like tensiometers or electric resistance blocks are the most highly recommended by the authors, as well as many other irrigation specialists. Detailed discussion on soil moisture sensor options and installation can be found later in this chapter.

Below are several water management tips that a first time operator especially should consider in the planning stage as well as during the growing season. These are based on the authors' field experiences with growers and with high tunnels at the University of Minnesota North Central Research and Outreach Center at Grand Rapids:

- Learn about the soil texture and profile characteristics of the soil resources within the high tunnel.
- Order an appropriate number of soil moisture sensors for each crop and tunnel unit well in advance of the planting season to have them ready for installation shortly after transplants are placed in the tunnel. Sensor options and installation instructions are given later in this chapter.

- Run the new drip irrigation system for at least two-hours shortly after spring tillage of the rows/beds and before plastic mulch and transplants are installed to observe how the applied irrigation water distributes itself within the soil profile. To observe the distribution, dig a cross section into the soil profile at 30, 60, 90 and 120 minutes intervals after the irrigation is started and visually observe the wetted area's width and depth movement over this time. This wetted area over the course of the growing season may change a little as the soil profile compacts slightly over time. This practice also serves at getting the soil bed moisture content ready for transplanting.
- After the plastic mulch and transplants have been installed, identify the locations where you would like to have several pairs of soil sensors and then install the sensors (see installation instructions near the end of the chapter).
- Establish a schedule for reading the soil sensors every 1 to 2 days and chart the readings into a graphic format by using a computer spreadsheet or utilize a sensor data logger to take the measurement. Presenting the readings in a graphic format makes it very easy to observe how fast the soil moisture changes over time and how much the reading changes after an irrigation event. Also record the length of time each irrigation event operates and the date for each event.
- Examine the root development of several plants 40 to 50 days after planting to observe how they are interacting within the soil profile and the irrigation zone.



Soil Water Moisture Monitoring Options

Several soil water-monitoring tools are available to assist in irrigation scheduling. These include soil probe, soil moisture sensors, and crop water use estimators. When using drip irrigation and plastic mulch, it is strongly encouraged by the authors and many others that one choose some type of in-soil moisture sensing device that can be placed for the whole season. These should be located at two or more sites in the tunnel and at least two depths in the soil profile at each site. Regardless of the tool selected to assist the manager, the soil moisture status of a drip irrigated crop needs regular monitoring. This should be done at least every other day, if not daily, to assist the irrigation manager in making irrigation decisions.

Soil probe or small shovel is the most commonly used device by conventional large-field irrigators to monitor the soil moisture level. Small soil samples are obtained at different depths and then their feel and appearance are compared to a descriptive chart to make an estimation of its moisture deficiency. Since this method requires frequent probing, it will become very destructive to any plastic mulching material over time and also could very easily cut the drip tubing if one does not remember to check its location before probing. Hence, this method is not recommended by the authors for conducting regular soil water monitoring on plastic mulched beds in a tunnel. This method, however, could be used to

periodically check how far the irrigation water is penetrating in other areas of the tunnel not monitored by a sensor. A chart describing the soil appearance at different moisture levels can be viewed in the University of Minnesota Extension Service bulletin *Irrigation Management Consideration for Sandy Soils* at <http://www.extension.umn.edu/distribution/cropsystems/DC1322.html>

Soil water sensors come in several designs that monitor the soil moisture by either measuring the soil water tension, electrical resistance, or soil capacitance to estimate the actual available water in the profile. Soil water tension is a soil water property, expressed in centibars (cbs) of suction pressure, which indicates the energy required by plant roots to extract water from soil particles. A soil tension reading of 10 cbs or less means that, for a sandy soil, the water holding capacity is full. As the soil's moisture content decreases because of plant root uptake, the soil water tension in the soil profile increases. Table 3 lists estimated soil water depletion amounts (inches per foot) for several soil textures at different soil water tensions that were obtained in the lab from some Minnesota soils.

Soil water tension is best monitored in the field by tensiometers or estimated indirectly by the use of electrical resistance sensors (blocks) that are placed in the soil profile at various depths. A tensiometer has a vacuum- pressure gauge mounted to the waterfilled tube to observe the soil tension measurement at any time. The unit requires the tube to be filled with water and serviced to remove any entrapped air before installation into the soil. The tensiometer is installed in the soil with the porous ceramic tip placed at the desired depth. As the soil dries, water is pulled out the tube and the vacuum gauge indicates the soil water tension at that moment. When the soil is re-wetted, the soil water tension is lowered and the tube takes back some lost water. (Smajstrla. 2002. Tensiometers for Soil Moisture Measurement and Irrigation Scheduling. University of Florida; Harrison. 1993. Irrigation Scheduling Methods. The University of Georgia).

Tensiometers come in several lengths, such as 6, 12, 18 inches and longer. A 6 and 12-inch tensiometer would make an excellent pair of sensors at a given site. Tensiometers can be used many years if properly cared for at the end of each season.



Electrical resistance sensors consist of a formed block (3/4 inch in diameter and 1 to 2 inches long) that contains a water absorption material like sand or gypsum in which electrodes to measure the electrical conductivity of the solution are embedded. Electrical resistance between the electrodes varies with the soil water content, and this has been related to soil water tension. Gypsum based blocks generally will only last for one year while other sensors made with a more durable sandy material can be used for many years. (Thomson. 1996. Using Soil Moisture

Sensors for Making Irrigation Management Decisions. Virginia Cooperative Extension; Shock. 1998. Instrumentation for Soil Moisture Determination. Oregon State University)

Electrical sensors are read by a portable monitoring meter that is manually connected to each sensor each time it needs to be read. Alternatively, a small data logger could be used to monitor 4 to 8 sensors two or times a day and save the operator much time each day.

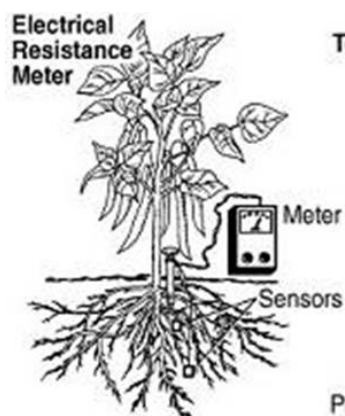
Resistance sensors generally work in a much wider range of soil textures and soil water tensions than tensiometers. Some sensor types like the Watermark granular matrix sensor

operate as well as a tensiometer in sandy textured soils and are more often preferred by users and the authors because of their ease of installation.

Tensiometers can cost between \$50 and \$75 dollars each depending on the length of tube. A service unit pump is also required to prepare the tubes for usage. Long lasting electrical resistance sensors may cost somewhere around \$30 each and the portable meter around \$275.



There are a few portable soil moisture probes, but the sensors that are placed in one spot for the whole growing season generally do the best monitoring of the soil water status within annual crops. Portable sensors are usually of a capacitance or time-domain (TDR) soil water measurement technique that estimates the volumetric water content. These devices are typically much more expensive than the tensiometers or resistance blocks and have to be inserted into the soil bed each time a reading is taken.

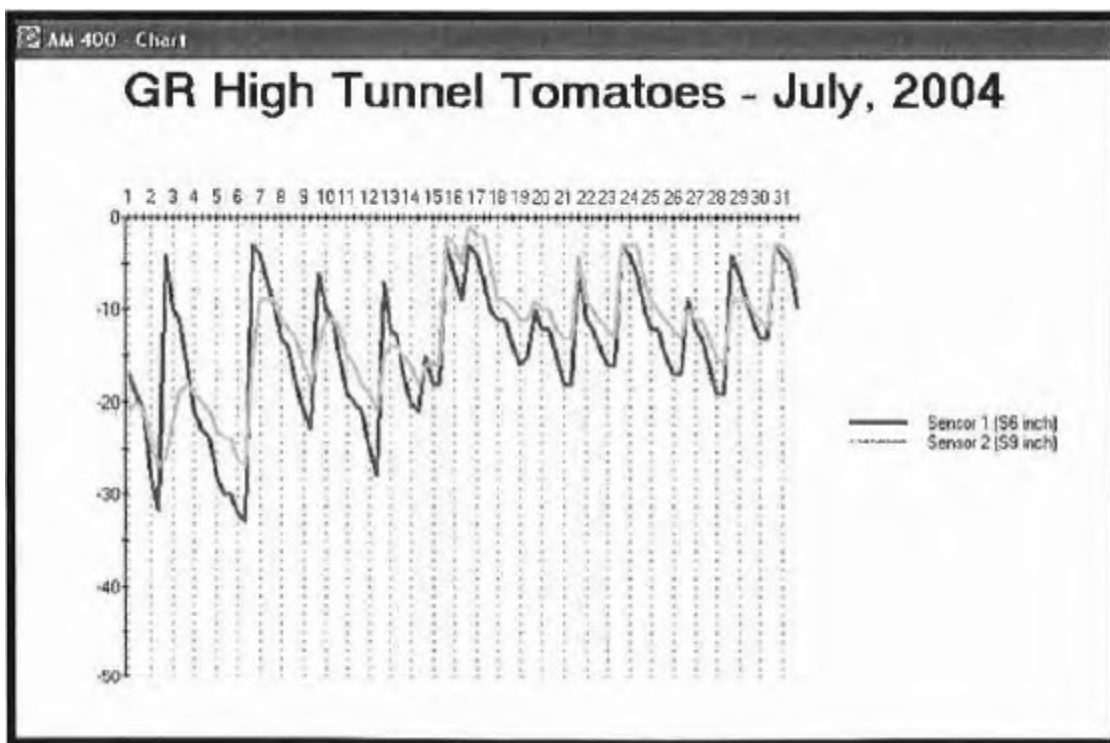


Soil moisture sensors like the tensiometer or the electrical moisture sensor should be installed into the plants' active rooting zone within 1 to 2 weeks after transplanting or emergence and removed only at the end of the season.



Soil water sensors should be used to monitor at least two soil depths (1/2 and 2/3 the active root zone) and at one to two sites within the same crop type. Sensors are typically installed at 4 to 6 inches and 8 to 12 inches below the soil surface and within 5 to 8 inches of a drip water-emitter device and a plant's main stem. Sensors should be regularly read every day or two at the same time of the day all through the growing season. The readings should be recorded and plotted on a time-based graph or spreadsheet for each assessment.

The graph below shows an example of how to present the measured readings over a one-month period.



Some low-cost soil moisture data loggers (e.g., <http://www.mkhansen.com/>, <http://www.irrometer.com/>, and <http://www.specmeters.com/>) that can be left in the field to record one or more times a day are also available. These devices can take readings from several sensors and produce summary graphics like the graph above. The actual data shown in this graph are from readings recorded by a Hansen data logger with Watermark soil moisture sensors at two depths used in drip irrigated tomatoes grown in a high tunnel at the North Central Research and Outreach Center in Grand Rapids. Irrigation events for most high tunnel vegetable crops when grown on sandy soils should be initiated whenever the shallower sensors read between 25 and 35 centibars. During critical growth periods, like fruit sizing in tomatoes, the sensor range might need to be kept even wetter, between 15 and 25 centibars in especially the upper 5-8 inches of the profile. If the deepest sensor does not respond to an irrigation event, it's possible that the amount of water applied was not sufficient in amount to move to the sensor. To correct this situation, one should run the next few irrigations slightly longer to see if the deeper sensors respond. If more than one crop is under the same irrigation system, soil sensors should be placed in each crop to assist an operator in assuring that no crop is over or under irrigated. For additional information on moisture sensors, check out the websites listed in the reference section or contact a local irrigation supplier or a web based product contact listed at the end of this chapter. Instructions on sensor installation are described in a later section of this chapter or can be found in the manufactures' literature.

Daily soil moisture accounting is an excellent method used by many conventional crop irrigators to estimate soil moisture by simply keeping a running balance sheet of the estimated daily crop water usage (ET) in relationship to the incoming rain and irrigation.

No research has been done in Minnesota to refine the current outdoor ET prediction models for usage within a high tunnel system; therefore this method is not an acceptable tool at the present time. Based on current open field ET research in Minnesota, however, we should expect that most high tunnel plants will take-up soil water and evaporate into the tunnel atmosphere at a similar ET range (0.05 inches to over 0.30 inches per day) for the same plant growth and the same climatic conditions. We should also expect that the actual ET within the tunnel will be somewhat higher (10-20%) than in the open field, as the average air temperature for given day might be 10 to 20 degrees warmer than outside conditions.



Table 4 presents expected outdoor daily ETs for a full-canopy crop within central Minnesota at different weekly periods based on long-term average outdoors solar radiation and maximum daily air temperature. Even though this Table was developed for outside conditions, it might be used to understand the ET potential difference between inside and outside conditions. The projected ET for a given outside air temperature for a given time could be compared to the projected ET for the tunnel air temperature that might be 10 to 20 degrees warmer for that same day. For example, if the air temperature for a day in July during the 9th week was 70°F outside and 90°F inside the tunnel, the Table would suggest that the outdoor ET would be around 0.17 inches. Inside the tunnel, the ET might be 0.25 inches for the same crop. Since this table is based on only average solar radiation for each time period, these ET estimates might be at least another 15 to 20% greater on cloud-free days in full sunlight.

Table 4. Estimated Average Water Use for Full Canopy Crops in Central Minnesota at Different Times of the Season						
		Temperature °F				
Week after Emergence		50-59	60-69	70-79	80-89	90-99
May	1	0.06	0.09	0.12	0.15	0.18
	2	0.07	0.10	0.14	0.17	0.20
	3	0.07	0.11	0.14	0.18	0.22
	4	0.08	0.21	0.15	0.19	0.22
June	5	0.08	0.12	0.15	0.19	0.22
	6	0.08	0.12	0.15	0.19	0.22
	7	0.09	0.13	0.17	0.20	0.24
	8	0.09	0.13	0.17	0.20	0.24
July	9	0.09	0.13	0.17	0.21	0.25
	10	0.09	0.13	0.17	0.20	0.24
	11	0.09	0.13	0.17	0.20	0.24
	12	0.08	0.12	0.16	0.20	0.24
August	13	0.08	0.12	0.16	0.20	0.24
	14	0.08	0.12	0.16	0.20	0.23
	15	0.07	0.11	0.14	0.17	0.21
	16	0.07	0.10	0.13	0.16	0.19
September	17	0.06	0.09	0.12	0.15	0.18
	18	0.06	0.09	0.12	0.15	0.18
	19	0.05	0.08	0.10	0.12	0.15

More information on Table 4 can be reviewed in the University of Minnesota Extension bulletin AGFO-1322 *Irrigation Scheduling-Checkbook Method* located on the internet at <http://www.extension.umn.edu/distribution/cropsystems/DC1322.html>.

Soil Moisture Sensor Installation Procedures

To install electrical resistance type soil water sensors, like the Watermark soil moisture sensors; tensiometers or other similar devices follow the steps outlined below along with the instructions given by the respective sensor manufacturer. Sensors should be placed in the plant row shortly after the transplants have been set or after the new seedlings have emergence.

1. First, soak all sensors in clean water for 1 to 2 hours to help remove the air and then allow each to dry for four or six hours. Repeat this step two more times. For tensiometers, a vacuum service pump should be used after each drying to help purge any trapped air. Prior to placing the sensors into the soil, soak them at least (5) minutes. If the sensors were used in a previous season, evaluate them for damage to the sensor surface, wire leads or suction gage on the tensiometer and discard the sensor if the sensor surface looks plugged or damaged.
- 
2. Next, select at least one or preferably two locations within the same crop for the sensors to be placed. All sensors should be located in a representative soil type in the tunnel and somewhere between 1/3 and 2/3rds of the way along the row at a point that will allow easy access to read the sensors. Each sensor should be positioned within the plant row approximately 4 to 6 inches from a healthy plant and also a similar distance from a drip irrigation emitter. At each site one sensor should be set 4 to 6 inches below the ground surface and another set at 8 to 12 inches below the surface depending on the crop's rooting zone. The deeper sensor must also be located within the drip wetted zone and active rooting area.
3. To install a sensor in the soil, first make a pilot hole with a soil probe or small spade a little deeper than desired. To get good sensor contact with the soil, pour a little dry soil and water into the new hole. The sensor maybe positioned in the pilot hole either vertically or at a slight angle. Then slightly push it into the wet soil and re-packed the hole with the excavated soil. Avoid over-packing the replaced soil. If the deeper sensor contains wire leads, draw the lead wire through a soil probe tube or a plastic pipe and hold the sensor on the end. Push the probe and sensor into the hole to the desired depth until set firmly. Fill the hole by adding some dry soil and a little water in short steps, and firm the soil with a tamping stick until the hole is filled.
- 
4. Mark each sensor to indicate its depth. For the sensors with wire leads, tag each sensor or creating one or more knots at the wire end to indicate the depth position (for example one knot means shallow and two knots means a deep sensor). Wrap the extra lead wire around a nearby stake to keep it from getting in the way of the walking paths.



5. Taking sensor reading one to two days after installation to allow the added water to become equalized in the soil. Sensors should be read every two to three days in the early season and then every day or two during rapid growth periods. Readings should be recorded in a notebook or spreadsheet along with each irrigation event (including time run). This will allow tracking of the soil water changes in the soil profile throughout the growing season.
6. Irrigate when the average readings of the shallow sensors within a given crop reach the desired threshold level (25 to 35 cbs.). The amount of water that should be applied depends on a lot factors and needs to be selected and refined based on previous irrigation events. Keep a watch on the deeper sensor and if the reading gets drier after an irrigation, lengthen the next irrigation event by 30 minutes.



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Irrigation Water Management Product Sources

NOTE: This is a partial list of local and web based suppliers of irrigation water management materials. Mention of the suppliers is not intended to be an endorsement of their product or a preference over other suppliers. *Use of trade names and equipment does not constitute endorsement by University of Minnesota nor is it a criticism applied of products not mentioned.*

Ag Resources, Inc. (*tensiometer, soil sensors, data monitor and accessories*)
35268 State Highway 34
Detroit Lakes, Minnesota 56501
phone # 218-847-9351 E-mail: dgbari@tekstar.com

Berry Hill Irrigation (*tensiometer, soil sensors, data monitor and accessories*)
3744 Highway 58
Buffalo Junction, VA 24529
phone # 1-800-345-3747 or website: <http://www.berryhilldrip.com>

GEMPLER'S (*soil probe, tensiometer, soil sensors and accessories*)
P.O. Box 44993
Madison, WI 53744-4993
Phone: 1-800-382-8473 or website: <http://www.gemplers.com/>

Irrrometer Company (*tensiometer, soil sensors, data monitor-logger and accessories*)
P.O. Box 2424
Riverside, CA 92516
Phone: (951) 689-1701 or website: <http://www.irrometer.com>

Jordan Seeds
6400 Upper Afton Rd.
Woodbury, Minnesota 55125
phone # 612-738-3422

M. K. Hansen Company (*soil moisture data monitor -logger and soil water sensors*)
2216 Fancher Boulevard
East Wenatchee, WA 98802
Phone: (509) 884-1396 or website: <http://www.mkhansen.com/>

Spectrum Technologies, Inc (*tensiometer, soil sensors, data monitor and accessories*)
23839 W. Andrew Rd.
Plainfield, Illinois 60544
phone# 800-248-8873 or website: <http://www.specmeters.com/>

TRICKL-EEZ Company (*tensiometer, soil sensors, data monitor and accessories*)
4266 Hollywood Rd
Saint Joseph, MI 49085
phone # 269-429-8200 or website: <http://www.trickl-eez.com>

Soil Fertility and Fertigation

Carl Rosen, Jerry Wright, Terry Nennich, and Dave Wildung, University of Minnesota

FERTILITY MANAGEMENT

Growing horticultural crops in high tunnels requires that growers develop some new ideas about how to provide for plants' needs. The growing season is typically longer and growing conditions more conducive to plant health and vigor. Both plant biomass production and yield are greatly increased. Nutrient needs of high tunnel plantings can be *much* greater than needs of field-grown crops.

The planting environment inside the tunnel has much in common with a container: the root zone can be quite limited. Since rain is not falling over the entire area, and moisture is only being applied to the soil in a strip down the center of the row, root growth can be restricted by dry soil even though there is apparently plenty of space for root development. Soils with high organic matter allow moisture to move away from the drip irrigation emitters, and allow roots to grow out farther. For this reason, all high tunnels should have abundant compost tilled into the soil at the beginning of the season, not just tunnels for certified organic produce. This is especially important in sandy soils with low water-holding capacity.

Soil Testing

Native soils are generally used as the growing medium in most high tunnel systems and therefore the first step in managing fertility in a high tunnel is to obtain a routine soil test. Soil pH, P, K, Ca, Mg, and micronutrients should be monitored every two to three years or more often if problems are occurring.

In addition, a soluble salts test (also known as an electrical conductivity test) is recommended each year to ensure that salts are not building up. Most soils in the Upper Midwest have low soluble salts, but with the use of fertigation and the absence of leaching rainfall, salts may accumulate in a high tunnel. If salt levels become excessive, leaching of the growing beds or removal of the soil may be necessary.

A nitrate-nitrogen soil test should also be done on an annual basis. Nitrate-N is a plant-available form of N that can carry over in the soil from the end of one growing season to the beginning of the next. Collect soil samples for nitrate-N from the upper one foot of soil, rather than the standard six inch sampling depth for other soil tests. The amount of nitrate-N in the soil before planting can be subtracted from the N fertilizer requirement for the crop.

Based on experiences at the high tunnel research site at the Central Lakes State College Ag Center in Staples, MN, irrigation water should also be tested for nutrient levels. Water used for irrigation at this site contained 24 ppm nitrate-N, which contributed the equivalent of about 80 lbs N/A over the growing season.

For most situations, adjustment of pH, phosphorus fertility, and micronutrients should be done before planting. Soil pH should be in the range of 5.5 to 7.5: somewhat acidic to very slightly basic. Incorporation of calcitic or dolomitic limestone to raise pH, or of sphagnum peat or elemental sulfur to lower pH, should be done in the year before planting according to soil test recommendations. Refer to the University of Minnesota Extension Service bulletin

“Nutrient Management for Commercial Fruit & Vegetable Crops in Minnesota” for information on obtaining a soil test, soluble salt levels tolerated by different crops, and adjusting pH and fertility based on the soil test:

<http://www.extension.umn.edu/distribution/cropsystems/DC5886.html>

Organic Matter

The ideal soil for high tunnel production is a well-drained sandy loam to silt loam. Soil organic matter should be medium to high, in the range of 3.5% to 6%. Compacted soils should be plowed to relieve the compaction. Considerable soil compaction can occur during the construction process, so tillage is necessary after the structure is completed.

Planting and then plowing in a green manure cover crop before and after constructing the high tunnel is a good idea. Green manures such as rye, oats, sorghum-sudan grass, and legumes including field peas and clover help control weeds and add organic matter to the soil.

As a source of organic matter and fertility, consider incorporating good quality compost at a rate of one to five pounds per square foot, depending on quality and composition. Composted livestock manure and composted yard waste are both recommended, but be careful that yard waste compost does not contain herbicide residue. Manure-based compost has a higher nutrient content than yard waste compost and can be applied at the lower rates. The compost should be incorporated in the soil to a depth of 6 to 8 inches before planting.

Calculating Nutrient Needs

The yield potential of vegetables and fruit in a high tunnel system is generally two to four times higher than in open field production. As yield potential increases, the need for nutrients also increases. For tomatoes and peppers, the approximate nutrient requirements per ton of fruit and associated vegetative growth are as follows:

Table 1. Approximate nutrient requirements/ton of fruit.

	Plant Part	N	P	K
		----- Lb./Ton Fruit Weight-----		
Tomato	Fruit	3.4	0.4	6.0
	Vines	2.6	0.4	3.4
	Total	6.0	0.8	9.4
Pepper	Fruits	4.0	0.6	4.4
	Shoots	8.4	0.6	8.0
	Total	12.4	1.2	12.4

D. Maynard and G. Hochmuth. 2007. Knott's Handbook for Vegetable Growers, 5th ed, John Wiley & Sons.

In high tunnels in Minnesota, tomato yields equivalent to 50 tons per acre are not unusual, requiring 300 lbs N per acre, 40 lbs P per acre (92 lbs P₂O₅ per acre), and 470 lbs of K per acre (564 lbs K₂O per acre) based on the above data.

In studies at the Staples high tunnel research site, actual nutrient budgets for the season were calculated for tomato and cucumber crops. The NPK requirements of fruit and vines per ton of fruit harvested were as follows:

Table 2. Nutrient budget calculated for tomato and cucumber.

		N	P	K
		----- Lb./Ton Fruit Weight -----		
Tomato	Plant Part			
	Fruit	2.5	0.5	4.0
	Vines	1.7	0.2	1.7
	Total	4.2	0.7	5.7
<hr/>				
Cucumber	Fruits	1.5	0.3	2.1
	Shoots	1.3	0.2	1.4
	Total	2.8	0.5	3.5

For a tomato crop equivalent to 60 tons/acre, actual N uptake was 251 lbs/acre, actual P uptake was 41 lbs/acre (94 lb P_2O_5/A), and actual K uptake was 345 lbs/acre (414 lb $K_2O/acre$). For a cucumber crop equivalent to 144 tons/acre, actual N uptake was 388 lbs/acre, actual P uptake was 64 lbs/acre (147 lb $P_2O_5/acre$, and actual K uptake was 485 lbs/acre (582 lbs $K_2O/acre$).

Ounces per 100 Feet of Row Scale

Because the area within a high tunnel is only a fraction of an acre, ounces of nutrient per 100 linear feet of row is a more practical scale than pounds of nutrient per acre. A new set of nutrient recommendations has been developed using this scale. These recommendations assume four feet between rows. (The conversion factor is pounds/acre x 0.147 = ounces/100 linear foot of row.) The nutrient recommendations in Tables 1 to 4 are given in both lbs/A and oz/100 linear row ft.

Fertilizers

For conventional production, use of soluble fertilizers is suggested for optimum growth.

Nitrogen requirements are based on organic matter and nitrate-nitrogen soil tests. If compost is applied, account for the available N in the compost. Using the recommended rates of N, incorporate one-fourth to one-half the total amount before planting. The remainder can be fertigated as described below. Preplant N sources include urea, monoammonium phosphate, diammonium phosphate, and ammonium sulfate. Soluble N sources for fertigation include calcium nitrate, potassium nitrate, and urea-ammonium nitrate (28% N in a liquid form).

If the tunnel lacks a drip irrigation system for fertigation, controlled-release N fertilizers, such as Osmocote and coated urea, can be incorporated. Choose a product with a 50 to 70 day release, but be aware that higher temperatures within the high tunnel will lead to faster release of N. Controlled release fertilizers are more expensive than conventional fertilizers.

Phosphorus levels are fairly high in many soils in the Upper Midwest. If a soil test indicates that P fertilization is necessary, incorporate the fertilizer before planting. Phosphorus sources include monoammonium phosphate and diammonium phosphate. Application of a starter solution high in P is recommended for transplants at the time of planting. Follow label recommendations for rates to apply.

Potassium accumulates in fruits, and is removed from the farm when produce is picked and sold, therefore, K will probably need to be supplemented each year. One-third of the total recommended amount of K should be incorporated before planting, and the remainder applied using a fertigation system. Potassium nitrate and potassium chloride are water-soluble forms of K that can be used in fertigation. Alternatively, most or all of the K could be incorporated prior to planting, as potassium chloride, potassium sulfate, or potassium magnesium sulfate.

When **Secondary** and **Micronutrients** are required, they should generally be incorporated before planting. Calcium and magnesium are usually adequate if soil pH is maintained in the optimum range through liming. Dolomitic lime supplies both Ca and Mg. If lime is not required, gypsum (Ca-sulfate) and Ca-nitrate can be used to supply Ca. Epsom salts (Mg-sulfate) and potassium magnesium sulfate will supply Mg without changing pH. Sources of the secondary nutrient sulfur include a variety of sulfate compounds, such as gypsum, Epsom salts, potassium sulfate, and potassium magnesium sulfate.

Minnesota soils generally contain adequate amounts of micronutrients, but deficiencies may occur under certain soil conditions and on crops with high demand for specific nutrients. Refer to the University of Minnesota Extension Service bulletin “Nutrient Management for Commercial Fruit & Vegetable Crops in Minnesota” for information on fertilizer sources of micronutrients: <http://www.extension.umn.edu/distribution/cropsystems/DC5886.html>. Use of compost will help supply micronutrients and soluble micronutrient fertilizers can be applied through fertigation. Foliar sprays may be useful in alleviating micronutrient deficiencies that occur during the growing season.

Soil and Fertility Management in Organic Production Systems

In a high tunnel production system, the greatly lengthened growing and harvest seasons mean more plant demand for nutrients. In conventional high tunnel systems using synthetic fertilizer, plant nutrient needs are met through high nutrient levels in the soil, as well as fertigation to provide water-soluble nutrients directly to the root zone. Under organic management systems, nutrient demand must be met by various preplant incorporated composts and ideally this should be coupled with fertigation using water soluble OMRI (Organic Materials Review Institute)-approved fertilizer.

However, such naturally-derived soluble fertilizers are more expensive and difficult to use than conventional soluble fertilizers. Clogging of drip emitters is a typical problem. When emitters clog, not only will fertilizer not reach the plants, but they will also be subject to drought conditions. This is one of the ways in which, just as in other organic production systems, more intensive management is necessary as compared with conventional production.

Soil Amendments

Always start by testing the soil for macro- and micronutrients, pH, and soluble salts as described above.

In some heavier soils, the addition of sand to achieve a more porous loam soil may be advisable. At the Northwest Minnesota high tunnel research site in Crookston, one cubic

yard of sand was added per 100 sq ft of area to change soil texture from a heavy clay to a sandy clay loam. Before buying and incorporating sand, be sure to test it for pH.

In both conventional and organic production, the soil in the planting area must be amended with nutrient-rich compost. The compost should be fertile enough to provide adequate plant nutrition for the entire season.

It's important to test for nutrients in compost: depending on the original material, the age of the compost, and how it was stored, nutrient levels may be very high or very low. While compost with low nutrient levels can be useful as a soil conditioner, raising the organic matter content, compost used for organic high tunnel production should be nutrient rich.

Composted manure is the best source of nutrients for organic production in tunnels. Rates of compost to apply will depend on the type of compost used, moisture content, and the crop being grown. Approximate rates of composted dairy or poultry compost to apply are as follows:

Composted dairy manure: 2700 lbs of compost (fresh weight basis) per 1000 square feet.
Composted poultry manure: 900 lbs of compost (fresh weight basis) per 1000 square feet.

These rates are based on supplying about 100 lbs of available N per acre (14.7 ounces of available N/100 linear feet of row) and assume that 30% of the total N is available for poultry compost and 14% of the organic N is available for dairy compost. A moisture content of 55% was assumed for both composts.

For a more accurate assessment of application rate, it is recommended that compost be analyzed for organic N content and moisture content. Information on calculating the amounts of plant-available nutrients in compost and compost application rates can be found in the University of Minnesota Extension Service publication "Using Manure and Compost as Nutrient Sources for Vegetable Crops":

<http://www.extension.umn.edu/distribution/horticulture/M1192.html>. Raw manure should not be used in high tunnels.

For additional information on nutrient sources and nutrient management for organic production refer to the University of Minnesota Extension Service publication "Maintaining Soil Fertility in an Organic Fruit and Vegetable Crops System":

<http://www.extension.umn.edu/distribution/horticulture/M1191.html>

Drip Irrigation and Fertigation

A soluble fish-based solution (nutrient analysis 4-1-1) was tested in research at the Crookston research site in 2008 and 2009, and found to be compatible with drip tape. One-half of tomato and cucumber plantings were fertigated on a continuous flow basis, using two fluid ounces of fish solution (0.09 ounces of N by weight) per 100 feet of tape early in the season, increasing to six fluid ounces (0.28 ounces of N by weight) per 100 feet as plants grew and their nutrient needs increased.

Manure based compost was incorporated before planting over the entire area. Control plants received only water through the irrigation tubing, while test plants received the equivalent (over the entire season) of 280 lbs/acre N (41 oz N/100 linear ft of row), 70 lbs/acre P (10 oz P/100 linear ft of row), and 70 lbs/acre K (10 oz K/100 linear ft of row).

Results in the following table show that fertigation increased tomato yields in both years and cucumber yields in one of the two years.

Table 3. Yield study using ‘Cobra’ tomato and ‘Sweet Success’ cucumber.

Yield of field study using fertigation with tomato and sweet cucumber				
	2008		2009	
	----- yield in pounds per plant -----			
	Tomato	Cucumber*	Tomato	Cucumber
Control	45	18	25	28
Fertigated	49	13	31	42

*Low cucumber yields in 2008 were due to early harvest.

FERTIGATION



Fertigation is the process of injecting one or more agricultural plant nutrients into irrigation water for application to the plant-soil root zone, to meet a portion of a crop's fertilizer needs. A well designed drip irrigation system can provide an excellent partner for utilizing fertigation with commercial vegetable crops, especially when plastic mulch beds are also used.

Nitrogen and potassium fertilizers are the most common nutrients applied by fertigation to vegetable crops. Some formulations of phosphorus and micro-nutrients can also be used if compatible with the irrigation water (pH should be less

than 6.5). In addition, because of precipitation problems, special precautions must be made not to mix P fertilizers with calcium nitrate and iron. To avoid precipitation problems, two stock tanks should be used, one for calcium nitrate and iron chelate, and the other for the remaining fertilizers. Applying and incorporating all the P before planting, based on a soil test as discussed above, is another way of avoiding precipitation problems.



Timing

Fertigation is typically practiced during several irrigation events over the course of the growing season to “spoon-feed” one-half to three-fourths of the plants’ total nitrogen needs for the season. In high tunnel plastic-mulched rows, the frequency of fertigation can vary from once a month, to once a week, to each day there is an irrigation event, depending on the plant stage of growth. *In general, the frequency of application is not as important as the total rate applied.*

In most high tunnels, multiple crops are grown with varying fertilizer requirements. In order to meet demands of various crops in one house, two approaches can be taken: 1) fertigate the crops at different times to allow for varying rates to be applied or 2) fertigate to meet the demands of the crops requiring the lowest amounts of nutrients and make up the difference with pre-plant fertilizer.

Suggested N and K fertigation schedules for tomatoes and peppers are provided in Tables 1 through 4. Recommendations are made on both a pounds per acre basis and an ounces per 100 linear feet of row basis. Even though the area in tunnels is far less than an acre, pounds per acre is the conventional method of making fertilizer recommendations. For convenience, these fertilizer rates are converted to ounces per 100 linear feet of row, assuming four foot between-row spacing.

An example of how to calculate fertilizer rates based on these recommendations is presented below in the fertigation calibration section. Note that as fruiting begins, the need for potassium increases dramatically.

Research on other crops grown in high tunnels is not adequate to provide detailed fertigation schedules at this time, but the information for tomatoes and peppers in Tables 1 to 4 can be used as a starting point to develop general guidelines. Begin with the total N and K fertilizer recommendations, decide how much of each will be applied preplant (about 25 to 50%), and set up a preliminary fertigation schedule for the remainder of the fertilizer using proportions similar to those shown for tomatoes and peppers. After the growing season begins, monitor plant nutrient status through tissue analysis and revise your preliminary fertigation rates as necessary (see the next section on “Tissue Analysis”).

In organic production systems, preplant compost application is the primary nutrient source and fertigation during the growing season should be considered only as a supplement to compost. Therefore, preplant application of available N and K should account for much higher proportions of the total nutrient requirement than the rates suggested for conventional production in Tables 4 to 7. Similar to conventional production, fertigation rates in organic production can be adjusted through plant tissue analysis.

Tissue Analysis

Tissue analysis can be used to help determine if nutrients are limiting or at excessive levels. Sufficiency ranges for selected crops are presented in Table 8. Petiole analysis can also be used to help predict the need for nitrogen. Sufficiency levels based on petiole nitrate-N are presented in Table 9. These results can be used to adjust N and K fertigation rates or as a basis for applying other nutrients that are below sufficiency levels. Refer to the University of Minnesota Extension Service publication bulletin “Nutrient Management for Commercial Fruit & Vegetable Crops in Minnesota” for information on how to sample leaves and petioles of various crops for tissue analysis:

<http://www.extension.umn.edu/distribution/cropsystems/DC5886.html>

Table 4. Suggested N and K fertigation scheduling for tomatoes (pounds/acre).

	Daily N	Weekly N	Seasonal N	Daily K ₂ O	Weekly K ₂ O	Seasonal K ₂ O
Days after Planting	-----lb/A-----					
Preplant	-----	-----	50.0	-----	-----	100.0
0 – 21	0.5	3.5	61.5	1.0	7.0	121.0
22 – 49	0.7	4.9	81.1	1.4	9.8	160.2
50 – 70	1.0	7.0	102.1	2.0	14.0	202.2
71 – 91	1.1	7.7	125.2	2.2	15.4	248.4
92 - 112	1.0	7.0	146.2	2.0	14.0	290.4

Table 5. Suggested N and K fertigation scheduling for tomatoes (oz/100 linear ft of row¹).

	Daily N	Weekly N	Seasonal N	Daily K ₂ O	Weekly K ₂ O	Seasonal K ₂ O
Days after Planting	-----oz/100 linear Row Ft.-----					
Preplant	-----	-----	7.3	-----	-----	14.7
0 - 21	0.07	0.50	9.0	0.15	1.1	17.8
22 – 49	0.10	0.70	11.9	0.21	1.5	23.5
50 – 70	0.15	1.05	15.0	0.29	2.0	29.7
71 – 91	0.16	7.7	18.4	0.32	2.2	36.5
92 - 112	0.15	7.0	21.5	0.29	2.0	42.6

¹ Assumes 4 ft spacing between rows. Conversion: lb/ac X 0.147 = oz/100 linear ft of row.

Table 6. Suggested N and K fertigation scheduling for peppers (pounds/acre).

	Daily N	Weekly N	Seasonal N	Daily K ₂ O	Weekly K ₂ O	Seasonal K ₂ O
Days after Planting	-----lb/ac-----					
Preplant	-----	-----	50.0	-----	-----	100.0
0 - 21	1.0	7.0	71.0	1.0	7.0	121.0
22 – 42	1.2	8.4	96.2	2.4	16.8	202.2
43 - 56	1.8	12.6	121.4	3.6	25.2	252.6
57 - 84	2.2	15.4	183.0	4.4	30.8	375.8
84 - 98	2.4	16.8	216.6	4.8	33.6	443.0

Table 7. Suggested N and K fertigation scheduling for peppers (oz/100 linear ft of row¹)

	Daily N	Weekly N	Seasonal N	Daily K ₂ O	Weekly K ₂ O	Seasonal K ₂ O
Days after Planting	-----oz/100 linear ft of row-----					
Preplant	-----	-----	7.3	-----	-----	14.7
0 - 21	0.15	1.1	10.4	0.15	1.1	17.8
22 – 42	0.18	1.3	14.1	0.35	2.5	29.7
43 - 56	0.26	1.8	17.8	0.53	3.7	37.1
57 - 84	0.32	2.2	26.9	0.65	4.6	55.2
84 - 98	0.35	2.5	31.8	0.71	5.0	65.1

¹ Assumes 4 ft spacing between rows. Conversion: lb/ac X 0.147 = oz/100 linear ft of row.

Table 8. Nutrient concentration sufficiency ranges for fruit and vegetable crops.

Crop	N	P	K	Ca	Mg	S	Fe	B	Cu	Zn	Mn	Mo
	-----%-----					-----ppm-----						
Bean, snap	5.0-6.0	0.25-0.75	2.2-4.0	1.5-3.0	0.25-0.70	--	50-300	20-60	7-30	20-60	50-300	>0.4
Beets, table	3.5-5.0	0.25-0.50	3.0-4.5	2.5-3.5	0.30-1.00	--	50-200	30-80	5-15	15-30	70-200	--
Blueberries	1.7-2.1	0.10-0.40	0.4-0.7	0.35-0.8	0.12-0.25	0.12-0.30	70-200	25-70	5-20	9-30	50-600	--
Broccoli	3.2-5.5	0.30-0.70	2.0-4.0	1.2-2.5	0.23-0.40	0.30-0.75	50-150	30-100	4-10	20-80	25-150	0.3-0.5
Cabbage	3.6-5.0	0.33-0.75	3.0-5.0	1.1-3.0	0.40-0.75	0.3-0.75	30-200	25-75	5-15	20-200	25-200	0.4-0.7
Cantaloupe	4.5-5.5	0.30-0.80	4.0-5.0	2.3-3.0	0.35-0.80	0.25-1.0	40	50-300	25-60	7-30	20-200	50-250
Carrots	2.5-3.5	0.20-0.30	2.8-4.3	1.4-3.0	0.30-0.50	--	50-300	30-100	5-15	25-250	60-200	0.5-1.5
Cauliflower	3.3-4.5	0.33-0.80	2.6-4.2	2.0-3.5	0.27-0.50	--	30-200	30-100	4-15	20-250	25-250	0.5-0.8
Cucumbers	4.5-6.0	0.30-1.25	3.5-5.0	1.0-3.5	0.30-1.00	0.30-0.70	50-300	25-60	5-20	25-100	50-300	--
Eggplant	4.2-5.0	0.45-0.60	5.7-6.5	1.7-2.2	0.25-0.35	--	--	20-30	4-6	30-50	15-100	--
Garlic	3.4-4.5	0.28-0.50	3.0-4.5	1.0-1.8	0.23-0.30	--	--	--	--	--	--	--
Grapes	1.6-2.8	0.20-0.46	1.5-2.0	1.2-2.5	0.30-0.40	--	40-180	25-50	5-10	25-100	25-100	0.2-0.4
Lettuce	2.5-4.0	0.40-0.60	6.0-8.0	1.4-2.0	0.50-0.70	--	50-500	30-100	7-10	26-100	30-90	>0.1
Onions	4.0-5.0	0.35-0.50	4.0-5.5	1.5-3.5	0.30-0.50	0.50-1.0	60-300	30-45	5-10	20-55	50-65	--
Peas	4.0-6.0	0.30-0.80	2.0-3.5	1.2-2.0	0.30-0.70	0.20-0.40	50-300	25-60	5-10	25-100	30-400	>0.6
Peppers	3.5-4.5	0.30-0.70	4.0-5.4	0.4-0.6	0.30-1.50	--	60-300	30-100	10-20	30-100	26-300	--
Potatoes	3.0-6.0	0.25-0.50	4.0-6.0	0.5-0.9	0.25-0.50	0.19-0.35	30-150	20-40	5-20	20-40	20-450	--
Radishes	2.2-3.5	0.30-0.70	4.0-7.5	3.0-4.5	0.50-1.20	0.20-0.40	50-200	30-50	6-12	20-50	25-130	--
Raspberries	4.2-5.2	0.20-0.50	1.1-3.0	0.6-2.5	0.25-0.80	0.20-0.30	50-200	25-300	4-20	15-60	25-300	--
Spinach	2.1-2.9	0.30-0.60	5.0-8.0	0.6-1.2	0.60-1.00	--	60-200	25-60	5-25	25-100	30-250	>0.5
Strawberries	2.8-3.5	0.20-0.35	1.1-2.5	0.6-1.8	0.25-0.70	0.20-0.30	90-150	25-60	6-20	20-50	30-100	--
Sweet corn	2.8-3.5	0.25-0.40	1.8-3.0	0.6-1.1	0.20-0.50	0.20-0.75	50-300	8-25	5-25	20-100	30-300	0.9-1.0
Tomato	4.0-6.0	0.25-0.80	2.9-5.0	1.0-3.0	0.40-0.60	0.40-1.2	40-200	25-60	5-20	20-50	40-250	--
Watermelon	2.0-3.0	0.20-0.30	2.5-3.5	2.5-3.5	0.60-0.80	--	100-300	30-80	4-8	20-60	60-240	--

Table 9. Sufficiency nitrate-N concentration ranges for petioles/midribs of selected vegetable crops on a dry weight and sap basis. Petiole/midribs should be collected from the most recently matured leaf.

Crop	Tissue Sampled	Growth Stage	Nitrate-N	
			dry weight, %	sap, ppm
Broccoli	Midrib	Buttoning	0.9 - 1.2	800 – 1100
Cabbage	Midrib	Heading	0.7 - 0.9	NA
Carrots	Petiole	Midgrowth	0.75 - 1.0	550 -750
Cauliflower	Midrib	Buttoning	0.7 - 0.9	NA
Celery	Petiole	Midgrowth	0.7 - 0.9	500 -700
Cucumbers	Petiole	First blossom	0.75 - 0.9	800 - 1000
		Early fruit set	0.5 - 0.75	600 - 800
		First harvest	0.4 - 0.5	400 - 600
Eggplant	Petiole	Initial fruit	NA	1200 - 1600
		First harvest	NA	1000 - 1200
Lettuce	Midrib	Heading	0.6 - 0.8	NA
	Petiole	First blossom	1.2 - 1.4	1000 - 1200
		Initial fruit	0.8 - 1.0	800 - 1000
		First mature fruit	0.3 - 0.5	700 - 800
Peppers	Petiole	First flower	1.0 - 1.2	1400 - 1600
		Early fruit set	0.5 - 0.7	1200 - 1400
		Fruit 3/4 size	0.3 - 0.5	800 - 1000
Potatoes	Petiole	Vegetative	1.7 - 2.2	1200 - 1600
		Tuber bulking	1.1-1.5	800 - 1100
		Maturation	0.6 - 0.9	400 -700
Tomatoes	Petiole	Early bloom	1.4-1.6	1000 - 1200
		Fruit 1 inch diameter	1.2 - 1.4	400- 600
		Full ripe fruit	0.6 - 0.8	300 - 400
Watermelon	Petiole	Early fruit set	0.75 - 0.9	1000 - 1200
		Fruit ½ size	NA	800 - 1000
		First harvest	NA	600 - 800

NA = Not available.

Getting Started in Fertigation

To set up and manage a fertigation system that applies the desired nutrient amounts adequately and uniformly with the irrigation water, the steps below should be accomplished. There are several very good Extension publications written on these topics and the authors of this section strongly recommend that in addition to this publication, the website publications listed below and at the end of this paper be carefully reviewed before initiating any equipment selection, setup, and operation of a fertigation system.

1. Review all available literature below as well as local fertilizer recommendations.

Fertilizer Application and Management for Micro (Drip)-Irrigated Vegetables in Florida.
<http://edis.ifas.ufl.edu/CV141> University of Florida Extension Service.

Fertigation: The Basics of Injecting Fertilizer for Field-Grown Tomatoes. Publication 2037. <http://msucares.com/pubs/publications/p2037.htm> Mississippi State University Extension Service

Minnesota Chemigation Safety Measures. Bulletin 6118. <http://www.extension.umn.edu/distribution/cropsystems/DC6122.html> University of Minnesota Extension Service

Drip Chemigation: Injecting Fertilizer, Acid, and Chlorine Bulletin 1130. <http://pubs.caes.uga.edu/caespubs/pubcd/B1130/B1130.htm> University of Georgia Extension Service.

Injection of Chemicals Into Irrigation Systems: Rates, Volumes, and Injection Periods. Bulletin 250. <http://edis.ifas.ufl.edu/AE116> Florida Cooperative Extension Service

Micro-irrigation in Mulched Bed Production Systems: Irrigation Depths. Bulletin AE72. <http://edis.ifas.ufl.edu/AE049> Florida Cooperative Extension Service

Greenhouse Vegetable Production, Tomato Bulletin 1182. <http://pubs.caes.uga.edu/caespubs/pubcd/B1182/B1182.htm> University of Georgia Extension Service.

Nitrogen Application with Irrigation Water-Chemigation. Bulletin 6118. <http://www.extension.umn.edu/distribution/cropsystems/DC6118.html> University of Minnesota Extension Service

Fertigation of Vegetable Crops -Commercial Vegetable Production. Bulletin MF-102. <http://www.ksre.ksu.edu/library/hort2/mf1092.pdf> Kansas State University Extension

2. Review the Minnesota Chemigation/Fertigation Permit Application and Safety Requirements <http://www.mda.state.mn.us/en/chemicals/fertilizers/chemigation.aspx>
3. Determine the irrigation operating time required by the selected drip system to apply an average depth of an inch of irrigation water over the desired wetted area of a row. See Table 3 in the "Drip Irrigation" chapter that shows how the irrigation flow rate influences the average hourly water application rate for different potential wetted widths or use the equations listed below in the drip irrigation discussion.
4. Determine the maximum amount of chemical solution that is necessary for doing a single fertigation application within the given high tunnel planting to meet the recommended application rate of the product for the given crop. (See Tables 1 and 2 for recommendations.)
5. Select the appropriate size of injection equipment to contain the needed fertigation chemical and to apply one-half inch or less water during the fertigation event. The set-up should have an injection rate that will apply the desired fertilizer during the first half of the required operating time.
6. Install the appropriate anti-pollution and safety devices recommended by the MDA. In general, the type of devices selected is very dependent on the size of the main water line, source of water supply, and irrigation system. (MDA information and contacts below.)

7. Install the injection unit to the main water line as close as possible to the drip irrigation tubing using a by-pass piping arrangement, **upstream** of the last filtering device and pressure regulator, and always **downstream** of the anti-pollution equipment.

8. Submit the Minnesota Chemigation/Fertigation Permit Application to MDA

9. Conduct one or more test runs to observe the performance of the fertigation system injecting a desired solution amount (use plain water during test) and measuring how much time it takes to complete the injection in relationship to the length of the irrigation event. One should always try to have run the irrigation system at least 30 minutes after the injected solution has been completed, to help move most of the compound out of the drip tubing and into the soil profile, but not so long as to cause any leaching of the product.

10. Periodically inspect the anti-pollution equipment performance.

MDA Chemigation/Fertigation Safety Equipment and Permit Requirement

In Minnesota the Minnesota Pesticide and Fertilizer Chemigation Regulations (Minn. Stat 18B.08 and 18C.205 and Minn. Rules Part 1505.2100-1505.2800) requires that the owner/operator of any irrigation system intending to practice chemigation including fertigation in Minnesota have a MDA chemigation system user permit; install and maintain several safety (antipollution and safeguard) devices; comply with Minnesota Department of Health's (MDH) well separation distance rules, and implement several recommended management measures.

A Minnesota chemigation permit is very easily granted as soon as the operator completes an application form, pays \$50 application fee and submits the signed application form certifying that the system contains all of the required MDA/MDH antipollution equipment and will keep the required application and maintenance records. Once the permit has been mailed, the operator is granted approval by the "permit-by-rule" law and it does not need to be inspected by any MDA staff prior to use. However, inspections are conducted by MDA staff on most sites sometime shortly after the permit has been received, and if violations are found at a site that was certified on the application to be in compliance, enforcement action can and has been taken.

A chemigation user permit application form and details on antipollution safety equipment requirements is available from the Minnesota Department of Agriculture website <http://www.mda.state.mn.us/en/chemicals/fertilizers/chemigation.aspx>. For additional help, contact MDA Chemigation Advisor, Mike Fick (218-863-2984), or Chemigation Supervisor, John Peckham (651-201-6276).

In general, when the irrigation water is coming directly from a public water supply system, a RPZ backflow preventer device is normally the only type allowed for usage between the water source and the injection system. If however drip system is connected to a non-public water supply like a domestic well, the simplest type of backflow preventer valve for a single 100-foot high tunnel might be an atmospheric vacuum breaker if the device can be located on the non-pressure side of the last control valve and can be installed at least 12 inches above the highest irrigation drip emitter outlet. The fertigation device then needs to be located between the vacuum breaker device and the drip irrigation tern.

If the breaker device needs to be installed upstream of the last automatic control valve, the device must be a pressure type vacuum breaker and likewise installed at least 12 above the highest irrigation drip outlet.

More general information on the Minnesota chemigation requirements can also viewed from the following two Extension bulletins:

Nitrogen Application with Irrigation Water-Chemigation. Bulletin 6118.
<http://www.extension.umn.edu/distribution/cropsystems/DC6118.html> University of Minnesota Extension Service

Minnesota Chemigation Safety Measures. Bulletin 6122.
<http://www.extension.umn.edu/distribution/cropsystems/DC6122.html> University of Minnesota Extension Service

Fertilizer Injector Options

There are several chemical injectors available that can be used to inject selective fertilizers into the irrigation water but each has its limitations to adequately work depending on the area and rate to be fertilized, available operating pressure and water flow rate. The most basic forms of injector are the pressure differential tank and the venturi system, and both should work very well for a high tunnel system.

The tank system is based on the principle of a pressure differential being created by a special valve in the main water line that forces water through a bypass pipe into a pressure tank and out again, carrying a small amount of the dissolved fertilizer from the tank. The venturi system basically draws the liquid fertilizer solution from a container by differential pressure created with venturi device and then injects the fertilizer into the irrigation water line at a controlled rate. Both of these systems should be installed into the main water line as close as possible to the drip system and in a by-pass piping arrangement to be able to be easily connected or disconnected from the system at any time as well as to help in creating the needed differential pressure or controlling the injection rate. Regardless of the injection device, it should always be installed up-stream of the last filtering unit to be certain the filter removes any undissolved solids before entering the drip tubing.

If the irrigated site has more than one tunnel and or open field acres, and one desires to inject a more constant rate of nutrient at each time irrigation, the next step up would be to install a proportional injection pump that could be more easily controlled and that could handle a higher rate of nutrient injection.

To research fertigation options, check with the suppliers listed on the last page of this chapter, or visit the Irrigation Association website at <http://www.irrigation.org>.

Regardless of the type and size of unit needed for the drip system, the injector system should be connected into the main water line via a by-pass piping arrangement with the appropriate valves and as near as possible to the drip tubing but always up stream of the last filter before the drip tubing header. The injecting device should also always be located downstream of the necessary backflow prevention equipment to provide protection to the water supply.

Drip Irrigation

To manage the irrigation and fertigation system effectively one needs to know about the watering performance characteristics of the irrigation systems such as water application rate (inches of per hour), water discharge rate (gallons per minute) of all of the drip tubing, amount of time to make an application event, the fertigation injection rate range and the uniformity of water application distribution. In addition one also needs to know the desired fertilizer chemical solution application rate (units per acre).

The water application rate for a trickle system depends greatly on operating pressure, emitter size and emitter spacing. Manufacturers give the flow rate for a given product by either gallons per unit of time (hours or minutes) per emitter, or gallons per unit of time (hours or minutes) per 100 feet of tubing at a given emitter spacing. Manufacturers usually have charts in their literature to help a user determine the application rate per hour for a given wetted width and length of run.

Table 3 in the Drip Irrigation chapter of this manual also shows how the flow rate influences the average hourly water application rate for different potential wetted widths. The University of Georgia Extension Service states in the Bulletin *Plasticulture for Commercial Vegetable Production* that "if fertilizer is to be injected, make sure that the flow rate of the selected drip tube will discharge the desired amount of fertilizer during the feasible 'run time' of the system". This becomes very critical during periods when water demand is greatest. Hence, it's best to select a tubing with a flow rate of .45 or less gpm/100-foot so as to provide at least a 1 to 2 hour operating time during critical water and fertigation needs.

Below are equations that can be used to estimate the water application rate coverage of a system operating at the manufacturers suggested pressure and flow rate.

To determine the average water application depth (inches/hour) at 95% efficiency for a given wetted width:

$$\frac{19.25 \times \text{emitter rate (gallons/hour)} \times 0.95}{\text{Wetted width (feet)} \times \text{emitter spacing (inches)}} = \text{application depth/hour (inches)}$$

$$\text{Example: } \frac{19.25 \times 0.5 \text{ gph} \times 0.95}{2 \text{ ft} \times 12 \text{ inches}} = 0.38 \text{ net inches of water/hour, over 2 ft width}$$

To determine the irrigation time (hours) to apply a desired amount of water (inches):

$$\frac{\text{desired application depth (inches)} \times \text{wetted width (ft)}}{\text{emitter spacing (inches)}} = \text{time (hours)}$$

$$19.25 \times \text{emitter rate (gallons/hour)} \times 0.95$$

$$\text{Example: } \frac{0.60 \text{ inches} \times 2.0 \text{ ft} \times 12 \text{ inches}}{19.25 \times 0.5 \text{ gph} \times 0.95} = 1.57 \text{ hours to apply 0.60 inches over 2 ft width}$$

Most of the emitters used with trickle have very small orifices; hence filters are a must for most water supplies to prevent clogging from the irrigation water. If *any* clogging occurs,

even very little, the water application rate can be greatly reduced from the manufacturer's suggested discharge rate, and this could significantly change the overall water distribution uniformity between emitters. To observe the water uniformity, collect the discharge from 15 to 20 emitters, selected randomly, for a given period of time. From these, you can also determine the actual emitter flow rate in gallons per hour, when you know the volume collected versus the time to collect the sample.

To determine the flow rate of one emitter in gallons/hour:

3600 sec/hr x emitter volume (ml) = flow rate (gallons/hour)
3785 ml/gal x collection time (sec)

Example: $\frac{3600 \times 150 \text{ ml}}{3785 \times 120 \text{ sec}} = 1.18 \text{ gallons/hour flow rate}$

Fertigation Calibration and Calculations

For drip systems, a batch-loading fertigation approach is generally used, and the volume of a total nutrient is the main calibration component. Total volume of the chemical for batch loading depends on the area of the irrigated zone and the desired nutrient rate. The injection rate does not need to be precisely controlled. However, the injector should apply the chemical solution in a time period that does not result in over-irrigation, or in leaching of any previously applied chemical and should not be damaging to any part of the irrigation system or crop.

The volume of the nutrient needed per acre or per 100 linear feet of row depends on the concentration of the chemical source and the desired application rate. Table 10 below lists the gallons of 28% liquid UAN (urea-ammonium nitrate = 28-0-0) solution per acre for a few selected application rates. Concentration for some other the products commonly used can found in the following web sites:

Fertilizer Application and Management for Micro (Drip)-Irrigated Vegetables in Florida.
<http://edis.ifas.ufl.edu/CV141> University of Florida Extension Service.

Fertigation of Vegetable Crops—Commercial Vegetable Production. Bulletin MF-102.
<http://www.ksre.ksu.edu/library/hort2/mf1092.pdf> Kansas State University Extension.

For example, to apply 10 pounds of N as liquid urea-ammonium nitrate (28-0-0) per acre: Divide the 10 pounds by the N chemical concentration (3 lbs N per gallon of 28-0-0 solution or 0.375 solid ounces of N per fluid ounce of 28-0-0), which then means 3.33 gallons of 28% N is needed per acre.

For an area less than one acre, such as 200 linear ft of row with 4 ft between rows: The area to fertilize is 800 sq ft or 0.018 acres ($800 \div 43,560 = 0.018$ acres). Apply the acreage fractional proportion times the N rate of 3.33 gallons per acre. Hence, for this tunnel only about 0.06 gallon (or 7.8 fluid ounces) of 28% UAN is required by the injection system to place 10 pounds of N per acre through the drip system ($3.33 \text{ gallons per acre} \times 0.018 \text{ acres} = 0.06 \text{ gallons} = 7.8 \text{ fl oz}$ ($0.06 \text{ gal} \times 128 \text{ fl oz/gal}$)).

Table 10. Amount of 28-0-0 UAN solution for various N rates/acre.

N rates lbs/ac	1	2	3	4	6	8	10
28% gallons/ac	0.33	0.67	1.0	1.33	2.0	2.67	3.33
28% fl. oz/100 linear ft of row ¹	0.39	0.78	1.16	1.55	2.32	3.10	3.88

¹ Assumes a between-row spacing of 4 feet.

Additional examples are listed below. If chemical formulation or irrigation system presents a more complicated calibration situation, assistance may be described in one of the web sites list above, or contact an Extension specialist. For solid fertilizers such as potassium nitrate, the calculation to determine the amount of this fertilizer needed to supply a given amount of N is as follows: From Table 2, the weekly N rate to apply for the first 3 weeks is 3.5 lb N per acre or 0.49 oz N per 100 linear feet of row and the weekly K₂O rate is 1.1 oz per week.

Suppose a high tunnel has 150 linear feet of row. How much potassium nitrate would need to be dissolved in a gallon of water and then injected into the system to supply the required N?

Use the following formula:

$$\frac{\text{Actual N recommended per 100 linear feet} \times \text{linear feet of row irrigated}}{\% \text{ analysis of fertilizer} \times 100 \text{ linear ft.}}$$

$$0.49 \times 150 = 5.7 \text{ oz. (or 0.35 lb.) of potassium nitrate would be required for that week.}$$

Based on the solubility chart in Table 11, this amount of potassium nitrate would dissolve in a gallon of water. In addition, you would also be supplying 2.5 oz of K₂O (5.7 x 0.44) when supplying 0.49 oz N. This is more than twice the amount of K₂O recommended. To account for this extra K₂O, a different N source without K should be used the following week. An alternative approach would be to use less potassium nitrate and supplement the N with urea, ammonium nitrate, or the combination of these sources in liquid form (28% N).

For liquid fertilizer use the following formula:

$$\frac{\text{Actual N recommended per 100 linear feet} \times \text{linear feet of row irrigated}}{\text{oz. of N per fluid oz.} \times 100 \text{ linear ft.}}$$

$$0.49 \times 150 = 2.0 \text{ fluid oz. of 28-0-0 required to supply 0.49 oz. of N for 150 linear ft. of row.}$$

Table 11. Solubility of common fertilizers used for drip irrigation.

Material	Composition			Salt Index	Solubility Lbs/gal H ₂ O
	%N	%P ₂ O ₅	%K ₂ O		
Calcium nitrate ¹	15.5	0.0	0.0	53	8.5
Potassium nitrate	13.0	0.0	44	73	1.1
Ammonium nitrate	33.5	0.0	0.0	105	9.8
Urea	46.0	0.0	0.0	75	6.5
Ammonium sulfate ²	21.0	0.0	0.0	69	5.9
Potassium chloride	0.0	0.0	60	116	2.3
Potassium sulfate ²	0.0	0.0	50	46	0.6
Diammonium phosphate ²	18.0	46	0.0	30	3.6

¹ May cause clogging if irrigation water is high in bicarbonates

² Not recommended for use with calcium nitrate or if irrigation water is high in calcium.

Fertigation Checklist

The following checklist of precautions is recommended for review by any producer who is starting to operate a new fertigation system. From Mississippi State University Extension Specialist, Richard Snyder, in Publication 2037 “Fertigation: The Basics of Injecting Fertilizer for Field-Grown Tomatoes”

<http://msucare.com/pubs/publications/p2037.htm>

- Be sure the placement of the drip tubing does not interfere with the production system. For example, if planting tomatoes down the center of a raised bed, place the drip tubing about six inches off center. This will prevent damaging the tubing when cutting holes for the transplants and when inserting tomato stakes.
- Make sure the fertilizer is compatible with the water into which it is being injected. Some fertilizers can cause a precipitant that will clog the drip system or filter system. For example, calcium and phosphorus fertilizers would not be mixed with sulfates in a concentrated solution.
- The suction line in the fertilizer tank should not rest on the bottom. Keeping the intake end of the tube about a foot above the bottom of the container will help prevent undissolved solids from entering the system. Calcium nitrate and potassium nitrate will sometimes leave a scum of impurities on the surface; skim off the scum.
- A small screen should be put on the end of the suction line to help prevent solid particles or undissolved fertilizer from entering the system and stopping it up.
- Do not inject fertilizers in combination with pesticides or chlorine.
- The injection point must be upstream of the filter system so the filter will remove any undissolved fertilizer or precipitants that occur.
- Before beginning injection of fertilizer, bring the drip irrigation system up to operating pressure. At this point, even the part of the irrigation system farthest from the source should be pressurized.
- After all of the fertilizer is injected, irrigate with plain water so the lines are flushed out and fertilizer is washed into the plant beds.
- Select fertilizer solutions to help adjust water pH if necessary.
- The length of time needed to distribute the fertilizer needs to be less than the length of time needed to supply enough water to the field; otherwise, too much water will be applied. Do not over-water because this will leach some of the fertilizer out of the root zone. If the amount of fertilizer that must be applied is too much for the irrigation interval, split the application over time (i.e., twice per week or some other arrangement).

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Plastic Mulches: Benefits, Types, and Sources

Vincent A. Fritz, Professor and Extension Vegetable Specialist, Southern Research and Outreach Center Waseca, MN

Since the early establishment of black plastic mulch as an effective tool in the cultivation of many fruits and vegetables, the more recent innovations in plastic mulch technology have given producers an even larger line of products to choose from. Understanding all of the properties of plastic mulches and how they interact with traditional cultivation methods is the key to maximizing the benefits that mulch has to offer.

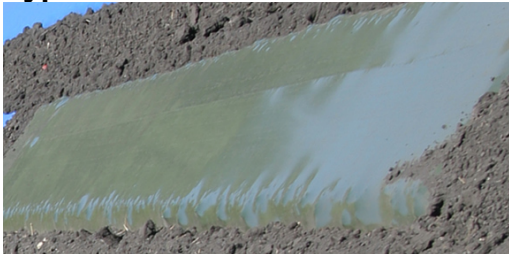
Principle Benefits of Mulch

Perhaps the most significant benefit from using plastic mulch is soil warming that significantly improves germination and stand establishment of many vegetable crops, particularly warm season vegetables.

Another significant benefit is weed suppression. Weed competition in both the garden and commercial field can effectively strip the yield potential from many fruits and vegetables. Clear plastic mulch can offer greater soil warming capabilities over black plastic, however clear plastic promotes weed growth that in turn robs both soil moisture and nutrients from the crop. The adverse effects from this are very significant during stand establishment early in the season. If clear plastic mulch is used, it is critical to provide chemical pre-emergent weed control.

In addition to the primary benefits mentioned above, plastic mulch is also very effective in conserving soil moisture and fertilizer due to reduced leaching from normal rainfall events. This is a particularly significant benefit on light textured soils that are low in organic matter and naturally, very well drained (ie. Sandy and sandy loam soils). Mulches also provide an effective barrier between the soil surface and the crop that often results in clean, disease free produce.

Types of Plastic Mulch



Row covered in black plastic mulch

Black plastic mulch continues to be the most widely used mulch; and for two main reasons - early season soil warming and weed control. This mulch alone has enabled producers in northern states to extend their growing season and grow many warm season vegetables that would not ordinarily mature and/or yield sustainable, positive, economic returns. Black plastic mulch is available in various widths and thickness (mils).

Clear plastic mulch can provide greater warming benefits but offers no protection from weed growth (see above). Like black mulch it is available in various widths and thickness and is more economical than the more technologically advanced mulches.

Selective Light Transmittance (SLT) or Infrared Radiation Transmitting (IRT)



A variety of colored mulches

Although these new types of mulches have been available for quite a few years now, understanding the unique properties they offer a producer has probably been a primary limiting factor to more widespread use. This new technology effectively allows infrared energy from the sun to penetrate the plastic and warm the soil. However, visible light that promotes weed growth is blocked.

Some of the most common SLT or IRT mulches currently available are either a translucent green or brown color. These types of mulches can also be co-extruded (top layer and a bottom layer with different colors) to provide an added benefit for crop growth. Different colors on the upper surface of the mulch change the quality of light that is reflected back in and around the crop canopy.

Depending on the quality of the light reflected, crop growth can be altered. An example of such an application is the use of red IRT mulch on tomatoes. The mulch can increase fruit yield by as much as 20% as well as improved fruit color and taste. Since the light needs to be reflected back into the crop canopy to have the effect, the plants need to be vertically staked or trellised to maximize the benefit. Any prostrate crop growth habit that will prevent light from being reflected will prevent the colored mulches from doing their job. Other colors continue to be developed.

Why Use Raised Beds with Plastic Mulch?

Benefits from using plastic mulch are maximized by installing them over a substantial and firm raised bed. These beds can be formed by hand on a small scale, however sled type raised bed forms are used commercially. Raised beds are particularly beneficial when using plastic mulches because they can enhance early season drainage, expose more surface area under the mulch for more uniform warming, and help to keep produce clean. Raised beds also facilitate a tight fit of the mulch during installation which ensures maximum heat transfer through to the soil. A loosely installed mulch will lead to loss of heat transfer, tearing of the mulch during windy conditions, and possible crop damage.

Is Trickle Irrigation Necessary When Using Plastic Mulch?

Although plastic mulches help to retain soil moisture, they can also prevent normal precipitation from penetrating through to the crop where it may be needed most. This can be especially critical when plastic mulch is used on a very light textured (sandy) soil that has very little water holding capacity. Trickle irrigation will ensure that the crop will get the needed moisture at critical periods (ie. flowering, fruit set and maturity) and maximize the benefits from plastic mulch. The use of plastic mulch without trickle irrigation is not recommended.

Other Mulches

Photodegradable, biodegradable, and paper mulches may offer additional options in the future, however further development and calibration of these materials with specific crops in northern climates are critical to their success. Both photodegradable and biodegradable mulches promote the desirable characteristics of self-destruction in the field, however performance has been inconsistent. Paper mulches are another alternative but they can also prematurely deteriorate at the point where it is buried in the soil (see photo). This makes the mulch susceptible to wind and puts the crop at risk. Areas not susceptible to wind may be appropriate for those who prefer to use paper based products. Of course, a broad array of organic plant material can be used as mulch. Some mulches offer allelopathic protection from weed growth and can effectively reduce soil moisture loss. However, many of these types of mulches serve us poorly if the prime objectives is to warm the soil.

Sources of Plastic Mulches

Jordan Seeds, Inc.
6400 Upper Afton Road
Woodbury, MN 55125
Phone: 651-738-3422
Mulches: red, black, clear, blue, white, green IRT, photodegradable
<http://www.jordanseeds.com/>

Ken Bar, Inc.
25 Walkers Brook Dr.
Reading, MA 01867-0704
Phone: 781-944-0003
Mulches: red, black, silver

Agway
North Collins, NY
Phone: 800-337-3156
Mulches: green IRT and photodegradable

Clarke Ag Plastics
P.O. Box 238, Rte. 691
Greenwood, VA 22943
Phone: 540-456-4578
Mulches: many colors

Ginegar Plastic Products, LTD
Kibbutz Ginegar 30053
ISRAEL
Mulches: yellow

Plant Diseases in High Tunnels: Their Pathology and Control

Beth Gugino, Pennsylvania State University

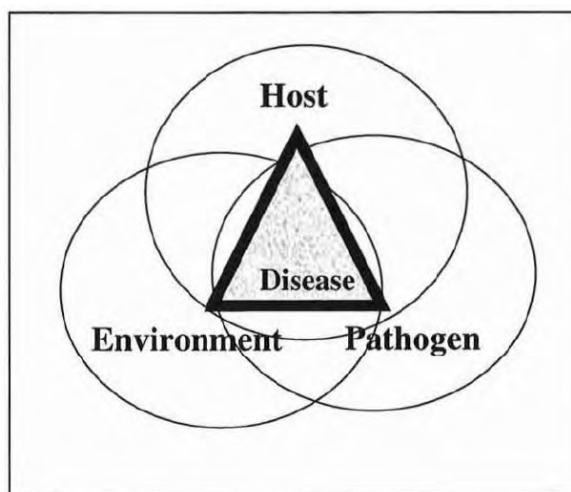
Plant pathologists describe the relationship between plant, disease, and environment with the **Disease Triangle**. Only when all three “sides” of the triangle are suitable, can a plant disease occur. Diseases will not occur in the absence of the environmental conditions necessary for the existence of the pathogen that causes them.

Environment: Where the plant is located and the weather conditions affecting it. Some environmental conditions favor certain pathogens over others.

Pathogen: The disease-causing agent. Common disease-causing agents include:

- Fungi
- Bacteria
- Viruses
- Nematodes

Host: The susceptible plant that can develop disease.



Growing crops in high tunnels can prevent or reduce the likelihood of many plant diseases by preventing the pathogen from contacting the host, and by creating an environment unfavorable to disease development. Growers can make plant disease even less likely by selecting non-susceptible plants, and by controlling the environment and the contact of pathogen with plant. This chapter examines best practices for plant disease management, and also lists the most common plant pathogens of vegetables grow in high tunnels.

Part I: Plant Disease Management in High Tunnels

A sound disease management program should not and cannot rely on fungicides alone! Focus on maintaining plant health. This involves sound cultural practices, selection of resistant cultivars, and proper use of fungicides that are selected based on accurate disease diagnosis.

Note that many plant disorders may appear to be diseases, but are actually physiological responses to other factors. Sunscald leading to necrosis of tomato or pumpkin tissue is an example of a disorder that is not caused by a plant pathogen. Be sure to rule out environmental, nutritional, or other physiological responses before you assume a disorder is a disease.

Plant pathogens do cause diseases, though, and the grower must be prepared to manage the high tunnel environment to minimize disease, and to respond to disease if it does develop.

There are really four stages of disease management for high tunnels. Disease must be prevented, managed, and treated at each of these stages.

1. Pre-Tunnel Establishment: before the tunnel has even been constructed.
2. Pre-Season: before the growing season begins.
3. Transplant Production: usually in a separate greenhouse.
4. Crop Production: in the high tunnel.

1. Pre-High Tunnel Establishment

Disease management begins before the high tunnel is even established. Set up the tunnel and plan to operate it in such a way as to make the environment inside as inhospitable to plant disease as possible.

As noted in the “Site Selection” chapter, the tunnel should be oriented east-west to maximize sun interception. Avoid any shading at all. Maximize air flow by orienting single-bay tunnels perpendicular to prevailing winds, and multi-bay parallel to the prevailing winds. Some say the Minnesota has no prevailing winds, that the wind can and does blow strongly from any direction, but in most parts of the state, during most of the growing season, winds are coming from south, southwest, and west. So a grower orienting a single-bay tunnel along a north-south axis will be placing the tunnel more or less perpendicular to prevailing winds, but will not have maximized light interception early and late in the season.

Optimizing temperatures will help keep plants healthy, more naturally resistant to pathogens. The tunnel certainly provides a warmer environment in early spring and late in fall. In early spring, drier soil and warmer soil temperatures will help prevent root rots. Black plastic mulch can help warm soil faster and more in spring when the sun is bright but the soil is still cool.

Optimizing humidity during the growing season usually will mean keeping humidity as low as possible. Pay close attention to venting the tunnel early in the morning and late in the day, as temperatures will rise quickly once the sun is shining on the tunnel, increasing relative humidity. Later in the day, warm moist air will release dew as the tunnel cools. Minimize leaf wetness, by using drip irrigation rather than overhead.

2. Pre-Season Disease Management

Sanitation and Hygiene

Make sure high tunnel and surrounding area is weed-free and that crop debris has been removed or has completely decomposed. Disinfest all high tunnel equipment including stakes, clips, irrigation system, and any other tools or supplies used in the tunnel. A number of sanitizers/biocides are available, including:

- Quaternary ammonium (e.g. Greenshield)
- Household bleach
- Hydrogen dioxide (e.g. Oxidate, ZeroTol)
- Chlorine dioxide (e.g. Selectocide)

Follow label instructions in using any sanitizer.

Crop Rotation

Plan a crop rotation or cropping sequence. Especially for growers with only one tunnel, this will be very challenging, but it's needed to break pathogen lifecycles and improve soil health.

Grafting onto Resistant Rootstocks

Where it is simply impossible to not plant the same crops year after year into the same high tunnel, one strategy is to graft desired cultivars onto resistant rootstocks. This is commonly done for tomatoes.

Cover Crops as Biofumigants

Another possibility is the use of biofumigant cover crops. These crops would be sown over part or all of the tunnel area. When the cover crop dies and senesces, chemicals are released that inhibit the growth of plant pathogens, nematodes, and/or some weeds.

Biofumigant plants include:

- Brassicas: mustards, rapeseed, oilseed radish
- Sudangrass and sorghum-sudangrass hybrids
- Forage pearl millet
- Marigold
- Flax

Disease-Resistant Cultivars

Disease resistant cultivars are the first line of defense against plant pathogens. Use of disease-resistant plants can often delay the onset of the disease and slow disease development (for example, plants may retain leaves longer), but most disease-resistant cultivars are not truly immune, and can become severely infected by the end of the season.

Certainly, planting disease-resistant cultivars can reduce the number of fungicide applications. Planting disease-resistant cultivars also should eliminate or at least reduce the amount of pathogen available to initiate disease in other plants.

3. Transplant Production

Hot Water Seed Treatment

Start transplants from disease-free seed. If there is a chance seed could bear pathogens, use a hot-water seed treatment. This will kill most bacterial pathogens on and within seeds. Hot-water treatment is suggested for eggplant, pepper, tomato, carrot, spinach, lettuce, celery, cabbage, turnip, radish and other brassicas. It is not for use on cucurbit seed or other large seeded crops. Seed can be damaged!

Different seeds have different requirements for time intervals and water temperatures. The process is very specific to each type of seed, and treating seeds in the wrong manner can kill them.

Seed type	Water temperature	Minutes
Brussels sprouts, eggplant, spinach, cabbage, tomato	122°F	25
Broccoli, cauliflower, carrot, collard, kale, kohlrabi, rutabaga, turnip	122°F	20
Mustard, cress, radish	122°F	15
Peppers	125°F	30
Lettuce, celery, celeriac	118°F	30

Practice good sanitation in the greenhouse

If you have a greenhouse and grow your own transplants, these are guidelines to follow. If you purchase transplants from another grower, make sure your supplier is following them as well.

Use new or sanitized plug trays or flats, and pathogen-free mixes. To sterilize potting mix, use aerated steam at 145°F to 160°F for 30 minutes. Before planting, sanitize all equipment. Greenhouse floors should be solid, and seedling trays should not rest on the floor. Avoid having ornamentals and vegetables in the same greenhouse.

Overhead irrigation is the norm in seedling production; make sure to water early in the day. Good air circulation and ventilation is essential. Avoid clipping, pruning, or injuring transplants, as the injury sites provide an entry point for the bacteria.

Scout greenhouses regularly. Rogue out diseased plants and surrounding “asymptomatic” ones. Maintain a regular spray program in the greenhouse. The seedling stage is no time for taking chances.

Limit movement of personnel and equipment between greenhouses. After the seedlings have been transplanted out, take the time to thoroughly clean the greenhouse, benches, and equipment.

4. Crop Production

Maintain good weed control inside and outside the high tunnel. Weeds are hosts for many crop plant pathogens.

Use plant spacings that will allow air circulation, and trellis as needed to maintain air flow between plants. After fruit-set, remove any senescing leaves below fruit and remove them from the tunnel. Don't have a cull pile right outside the tunnel. The farther away, the better, and no cull pile at all would be best.

Ideally, and typically, high tunnels in Minnesota have drip irrigation. However, if a tunnel has only overhead irrigation, water early in the day and avoid working with the plants until they have dried. Consider installing drip tubing for the next season! So many of the benefits of high tunnels come from not having water contact the leaves and fruits.

Raise and lower the tunnel sides as needed to regulate temperature and relative humidity. Many plant pathogens don't need free water to flourish, instead multiplying when there is high relative humidity.

Hygiene

Don't smoke in high tunnels or greenhouses. Require employees to wash their hands frequently, between rows and between high tunnels. (Wearing gloves won't solve the problem of pathogen transfer from plant to plant, unless gloves are changed as often as hands would be washed.) Disinfect equipment frequently, and minimize movement between tunnels. Set up a hand and equipment cleaning station convenient to the high tunnels.

Scouting and Treatment of Diseases

Scout for diseases and other pests on a weekly basis. Keep complete records of all production practices, including pesticide applications, but also of fertilization or fertigation, harvest, temperatures inside and outside the tunnel.

Fungicides can often be applied as soon as disease is detected. Biological products need to be applied preventatively.

What constitutes legal use of pesticides in a high tunnel?

In Pennsylvania, the guidelines are:

- That the crop must be on the pesticide label.
- The position of the tunnel sides determines whether to use greenhouse or field pesticides. If the high tunnel sides are down, the application is considered a greenhouse application. If the sides are up, it's a field application.
- Some pesticides have a label that precludes their use in greenhouses. Even if the sides are up, these should not be used in high tunnels.

Part II: Diseases of Concern in High Tunnels

Leaf Mold on Tomato (*Fulvia fulva*)

Symptoms

- White spots that rapidly enlarge and become yellow on upper leaf surface.
- Can be confused with early powdery mildew symptoms.



Leaf mold on tomato (Michelle Grabowski, University of Minnesota)



Leaf mold on tomato (Michelle Grabowski, University of Minnesota)

Sources of Inoculum

- Persists in plant debris and volunteer tomatoes inside and outside the tunnel.
- Soil (conidia and sclerotia), contaminated seed.

Secondary spread

- Spores are readily blown throughout the high tunnel on the wind.
- They can also be spread by workers, tools, and insects.

Disease Development

- Highly dependent on high relative humidity and temperature.

- Conidia germination requires RH > 85%; optimal temperature 68 to 77°F.
- Conidia can survive at least one year in the soil.
- Disease rarely occurs below 50°F.
- Numerous strains exist.

Early Blight on Tomato and Potato (*Alternaria tomatophila*)

Symptoms

- Leaf lesions often develop on mature foliage and first appear as irregular, dark brown to black dead spots. Larger lesions have a characteristic concentric ring pattern.
- Stem lesions occur at any age, and are initially small, dark and slightly sunken, then enlarge and form concentric rings, usually at point of stem attachment. Can involve the entire upper portion of fruit, which can be infected at green or ripe stage through growth cracks or other wounds. Infected fruit often drop before mature.



Leaf lesion caused by early blight (Clemson University - USDA Cooperative Extension Slide Series, Bugwood.org)



Stem lesion caused by early blight (Clemson University - USDA Cooperative Extension Slide Series, Bugwood.org)

Disease Development

- Heavy dews, rain, or overhead irrigation needed to provide the free water the pathogen requires.
- Optimum temperature for development: 82° to 86°F for 2 to 3 days, but early blight can occur at temperatures ranging from 42°F to 93°F.

Late Blight on Tomato or Potato (*Phytophthora infestans*)



Late Blight on tomato leaves
(Division of Plant Industry Archive, Florida
Department of Agriculture and Consumer
Services, Bugwood.org)

Symptoms:

- Water-soaked, olive-brown to black lesion.
- White sporulation on the underside of the leaf after periods of high humidity or moisture.

Disease Development

- Each lesion can produce 100,000 to 300,000 sporangia per day, so a late blight infection quickly becomes an epidemic.
- Optimum temperatures 60 to 75F day; 50 to 60F night

Sources of Inoculum

- Requires a living host including: tomato, potato, pepper, eggplant, petunia (avoid transplants and bedding plants in greenhouse) nightshade weeds
- Management begins with monitoring for and eliminating volunteers and removing any cull piles!

Powdery Mildew (*Podosphaera* spp., *Erysiphe* spp.)

Although powdery mildew is quite a common pest in horticulture, until recently, it was not found in the United States or in Canada. It was introduced only in the 1990s. Now that it's here, growers have to deal with it. It has a wide range of hosts that may be grown in high tunnels, including rosemary, bedding plants, tomato, and eggplant.



Powdery mildew on beet leaves (Howard F.
Schwartz, Colorado State University,
Bugwood.org)



Powdery Mildew on pumpkin leaves (Michelle
Grabowski, University of Minnesota)

While keeping leaves and fruit dry is helpful in prevention of many plant diseases, powdery mildew is able to infect even dry tissue. Only high relative humidity, above 50%, is necessary. Optimum temperature range for the pathogen is from 68-86°F. Without excellent ventilation to control temperatures and humidity, a high tunnel can be very conducive environment for this disease.

Gray Mold (*Botrytis cinerea*)

Botrytis has a wide host range and is considered a “disease of opportunity” that can be managed with cultural and environmental methods. Optimum conditions: 65-75°F, high relative humidity and overhead irrigation. Temperatures above 82°F suppress growth and spore production.

Sources of Inoculum:

Persists in plant debris, other hosts in the same tunnel, including weeds inside and outside.

Secondary spread:

Spores are readily blown through high tunnel in wind and can also be spread by people

Symptoms:

Stem lesions, cankers and soft rots affect all above ground plant parts. Often associated with wounds and senescing plant material. “Ghost spots” on fruit result from aborted infections.



Gray mold on strawberry (T. McCamant, Northland Community College)



Gray mold on a bean pod (Howard F. Schwartz, Colorado State University, Bugwood.org)

Fusarium Wilts

Fusarium oxysporum f. sp. *lycopersici* (tomato)

F.o. f.sp. *melongenae* (eggplant)

F.o. f.sp. *vasinfectum* (pepper)

Fusarium oxysporum f.sp. *cepae* (onion and garlic)

Sources of Inoculum:

The fungus is present in all soils and is usually considered a secondary invader because it attacks plants already weakened by insects, mechanical damage, or other diseases. *Fusarium* is most active at high temperatures. This disease is controlled by proper crop

rotation with non-susceptible crops for four years, removal of infected plants, and planting disease-free seed.

Secondary spread:

Onion or garlic bulbs infected with Fusarium may decay further in storage.

Symptoms:



Infected tomato stem showing brown streaks
(Michelle Grabowski, University of Minnesota)

In tomato, oldest leaves wilt first. wilting of the oldest leaves. If plants are infected early in the growing season, and if temperatures are high for an extended period, little or no normal fruit will be produced.

When a wilted plant is removed and the stem sliced near the soil line, a brown discoloration of the woody tissue can be seen between the pith and the outer, green part of the stem. The brown discoloration can extend to the top of the plant if wilting is severe.



Infected onion plants (Howard F. Schwartz, Colorado State University, Bugwood.org)

In onion and garlic, symptoms include premature yellowing and dying of older leaves, stunting, and leaf tipburn, followed by destruction of the root system, shoot dieback, and rotting of the bulb

Verticillium Wilts

Verticillium albo-atrum and *V. dahliae*

Verticillium has a wide host range, including potato, pepper, eggplant, strawberry, raspberry, beet, cucurbits, some crucifers, alfalfa, numerous weed species and woody plants.

Tomatoes are often grafted for disease resistance. The characteristics of the scion cultivar are maintained, while the disease-resistant rootstock provides resistance to the scion as well. Seed houses sell grafting supplies, and greenhouse operators should be able to produce grafted plants.

Symptoms:

Outer and older leaves droop, wilt, turn dry and become reddish-yellow or dark brown at the margins and between veins. Severely infected plants may appear stunted and flattened,

with small yellowish leaves. In tomatoes, leaves develop a yellow wedge shaped lesion on with a brown center. In a lengthwise cut of the stem near the soil line, veins are tan and the center is green. In strawberries, brownish to blue-black streaks or blotches may appear on the runners or petioles. In severe infestations rapid plant death can occur.



Lengthwise cut of tomato stem (Elizabeth Wiggins)



Verticillium wilt infected strawberries (M. Ellis, Ohio State University)

White Mold/Timber rot (*Sclerotinia*)

Sclerotinia sclerotiorum

Sclerotinia produces long-lived reproductive bodies, sclerotia, that reside in the soil. Sclerotia require several weeks in moist, cold soil (<39°F) to be “preconditioned.” In spring, after at least a week in moist, cool soil, at 59 to 65°F, the preconditioned sclerotia produce apothecia. For 5 to 10 days, the apothecia release infectious ascospores, right around the time the plants have grown a dense canopy.



Sclerotia inside of a tomato stem (Michelle Grabowski, University of Minnesota)

Symptoms:

Older leaves of onion and garlic yellow prematurely, and die back. Eventually the root system is destroyed and the bulb rots. Inside the infected bulb small, hard, black poppy seed like fungal structures form. A white fuzzy growth may form on the outside of the bulb. In tomato, stems develop dark, watersoaked lesions on the stem. Stems eventually turn white and die.

A high tunnel left in the same place for years will probably be home to a large population of sclerotia in the soil.

Viral Diseases

There are no chemical treatments for plant viruses. Infected plants must be removed from the tunnel and disposed of to prevent transmission of the virus to other plants. Planting resistant cultivars is a good strategy, but resistance to some viruses is not available. Excellent sanitation, keeping tunnels weed-free, and controlling vectors, such as thrips, aphids, and cucumber beetles are the primary strategies to control viruses.

Viral Diseases of Tomato			
	Tobacco Mosaic, Tomato Mosaic (TMV and ToMV)	Cucumber Mosaic (CMV)	Tomato Spotted Wilt (TSWV)
Host Range	Broad: many ornamentals and weeds		
Transmission	Seed and mechanical	Aphids	Thrips
Resistance	Available	Not Available	Limited



Tomato exhibiting virus-like symptoms (Michelle Grabowski, University of Minnesota)



Squash exhibiting virus-like symptoms (Michelle Grabowski, University of Minnesota)

Viral Diseases of Cucurbits					
	Papaya ringspot (PRSV)	Zucchini Yellow Mosaic (ZYMV)	Cucumber Mosaic (CMV)	Squash Mosaic (SqMV)	Watermelon Mosaic (WMV)
Host Range	cucurbits	cucurbits	broad, many ornamentals and weeds	cucurbits	cucurbits, legumes, others
Transmission	aphids	aphids, seedborne, mechanical	aphids	cucumber beetles, seedborne, mechanical	aphids
Resistance	limited, cucumbers and melons	available, cucumbers	available, cucumbers	not available	limited

High Tunnel Integrated Pest Management (IPM): Insects and Mites

Cathy E. Thomas, Pennsylvania Department of Agriculture, Eric P. Burkhart, Pennsylvania State University, and Terrance T. Nennich, University of Minnesota

During the six years of high tunnel production and research in Minnesota insects have not generally been a serious problem in our high tunnels. From time to time we would have some problem with slugs; however this usually happened with high tunnels that were located on heavier type soils or those that were not ventilated properly. There has been no problem with slugs where high tunnels have been located on sandy type soils.

The other problem that we encountered for the first time in late 2004 was white flies at the Grand Rapids research site. This was the only site that we had white fly problems. While other states have had problems with aphids we did not encounter aphids in our high tunnel research projects. There have been times that we have had aphid problems with our low plastic production research with peppers and like crops.

It is extremely important that high tunnel vegetable and fruit producers in Minnesota be aware that we might encounter new and different insect problems in high tunnel production as this new technology develops in Minnesota. Minnesota high tunnel producers must monitor daily and be on the alert for new and unexpected insects in their high tunnels. Producers should contact their extension personnel if insects appear in high numbers or insects need identification. Remember that in the ideal environment of high tunnels, insects can multiply at very fast rates and waiting too long for control measures could cost you the crop.

At this time I would like to acknowledge the cooperation of Bill Lamont, Cathy Thomas and Eric Burkhart from Penn State who have graciously allowed us to incorporate their research and materials into the insect section of the Minnesota High Tunnel Production Manual. Integrated pest management (IPM) is an approach to dealing with pest problems that relies upon a variety of tactics to maintain pest numbers below economic levels. Any good IPM program begins with prevention, but may progress to use of pesticides or introduced biological controls as circumstances warrant.

Research being conducted at The Penn State High Tunnel Research and Education Facility has continued to note that pest and disease problems common to greenhouse production also predominate in high tunnel systems. An important difference, however, is that economically significant pest problems in high tunnels during the winter cropping months (November-March) are generally uncommon. This feature makes winter cropping an attractive option for market farmers with year-round outlets. It also makes pest control less overwhelming since there are only certain times of the year when one would expect to find severe infestations.

As with greenhouse production, a combination of biological control with other tactics should prove to be successful in managing insects within high tunnels. The present challenge for researchers and growers is to determine which of the integrated pest management (IPM) tactics developed for greenhouse production are effective and economical for high tunnel systems. Until there are more thorough studies of biological control in high tunnels, recommendations can only be cautiously generated and adopted. Nevertheless, the application of biological control to tunnel cropping has great potential and should be strongly considered by growers.

The Use of Pesticides in High Tunnels

There may be circumstances in which it is necessary to control insect pests through pesticide applications. Growers should begin by selecting materials that are least toxic to both humans and beneficial insects, including pollinators. Pesticides that are low in acute toxicity and also display a low residual activity are often referred to as "soft" pesticides. These materials should be strongly considered in high tunnel cropping because of the "closed" nature of the system, which may prolong any residual activity of applied pesticides.

Common examples of "soft pesticides" include insecticidal soap, horticultural oils, and biological pathogens such as *Bacillus thuringiensis* (Bt) and *Beauveria bassiana*. In addition, many of the botanical pesticides available to growers are also regarded as "soft," including neem (azadirachtin) and ryania. These materials usually provide adequate control of pests and are compatible with biological control programs. However, the toxicity of each material to humans can vary greatly and so caution must always be exercised.

Pesticide applications should be timed to avoid beneficial insect and pollinator activity. Generally, this means that applications should be made in early morning or late evening. If possible, applications should also be strategically localized. This will require scouting to determine where pest "hot spots" occur. If pest problems are restricted to a small area or several small areas in high tunnels, then applications should be limited to these "hot spots." This simple practice will save money, labor, and time but will also allow beneficial insects or biological control agents to "retreat" to safe (untreated) spots. In this manner, one can effectively conserve introduced and/or background beneficial insects and pollinators, while simultaneously using multiple pest control tactics.

The Use of Biological Control in High Tunnels

The three insect pests most frequently encountered in high tunnels at Rock Springs, PA are whiteflies, aphids, and mites. Fortunately, all of these pests are manageable by combining tactics such as biological control (bio-control), with judicious use of "soft" pesticides like insecticidal soap. Table 7A lists a number of biological control agents that can be used by growers against these three major pests of high tunnel crops. To date, there has been limited research into the performance of these bio-control agents in high tunnel cropping systems and so growers should begin cautiously.

There is much to gain by adapting greenhouse biological control to high tunnel systems. If done correctly, the use of bio-control can reduce pesticide applications dramatically. This, in turn, limits or eliminates pesticide residues on product and can be a strong selling point to customers. In addition, fewer pesticide applications make the tunnel environment safer and allow work to proceed uninterrupted without the need to be concerned about reentry intervals.

The transition from relying on pesticides to biological control may seem like a daunting challenge, however. It requires that a grower become more knowledgeable about both pest and potential bio-control options. It will also probably require a few shifts in management style. Managing pests with biological controls requires thoughtful, careful planning and the realization that every crop cycle may present a unique situation. Results are not instantaneous and so patience and diligence is absolutely necessary. The results, nevertheless, can be highly rewarding---both personally and financially.

How to Get Started With a Biological Control Program

1. *Start small*

As with any new technology, start small. Learn the system in one high tunnel and expand as you gain confidence and knowledge.

2. *Eliminate pesticide residues*

Discontinue using insecticides with residual activity at least one to two months prior to introducing bio-controls. Pesticide residues on plants and high tunnel coverings can be deadly to bio-control agents. Consult bio-control suppliers for information on specific products if you want to be certain about the compatibility of a compound that has been applied.

3. *Use "soft" pesticides*

Consider the use of "soft" or "reduced risk" compounds for treating "hot spots" or pests that are not being controlled biologically. Have products on hand before outbreaks occur. Some bio-control suppliers sell these products, and can provide compatibility information. If there is uncertainty about the compound, consult a bio-control supplier before spraying. Some growers find it beneficial to have a sprayer designated for soft pesticides only, avoiding contamination with more toxic insecticides.

4. *Practice strict sanitation*

Weed management is critical to the success of a bio-control program both before and during crop production. Weeds serve as reservoirs for pests and diseases and may upset the predator-prey balance that is trying to be established in the crop. It is also critical to maintain a weed free zone around the outside perimeter of the high tunnel for the same reason. Using an herbicide to quickly knock down a well developed weed population will have pests scrambling for another food supply, which will probably be a crop. Remove weeds and destroy on a continuing basis.

5. *Use clean transplants*

In many cases, serious pest and disease problems that plague growers throughout the growing season result from purchasing infested transplants. Selection of a reputable grower ensures a quality transplant. Inspect purchased plant material carefully. If producing transplants, follow strict sanitation procedures and inspect seedlings weekly for pest and disease development. Preventing a problem from becoming established can save a lot of time, effort and expense.

6. *Start early*

Begin introductions of bio-control agents when pest populations are at low levels so that the bio-control species is not overwhelmed. This can be determined by weekly crop inspection. For example, even though *Encarsia formosa*, a tiny parasitic wasp, is an excellent control for whiteflies, the wasp will not be as effective if it is released too late. This is because high populations of whiteflies produce sticky honeydew that will interfere with the parasitoid's walking and searching speed and may even cause them to become trapped and die.

Production, Distribution and Quality Control of Biological Control Organisms

Most of the successes in greenhouse biological control have occurred in the Netherlands and the United Kingdom, mainly because these countries together contain more than half of the world's greenhouse acreage. An important event occurred when Koppert entered the natural

enemy business in 1967; Koppert is currently the international market leader in the field of biological crop protection. Large scale production of natural enemies such as *Encarsia formosa* and *Aphidius colemani* takes place in their main facility located in the Netherlands. In addition to Koppert, there are several other large producers such as Biobest (Belgium) -a leader in bumblebee pollination, Syngenta (England and California), and Applied Bio-Nomics Ltd. -Canada's largest producer of biological controls. There are also some small companies in the United States that specialize in the production of predatory mites, lacewings and parasitoids.

Regional distributors for these large bio-control producers are found throughout the United States and Canada. For example, International Technology Services (ITS), Lafayette, CO is the U.S. distributor for Biobest Biologicals. Together with the technical support staff at Biobest, they have a full-time entomologist to answer pest control and pollination questions.

A list of distributors in the United States can be found on the internet (see Appendix C). A list is maintained by the Association of Natural Bio-control Producers. Most distributors require orders to be placed by Thursday (since they must be shipped from Europe or Canada) for delivery the following Wednesday. Products are delivered directly to farm or greenhouse via UPS, Airborne or FedEx. Growers should insist on guaranteed live delivery and overnight express only. The large natural enemy producers screen for quality and use expiration dates. Check bio-control shipments for this date and be cautious of suppliers who do not put dates on the material. A non-reputable supplier could have material that is weeks old and not viable.

When bio-control orders arrive at the farm, growers should immediately check for viability. Predatory mites can be examined by shaking material onto a white sheet of paper and looking for movement. Parasitoids such as *Aphidius colemani* are shipped in bottles. Within 24 hours after placement in the greenhouse check bottles for parasitoid emergence. If high mortality of parasitoids is observed, call the distributor immediately. During warm weather months, bio-control insects should be shipped with cooling material. Employees should be informed that bio-controls are expected so that they can be stored in a cool area if they cannot be released or distributed right away.

Biological Control of Whiteflies in High Tunnels

Whitefly development can be controlled with several different natural enemies. It is important to identify the species attacking your crop before ordering a bio-control.

Identification of Whitefly Species

There are several species of whiteflies that attack greenhouse crops, especially greenhouse vegetables. The most common whitefly found to infest greenhouse vegetables is Greenhouse Whitefly (*Trialeurodes vaporariorum*). In a fall crop, the outdoor species, Bandedwinged Whitefly (*Trialeurodes abutiloneus*), is observed on yellow sticky cards and occasionally feeds on plants. Another more serious whitefly is the Silverleaf whitefly (*Bemisia argentifolii*), a common pest on Poinsettias that is difficult to control due to its high reproductive rate and resistance to insecticides.

Whiteflies have sucking mouthparts and cause direct plant damage by feeding on plant sap. Both the adult and nymphal stages feed on plant sap and secrete the excess in the form of a sticky, sweet substance known as honeydew. Honeydew serves as a substrate for sooty mold development, which can occur on foliage and fruit covered by honeydew. Sooty mold

can reduce plant yields by interfering with photosynthesis. The mold that develops on fruit creates extra handling time and can impact market value. Indirect damage by whiteflies is caused by transmission of several viral diseases.

Whiteflies in general have, six life stages: adult, egg, three nymphal instars and the fourth instar or pupa. All occur on the underside of the leaves. During the pupal stage the red eyes of the developing adult are often visible. After the adults emerge from the pupal case, a t-shaped opening can be observed. Development time varies with species, host plant, and environmental conditions. Identification of these species is critical since they respond differently to control strategies, both chemical and biological. Experienced growers may be able to identify species in the adult stage; however, a more reliable method is to examine the pupal stage. Identification requires a hand-lens capable of 10 -20x magnification.

Greenhouse Whitefly (*Trialeurodes vaporariorum*)



Greenhouse whitefly (Whitney Cranshaw, Colorado State University, Bugwood.org)

Greenhouse whitefly is the most common species to infest greenhouse vegetables. Widespread resistance to many different classes of insecticides has created the need for integrated approaches to management that include bio-control.

The adults have wings that are held flat (horizontal) over their body. The pupal stage is white, with straight elevated sides and a fringe of wax filaments around the edge.

Banded-wing Whitefly (*Trialeurodes abutilonia*)



Banded-wing whitefly (Ronald Smith, Auburn University, Bugwood.org)

Banded-wing whitefly is a species found outside in high populations in the fall on weeds and ornamental plants. As their host plants decline, they begin to seek plants and commonly make their way into the greenhouse through vents and doors. This species may feed on plants and lay eggs at a low rate although they usually do not complete their life cycle. High levels on sticky cards may alarm growers resulting in needless pesticide applications.

The adult looks much like a greenhouse whitefly adult with the horizontal wing span; however, they can be distinguished by the two gray bands that form a zigzag pattern across each forewing. The pupal stage is similar as well except for a black band down the center of the pupal case.

Silverleaf Whitefly (*Bemisia argentifolii*)



Silverleaf whitefly larva (Jeffrey W. Lotz, Florida Department of Agriculture and Consumer Services, Bugwood.org)

Silverleaf whitefly (SLWF) can be found on a wide range of host plants. In Pennsylvania greenhouses, this species is most commonly found as a pest of poinsettias. In addition to causing damage by sucking the leaf tissue and secreting honeydew, SLWF is an important carrier of damaging viruses, transmitting more than 25 viruses and many other virus-like diseases. Avoid colonization of this pest in vegetables by separating vegetable and ornamental crops. If you produce your own vegetable transplants, and also grow ornamental crops, isolate a separate area for vegetable transplant production.

The silverleaf adult is smaller than greenhouse whitefly and holds its wings close to the body. The pupal stage is a bright yellow with a few waxy filaments. The pupa does not have a high profile like the greenhouse Whitefly.

Biological Control of Whiteflies:

Parasitoid wasp (*Encarsia formosa*)



Encarsia formosa adult (David Cappaert, Michigan State University, Bugwood.org)

The parasitoid (*Encarsia formosa*) is tiny wasp (0.6 mm) that consumes and eventually kills its host the Greenhouse whitefly. In Pennsylvania, *E. formosa* is used successfully in greenhouse vegetable production to control whiteflies. It is important to accurately identify the pest you are trying to control with a parasitoid. Inform the bio-control supplier of the pest species in your crop so they can recommend the most effective parasitoid for the pest and crop situation.

Biology

The adult female wasp lives for about 15 -30 days. Longevity of a female parasitoid diminishes rapidly with increasing temperatures. Adults obtain energy and nutrients by consuming honeydew produced by the whiteflies and by feeding on whitefly larvae. A population of *E. formosa* consists mainly of females.

E. formosa searches the plant canopy for whitefly larvae. Upon finding the correct size to parasitize (third or early fourth instar larva) she inserts an egg into the whitefly larva with her ovipositor. All stages (egg, larva, pupa, adult) of *Encarsia formosa* develop in the whitefly larva or pupa. One female adult *Encarsia* can lay about 3 -70 eggs.

Introduction interval and duration

Encarsia is introduced weekly at a curative level when whitefly stages are found until sufficient parasitization is reached. If at least 80% of the whitefly pupae are parasitized (black

in case of the greenhouse whitefly), parasitism levels are high enough to cease introductions. It is important to continue to monitor the whitefly populations after introductions are stopped.

Methods of dispersal

Encarsia formosa is supplied in two different manners. The parasitic wasps are supplied either as pupae glued on cards (*Encarsia* cards) or as loose pupae packed in tubes. Both systems have their own specific use in practice. Introduce bio-controls immediately into the greenhouse when they arrive. Most suppliers ship bio-controls via overnight delivery.

How to determine if *E. formosa* releases are reducing whitefly numbers



Parasitized whitefly pupae (David Cappaert, Michigan State University, Bugwood.org)

A healthy whitefly pupa is creamy white in color. Approximately eight days after being parasitized, the effected whitefly pupa will begin to turn grey. As the parasitoid larva grows, the pupal case changes in color from grey to black. It is at this point that a parasitized pupa can be easily recognized. The entirely blackened appearance indicates that the *E. formosa* larva has developed to the pupa and maturation of the adult wasp begins. Within seven days, a mature wasp emerges through a round hole chewed in the head portion of the top surface of the pupa. The duration of this life cycle at 73.4 is approximately 19 -21 days. The life cycle duration is completely dependent upon temperature.

Considerations

- At a temperature below 64.4°F, the parasitic wasps will not frequently fly, and their searching ability is limited. At temperatures above 86°F, the adult life span is considerably reduced
- Certain pesticides (e.g. pyrethroids) can have a long residual effect on *Encarsia*.
- Consult a bio-control supplier for information on pesticide residues.
- If *Encarsia* is introduced too late, honeydew excreted by the whitefly on the leaf hampers the mobility of *Encarsia* and consequently parasitism.
- By removing lower leaves too early, parasitized pupae that have not yet emerged, may be removed from the greenhouse.
- Consult the supplier about introduction rates. This will require crop inspection (scouting) to determine whitefly population levels.

Benefits

- Applicable in a wide range of crops
- Efficient searching ability
- Parasitized (black) pupae are easily recognized
- Adults feed on small whitefly instars
- Easy to introduce
- Reliable results
- Economical

Biological Control of Whiteflies:

Parasitoid wasp (*Eretmocerus eremicus*)



Eretmocerus eremicus (United States Department of Agriculture, WHITEFLY KNOWLEDGEBASE)

Eretmocerus eremicus is a fairly new agent for whitefly control and is more effective in controlling SLWF than *Encarsia formosa*. It will also parasitize greenhouse whitefly. Generally, *Eretmocerus* is more resistant to pesticides than *Encarsia formosa*. The primary supplier, Biobest, is currently carrying out numerous experiments to determine the side effects of pesticides on this parasitoid.

Biology

The adult female wasp is lemon-colored with thick antennae. *Eretmocerus* can develop in any larval stage of the whitefly, but it prefers the second and early third stage. This wasp will also feed on whitefly larva. *Eretmocerus eremicus* lays its eggs under the whitefly larva. Introduction interval and duration

Eretmocerus is introduced weekly at curative levels when whitefly stages are found until sufficient parasitism is observed. If at least 80% of the whitefly pupae are parasitized (brown in color for greenhouse and silverleaf whitefly), parasitism levels are high enough to cease introductions. It is important to continue to monitor whitefly populations after introductions are stopped.

Methods of Dispersal

Eretmocerus eremicus is supplied in two different forms. The parasitic wasps are supplied as pupae glued on cards or as loose pupae packed in tubes. Both systems have their own specific use in practice. Introduce bio-controls immediately into the greenhouse when they arrive. Place cards underneath plant canopy, out of direct sunlight. Most suppliers ship bio-controls via overnight delivery.

How to determine if *E. eremicus* is reducing whitefly numbers

Two weeks after the egg is laid in the whitefly larva, the pupa stage of the whitefly will turn yellow instead of black as with *Encarsia*. In order to exit the host, *Eretmocerus* will make a small round hole in the top of the whitefly pupa and emerge. The complete life cycle takes 17 to 20 days, depending on temperature and the larval stage of the whitefly. Whitefly levels must be monitored each week of the crop cycle by inspecting the larvae on the foliage to determine if it has been parasitized. A 16 -20x hand lens is necessary for examining foliage for signs of parasitism.

Considerations

- At temperatures above 70°F, it is recommended to introduce about six parasitic wasps per square meter for several weeks (whitefly larva needs to be present to introduce *Eretmocerus eremicus*).
- In some crops, introduction can begin at first signs of infestation (e.g. eggplant). In other crops (e.g. tomato), introductions should occur when daytime tunnel temperatures are at

least 70°F. Introduce one *Eretmocerus eremicus* per square meter weekly, until sufficient parasitism is noted.

- When pruning leaves, a few should be examined for signs of parasitism. Leaves on which parasitized whiteflies are found should be left in the high tunnel in order for a new generation of parasitoids to emerge. Employees should be trained in recognizing parasitized whitefly pupae.

Benefits

- *Eretmocerus eremicus* is more tolerant to pesticides than *Encarsia formosa*
- *Eretmocerus eremicus* can tolerate high temperatures
- Both greenhouse whitefly and silverleaf whitefly can be parasitized by *Eretmocerus*
- Parasitized pupae are very easy to recognize due to their yellow color

Biological Control of Aphids in High Tunnels

Effective and timely control of aphid populations in high tunnel production is important due to their ability to develop into large populations quickly. Identification of aphid species is integral to selecting an appropriate bio-control agent. Aphid parasites in particular are host specific and the correct parasite must be applied for timely aphid control. Aphid parasites are effective in searching for isolated aphids, winged aphids and aphid colonies. If identification is uncertain for the aphid species attacking a crop, consider using a general predator rather than a parasite.

Feeding aphids secrete excess sugars from their abdomen in the form of sticky 'honeydew'. Honeydew supports the growth of black sooty mold, reducing plant photosynthesis and often plant yields. Removing sooty mold from fruit increases handling time and can render fruit less marketable. In addition to the direct damage caused by honeydew excretion, aphids are vectors of a wide range of viruses and so can cause indirect damage as well.

Identification of Aphid Species

There are many different aphid species that are reported in Pennsylvania greenhouse production including the green peach aphid, potato aphid, and melon aphid. The aphid that is usually found to infest vegetable crops, especially tomatoes and other Solanaceous crops (peppers, eggplant), is the potato aphid (*Macrosiphum euphorbia*).



Potato aphid (Whitney Cranshaw, Colorado State University, Bugwood.org)



Green peach aphids (David Cappaert, Michigan State University, Bugwood.org)

The most outstanding characteristic for identifying aphids is by the two cornicles ("tail pipes") on the rear of their abdomen. Color is variable among species and is not accurate for

identification. As aphids increase in size, they shed their exoskeletons (cast skins). These white cast skins, often mistaken for adult whiteflies, can be found on leaves or stuck in honeydew excretions

Biology

In protected environments such as greenhouses and high tunnels, aphids are very prolific. Instead of reproducing by eggs, female aphids (stem mother) give birth to live offspring (3-10 per day) that start to feed immediately. Within a week, this offspring will be ready to reproduce. Aphids can have two forms: winged or Wingless. As colonies enlarge, aphids develop wings to migrate to less populated areas in the crop.

Monitoring

Plant monitoring should begin at the seedling stage and continue through the duration of the crop cycle. Start plant inspection on lower leaves and continue up the plant to the growing tips. As aphids feed on growing tips, the leaves curl, sometimes looking like virus symptoms. Yellow sticky cards are useful in detecting winged aphids. Hang sticky cards 4 to 6 inches from growing tips. The presence of ants in the greenhouse may indicate aphid development, since the ants feed on the excreted honeydew and thus protect the aphids. When introducing natural enemies, place them in an area protected from ants and control ants with baits or traps.

Biological Control of Aphids:

Lady Beetles (*Hippodamia convergens*)



Ladybeetle larva feeding on aphids (Clemson University - USDA Cooperative Extension Slide Series, Bugwood.org)

Lady beetles are general predators that feed on a number of soft-bodied insects including aphids, whiteflies (immature stages), scale, and thrips. Because they are excellent at seeking out prey, they are effective for cleaning up "hot spots." This feature, combined with their propensity to establish under the appropriate conditions, makes them good candidates for high tunnel bio-control agents.

Biology

There are 500 species of lady beetles reported to occur throughout North America. The most commonly recognized of the species are those that have an orange to orange-reddish body with black spots; these are recognizable even to children who learn them as "ladybugs."

Most lady beetles consume mites and soft-bodied insects, while a few feed on fungi. A small number feed on plants and these are notable pests such as the Mexican bean beetle and Squash beetle. When the insect feeding species lack prey items, they often survive on

nectar, honeydew, and/or pollen. Under such conditions, however, they typically do not reproduce.



Adult *H. convergens* (Russ Ottens, University of Georgia, Bugwood.org)

The Convergent lady beetle (*Hippodamia convergens*) is the most commonly used species for biological control, although many other species are effective background predators if allowed to establish naturally. The life cycle of the Convergent lady beetle consists of four distinct stages: an egg stage; a larval stage (with numerous sub-stages of development); a pupal stage; and an adult stage. The larval and adult stages are the two stages when predatory feeding occurs.

Many species of lady beetle including the Convergent lady beetle aggregate during certain times of the year. This feature permits easy collection/rearing and release, but it also presents difficulties. For example, without proper enticement or containment, lady beetles will often leave the area where they were released. For this reason, it is critical that growers follow a few simple guidelines for release (outlined in the next section) as well as provide adequate enticement in the form of prey (for eating) and moisture (for drinking). If lady beetles establish within the high tunnels, satisfactory control of pests such as aphids can be expected.



Lady beetle eggs (Joseph Berger, Bugwood.org)



H. convergens larva (Louis Tedders, USDA Agricultural Research Service, Bugwood.org)

If well-timed, female Convergent lady beetles will seek out aphid groups and lay eggs in the vicinity. The eggs will hatch in about a week and give rise to alligator-shaped larvae that will begin to feed voraciously on adjacent aphids. Each lady beetle adult and larvae can eat anywhere from several dozen to several hundred aphids. Pupation follows several stages of larval development.

Method(s) of dispersal

Ladybeetles are sold as adults in pints, quarts and gallons. They are dispersed by placing the shipping medium (typically fibrous) plus loose beetles throughout the high tunnel structure.

Introduction interval and duration

Releases can be made from late spring to early summer onwards on a prophylactic basis, but are most economical when timed to synchronize with aphid population development. Releases within high tunnels should occur in the evening, and should be done while the structure is completely closed (i.e. not ventilated). This will encourage the beetles to investigate conditions within the tunnel(s), rather than to flyaway. A hand-full or so of beetles should be placed at each "hot spot" in the tunnel to assure that the beetles find food easily and quickly. Some growers use sugar water to coat the beetles at release so that they find it difficult to fly. This will further encourage investigation and, hopefully, establishment.

The next day following release(s), high tunnels must be ventilated before temperatures become too great. In the summer months, this should occur no later than 9:00 - 10:00 AM, unless the weather is unseasonable cool or cloudy. The objective is to contain the beetles for as long as possible without causing detriment. Experience at the Penn State High Tunnel Research and Education Facility suggests that effective numbers of adult beetles will remain in tunnels, on average, for two to four weeks following release. However, if the adults have laid eggs, one can expect a permanent presence for as long as food and water are available.

Considerations

- Make sure favorable (temperature) conditions for containment exist before releasing beetles into high tunnels.
- Place beetles near "hot spots" for rapid feeding and control.
- Monitor beetle establishment by scouting for eggs and larvae in the weeks following release(s).

Benefits

- Effective against a variety of soft-bodied pests
- Economical
- Can be readily encouraged to establish in high tunnels

Biological Control of Aphids:

Lacewings (*Chrysoperla* spp.)

Lacewings are voracious predators of a wide variety of soft-bodied arthropods. In addition, some species exhibit tolerance or resistance to certain insecticides, which makes the predator more compatible with IPM systems. Green lacewing larvae, also known as "aphid lions", possess excellent searching qualities, exhibit high dispersal ability, and are particularly active against aphid pests.



Green Lacewing adult (Frank Peairs, Colorado State University, Bugwood.org)

Green lacewing adults are typically $\frac{3}{4}$ inch long, have long netlike wings, slender pale green bodies, and golden eyes.

Larvae are "alligator" shaped, with long, forcep-like, curved tubular mandibles, and have colorations ranging from grey to brown.

The pupa is formed inside a spherical silken cocoon that is attached to vegetation.

Eggs are green, oval-shaped, and attached to the end of a hair-like filament.



Green lacewing larva feeding on an aphid (Bradley Higbee, Paramount Farming, Bugwood.org)



Lacewing egg (John Ruberson, University of Georgia, Bugwood.org)

Lacewings are sold as eggs and larvae.

Biological Control of Aphids:

Predatory Midge (*Aphidoletes aphidimyza*)



Aphidoletes aphidimyza feeding on aphids (Whitney Cranshaw, Colorado State University, Bugwood.org)

The predatory midge, *Aphidoletes aphidimyza*, is a general aphid predator that attacks many different species of aphids. It can be used alone or combination with a parasite for rapid control. This predator is most effective where aphid "hot spots" (clumped populations) are found to occur. The main advantage to using *Aphidoletes* is its usefulness in a variety of crops (peppers, eggplants, cucumbers, etc.) on which different species of aphid occur.

Biology

Aphidoletes is a predatory gall midge that attacks over 70 different aphid species. The adult midge is about 2.5 mm long, with long legs and a slender body. It is mainly active at night, lives for 7 to 10 days on average, and commonly feeds on honeydew.

After dusk, the female midge deposits her eggs in aphid colonies. She is attracted to aphid colonies by the smell of honeydew. The eggs hatch into tiny larvae (0.3 -3.0 mm) that search the leaf for suitable prey. Upon finding an aphid, a larva injects a paralyzing toxin which dissolves the body contents. It then attaches it's mouthparts to the aphid and feeds on the dissolved contents.

Each larva needs to feed on about five aphids to complete its development; however, it will devour more if they are available (up to 65 aphids). Initially, the larva is transparent orange but becomes orange, red, brown or grey---depending on the food source. In about 7 to 14 days, the larva falls from the plant into the soil, using the soil particles to make a cocoon. Within 7 to 10 days after forming a cocoon in the soil, a new adult gall midge will emerge.

Method(s) of dispersal

Aphidoletes aphidimyza is usually shipped as pupae in a vermiculite carrier. Adults will emerge from pupa when placed in a warm greenhouse or high tunnel. Introductions should be made throughout the plant canopy, away from direct sunlight. They should also be made in early morning or evening near aphid colonies. *Aphidoletes* can be obtained through most biological control distributors.

Introduction interval and duration

Reduce or eliminate the use of toxic or residual pesticides before introducing *Aphidoletes* or any other natural enemy; this predator is very sensitive to pesticides. Release on a preventative basis or introduce at a higher rate (curative) when aphid colonies are first found. Consult the supplier for exact rates.

Considerations

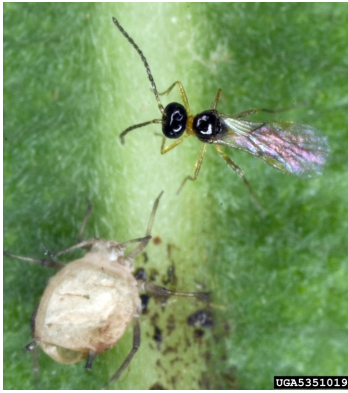
- Three to four successive introductions are needed to build a sustaining population of *Aphidoletes*. Augment with new introductions throughout the season on an as needed basis.
- When pruning, examine leaves for orange larvae. These leaves should be left in the greenhouse so that the larva can complete the life cycle. All employees should be trained in recognizing this life stage.
- When introducing into the greenhouse, protect predators from ants. Ants feed on honeydew and thus protect the aphid colonies from natural enemies. Install traps for ants.
- Monitor the effectiveness of this predator by looking for aphids that appear to be shriveled and eventually turn brown and/or black and decay. Use at least a 10x hand lens when inspecting.
- In soil cultures, larvae can pupate in the ground and successive generations will occur. This eliminates the need for continual introductions.
- If soil is covered by plastic, there are no appropriate sites for pupation and many will die. Successive generations do not occur and continued releases are required.
- The larva enters hibernation (lower temperatures, shorter days), starting in late September unless you add supplemental light (one 60 watt bulb per 30 feet, or 100 watt bulb per 65 feet). If you are growing a fall crop, a better strategy would be the application of a parasite such as *Aphidius ervi* or *Aphelinus abdominalis*.

Benefits

- Control all aphid species
- Can be applied in several crops
- Excellent searching ability
- Curative control of aphid colonies
- Long lasting effect in soil

Biological Control of Aphids:

Parasitic Wasps (*Aphidius colemani*, *Aphidius ervi*, and *Aphelinus abdominalis*)



Aphidius colemani (David Cappaert, Michigan State University, Bugwood.org)



Aphid "mummy" (W.D. Hutchison, University of Minnesota)

Aphidius colemani is a tiny parasitic wasp that is used to control green peach and melon aphids. The adult wasp lays an egg in the aphid. The egg hatches into a larva which spins a cocoon, producing a new wasp. The wasp exits the aphid body, leaving behind a brown shell called an aphid "mummy."

Aphidius ervi is used to control potato aphids. It is a parasite that is similar appearance and biology to *Aphidius colemani* but is about twice the size.

Biological Control of Aphids:

Parasitoid wasp (*Aphelinus abdominalis*)



Aphelinus abdominalis with aphid prey (Frank Peairs, Colorado State University, Bugwood.org)

Aphelinus is a very tiny wasp, about 3.0 mm long, with short legs and antennae. The female has a black thorax and a yellow abdomen. The female can parasitize any aphid stage including winged aphids. When the female wasp finds an aphid, she injects her ovipositor and deposits an egg. The parasite larva develops inside the aphid body transforming it into a black mummy. The new wasp will emerge through a hole chewed in the aphid exoskeleton. *A. abdominalis* will also feed on aphids that she does not parasitize.

Method(s) of dispersal

Aphelinus abdominalis is usually shipped as adults or mummies. These can be stored in darkness for up to two days at 47 -50° F; however, it is best to distribute parasites immediately. Release wasps by tapping them onto leaves of infested plants (hot spots) in the morning or evening, avoiding direct sunlight. These wasps are not very mobile so placing them close to infestations will increase effectiveness.

Introduction interval and duration

Reduce or eliminate the use of toxic or residual pesticides before introducing *Aphelinus*. Consult a bio-control supplier for specific information regarding pesticide use. Release *A. abdominalis* on a preventative basis or introduce at a higher rate (curative) when aphids are first noted. When aphids are first observed, introduce *Aphelinus* at a curative rate for 3 introductions at 1 week intervals. Monitor weekly for the development of black, mummified aphids. When 80% of the aphids are parasitized a parasite to prey balance has been achieved and no further introductions are needed. Augment with further introductions as required since aphid migration from outside may occur in warmer months.

Considerations

- When pruning leaves, check for parasitized aphids (black mummies). If mummies are present keep these leaves in the greenhouse until new parasites hatch.
- When aphid populations are heavy, the production of honeydew can interfere with the searching ability of the parasite. Heavy aphid populations can be reduced with soft, compatible compounds or by using ladybeetles.
- Protect parasites from ants. Ants feed on honeydew and thus protect the aphid colonies from natural enemies. Install traps to control ants.
- Activity of parasites is reduced at high temperatures (above 86° F).
- Determine specific release rates with a bio-control advisor or consultant.

Benefits

- Long lasting form of aphid control
- Black parasitized aphids are easy to recognize
- Parasitize and feed on aphids

Biological Control of Mites in High Tunnels

The spider mite was the first greenhouse pest to be controlled by a commercial application of predatory mites. There are a limited number of pesticides available for treatment of this pest in greenhouse and high tunnel production; consequently, an integrated approach using biological control in conjunction with compatible bio-rational materials is recommended.

The Two-Spotted Spider Mite (*Tetranychus urticae*)

The two-spotted spider mite is the most problematic spider mite in greenhouse crops and can infest a variety of crops including tomatoes, peppers, eggplants and ornamental plants. Most of the difficulty involved in controlling this pest is initial detection for timely treatment. Since there is no winged stage, sticky traps are ineffective; consequently, plant inspection is the only reliable method for determining the presence of mites and assessing their numbers.

Damage is caused by larvae, nymphs and adults piercing the plant cells and sucking out the contents. The damaged cells appear as yellowish white spots on the upper surface of the

leaf, due to the loss of chlorophyll. As populations increase, the whole leaf will eventually turn yellow. Crop losses may occur when about 30% of the leaf surface is damaged.

A population of two-spotted spider mites can increase rapidly during hot, dry periods. Both chemical and biological control treatments must be initiated when spider mite numbers are low for greatest efficacy.

Biology

Two-spotted spider mite has five life stages, egg, larva, first nymphal stage (proto-nymph), second nymphal stage (deutonymph), and the adult mite. The female deposits round eggs on the underside of the leaf. These eggs hatch into larva with six legs that begin feeding immediately. After they have eaten, their color changes and two dark spots appear in the middle of the body. The larvae take in enough food before they settle on the leaf with their legs drawn in until they develop into the proto-nymph.



Two-spotted spider mite adult (Frank Peairs, Colorado State University, Bugwood.org)



Two-spotted spider mite damage (Whitney Cranshaw, Colorado State University, Bugwood.org)

After a period of feeding the proto-nymph develops into the deutonymph. The two body spots are very visible on these two stages compared to the larvae. The total development time varies with temperature, humidity and the host plant. Approximate development time (egg to adult) at 86°F is 7 days. Nymphs and adults produce webs and if populations are high the plant can be completely covered with webs. At this point, obtaining control is difficult and biological control is not effective.

Monitoring

Mites usually develop on the undersides of leaves and are often found at certain spots in the greenhouse. These areas have a more favorable climate for development (dry, warm). Inspect plants for mite development near heaters, doors and vents. It is important to have at a 16x hand lens to monitor for this pest. If you have difficulty detecting mites on leaves, tap the leaves over a sheet of white paper. This technique dislodges mites (and other pests) and provides for easier identification.

Remember to maintain broadleaf weed control inside the greenhouse and at least 20 feet around the outside. In many cases, spider mite infestations develop from weeds left in the greenhouse from the previous crop season. Remove the weeds and destroy!

Biological Control of Spider Mites:

Predatory Mite: *Phytoseiulus persimilis*

Phytoseiulus persimilis is a predatory mite and the mainstay in spider mite control since it can be used on many crops including tomato, pepper, cucumber, squash, beans, flowers and interior landscapes. It can also be an effective predator in field crops such as strawberries and other small fruits.

Biology



Phytoseiulus persimilis (Copyright 2007 Regents of the University of California)

The adult mite is pear shaped and shiny orange, while the nymph stage is pale salmon-colored. Predatory mites have longer legs than the pest mites. A *Phytoseiulus* adult deposits her eggs (oval shaped compared to round spider mite eggs) near spider mite colonies. The larval stage is followed by the proto-nymph, deuto-nymph and adult stage.

Development time from egg to adult is 5 days at 86°F. Usually, *Phytoseiulus* will develop faster than the spider mite if the temperature is below 86°F and humidity above 60%. At low humidity, the egg of the predatory mite will die. The activity of *Phytoseiulus* can be extended by creating high humidity by spraying water through a fine nozzle and high pressure.

The adult mite will feed on all stages of spider mites, while the nymphs will feed only on eggs, larvae or proto-nymphs. Upon finding prey, *P. persimilis* kills the mite and consume the body contents. If spider mite populations are high and webbing is evident, these populations should first be treated with soft pesticides before introducing predatory mites. Consult a bio-control supplier for information on compatible compounds.

Method(s) of dispersal

Phytoseiulus persimilis is supplied in tubes of 1000 to 2000 adults mixed with vermiculite or wood chips. Shake the tube to mix the predatory mites equally in the carrier before application.

Scout crop and flag active spider mite colonies. Return to these flagged areas to monitor the effectiveness of the introduction. A 10x hand lens is required when inspecting for spider mites life stages. Concentrate predator introductions at spider mite hot spots (flagged areas) as soon as possible after delivery.

Introduction interval and duration

Introduce predators weekly for three weeks or until desired control is achieved. Spider mite colonies should clean-up within 2 to 3 weeks. If adequate control is not achieved, increase the rate of predatory mites.

Considerations

- Start early to control spider mite populations since spider mites reproduce faster than predatory mites at high temperatures and low humidity.
- Monitor for effectiveness by inspecting plants for dead spider mites that appear as tiny black dots on plants. Inspect spider mite colonies for the oval predator mite eggs and the adult predator mite.
- Consult a bio-control supplier for precise rate determination.

Benefits

- Active year round -no diapause
- Feeds on spider mite eggs, larvae, nymphs and adults
- Reproduction is faster than spider mite at 86°F
- Can be used on a variety of vegetable crops and ornamental plants

Biological Control of Spider Mites:

Predatory Midge: *Feltiella acarisuga*

The predatory midge, *Feltiella acarisuga*, is a natural enemy that can be used in conjunction with predatory mites. *Feltiella* is good at finding hot spots, so the two predators are complimentary.

Feltiella can be an effective year-round predator and is particularly useful on hairy leaved plants (such as tomatoes). This is a predator that may occur naturally in greenhouses and high tunnels if spider mites densities are high and pesticides are not being used.

Biology



Feltiella acarisuga larva (Whitney Cranshaw, Colorado State University, Bugwood.org)

The adult is a delicate, pink-brown fly, only about 1 mm long, with long legs. They do not feed and only live 3 to 4 days after emerging from the cocoon. High humidity improves midge emergence. Optimal conditions for *Feltiella* are 68-81°F and relative humidity greater than 60%. Larvae can tolerate a wider range of conditions than the adult.

Adults actively search for spider mite colonies. Each female lays an average of 30 shiny yellow eggs near high densities of mites, usually where webbing occurs. The tiny eggs hatch in 5 to 7 days. The brownish yellow midge larvae grow to about 2 mm long. Upon hatching they move to a spider mite, sink their mandibles in, and suck out the contents. They can consume over 300 mite eggs as they complete their development in about a week in the greenhouse. Under cooler conditions the larval stage may take up to a month to complete. They spin fluffy white cocoons on the underside of leaves, usually along a leaf vein, in which to pupate. The pupal stage lasts approximately one week in the greenhouse, but longer under cooler conditions.

Method(s) of dispersal

Feltiella acarisuga is shipped to the grower as pupae on leaves in units of 250. Open the box containing predators in the high tunnel and place as close as possible to spider mite infestations. Let the box stand for at least one week until adults have emerged.

Introduction interval and duration

Start early to control spider mite populations since spider mites reproduce quickly at high temperatures and low humidity. Concentrate predator introductions at spider mite hot spots as soon as possible after delivery. Monitor for predator activity by checking spider mite colonies for larval development and for shriveled mites that have been fed upon. Monitoring should be done once a week, consistently.

Considerations

- Always use *Feltiella acarisuga* in conjunction with a predatory mite' such as *Phytoseiulus persimilis*.
- *Feltiella* larva feeds on eggs, nymphs and adults of two-spotted spider mites.
- Consult your supplier for rates and introduction schedule.

Benefits

- The adult midge is capable of flying and locating colonies of spider mites.
- Applicable in crops where scouting is difficult (ie. ornamentals)
- Can and should be introduced with predatory mites such as *Phytoseiulus persimilis*.
- Active in cold and dark weather in spring and fall.
- May provide long lasting protection with several introductions.

Biological Control of Spider Mites:

Predatory mite (*Neoseiulus californicus*)



Neoseiulus californicus (L. Buss, University of Florida)

Neoseiulus californicus is a predatory mite that can be introduced on preventative basis since it can survive in the absence of prey. It is also a desirable option because it doesn't require high relative humidity for reproduction.

Biology

The five different stages of this mite are the egg, larva, protonymph, deutonymph and adult. The adult predatory mite lives about 20 days and can lay up to 3 eggs a day. It is able to consume 5 adult spider mites daily in addition to feeding on eggs and larvae. The life cycle can be completed within 4 days with high temperatures.

Method(s) of dispersal

N. californicus is shipped to the grower as mobile stages. Introduction interval and duration Start early to control spider mite populations since spider mites reproduce quickly at high temperatures and low humidity. If used on a curative basis, introduce *N. californicus* with *Phytoseiulus persimilis* to clean up hot spots. Concentrate predator introductions at spider mite hot spots as soon as possible after delivery.

Monitor for predator activity by checking spider mite colonies for larval development and for shriveled pest mites that have been fed upon. Monitoring should be done once a week, consistently to determine if future introductions of predatory mites are needed.

Considerations

- Can be used on outdoor crops.
- *N. californicus* also attacks the broad mite (*Polyphagotarsonemus latus*) and the cyclamen mite (*Tarsonemus pallidus*).

Organic Production in High Tunnels

Kelley Belina and Terry Nennich, University of Minnesota, and Meg Moynihan, Minnesota Department of Agriculture

Introduction: Rules and Recommendations

High tunnels have several characteristics that make them ideal for growing organic vegetables and fruits. Many of the overall stresses associated with outdoor production are eliminated in a high tunnel. Plants grown in high tunnels are protected from rain and constant wet foliage caused by dew, which is often a major cause of disease problems. Daily water needs can be supplied by drip irrigation, which can prevent erratic soil moisture conditions that are often the cause of fruit cracking. Plants are also protected from high winds, which can cause micro-bruises of plant tissue and allow disease organisms to invade the plants.

The high tunnel structure can provide a safe haven for predatory insects to live and thrive, whether they are natural or introduced. This gives the organic high tunnel producer a major tool to control pest insects. In addition, in properly managed high tunnels there is little leaching of plant nutrients from the soil, giving the organic producer an opportunity to efficiently use organically approved soil fertility products that may be too costly or time-consuming to use in outside applications. Because of the increase in both growing days and heat units, producers have an opportunity to use cover crops and other methods to help comply with the national organic recommendations and requirements.

When high tunnels are used with good management, organic producers have an excellent opportunity to produce high quality produce at an economical cost, which will bring premium prices in the marketplace.

Organic Production

Organic growers are committed to using environmentally sound production practices and improving the quality of their land. This commitment, and the lack of synthetic inputs, is what draws consumers to organic products, and what brings premium prices for organics at the marketplace.

However, organic production involves intensive field monitoring and record-keeping, and a certification process is necessary to use the organic label. This is a management-intensive system of farming that relies on biology, timing, and ecological cycling to create vigorous crops and to manage insect pests, weeds, and disease. Organic is a regulated claim: there is a set of national standards, administered by the USDA National Organic Program, with which growers must comply in order to legally use the term “organic” for a product they sell.

Getting Started

The processes and regulations for organic certification of high tunnels are no different than certification of field production. The most basic requirements for certification are:

1. land must not have any prohibited materials applied for three years before harvest **and**
2. a written, comprehensive organic system plan that describes in detail the management of the land for which you are seeking certification.

Organic production at any level requires intensive record keeping so consumers can be assured the product they are purchasing is truly organic.

Organic growers must understand that there are few, if any, controls for major outbreak of production problems as with conventional production. Therefore it is of extreme importance that organic producers fully understand insects, disease and weed cycles and implement preventative strategies, anticipating problems before they happen.

Before you start organic production, think about the changes that you and your operation will need to undergo. Talk with other successful organic producers. You may qualify for exemption from certification if you grow less than \$5,000 of organic product per year AND farm in full compliance with the National Organic Standards. However, you should talk to one or more accredited organic certifying agencies so that you get a complete understanding of what organic production is really about. And remember that the \$5,000 exemption does not exempt you from any organic requirements, only from inspection and certification. Your produce must be as traceable through intensive record-keeping as products grown by certified producers.

An excellent resource for a high tunnel grower thinking about, or currently in the process of, transitioning to organic production is “Organic Certification of Vegetable Operations” <http://swroc.cfans.umn.edu/organic/vegetable.pdf>. This comprehensive publication outlines and explains all of the requirements for organic vegetable production. It includes, among other things: the organic transition process, how to choose a certification agency, and requirements and examples of record keeping.

What do you mean, “organic?”

“Organic” is a guarantee about how an agricultural food or fiber product was grown and handled before it reached the consumer. It’s also a set of standards for farmers who grow plants and animals, and for processors and handlers who turn it into food or clothing products.



Farmers and food processors that make organic claims must meet national organic standards, maintain careful records, and be certified by a USDA-accredited organization, a process that includes on-site inspection.* Certification assures consumers that the product was grown and processed organically. There are stiff penalties for fraud, which means representing a non-organic product as organic.

What do the standards require?

Organic crops must be grown on land managed to reduce erosion and improve soil quality. The transition takes three years: no synthetic inputs may be used for 36 months prior to harvest of the first organic crop.

Weeds, insects, and other pests are controlled using practices like crop rotation, mulching,



tillage, variety selection, and biological control. Most synthetic herbicides and pesticides are prohibited, although a few synthetic nutrients and soil additives appear on a special National List and are allowed. There are strict manure and compost guidelines. Sewage sludge is prohibited. Organic farmers may not use genetically modified seed.

*Farms that gross less than \$5,000 in organic sales may be exempt from certification. *Excerpted with permission of Minnesota Department of Agriculture, Feb. 2010*

Organic High Tunnels at the University of Minnesota

The University of Minnesota is currently conducting organic high tunnel research in two locations: Crookston, at the Northwest Research and Outreach Center (NWROC), and Lamberton, at the Southwest Research and Outreach Center (SWROC).

NWROC - Crookston, MN

At Crookston, current research concerns fertility and fertilization of organic production in tunnels. A soluble fish-based solution (nutrient analysis 4-1-1) was tested in 2008 and 2009, and found to be compatible with drip tape. One-half of the tomato and cucumber plantings were fertigated on a continuous flow basis, using two fluid ounces of fish solution (0.09 ounces of N by weight) per 100 feet of tape early in the season, increasing to six fluid ounces (0.28 ounces of N by weight) per 100 feet as plants grew and their nutrient needs increased.

Manure-based compost was incorporated over the entire area before planting. Control plants received only water through the irrigation tubing, while test plants received the equivalent (over the entire season) of 280 lbs/acre N (41 oz N/100 linear ft of row), 70 lbs/acre P (10 oz P/100 linear ft of row), and 70 lbs/acre K (10 oz K/100 linear ft of row). Results in the following table show that fertigation increased tomato yields in both years and cucumber yields in one of the two years.

Yield study using 'Cobra' tomato and 'Sweet Success' cucumber				
	2008		2009	
	----- yield in pounds per plant -----			
Treatment	Tomato	Cucumber*	Tomato	Cucumber
Control	45	18	25	28
Fertigated	49	13	31	42

*Low cucumber yields in 2008 were due to early harvest.

For information and recommendations for preparing the soil and providing plant nutrients in organic systems, see the chapter, "Fertility and Fertigation Management."

SWROC - Lamberton, MN

Introduction

The organic high tunnel vegetable project in Lamberton is still in its early stages. Our primary goal in managing an organic high tunnel over a number of years is to observe benefits and to troubleshoot problems a high tunnel operator in this region would likely

experience. With this information we hope to develop recommendations to alleviate some of the risk associated with starting an organic high tunnel.

Our experimental trials at the SWROC high tunnel include:

- Comparison of harvest dates and yield and quality of produce to outdoor production.
- Optimal planting and harvest dates for extended season greens production, including using additional row covers inside the high tunnel.
- Fall planting of a leguminous green manure crop for soil-building and increased fertility.

The third point above addresses what may be the primary concern in organic verses conventionally managed high tunnels—sufficient soil fertility. Due to the high production rates achievable in high tunnels, fertility can be a major concern. This is especially true in organic high tunnels, where synthetic fertilizers are prohibited. In organic high tunnels, pre-plant compost addition is the primary source of plant nutrients. We are closely tracking soil and plant tissue nutrients in our high tunnel.

Management

The first season of organic vegetable production in the Lamberton high tunnel was 2009. Composted beef cattle bedding is our primary nutrient source. This is worked into each bed in the high tunnel in the spring before planting, with application rates based on our soil and compost nutrient test results. We use a drip irrigation system. After the beds are shaped and drip lines put down, each bed is covered with black plastic mulch. Our vegetable plants are started in a greenhouse and were transplanted into holes in the mulch in mid-April in 2009.

In 2010, transplants will be put in the high tunnel the first of April, two weeks earlier than last year. In case of cool temperatures, especially at nighttime, we will test using a portable propane heater in the high tunnel (L.B. White, Onalaska, WI, model CP155, 155,000 BTU for our 48' x 30' high tunnel). This is a thermostatically controlled heater we will set to keep temperatures in the high tunnel above 60°F after transplanting. We are interested to see how much propane this supplemental heating will consume, and if this additional cost pays off with earlier and higher quality vegetables.



Figure 1. Organic high tunnel and outdoor plot in Lamberton, MN, 2009.

In our high tunnel we are growing determinate tomatoes, indeterminate tomatoes, cucumbers, and peppers, each in their own bed. We also have one bed dedicated to early and late season greens (lettuces, spinach, arugula, etc.). Crops are rotated among beds each year. Indeterminate tomatoes and cucumbers are trellised and pruned as in greenhouse production. A beneficial flower mix is planted along the edges of the high tunnel to attract pollinator and predator insects.

In 2009 we began fall planting a leguminous green manure crop, on half of each bed, for spring incorporation. This should add additional nitrogen and improve soil structure in the high tunnel beds, compared to compost only. However, because of the season extension capabilities of high tunnels, post-harvest and pre-plant windows for establishing and cultivating a green manure crop are limited. In addition to soil amending, we will observe if any fertility benefit is desirable given the potential cost increase of the salable product.

First Year Results

In 2009, as expected, our high tunnel extended the harvest season, ranging from six weeks (lettuces, tomatoes) to ten weeks (red bell peppers) earlier than outdoors. More produce was harvested from the high tunnel compared to outside (some of the largest differences were approximately two times as many Diva cucumbers and Ace peppers). Fall greens were harvested into the last week of November. The use of the drip irrigation and mulch effectively eliminated weeds in the high tunnel.

In this first year, we should note that the setbacks we encountered were not related to growing organically, but to chance occurrences and general management practices. First, we encountered a virus which forced us to pull some tomato and pepper plants. Luckily the disease did not spread far. Second, as we did not use supplemental heat or shading this year, our temperatures inside the high tunnel fell low in the spring and climbed high in the summer. We believe this especially affected our tomato production with much of the determinate and indeterminate tomatoes showing “green shoulders.” Thus lessons from our first year included the importance of continuously scouting for diseases and pests and the need for close temperature regulation.

In 2010 we are building two additional high tunnels at the SWROC, for production in 2011. We are also holding our first Season Extension Day in May. As more growers in Southwest Minnesota, around the state, and in the Upper Midwest construct high tunnels, we hope to build a knowledge base of information to share at field days and in publications such as this. We will continue to update this section of the manual as we gain more information.



Figure 2. Organic ‘Diva’ cucumbers, ‘Cobra’ tomatoes, and ‘Carmen’ sweet Italian peppers from the SWROC high tunnel in 2009.

Resources

In addition to the “Organic Certification of Vegetable Operations” <http://swroc.cfans.umn.edu/organic/vegetable.pdf> cited above, each year there are more good informational resources for high tunnel growers. The National Sustainable Agriculture Information Service has a publication called Organic System Plans: Market Farms and Greenhouses, which is clear, concise and relevant to high tunnels and others about managing insects in and producing specific crops. You can get a copy at www.attra.org or by calling 1-800-346-9140 (800-411-3222 Español).

Where can I get a copy of the national organic standards?

www.ams.usda.gov/nop (under NOP Regulations)

Where can I find a list of certifiers that operate in Minnesota?

www.mda.state.mn.us/news/publications/food/organicgrowing/usdaaccredited.pdf

Where can I contact a real, live certified organic farmer for information and advice?

<http://mofie.coafes.umn.edu>

Where can I find information about inputs that are allowed (or prohibited) in organic production?

www.ams.usda.gov/nop and www.omri.org

Where can I get information about being exempt from certification?

<http://www.mda.state.mn.us/en/food/organic/exemptions.aspx>

Where can I find information about current organic vegetable, fruit, and crop prices?

<http://www.rodaleinstitute.org/Organic-Price-Report>

Where can I find sound, reliable organic production information for various crops?

<http://www.attra.org/organic.html>

How and to whom do I report suspected pesticide drift onto my operation?

<http://www.mda.state.mn.us/chemicals/spills/incidentresponse/guidelist/guidance-doc-1.aspx>

Are there loans available for organic growers?

<http://www.mda.state.mn.us/grants.aspx> also, contact your local USDA Farm Service Agency (FSA) office and local lenders.

<http://attra.ncat.org/guide> Building Sustainable Places outlines and explains Federal programs for sustainable agriculture, forestry, entrepreneurship, conservation and community development.

What are some other good sources of information about organic agriculture?

Midwest Organic and Sustainable Education Services www.mosesorganic.org

Northern Plains Sustainable Agriculture Society www.npsas.org

Organic Ag Info www.organicaginfo.org/

Organic Farming Research Foundation www.ofrf.org

Organic Research at University of Minnesota <http://organicecology.umn.edu>

Organic Trade Association <http://www.ota.com/index.html>

Rodale Institute <http://www.rodaleinstitute.org>

Managing Pollination in High Tunnels

Marla Spivak, University of Minnesota



Honeybee on an apple blossom (Carl Dennis, Auburn University, Bugwood.org)

Tomatoes, peppers, eggplants, cucumbers, squash, melons, strawberries, raspberries: although some of these crops are commonly called “vegetables,” the plant part that is sold and eaten is botanically a *fruit*. Plants produce fruits following pollination of a flower, so for all of these high tunnel crops, pollination must be one of a grower’s concerns.

For many of the crops grown in high tunnels, including leafy greens, onions, and cut flowers, pollination is not necessary. For these crops what is sold is not the fruit.

Pollination of Vegetables in High Tunnels

Tomatoes, eggplants, and peppers are self-fertile, and their flowers contain both pollen and ovaries. Fruit quality and size are improved by having pollen shaken from the anthers onto the pistils. Cucumbers, melons, and squash have separate male and female flowers, so pollen must be moved from the male flowers to the pistils in the female flowers. Bumble bees and other insects are excellent pollinators of these crops, but in most of Minnesota, their populations are usually not large enough to provide this service until June or even July.

For earlier crops of tomato, pepper, and eggplant, growers could try blower pollination using a leaf blower. Every day or every other day, walk the rows of plants, aiming the leaf blower at the flower clusters. For a full description of various mechanical pollination aids, as well as information about how weather conditions affect pollination, see the University of Florida Extension bulletin “Production of Greenhouse Tomatoes” <http://edis.ifas.ufl.edu/pdffiles/CV/CV26600.pdf>.

Cucumbers, melons and squash could be hand-pollinated, but this practice is probably not economically feasible. Instead, either provide bumble bee colonies, or schedule these crops so that they flower in July, August, and September, when native pollinators are abundant. Plan to place the bumble bee colonies in the high tunnel about three weeks after transplanting.

Some cucumber varieties are parthenocarpic; that is, they set fruit without pollination. Parthenocarpic fruit is seedless. For early crops, these varieties can produce before local bee populations are strong enough to help out.

Pollination of Berries in High Tunnels

Strawberries are self-fertile. It's estimated that pollen simply dropping from anther to stigma accounts for about 50% strawberry flower pollination. Wind movement of pollen adds another 15% to 20%, and insect pollination adds another 25%. The more individual pistils to receive pollen, the larger and better shaped the berries will be. Early bloom in high tunnels will require managed pollinators, such as bumble bees.

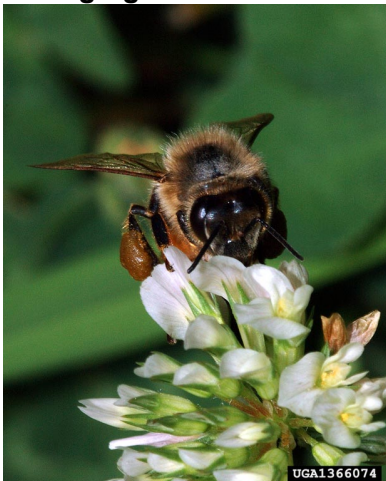


The left and middle berries were self-pollinated and the berry on the right was insect pollinated. (Jim Cane)

For fall-bearing raspberries, native populations of bumble bees are at their strongest in late summer and early fall. As the season progresses and temperatures get cooler, the bees may tend to settle inside the high tunnel, providing pollination services. Pollination of fall-bearing raspberries in high tunnels by unmanaged local bee populations has been very successful.

Summer-bearing raspberries in high tunnels require managed pollination to produce large, firm, coherent berries. This is another reason that fall-bearing raspberries are considered a better choice for high tunnel production.

Managing Bees for Pollination in High Tunnels



Honeybee (Susan Ellis, Bugwood.org)

Honeybees are *not* ideal pollinators for high tunnels. It is the difference in foraging habits that makes bumble bees a better choice. Honey bees communicate with each other as to the best resource in an area and will concentrate their pollen and nectar collecting on that area, which could well be outside the tunnels. Bumble bees do not communicate with each other about the quality of resources and so are much more likely to collect pollen and nectar from whatever is in front of them when they leave their hive. If a colony of bumble bees is located inside or near a high tunnel, the bees will pollinate the flowers in the tunnel.

For growers interested in bees, raising local species of bumble bees could be enjoyable. However, in order to have a strong colony of bees ready to pollinate flowers in May or June, the mated queens would have to be awakened from diapause (a form of hibernation) in February or March. Normally, mated queens emerge in April.



Bumble bee (Russ Ottens, University of Georgia, Bugwood.org)



Bumble bee (Whitney Cranshaw, Colorado State University, Bugwood.org)

Growers may choose to purchase bumble bee colonies to pollinate early crops. The species of bee available commercially, *Bombus impatiens*, is native to Minnesota. Commercially supplied bumble bees are somewhat expensive, but the investment can easily be worthwhile, depending on the size of the tunnel and the value of the crop.

Two companies can ship bumble bee colonies to growers in Minnesota: Koppert and Biobest. A single colony should be sufficient for one or two tunnels, possibly more, depending on how close the tunnels are, and how they are laid out. The colony should not be placed directly on the ground, as it's important that the bees stay dry.

Allow the bees to leave the tunnel: don't screen them in. They need an abundant and varied diet. It may also be harmful to fruit quality of peppers, for example, and perhaps other crops, to have flowers visited too many times by bees desperately seeking nourishment.

Honey bees sometimes steal honey from bumble bee colonies. Be sure that honey bee hives are not located close to the tunnel where you place the bumble bee colony.

For information on raising bumble bees you catch yourself, see the University of Minnesota Extension Service guide, ***Befriending Bumble Bees***.

<http://shop.extension.umn.edu/PublicationDetail.aspx?ID=1902>.

For information on managing other wild/native pollinators, see the new book, **Managing Alternative Pollinators**, by E. Mader, M. Spivak and E. Evans, NRAES 186, SARE Handbook 11.

Tomatoes

David Wildung, Terry Nennich, and Pat Johnson, University of Minnesota

In cooler climates like Minnesota, tomatoes may be the crop for which high tunnels are most suited. Certainly in the two seasons that high tunnels have been evaluated at NCROC, tomatoes have been the most successful crop grown. In 2004, without high tunnels, very few ripe tomatoes would have been produced in northern Minnesota. Because of their potential, the high tunnel program at NCROC has devoted more time to tomato studies than any other crop. The results of these studies are reported here.



Tomato high tunnel studies at NCROC have addressed several questions but have been devoted to two main objectives: cultivar evaluation of both determinate and indeterminate types and cultural studies to determine aspects of how to grow the crop more successfully. Except for some of the cultural studies, the basic cultural systems used were as follows. All tomato plants were grown using 6 to 8 week old transplants that were transplanted into the high tunnels during the first week in May. Transplants were planted into black plastic covered raised beds that were 3 to 4 inch high and 16 to 18 inches wide. All plants were trickle irrigated, with the trickle tube laid into a 1 inch deep furrow made in the center of the bed under the black plastic covering. The plant spacing was 18 inches apart in the row with rows 4.2 feet apart. Plants were planted in a staggered row system alternating on each side of the trickle tubing. All

determinate type tomatoes were trained to a modified Florida Weave system (see Tunnel Layout-Section 6). All indeterminate type tomatoes were trained to a single wire trellis system. In the early season, pruning and training were done at least once a week, and all plants of both types were pruned to a single stem. Irrigation was done 2 to 3 times a week and monitored using moisture block sensors. Fertilizer was injected through the trickle system on a weekly basis. Each treatment plot contained five plants. Because of the many studies and the small area of the high tunnels, only single plot treatments were evaluated. Harvest was done 2 to 3 times a week as needed. At each harvest date, fruit numbers and weights were recorded. These data were used to calculate the information contained in the tables that follow.

The 2003 season had above average temperatures, and the plants got off to a fast start with excellent early fruit set and good production. Production on the determinate cultivars was excellent. Early in the development of the plants, leaf roll symptoms developed on the older leaves. Both the irrigation frequency and the amount of fertilizer applied were increased, but neither practice improved the situation. Because of the leaf roll, in 2004 a double line trickle irrigation study was conducted. Tomato leaf roll has remained present throughout both seasons, but it only appears on the older foliage and does not seem to negatively affect the plants or their production. A second more damaging problem occurred in 2003 early in the harvest when blossom end rot began to reduce marketable fruit. It affected all cultivars, some more than others. It was at that time that data was recorded on spoiled fruit. This information appears in the tables in the "% good" column. In 2004, calcium nitrate was used

as one of the nitrogen sources, and use of this fertilizer noticeably reduced the incidence of blossom end rot.

During the 2004 growing season, slightly cooler high tunnel temperatures in late May and June reduced early fruit set and affected the earlier setting determinate cultivars. Later blooming indeterminate cultivars had better set and yielded better in 2004 than in 2003. Late in the 2004 growing season, white flies that were first a problem on eggplants moved from the eggplants to the cucumbers, then to the tomatoes. By mid-September they became a problem on the tomatoes, affecting both plant and fruit quality because of the honeydew they secreted during feeding. No control measures were applied, but all plant residues were removed and destroyed at the end of the season.

Cultivar Trials

Determinate Cultivars

Six cultivars were evaluated in 2003 (Table 1), and nine cultivars were evaluated in 2004 (Table 2). Cultivars were chosen in 2003 based on earliness and large fruit size from earlier field production studies. In 2004 additional cultivars were added based on earliness and discussions with seed company representatives.

Table 1. 2003 Determinate Tomato Production

Cultivar	Source	1 st Ripe	Lbs./Plant			Ripe Fruit Harvest		
			Early*	Ripe	%Good	# Fruit/ Plant	Lbs./Fruit	Lbs./ Sq. Ft.
Sunshine	SM	7/17	5.1	11.8	64%	25.0	0.473	1.87
#0336	SM	7/17	4.8	10.7	74%	17.5	0.612	1.70
Bush Early	BU	7/21	3.4	9.0	58%	20.8	0.431	1.43
Debut	SM	7/21	3.2	8.5	89%	17.0	0.499	1.35
Sunbrite	SM	8/1	0.7	8.0	62%	12.7	0.633	1.27
Florida 47	SM	7/24	2.3	4.2	41%	13.8	0.302	0.67

*Early Harvest Through 8/01/03

Table 2. 2004 Determinate Tomato Production

Cultivar	Source	1 st Ripe	Lbs./Plant			Ripe Fruit Harvest		
			Early*	Ripe	%Good	# Fruit/ Plant	Lbs./ Fruit	Lbs./Sq. Ft.
Mt. Crest	SU	8/9	0.0	9.6	80%	16.4	0.588	1.52
Daybreak	JS	7/26	2.2	8.9	82%	18.8	0.472	1.41
Sunshine	SW	7/26	0.9	7.5	68%	16.0	0.472	1.19
Sunstart	SM	7/23	1.2	7.0	80%	15.2	0.459	1.11
Seedway 10250	SW	8/6	0.3	7.0	68%	13.0	0.537	1.11
Sunchief	SM	7/23	1.3	6.0	58%	12.6	0.480	0.95
N0336	SM	7/26	1.1	5.8	70%	12.0	0.487	0.92
Red Pride	SA	8/21	0.0	5.2	80%	9.6	0.542	0.83
Debut	SM	8/4	0.3	5.1	67%	10.6	0.485	0.81

*Early Harvest 7/31/04 – 8/02/04

During the 2003 season, excellent early fruit set resulted in very good early production, with between 5.1 to 0.7 pounds per plant of early fruit harvested by August 1 (Table 1), compared to 2.2 to 0.0 pounds per plant of early fruit harvested by August 2, 2004 (Table 2). This early production can very positively affect marketing. The date of first ripe fruit was slightly earlier in 2003 than in 2004 (about 6 days earlier). Total yield of ripe fruit was good

both seasons, but also slightly favored the 2003 season. Production of 1.00 pound or more per square foot is equivalent to more than 20 tons of tomatoes per acre, which is considered to be an excellent yield for fresh market tomatoes. In 2003, 5 of 6 cultivars exceeded that amount with Sunshine leading the way at 1.87 pounds per square foot (Table 1). In 2004, 5 of 9 cultivars exceeded the 1.00 pound per square foot level (Table 2). Blossom end rot in 2003 affected fruit quality, which shows in the tables as a lower grade out (% good) comparing the 2003 and 2004 seasons. The cultivar Debut had the least blossom end rot (Table 1). Fruit size varied with the cultivars both years but overall was quite large except for Florida 47, which had done well in NCROC field production trials. Sunbrite (0.633 pound or 10.1 ounces per fruit) and #0336 (0.612 pound or 9.8 ounces per fruit) had exceptionally large fruit in 2003 (Table 1). During the 2004 season, (Table 2) all cultivars had good fruit size ranging from 0.459 (7.3 ounces) to 0.588 pound (9.4 ounces) each. Based on 2003 production (Table 1) early determinate cultivar suggestions would be Sunshine, #0336, and Debut. Sunbrite is a very large tomato, but it is also later to mature. In 2004, Daybreak, Sunstart, and Sunshine were the best early cultivars. Mt. Crest is a very large, uniform cultivar, but it is also late to mature.

Indeterminate Cultivars

Most indeterminate cultivars mature later, produce slightly smaller fruit, yield more fruit, and have much larger plants than determinate cultivars. Often these cultivars are considered full season cultivars, and most are not suggested for field production in Minnesota. Cultivars chosen for these trials were selected after consulting seed companies, producers from other areas of the country, and two cultivars (Ultra Sweet and Northern Exposure) based on field trials conducted previously at NCROC. In 2003 (Table 3) five cultivars were evaluated and in 2004 (Table 4) seven cultivars were trialed.

Table 3. 2003 Indeterminate Tomato Production

Cultivar	Source	1 st Ripe	Lbs./Plant			Ripe Fruit Harvest		
			Early*	Ripe	%Good	# Fruit/ Plant	Lbs./ Fruit	Lbs./Sq. Ft.
Cobra	ST	8/1	0.6	12.1	64%	33.2	0.364	1.92
Trust	JS	8/1	0.3	8.4	48%	22.2	0.377	1.33
N. Exposure	BU	7/21	1.8	4.8	41%	12.2	0.392	0.76
New Girl	JS	7/10	3.0	4.5	38%	26.3	0.171	0.71
Ultra Sweet	ST	7/21	1.7	4.2	38%	14.7	0.284	0.67

*Early Harvest Through 8/01/03



In 2003, Table 3 shows that while some early production occurred by August 1, the fruit size, grade out of fruit (% good), and total yield for the indeterminate cultivars evaluated were not particularly good. The performance of Ultra Sweet and Northern Exposure were especially disappointing. Cobra was the only indeterminate cultivar that did well, displaying very good yield (the best in the trial), good grade out, and moderate fruit size, (0.364 pound or 5.8 ounces per fruit).

In 2004, all of the indeterminate cultivars evaluated

did much better (Table 4). Early production was almost as good as with the determinate cultivars, but the total production for the season was generally much greater with up to 16.9 pounds of ripe fruit per plant produced by the cultivar First Lady.

Table 4. 2004 Indeterminate Tomato Production

Cultivar	Source	1 st Ripe	Lbs./Plant		% Good	Ripe Fruit Harvest		
			Early*	Ripe		# Fruit/Plant	Lbs./Fruit	Lbs./Sq. Ft.
First Lady	JS	7/26	1.8	16.9	93%	53.8	0.315	2.68
Octavio	JS	7/30	0.6	16.5	87%	86.8	0.190	2.62
Cobra	JS	8/9	0.0	15.7	87%	35.8	0.439	2.49
Ultra Sweet	ST	7/26	1.2	14.9	78%	33.2	0.447	2.36
Buffalo	JS	8/2	0.4	13.5	76%	30.2	0.447	2.14
Trust	JS	8/4	0.1	10.7	73%	22.0	0.489	1.70
N. Exposure	BU	7/28	1.4	9.9	67%	20.8	0.476	1.57

*Early Harvest 7/13/04 – 8/02/04

By field production standards, this is equivalent to over 55 tons of fresh market tomatoes per acre! Early production with First Lady, Ultra Sweet, and Northern Exposure was certainly acceptable. The grade out of fruit (% good) was over 70% for all cultivars except Northern Exposure (67%), which does produce a somewhat flattened fruit that is furrowed at the stem end. This grade out for all cultivars would have been even better, except that unripe fruit at the end of the season was included and counted as part of spoiled fruit. This decreased the percentage of good fruit recorded. The fruit size for First Lady (0.315 pound) and Octavio (0.190 pound) was small, but the grade out was excellent. Both cultivars are truss tomatoes that can be harvested individually or in truss clusters (tomatoes harvested in bunches—several to a stem). Octavio (Figure 3) has very good shelf life, and its plants are some of the strongest, largest stemmed plants ever grown at NCROC. The rest of the indeterminate cultivars all produced fruit of good size, with Cobra being the best cultivar overall for total production, grade out, and fruit size. Ultra Sweet did much better in the 2004 trials. Most of the indeterminate cultivars still were producing fruit well into September and would certainly be considered full season cultivars.

Based on these trial results, Cobra, Buffalo, and Ultra Sweet would be the main season cultivars of choice. Octavio and First Lady would be selected for early maturity and, possibly, as truss tomato cultivars for the specialty market. In a total marketing approach, start out with the selection of suitable determinate cultivars for the early market and large fruit size. Then select indeterminate cultivars for late maturity and heavy production. This approach would be effective to ensure dependable full season production in high tunnels in northern Minnesota. Use of truss tomatoes like Octavio and, perhaps, some cherry or grape cultivars would round out production nicely.

Cherry Tomato Cultivars

In both 2003 and 2004, two cherry tomato cultivars were evaluated in the high tunnels. The results of those trials are seen in Table 5. Typically in field production trials, cherry tomato plants are very large plants, and the fruit is slow to mature. With high tunnel production, the plants were extremely vigorous and their ripening date was the earliest of any tomato grown in the trials.

Table 5. Cherry Tomato Production

Table 6. Cherry Tomato Production								
Cultivar	Source	1 st Ripe	Lbs./Plant		% Good	Ripe Fruit Harvest		
			Early*	Ripe		# Fruit/ Plant	Lbs./ Fruit	Lbs./ Sq. Ft.
2003								
Favorita	JS	7/10	1.1	8.0	98%	202.0	0.040	1.27
Jolly Elf	ST	7/21	0.6	6.5	86%	261.8	0.230	1.03
2004								
Favorita	JS	7/13	1.2	6.8	94%	170.8	0.040	1.08
Sugary	AAS	7/15	1.2	4.9	91%	134.5	0.036	0.78

*Early Harvest 7/13/04 – 8/02/04

Favorita matured fruit first, by July 10, 2003 and July 13, 2004. The other two cultivars had ripe fruit on July 15, 2004 (Sugary) and July 21, 2003 (Jolly Elf). Early production of over 1.0 pound per plant by August 2 occurred each season with Favorita and in 2004 with Sugary. Total production was 8.0 and 6.8 pounds per plant with Favorita for 2003 and 2004, respectively (Table 5), 6.5 pounds per plant with Jolly Elf in 2003, and 4.9 pounds per plant with Sugary in 2004. The grade out (% good) on all cultivars was over 86%. Fruit from all cultivars was very uniform and attractive. Fruit of Favorita was slightly oval in shape and averaged the same size both years (0.040 pound each or 25 fruit per pound). Jolly Elf had the smallest fruit. Favorita can also be harvested and marketed as a cluster or truss tomato. All of these cultivars were larger than the grape tomatoes that are gaining in popularity.

Cultural Studies

Planting Date Study

One of the first objectives in the high tunnel project was to determine the optimum transplanting time for tomatoes. How early or late could tomatoes be transplanted, and what would be the effects of planting date on tomato fruit productivity? Both in 2003 and 2004, tomato plants were transplanted into the high tunnels at weekly intervals beginning on April 29 and continuing until May 20 with a final planting on June 13 when the field planting also was completed. The results of these studies are summarized in Tables 6 and 7.

Table 6. 2003 Tomato Planting Date Study (Cultivar – Debut)

Planting Date	1 st Ripe	Lbs./Plant		%Good	Ripe Fruit Harvest		
		Early*	Ripe		# Fruit/ Plant	Lbs./Fruit	Lbs./ Sq. Ft.
4/29/03	7/10	5.5	12.2	77%	22.8	0.537	1.94
5/06/03	7/21	2.8	5.5	56%	16.0	0.346	0.87
5/13/03	7/28	1.7	6.9	49%	18.6	0.373	1.10
5/20/03	8/08	0.4	10.2	64%	20.6	0.497	1.62
6/13/03	8/01	0.0	6.1	63%	12.0	0.510	0.97

*Early Harvest Through 8/01/03

Table 7. 2004 Tomato Planting Date Study (Cultivar – Sunshine)

Planting Date	1 st Ripe	Lbs./Plant			Ripe Fruit Harvest		
		Early*	Ripe	%Good	# Fruit/ Plant	Lbs./Fruit	Lbs./ Sq. Ft.
4/29/04	7/26	1.4	6.4	73%	13.8	0.463	1.01
5/4/04	7/23	2.4	9.8	76%	20.8	0.471	1.56
5/11/04	7/30	1.4	8.7	87%	17.6	0.492	1.38
5/18/04	8/4	0.2	6.5	69%	14.8	0.441	1.03
6/14/04	8/31	0.0	7.7	88%	13.4	0.577	1.27

*Early Harvest 7/13/04 – 8/02/04

Results from both years show a strong relationship between planting date and first ripe fruit and early yield in pounds per plant (Tables 6 and 7). Except for the first planting date in 2004 (4/29/04), Table 7, early yield was reduced noticeably for every week transplanting was delayed. In 2003, the best early yield (5.5 pounds per plant) was produced with the earliest planting date (Table 6). Delaying transplanting past the second week in May resulted in very little early fruit production both years of the study.

Based on these results, differences or trends in production from other factors evaluated in the study are not apparent. Total ripe fruit yield (pounds per plant), the percentage of good fruit, fruit number, and fruit size all varied among the planting dates both years. These results lead to the conclusion that, except for early production, the planting date had little effect on season-long production in the high tunnel. Total ripe fruit harvested per plant was at least 5.5 pounds per plant for all of the planting dates. This yield is certainly satisfactory. Most of the variation observed in these season-long factors may have been the result of the high tunnel environment and its effect on fruit set at the time the plant was in full bloom.

Could transplanting be done earlier than the last week in April? This decision depends on two things: transplant quality and frost protection costs. Good quality transplants that are large and vigorous are critical to the success of early plantings. In this study, we grew our own transplants. Seed scheduling and greenhouse growing conditions did not always provide the best quality transplants. The transplants that were planted on 4/29/04 were very small. Whenever transplanting is done, but particularly in the early plantings, growers need to secure the best quality and largest transplants possible. The likelihood of frost in northern Minnesota in mid to late April is a given. For early transplanting, a grower would need to have frost protection available. They must then decide if the extra cost of heating the high tunnel is worth the extra profit obtained in the sale of fruit produced with the early planting. Based on the results of two seasons, late April or early May seem like a good compromise for early high tunnel tomato plantings in northern Minnesota.

Trickle Irrigation Study

The specifics of high tunnel irrigation are covered in Section 7 of this manual. During the 2003 growing season moderate amounts of leaf roll were observed on the older leaves of the plants. This study was conducted during the 2004 season to determine if the use of double line trickle irrigation would reduce the amount of leaf roll occurring with the plants. Secondly, would double trickle irrigation have any effect on yield and fruit production. The results are summarized in Table 8.

Table 8. Tomato Trickle Irrigation Study (Cultivar – Sunshine)

Trickle Treatments	1 st Ripe	Lbs./Plant			% Good	Ripe Fruit Harvest		
		Early*	Ripe			# Fruit/ Plant	Lbs./ Fruit	Lbs./Sq . Ft.
Single Line	7/23	2.4	9.8		76%	20.8	0.471	1.56
Double Line	7/19	2.8	10.9		82%	22.8	0.477	1.73

*Early Harvest 7/13/04 – 8/02/04

All of the yield factors for both treatments were excellent, with production being equivalent to over 33 tons per acre even for the single line treatment. However, the results indicate that double line trickle may improve productivity of tomato plants growing in high tunnels. Fruit maturity was 4 days earlier, early fruit production was 16% better, ripe fruit production was 11% better, the percentage of good fruit was 8% better and fruit size was slightly larger with the double line trickle treatment. The additional amount of irrigation water did not affect leaf roll, as symptoms were still observed with both treatments.

Spacing Studies

The spacing within rows of tomato plants grown for field production is generally about three feet in Minnesota. When intense management systems with trellising and pruning are used in high tunnel production, what spacing within rows would be most effective? This study was conducted on both determinate and indeterminate tomato cultivars in 2003 and 2004. Generally, determinate tomato cultivars produce smaller plants with earlier maturing fruit than indeterminate cultivars. Three spacings within rows were used in this study: 12, 18 and 24 inches apart in the row.

Determinate Tomatoes

Table 9 presents the results of the determinate study. A different cultivar was used each year, Debut in 2003 and Sunshine in 2004. In 2003, with Debut, the 24-inch spacing produced the earliest fruit -- 4.0 pounds per plant -- but total yield favored the 12-in spacing.

Table 9. Determinate Tomato Spacing Study

Table 5. Determinate Tomato Spacing Study							
Spacing	1 st Ripe	Lbs./Plant			Ripe Fruit Harvest		
		Early*	Ripe	% Good	# Fruit/ Plant	Lbs./Fruit	Lbs./Sq. Ft.
2003 – Cultivar Debut							
12"	7/24	3.1	9.1	68%	16.7	0.558	2.17
18"	7/21	2.9	8.3	68%	18.0	0.476	1.32
24"	7/21	4.0	8.3	59%	13.7	0.583	0.99
2004 – Cultivar Sunshine							
12"	7/23	1.2	7.9	72%	17.0	0.467	1.88
18"	7/28	1.0	8.1	79%	17.8	0.458	1.28
24"	7/26	1.2	9.8	69%	17.8	0.550	1.17

*Early Harvest Through 8/02

In 2004, with the cultivar Sunshine, early yield was not affected, but the greatest total yield per plant was produced at the 24-inch spacing (9.8 pounds per plant). On a unit basis (lbs/sq. ft), the 12-inch spacing was far superior with both cultivars and both years (2.17 pounds per square foot in 2003 and 1.88 pounds per square foot in 2004). If large fruit is desired, the 24-inch spacing produced the largest fruit each year with both cultivars (0.583 pound in 2003 and 0.550 pound in 2004). However, fruit size with these cultivars is already

quite large, so the fruit size even at the 12-inch spacing may be large enough. In 2003, the cultivar Debut produced the most fruit on both a per plant basis (9.1 pounds per plant) and a square foot basis at the 12-inch spacing (1.88 pounds per square foot). In 2004, individual plants of the cultivar, Sunshine, produced more and bigger fruit at the 24-inch spacing, but the largest production on a square foot basis occurred at the 12-inch spacing. While the optimum spacing for each cultivar can vary, it would appear that determinate type tomatoes could be grown as closely as 12 inches apart and still produce excellent yields of fruit that have fruit size of at least 0.467 pound (7.4 ounces) each.

Indeterminate Tomatoes

The indeterminate cultivar Cobra was used during both years of this study. Table 10 presents the results of the study. During both years the best production was obtained on a per plant basis at the 24-inch spacing (Table 10).

Table 10. Indeterminate Tomato Spacing Study (Cultivar – Cobra)

Lbs./Plant					Ripe Fruit Harvest		
Spacing	1 st Ripe	Early*	Ripe	% Good	# Fruit/Plant	Lbs./Fruit	Lbs./Sq. Ft.
2003							
21"	8/8	0.1	9.6	59%	22.8	0.429	2.29
18"	7/28	1.1	11.8	58%	29.3	0.401	1.87
24"	8/1	0.6	15.8	72%	40.3	0.393	1.88
2004							
12"	8/9	0.0	13.7	77%	32.7	0.419	3.26
18"	8/6	0.1	14.1	76%	34.6	0.408	2.24
24"	8/6	0.1	21.6	82%	43.6	0.496	2.57

*Early Harvest Through 8/02

While only a small amount of early fruit was produced by August 2, the date of first ripe fruit was earliest at the 24-inch spacing both years. The 24-inch spacing had first ripe fruit 7 and 3 days earlier, for 2003 and 2004 respectively, than the 12-inch spacing. Both the percentage of good fruit and the number of fruit set per plant were greatest at the 24-inch spacing. In 2003, fruit size at the 24-inch spacing was smaller than at the 12-inch spacing, but in 2004 fruit size was much larger at the 24-inch spacing compared to the 12- and 18-inch spacing. Total ripe fruit production of 15.8 pounds per plant in 2003 and 21.6 pounds per plant in 2004 was the highest of any plots in the high tunnels. The 21.6 pounds per plant is equivalent to over 55 tons per acre of fresh market tomatoes! The results of this study clearly show the advantage of the 24-inch spacing for the vigorously growing vines of indeterminate tomatoes like the cultivar Cobra. The greater spacing for the larger plants results in earlier maturity, more fruit, better fruit, larger fruit, and greater productivity.

Pruning Studies

Several Minnesota high tunnel producers are growing tomatoes in regular matted rows with little or no pruning or trellising. Their results have been very impressive in terms of increased productivity and earlier production. At NCROC, close spacing and more intense management practices have been used. Plants have been pruned to single stems. Is one system more productive than another? This study was initiated to determine if there were differences. In 2003, a small study was done comparing single and double stem intense pruning using the determinate cultivar Debut. In 2004, both the determinate cultivar

Sunshine and the indeterminate cultivar Cobra were evaluated in single stem, double stem, and no-prune treatments.

Determinate Tomatoes

During both years of the study, comparing the single and double stem treatments only, the single stem treatment produced slightly more early fruit per plant. There also was a slightly better percentage of good fruit, and the fruit was larger (Table 11). However, for the season, the double stem treatment produced more total ripe fruit per plant.

Table 11. Determinate Tomato Pruning Study

Pruning Treatment	1 st Ripe	Lbs./Plant			Ripe Fruit Harvest		
		Early*	Ripe	% Good	# Fruit/ Plant	Lbs./Fruit	Lbs./Sq. Ft.
2003 – Cultivar Debut							
Single Stem	7/24	2.5	8.8	63%	17.0	0.534	1.40
Double Stem	7/21	1.9	12.3	58%	25.2	0.505	1.95
2004 – Cultivar Sunshine							
Single Stem	7/23	10.5	10.5	76%	19.6	0.534	1.67
Double Stem	7/26	12.1	12.1	73%	23.2	0.523	1.92
No Prune	8/9	22.1	22.1	81%	47.8	0.462	3.51

*Early Harvest Through 8/02

The double-stemmed plants had more fruiting surface, which resulted in more fruit set and greater productivity than the single-stemmed plants. The greatest differences were apparent when the pruning treatments were compared to the no-prune treatment. The no-prune treatment produced the first ripe fruit 14 days later than the double stem treatment and 17 days later than the single stem treatment. It produced no fruit by August 2. On the other hand, virtually no fruit was produced in the field before late August in 2004; therefore, mature fruit by August 9 in the high tunnels would be beneficial to marketing. Total ripe fruit produced per plant with the no-prune treatment was excellent and was over twice the single stem pruned treatment (22.1 pounds per plant compared to 10.5 pounds per plant). Grade out (% good) was better with the no-prune treatment (81% compared to 76% for the single stemmed plants). Fruit size with the no prune treatment was smaller than the other two treatments, but 0.462 pound, or 7.3 ounces, per fruit is still good. Plant growth for the no-prune treatment was very dense and lush; and with the 4.2-foot between-row spacing used in the high tunnel, it was difficult to get around the plants.

Results of this study indicate that for determinate tomato cultivars when intense pruning systems are used, double stemmed plants will be more productive than single stemmed plants. The double stem system will have slightly smaller fruit and slightly less early fruit produced per plant. A no-prune growing system will greatly delay fruit maturity and result in smaller fruit, but it will also result in more total ripe fruit produced per plant. Plants grown in a no-prune system in high tunnels will need much more space to develop than the 4.2 by 1.5 foot space provided in this study. At this close spacing, while no disease was evident during the 2004 growing season, the potential for disease is much greater (see Disease Management-Section 9).

Indeterminate Tomatoes

The indeterminate cultivar Cobra was grown in this study in 2004. The results are presented in Table 12. As with the determinate cultivars, the first ripe fruit date was delayed for the

double stem and no-prune treatments compared to the single stem treatments (6 and 13 days respectively).

Table 12. Indeterminate Tomato Pruning Study

Pruning Treatment	1 st Ripe	Lbs./Plant			Ripe Fruit Harvest		
		Early*	Ripe	% Good	# Fruit/ Plant	Lbs./ Fruit	Lbs./Sq. Ft.
Cobra Single Stem	8/6	0.1	15.5	74%	35.6	0.436	2.46
Cobra Double Stem	8/12	0.0	17.0	73%	46.4	0.367	2.70
Cobra No Prune	8/19	0.0	13.6	61%	47.8	0.286	2.16

*Early harvest 7/13/04 – 8/02/04

Virtually no fruit was ripe with any of the treatments by August 2. For the season, the double-stemmed plants had the greatest yield, at 17.0 pounds of ripe fruit per plant. The no-prune treatment had the smallest yield, at 13.6 pounds of ripe fruit per plant. The no-prune treatment had the most fruit set per plant (47.8), but the fruit size was small (0.286 pound or 4.5 ounces per fruit), and the grade out was less (61% good) than with the pruning treatments. Finally, with the bigger indeterminate plants, getting around the plants in the high tunnel and harvesting them were a major challenge. Indeterminate tomato cultivars respond much more to pruning and training than determinate tomato cultivars. Indeterminate cultivars respond to pruning systems by producing higher yields and more large fruit with a better grade out. Not pruning an indeterminate cultivar will result in an extremely vigorous, multistemmed, lush plant with late maturing fruit. Fruit production will be less and fruit size will be small. If indeterminate cultivars are grown in high tunnel production systems, pruning and training systems are recommended to maximize productivity and manage space efficiently.

Summary

From selecting cultivars and determinate-indeterminate types to choosing a planting date, from determining within-row spacing to deciding whether or not to prune the plants, there are many choices to be made about tomato production in high tunnels. The best thing is that high tunnel tomato production will result in better production of a larger, earlier crop than field production. The results reported in this section should provide answers to the questions regarding the best cultural systems to use for high tunnel tomato production.

Over-Wintering Garlic in High Tunnels

Terrance T. Nennich, University of Minnesota Extension Service



A promising crop for high-tunnel culture in the northern Minnesota, garlic is still the subject of research in Minnesota. Specific cultural recommendations are not yet available as for other high tunnel crops, so this chapter is a description of the research, and should give enough information for interested growers to experiment with growing garlic in high tunnels on their farms. See the publication “Growing Garlic in Minnesota” at

<http://www.extension.umn.edu/distribution/horticulture/M1259.html> for full cultural information.

Garlic is planted in late summer or autumn, and over-winters in the soil. Ideally, there is no above-ground growth until the following spring, when the cloves send up leaves and form new bulbs. Harvest is usually in June or July. While garlic can be planted in spring and harvested in late summer, spring-planted garlic usually does not attain a marketable size.

Garlic production has been limited to very hardy cultivars, typically hard-neck, grown in the southern half of Minnesota. High tunnel culture could allow production of this potentially very profitable crop farther north, where the fall-planted cloves are often killed over winter by extreme cold. High tunnel production may also be useful for production of less hardy, soft-neck cultivars in southern Minnesota.

Research at Bagley, MN

Recent research in high-tunnel garlic production examined survival rates of garlic planted inside the high tunnels and mulched with straw, just as the planting outside the tunnel was, but with no supplemental snow brought into the tunnel. The location of the research was Bagley, MN, about 25 miles west of Bemidji,. This location is in USDA hardiness zone 2.



The garlic research project was conducted over a three year period, with plantings in 2005, 2006, and 2007. The hard-neck garlic cultivar ‘Music’ was selected for all three years of this study. Two different high tunnel designs were used: Gothic V-roof, and small round.

Garlic Planting Dates		
Year	Outside the tunnels	Inside the tunnels
2005	September 21	October 20
2006	September 23	October 18
2007	September 19	October 22

Immediately following planting, six inches of straw was applied to the rows outside the tunnel, while the rows inside the tunnel received six inches of straw mulch about a month after planting.

It's important that the garlic cloves begin forming roots in fall, but that they not send leaves above the soil before winter. The soil and air in the tunnel remained warm longer than the soil outside, so the planting was later, and then the application of mulch was delayed until the soil had cooled off.

Winter Cold Temperature Data		
Year	Days below 0°F	Low temperature
2005-2006*	17	-37°F
2006-2007	24	-41°F
2007-2008	33	-38°F

*The winter of 2006-2007 included 8 consecutive nights below -20°F.

Snow Cover Outside Tunnel	
2005-2006	Ample but below average
2006-2007	Little snow cover
2007-2008	Average snow cover

Survival Rate			
Year	Outside	Inside Gothic tunnel	Inside round tunnel
2005-2006	69%	94%	92%
2006-2007	2%	92%	87%
2007-2008	79%	95%	94%

Harvest Data

Over the three years, harvest was on average 21 days earlier in high tunnels. The size of the garlic bulbs harvested from the high tunnels was about 30% larger than that of bulbs grown outside. However, the two cultural regimes during the growing season were quite different: different soils, irrigation versus rainfall.

Results

Extreme cold winter temperatures had little effect on winter survival of 'Music' hard-neck garlic grown in high tunnels. Drastic differences between survival inside tunnels and outside were noted in 2006 -2007 when there was very little snow cover outside. There was no significant difference in winter survival between the Gothic and round tunnel styles.

Garlic definitely shows promise as a high tunnel crop in the very cold northern part of Minnesota.

2008-2009 Research at Bagley

A trial of 15 cultivars, both hard-neck and soft-neck, was undertaken in 2008. Hard-neck garlic has better winter hardiness than soft-neck, while soft-neck garlic lasts longer in storage. Many Minnesota garlic growers have been limited to growing hard-neck garlic.

Planting inside the tunnels occurred on October 20, 2008, and rows were mulched with six inches of straw four weeks later. There was no planting outside the tunnels. After a typically cold winter in Bagley, with two overnight lows close to -50F, winter survival for all cultivars was above 85%.

Cultivars Tested (see photos, below)		
Hard-neck	Soft-neck	Intermediate
Asian Tempest	Inchelium Red	Burgundy
Chesnock Red	Moroccan Softneck	Blossom
Chinese	Silverwhite	Creole Red
Japanese	Spanish Red	
Montana Giant		
Moroccan Hardneck		
Music		
Russian Silverskin		

*'Burgundy,' 'Blossom,' and 'Creole Red,' while genetically related to soft-neck types, may form a scape under Minnesota conditions. Storage qualities vary among these cultivars. See <http://www.extension.umn.edu/distribution/cropsystems/DC7317.html> for in-depth information about garlic cultivars.

Cultivars Tested







Crop Mix Experiences at North Central Research and Outreach Center

David Wildung, Terry Nennich, and Pat Johnson, University of Minnesota



A large number of crops will do well in high tunnel production. In particular, crops normally grown in your zone, plus many that are beyond your zone. For the market gardener that needs a large variety of crops to sell, high tunnel production may offer the opportunity to expand the season and grow a better quality product. Decisions about which crops to grow should be made the same way a grower would decide which crops to grow in normal field production. The use of high tunnels cannot replace previous ideas on crop mix, only enhance them. In

Minnesota, the production of warm season crops offers the greatest chance for success with high tunnels. Therefore, the warm season crops should be the focus of high tunnel crop mix. Extending the early season with a cool season crop will only be successful if it does not conflict with the growing of the main season crop. If a cool season crop takes growing space and time away from the main season crop, the grower may not profit much. In choosing the crop mix, growers should select crops with similar temperature requirements to grow in the same high tunnel.



Several different crops have been evaluated in the high tunnels at NCROC. The comments that follow are observations on successes and failures.

Snap Bean

Cultivar: Jade (Siegers)

Seeded: 5/8/03 and 5/6/04

Spacing: Double rows 6 inches apart; 12-14 seeds per foot

Harvest: 7/14-7/24/03 and 7/13-7/26/04

Yields: 2003= 10.25 lbs/10 feet;
2004= 9.00 lbs/10 feet



Comments: Excellent quality, good yield, and slightly earlier maturity than with field production, but may not be that much better than what can be produced in the field.

Beets

Cultivars: Red Ace (Seedway) and Forono (Johnny's)

Seeded: 4/16/04

Spacing: Triple rows 4 inches apart; 14-18 seeds/foot

Harvest: Three=6/22/04 and 7/21/04-harvested the largest roots; 8/6/04-all remaining roots were harvested and marketed with the tops trimmed, but left on.

Yields: Red Ace=58.0 lbs marketable/10 feet.
Forono=51.4 lbs marketable/10 feet.

Comments:

Excellent quality, excellent color, and *very* good uniformity

Broccoli

Cultivars: Six different cultivars were evaluated in 2003 and 2004.

Seeded: Transplants were seeded in greenhouse about 7/20 both years. Transplants and direct seeding to the high tunnels was done about 8/20 both years.

Spacing: 8 inches apart in the row.

Harvest: November both seasons after frosts and cold weather damaged the plants.

Comments:

It was thought that broccoli would be the perfect crop to transplant after carrots, beets, or green beans had been removed. The broccoli plants would establish and grow well in late summer, develop heads in late September, and mature nice bunches in October. Unfortunately that did not happen either season. Plant development in August was very slow, probably because it was too hot in the high tunnels for broccoli plant growth. The slow plant development delayed floret development, and cold weather in late October and November ended the season before mature heads could be harvested. None of the six cultivars evaluated were any better than the others. Early spring planting may react entirely differently and certainly would be worth evaluating.

Carrots

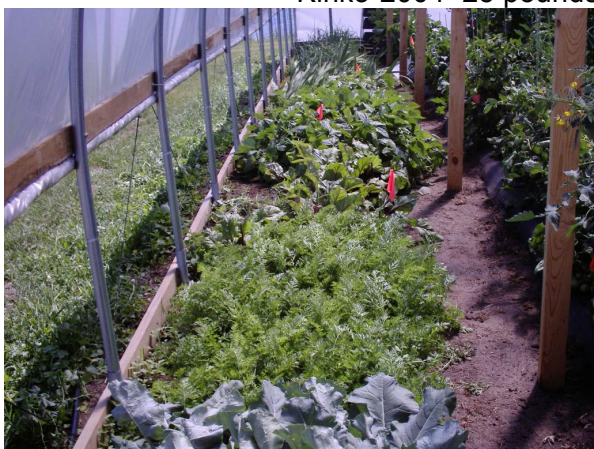
Cultivars: 2003-Mokum (Johnny's) and Ithaca (Johnny's)
2004-Mokum (Johnny's) and Kinko (Johnny's)

Seeded: 5/8/03 and 4/16/04

Spacing: Triple rows 4' apart; 16-18 seeds per foot

Harvest: Mokum-7/21 and 8/6/03; 6/22 and 7/21/04
Itasca-8/27/03
Kinko-6/22 and 7/21/04
All roots were harvested and marketed with tops trimmed but left on.

Yields: Mokum-2003= 55 pounds per 10 feet; 2004= 26 pounds per 10 feet.
Itasca-2003= 60 pounds per 10 feet.
Kinko-2004=25 pounds per 10 feet.



Comments:

The root color and uniformity were excellent. There were no doubles, splits, or cracked roots. Root quality and marketability were very good. There was no aster yellows evident in any of the roots. This factor is noteworthy because aster yellows is a serious problem in the Grand Rapids area in field grown carrots. These cultivars were selected because they all are short season maturing cultivars. It was felt that they could be grown and harvested, while still allowing enough time to successfully grow a second crop to maturity, perhaps

broccoli. In 2003, it took 90 days for Mokum to mature the crop; in 2004, 96 days were required. Even with the earlier planting date of 4/16/04, the harvest date was too late to grow a second crop to maturity.

Cucumbers (Tables 1 and 2 give the results of the high tunnel trials.)

Cultivars:	As listed. All were selected because they were gynoecious (all female), greenhouse forcing types.
Seeded:	All were seeded into 4-inch peat pots sown 4 weeks before transplanting. Transplanted to the high tunnel 5/8/03 and 5/6/04.
Spacing:	18 inches apart in rows 4.2 feet apart.
Training:	All trained to a single stem on a trellis.
Harvest:	2003=began 6/7/03. 2004=6/11/04-9/16/04; 33 harvests.
Yields:	As shown in Tables 3 and 4.

Comments:



Yields both years were very heavy, most over 3 pounds per square foot, making them the most productive vegetable of any grown in the high tunnels. The vine growth rate was heavy. The plants responded very well to pruning and training to the single stem training system and climbed easily up trellis string. Fruit began to mature about one month after transplanting, earlier than any other warm season crop. The fruit growth rate was fast and harvest needed to be done every day or, certainly, every other day to prevent the individual fruit from getting too big. Fruit is easy to harvest with this training system, as most of it is 3-4 feet off the ground within easy reach. Fruit set and development both seasons were good with few pollination problems. Depending upon the market, high tunnel production should probably be confined to greenhouse-forcing specialty types that will command a higher market price rather than the average slicing or pickling cucumber cultivar. The early market in June

before field ripe~ cucumbers become available is probably the best market window. Plants continue to be productive into September. Cucumbers are very compatible in high tunnels with tomatoes and peppers.

Orient Express exhibited very heavy production (4.55 lbs per square foot). The fruit was very long and slender, sometimes becoming slightly twisted in shape. The fruit also had heavy spines, which were somewhat offensive even though they could be rubbed off. Sweet Slice was the earliest cultivar to mature. It also had the most misshapen fruit. Fruit was sometimes dumbbell shaped, or there was uneven development at the ends of the fruit. Diva is a very smooth spineless fruit that is shaped more like a regular cucumber. Sweet Success and Carmen are long greenhouse-forcing types, which had excellent shape, color and productivity. Both cultures probably also have the best marketability.

Table 1. 2003 Cucumber Production

Cultivar	Source	1 st Ripe	Lbs./Plant		Ripe Fruit Harvest		
			Early*	Ripe	# Fruit/ Plant	Lbs./Fruit	Lbs./Sq. Ft.
Orient Express	BU	6/27	11.6	28.7	41.4	0.693	4.55
Diva	JS	6/30	7.3	22.0	31.4	0.700	3.49
Sweet Slice	ST	6/7	10.0	21.8	31.3	0.694	3.46
Carmen	ST	6/23	9.6	20.8	28.7	0.725	3.30
Sweet Success	BU	6/30	8.3	20.7	22.2	0.933	3.28

*Early Harvest Through 8/01

All of the cultivars evaluated in 2004 were greenhouse-forcing types except Niagara, which was a productive slicing type. Yields were not as heavy during the 2004 season because a more conscious effort was made to harvest fruit at a smaller size. The top yielding cultivar was Sweet Success, which was the poorest yielding cultivar in 2003. The cultivar Tasty Jade, an improved Orient Express, while not as productive, was of better quality than Orient Express. All cultivars in 2004 had very good shape with few misshapen or dumbbell fruit. Production in 2004 was terminated on September 16, due to a whitefly infestation that started on eggplants growing next to the cucumbers.

Table 2. 2004 Cucumber Production

Cultivar	Source	1 st Ripe	Lbs./Plant		Ripe Fruit Harvest		
			Early*	Ripe	# Fruit /Plant	Lbs./Fruit	Lbs./ Sq. Ft.
Sweet Success	HM	6/11	12.9	22.9	31.2	0.735	3.63
Niagra	ST	6/29	14.0	20.3	33.0	0.614	3.22
Carmen	ST	6/17	11.9	19.8	28.2	0.703	3.14
Tyra	JS	6/25	9.7	16.8	25.4	0.663	2.67
Tasty Jade	JS	6/29	8.6	15.3	24.2	0.631	2.43
Cobra	ST	6/14	9.8	13.0	29.6	0.440	2.06

*Early Harvest 6/11/04 – 8/02/04

Eggplants

Cultivars: Fairy Tale-65 days maturity (All America Selection) and Neon-117 days maturity (Johnny's).

Seeded: Seeded in the greenhouse into 4-inch peat pots on 4/13/04. Transplanted to the high tunnel on 6/14/04.

Spacing: Double rows 4 inches apart; 18 inches apart in the row.

Harvest: Fairy Tale-Harvest began on 8/16/04. Seven harvests were conducted. Neon-No fruit matured.

Yield: Fairy Tale=14.9lbs from 10 feet of row. Fruit was small and averaged 0.15 pound each with 8.3 marketable fruit per plant.

Comments:

The cultivar Neon had very large plants and did not mature any fruit. The fruit of Fairy Tale

was small, tubular in shape, very uniform, and had nice burgundy color. Both cultivars seemed like a magnet to white flies. They were the plants on which white flies were first seen; and despite repeated insecticide applications, white fly infestation worsened until all of the eggplant plants were pulled and destroyed on 9/15/04.

Snap Peas

Cultivar:	Super Sugar Snap-60 days- (Johnny's)
Seeded:	4/16/04
Spacing:	Double rows were 6 inches apart; 12-14 seeds per foot.
Trellising:	A five-foot high trellis wire was put between the rows for the plants to climb on.
Harvest:	11 harvest, each about 3 days apart. The first 6/14/04 (59 days)-final harvest was 7/19/04 (94 days).
Yield:	17.31bs per 10 feet; pod size was 6.6 pods per ounce.

Comments:

The plants were vigorous and very tall; easily reaching the top of the five foot tall trellis wire. The crop was easy to grow. No disease was evident. The harvest season was long with many pickings. The pods were uniform in size and had good quality, even late in the season when high tunnel temperatures were hot. This crop turned out to be a longer growing crop than was anticipated when it was selected as an early, cool season crop.

Peppers, Sweet (Tables 3 and 4 give the results of the high tunnel trials.)

Cultivars	As listed in Tables 3 and 4
Seeded:	All cultivars were seeded into 4-inch peat pots in the greenhouse. 2003 - 3/13; 2004 - 2/13. All were transplanted to the high tunnels on 5/6/03 and 5/6/04.
Spacing:	Double rows 4 inches apart; with individual plants 18 inches apart in the row.
Harvest:	2003 - harvest began on 7/17/03 and continued until late October. 2004- harvest began on 7/13/04 and continued until 11/5/04.
Yields:	As shown in Tables 3 and 4.



Comments:

During both seasons, the pepper plants grew very large in the high tunnels. Early in 2003, the young plants were staked with small support stakes, since light breezes through the tunnel blew them over. With light support the plants stood up well both years. At various times, serious flower abortion and loss of potential fruit set occurred. While yields were average to good, this flower drop undoubtedly reduced total yields. About 25% of the crop both seasons matured by August 2.



2003 Season --Table 3

During the 2003 season, some of the pepper fruit had blossom end rot which affected fruit grade out. This problem was reduced in 2004 by the addition of calcium nitrate in the fertilizer program. The cultivar Socrates was the earliest to mature and had good fruit size, but its yield was average. Aristotle and Paladin had the best production, the best grade out and nicest quality fruit.

Table 3. 2003 Pepper Production

Cultivar	Source	1 st Ripe	Lbs./Plant			Ripe Fruit Harvest		
			Early*	Ripe	% Good	# Fruit/ Plant	Lbs./ Fruit	Lbs./Sq . Ft.
Aristotle	ST	7/24	1.1	4.1	84%	11.2	0.364	1.08
Paladin	ST	8/1	0.7	4.0	72%	11.7	0.342	1.05
Socrates	SE	7/17	1.2	3.1	61%	8.6	0.356	0.81
Red Knight	SE	7/28	0.4	1.8	53%	5.3	0.332	0.47

*Early Through 8/01

The cultivar Ace was the earliest to mature and had good productivity; but the fruit size was small, and the fruit was often sunken and misshapen. Vivaldi also was early and was the most productive cultivar. It had good size. Aristotle and Paladin had the largest fruit with the nicest shape, but their yields were intermediate. With no blossom end rot problems, the grade out on all cultivars was excellent in 2004 compared to 2003.

Table 4. 2004 Pepper Production

Cultivar	Source	1 st Ripe	Lbs./Plant		% Good	Ripe Fruit Harvest		
			Early*	Ripe		# Fruit/ Plant	Lbs./ Fruit	Lbs./Sq. Ft.
Vivaldi	SW	7/19	1.4	5.4	97%	16.8	0.324	1.42
Ace	JS	7/13	1.6	5.2	98%	22.3	0.232	1.37
Paladin	ST	7/23	1.0	3.4	94%	10.0	0.340	0.89
Brigadier	ST	7/21	1.2	3.4	97%	10.7	0.314	0.89
Aristotle	ST	7/26	0.8	3.0	94%	8.4	0.356	0.79

*Early Harvest 7/13/04 – 8/02/04

Radish

Cultivar: Crunchy Royal (Johnny's Seed)

Seeded: 4/16/04

Spacing: Triple rows 4 inches apart; 14-18 seeds per foot.

Harvest: Between 5/25 and 6/7/04, harvesting the largest roots each time.

Yield: 19.2 pounds per 10 feet.

Comments:

All were marketed with tops trimmed but left on. All of the roots were very uniform, had excellent color, and excellent quality. The roots showed no root maggot damage, which is usually a serious production problem in the field. The first roots were harvested between 39 and 50 days of planting. With an early April planting, this crop could be the early filler crop used before the main crop is grown. Late plantings may also work well.

Day Neutral Strawberries

Cultivars: Tribute and Everist

Planted: 5/14/03

Spacing: Double rows 1 foot apart; plants were 9 inches apart in the row.

Harvest: Began 8/18/03 and continued until 9/29/03.

Yield: See Table 5

Comments:

This planting was made to compare high tunnel production with field production. Several



questions needed to be answered. One of the problems with production of day-neutral strawberries in the field is the long harvest season and the need of having to use many insecticide applications to control tarnished plant bug. Could high tunnel production reduce the damage from tarnished plant bug? The second question was could strawberry high tunnel production could be accomplished without introducing pollinating insects? Third, would the summer high tunnel environment be too hot for good dayneutral strawberry production to occur? Finally, would the

day-neutral strawberry plants be able to survive the snow-less environment of the high tunnel in the winter?

Table 5. 2003 Day Neutral Strawberry Production. High Tunnel vs. Field Grown

Cultivar	Location	Lbs./10 Ft.	Lbs./Acre	Grams/Berry	Season
Tribute	High Tunnel	4.3	4694	5.85	8/18 – 9.29
	Field Grown	6.9	7514	7.38	8/18 – 10/9
Everist	High Tunnel	3.2	3452	6.43	8/18 – 9/29
	Field Grown	4.3	4683	7.42	8/18 – 10/9

Table 5 shows the yields and fruit size that occurred during the 2003 fruiting season. Even in the field, yields were very average with small fruit size. The summer of 2003 was much hotter than average and was responsible for the poor yields that occurred. However, in the high tunnel yields were even worse than in the field. The high tunnel environment appeared to be too hot for day-neutral strawberry production. Pollination and fruit set did not seem to be a problem in the high tunnel nor was tarnished plant bug injury. The final question was answered in the spring of 2004, when the high tunnel plants did not survive the winter, despite heavy mulching. It appears that the type of high tunnels used at NCROC is too hot in the summer and too cold in the winter for day neutral strawberries to produce well.

Raspberry Production in High Tunnels

Steve Poppe, Emily Hoover, and Emily Tepe, Department of Horticulture, University of Minnesota

Introduction

Raspberry production in the Upper Midwest has a number of challenges. Fruit quality of summer-bearing, or floricanne-fruiting cultivars can be low due to hot temperatures during July harvest, and yields may be lowered due to winter injury. Locally-grown fruit harvested in summer competes with abundant and low-priced California berries for market share, and it can be difficult for smaller producers to sell their fruit at a profit.

Fall-bearing, or primocane-fruiting cultivars, which fruit on current-season's growth offer some benefits. Risk of winter injury is minimal because the canes are pruned to the ground after harvest and do not winter over. Fruit quality is often excellent because fall-bearing cultivars are harvested as the temperatures are cooling in late summer and fall. However, peak production may occur after the first average frost date. For example, in Minnesota in 2007 the first freeze occurred the night of September 17th. Fall-bearing raspberries that had not yet matured were lost to the freeze. Some growers estimated 80% of their crop was not harvested. High tunnels offer protection from frost events, and in University of Minnesota trials, fall-bearing cultivars continued fruiting into early November.

Season extension is not the only benefit high tunnels offer to raspberry production. In field production, yield losses to fungal infection can be high. Typically, growers manage fungal pathogens by pruning and thinning to improve air circulation, and judiciously applying fungicides. Raspberries grown under high tunnels are protected from rain, and have very little fungal growth due to the lack of moisture on the fruit and leaves. Raspberries in high tunnels can be grown with minimal or no application of fungicides.

Weed pressure is reduced in a high tunnel because the between-row paths do not need to be kept in sod, as there is very low risk of erosion under the tunnel. Additionally, through the use of in-row drip irrigation the aisles are never irrigated and weed seeds rarely germinate.

The insect pest complex is somewhat different from field production, more closely resembling that of greenhouse production. Spider mites, whiteflies and aphids are the most common insect pests found in high tunnels. In trials at Morris, Alexandria and Grand Rapids carefully-timed high pressure water sprays and biological controls have been extremely successful in controlling outbreaks.

Research at the University of Minnesota suggests that high tunnel raspberry production can be successful and profitable in Minnesota. In experiments between 2004 and 2009, researchers and farmers examined growing practices, yield potential, and cultivar selection. The recommendations in this section are based on these experiences and on work done in other northern states.

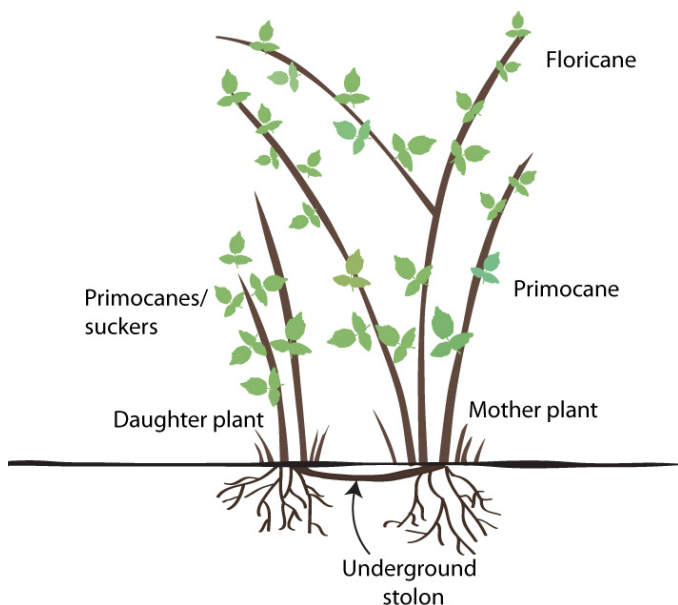
A well-designed, well-maintained raspberry planting can be productive for up to ten years. Typically the initial investment of the high tunnel and the plants is returned after the third year. Subsequent plantings, reusing hardware for a new planting, will be profitable even more quickly.

Before Planting

Primocane-fruiting Raspberries

Summer-bearing, or floricanes-fruiting cultivars produce fruit on second-year canes, or floricanes. These cultivars require a year of growth before the canes produce fruit, meaning the canes must be left to winter-over. Raspberry cultivars that produce fruit on first-year growth (primocanes) are known as fall-bearing, ever-bearing or primocane-fruiting. Primocane-fruiting cultivars will produce fruit on their floricanes the next year if left unpruned, however this will decrease the fall crop potential. Primocane-fruiting raspberry cultivars are used in high tunnel production for multiple reasons:

- No risk of cold-damage to overwintering canes
- Fruit quality is higher thanks to the cooler temperatures during the bulk of harvest in the fall
- Cleaning debris out of the rows is easier after pruning all canes to the ground, reducing disease incidence.
- Pruning is much faster, since all canes are pruned to the ground.



Cultivar Selection

Variety	Harvest Season	Productivity	Fruit Size	Attractiveness	Firmness	Flavor	Freezing Quality	Vigor	Thorniness
Autumn Bliss	mid	G	MED	VG	G	VG	VG		H
Polana	early	EX	MED	EX	F	F	G		M
Autumn Britten	mid	VG	L	EX	VG	EX	VG	M	M
Caroline	late	EX	L	EX	G	VG	VG	H	M
Joan J	mid	VG	L	EX	VG	VG	VG	M	thornless
F: fair; G: good; VG: very good; EX: excellent; M: moderate/medium; H: high; L: large									

Site Preparation, Layout and Planting

First rule of thumb if you are building a new high tunnel for a raspberry planting: build the tunnel the year before you intend to plant.

Site preparation is similar to planting field-grown raspberries. The usual recommendations for soil testing, ensuring adequate drainage, weed eradication and soil amendments should be followed.

Row orientation

Orienting the rows north/south will optimize light exposure. Row spacing depends on how vigorous the canes are expected to be.

Row spacing

For vigorous raspberries (black and red) spacing of 8-10 ft. between rows is recommended. For less vigorous red raspberry cultivars spacing between rows of 6-8 ft. is sufficient. Trials at Morris and Grand Rapids had a spacing of 8 feet, which was adequate for all varieties listed above.

Plant spacing

We have determined 18" to be ideal spacing for newly planted raspberries. Spacing is only significant in the first and second years, since canes will fill in the row in subsequent years and make original spacing irrelevant. In an Alexandria trial of Joan J at three spacings, 18" appeared to be the best choice for economy of initial planting and yields in the first and second years.

Total cumulative yield of plants spaced at 12" was virtually the same as plants spaced at 18". The yield per plant however, was significantly less. In addition, the expense of the extra plants needed to achieve a 12" spacing would increase the initial cost of establishing the planting.

Plants spaced at 24" had a lower total yield than those at 18". However, a calculation of yield per plant indicated virtually no difference. This means that the first and second year yields may be a bit lower due to fewer plants; however the savings in plant material to

establish the planting may be a good economic choice. In UM trials, 18” provided the perfect compromise between establishment costs and yield potential.

Plants and Planting

Tissue cultured, bare-root plants are the ideal choice for the high tunnel. Tissue culture ensures virus-free, more uniform plants. Sources for bare-root and tissue cultured plants can be found in the Resources section.

Raspberry plants should be transplanted as soon as the soil can be worked. In Minnesota this should be no later than early to mid-May. Follow standard guidelines for planting depth, watering in, etc.

Disturb the soil as little as possible to avoid turning up weed seeds.

In the alleys between the plant rows, landscaping fabric provides a good barrier to weeds, and should be rolled out and pinned down right after planting. Within the rows, expect to hand-weed throughout the season.

Drip Irrigation

In the UM trials, drip irrigation was installed following the guidelines in the Irrigation section. Two drip lines were run down each row, straddling the plants.

Maintenance

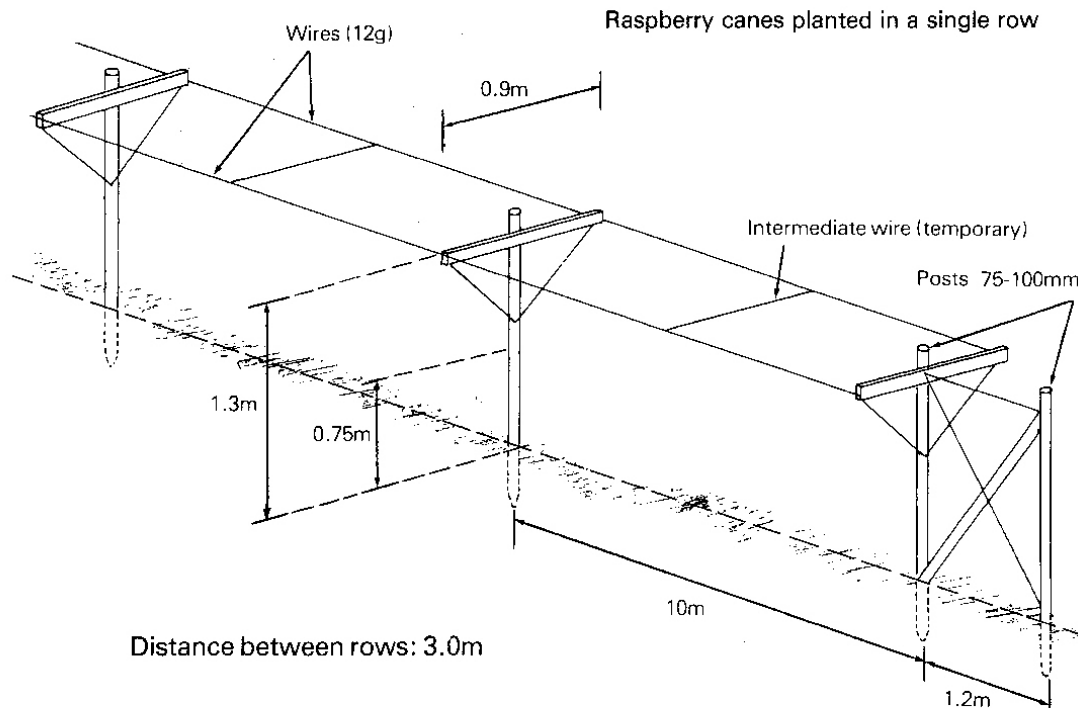
Trellis

Construction of a trellis should begin before the plants are tall enough to need it. In UM high tunnel raspberry trials, we have used a fairly simple system of steel fencing stakes as uprights, half-lengths of fencing stakes as cross-pieces, and baling wire or twine to support the canes.

In the high tunnel, raspberry primocanes can grow in excess of 6 feet tall. Trellis stakes should be approximately 5 feet tall after being pounded into the ground. The top cross-piece should be at that level, and additional cross-pieces should be attached at 4', 3', and 2'. Attach baling twine to these cross-pieces to ensure canes will be supported evenly along their length. This reduces the pressure of the canes on the twine, and thus reduces incidence of twine cutting into the canes. The more rows of twine, the less likely canes will be damaged by it. As the canes grow, they may need a little training to stay within the trellis. Simply tuck the canes behind the highest twine they reach to prevent unruly rows and breakage.

This type of trellis was used in trials due to its simplicity, effectiveness, minimal labor requirement and low cost. Many other trellis styles could be effective in high tunnels as well.

Figure 6. Worcester training system for raspberries.



Row Maintenance – Pruning & Thinning

Pruning at the end of the season is quite simple. All canes should be pruned to the ground and covered with a layer of straw to protect them from winter damage. High tunnel raspberry rows should be maintained at a width of 12", and no more than 18". This will promote taller canes, greater light penetration, higher yields and easier harvesting. As canes begin to emerge in spring, cut back any shoots that are growing outside the 12"-18" row.

Similarly, the rows require thinning to increase air circulation and light penetration, reduce disease incidence, and increase yields. The first canes to emerge will usually be the largest, and other smaller canes will fill in between those. Leave the largest canes and prune out the smaller canes, maintaining 6-8 canes per linear foot of row. Remember, the larger the cane diameter, the larger the fruit it will yield.

Temperature & Ventilation

Proper tunnel ventilation and temperature monitoring are necessary to ensure greatest plant growth and highest yield. This can be achieved with roll-up (or roll-down) sidewalls, end walls that can be opened, upper level vents, or a combination of the three. Thermostatically-controlled, automated sidewalls can be very helpful in maintaining proper tunnel temperature, reducing the time and labor required to manually raise and lower the sidewalls.

However, if an automated system is employed, it remains important to monitor tunnel temperature. A malfunction in the automated system could result in severely damaged plants. The temperature inside a closed high tunnel on a warm day can easily reach temperatures in the hundreds, which can severely damage plants and limit production. A single incidence of extremely high temperature in our 2008 trial caused severe dieback, stunted growth for the remainder of the season, and significantly reduced yield. The optimal temperature for raspberry plant growth is between 59 and 68°F.

The main purpose of a high tunnel for growing fall-bearing raspberries is to extend the season later into the year. Therefore the most important time to hold heat in the tunnel is in the fall when outdoor temperatures drop and threaten frost damage. For these reasons, it is unlikely to be beneficial to close the sidewalls in the spring as growth is just beginning, unless extreme cold and frost is forecast. If the tunnel is closed in the spring, the temperature inside the tunnel will, of course, increase which in turn will speed up growth. This may seem like a good idea, however if growth is advanced in the spring, the result is likely to be earlier fruit production (mid-August). This is undesirable considering the high heat inside a tunnel in August. Fruit held at high temperature has significantly reduced quality and shelf-life. If earlier growth and fruiting is desired, daily harvesting will likely be necessary to prevent heat-damaged fruit.

In Morris, MN trials, sidewalls are left open throughout the spring (day and night) unless extremely low temperature or frost is forecast. This practice allows for a normal rate of primocane growth throughout the early season.

Start monitoring tunnel temperature around May 1 or when new growth is visible.

Pest Control

The environment inside the high tunnel is very different from the field, and more closely resembles that of a greenhouse. Consequently, the pest complex and pest control practices also differ.

High Tunnel Raspberry Diseases

A significant benefit of high tunnels for raspberry production is the elimination of most of the common raspberry diseases. Protecting the foliage and fruit from water goes a long way to preventing many diseases. Protection from wind and other environmental factors reduces stress on the plants, making them less prone to attack.

Powdery mildew is one disease that tends to be more common inside high tunnels than in the field, due to the increased humidity and reduced airflow. Infection is most likely to occur when the side walls are down. The lack of air flow and transpiration saturating the air can result in condensation forming on the foliage optimizing the likelihood of infection. Risk of infection is greater if plant density is high, as overlapping plant tissues can result in localized high humidity. The following practices will help prevent an outbreak of powdery mildew in high tunnel raspberries.

Prevention

- Proper tunnel ventilation
- Good air circulation within the row (achieved by proper pruning and thinning)
- Drip irrigation to keep water off the foliage
- Scouting for disease occurrence throughout the season

Control

- Prune and thin the row
- Remove any dead plant material or debris from the tunnel

In UM high tunnel raspberry trials, no other diseases have been encountered. However, other common raspberry diseases can potentially occur in high tunnels.

High Tunnel Raspberry Insect Pests

Four insect pests were encountered in University of Minnesota trials at Morris, Alexandria and Grand Rapids. Spider mites, whiteflies, raspberry sawfly and aphids caused minimal to moderate damage and were rather easily controlled. The most common insect pest throughout two growing seasons was the spider mite.

Weekly scouting with a 10x hand lens revealed spider mites. If high pressure water spray does not eliminate spider mites, there are numerous predatory insects that have proven successful in combating mites. In the Alexandria trial, two releases of 1000 *Phytoseiulus persimilis*, two weeks apart provided control for a single 80' row in a 12' x 90' high tunnel.



A few details on *Phytoseiulus persimilis*

- Eats 5-20 mites or eggs per day.
- Must have mite prey or will disperse/starve
- Require high humidity to be effective (above 70%; best between 80-99%)
- Plants should be in contact for greatest effectiveness
- Best used where little or no spider mite damage can be tolerated.

Numerous other predatory insects are recommended for raspberry. Find information and sources in Resources.

General Insect Pest Prevention for High Tunnel Raspberries

- Keep area free of weeds
- Do not over-fertilize
- Keep plants well watered and vigorous
- Prune heavily infested plant material if possible before attempting control.

Economics

The following tables illustrate the estimated costs of establishing raspberries in one 30' x 48' high tunnel, potential income and return on investment. The figures in Table 1 are 2009 costs to construct and establish the high tunnel raspberry planting at the West Central Research and Outreach Center in Morris, MN and are to be used only as a guide, since many factors are dependent on the particular circumstances of each site. For example, choosing to manually raise and lower the sidewalls would contribute savings. Similarly, different styles of high tunnels will carry varying costs.

Table 1. Cost of construction and planting in a 30' x 48' high tunnel. Dollar amounts are from 2009.

FarmTek Growers Supply 30' x 48' High Tunnel	\$2700.00
Hired labor to construct	\$1778.00
Thermostatically controlled roll-up sides	\$1600.00
Electrical	\$1200.00
Wood materials with door	\$800.00
Drip irrigation	\$160.00
Cost of Plants (NUMBER OF PLANTS X COST OF PLANTS)	XXXXXX
Total Initial Costs	\$8238.00

Table 2 illustrates the potential income from a 30' x 48' high tunnel in its first full production year, or year 2 of the planting. Yield is based on highest yields of 'Autumn Britten' in the WCROC high tunnel raspberry planting in 2010. Number of containers filled is calculated by weight, and the price per container is an average price asked at local MN farmer's markets. The matrix in table 3 shows income based on various price points and a range of yields.

Table 2. Potential income from a 30' x 48' high tunnel raspberry planting in the second year (first full harvest year).

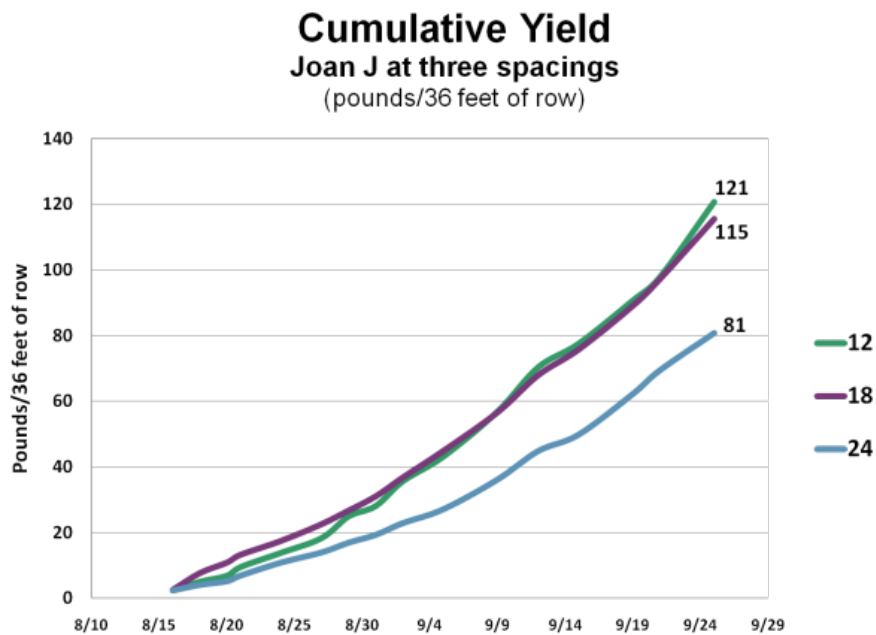
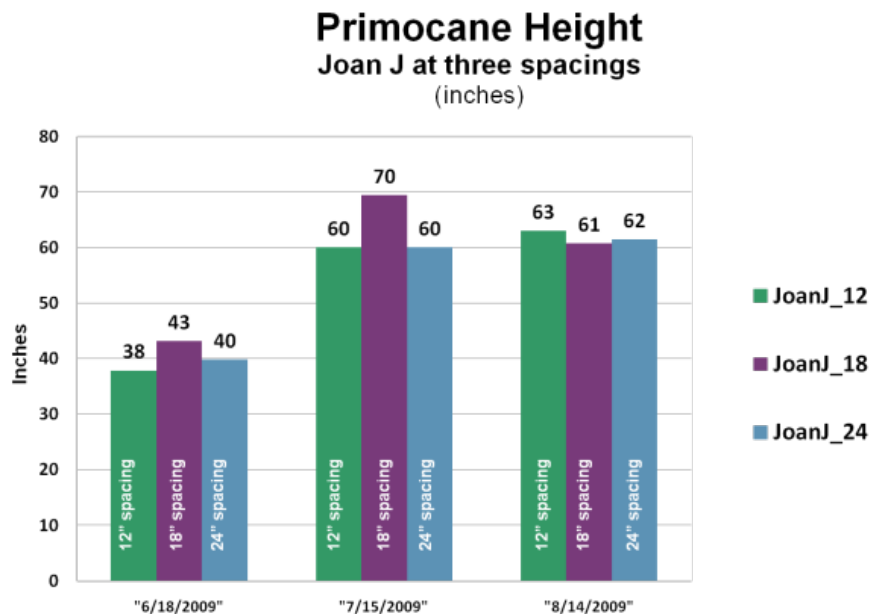
106.32 pounds/36 feet of linear row x 3 rows per 30'x 48' high tunnel	318.96 pounds
Number of 6oz. containers filled	850
Price per 6 oz. container	\$4.50
Total per 30' x 48' high tunnel in the second year (first full harvest year)	\$3825.00

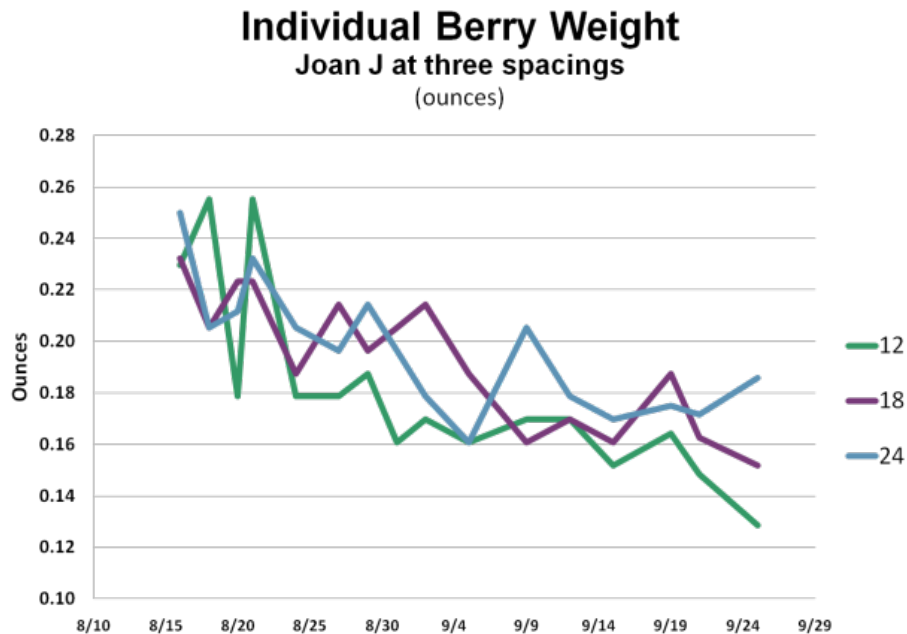
Table 3. Potential return on investment from a 30' x 48' high tunnel raspberry planting.

Planting Year	1/3 of full harvest potential	\$1275.00
Second Year	Full harvest	\$3825.00
Third Year	Full harvest	\$3825.00
Total income after third year		\$8925.00

Yield and Cane Growth

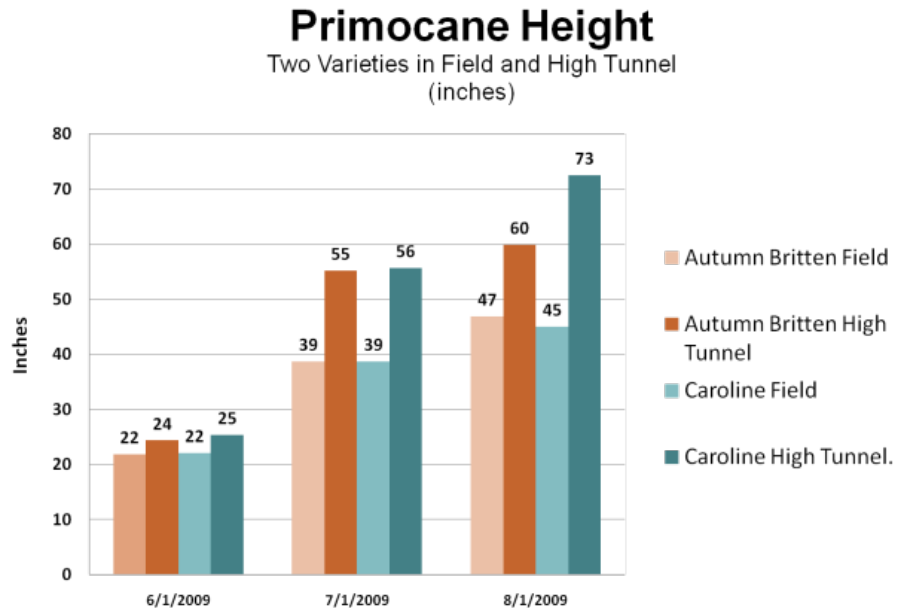
Effect of spacing on 'Joan J' plant growth, yield and berry size. Trial at Berry Ridge Farm, Alexandria, MN.





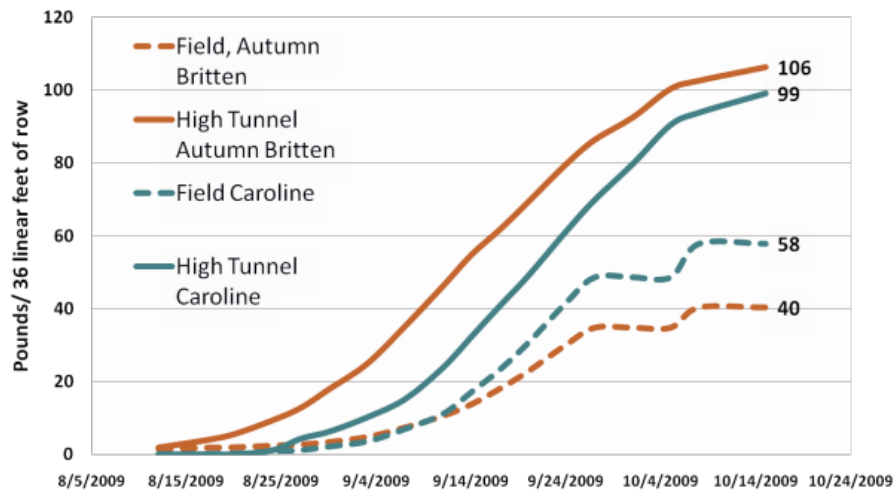
Yield and Cane Growth

Trial of two cultivars, 'Autumn Britten' and 'Caroline' in a high tunnel and in the field. Morris, MN



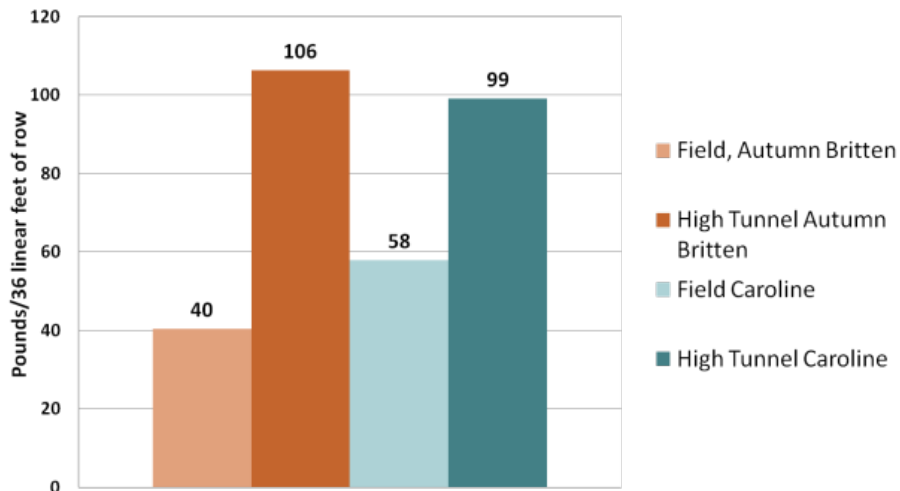
Cumulative Yield

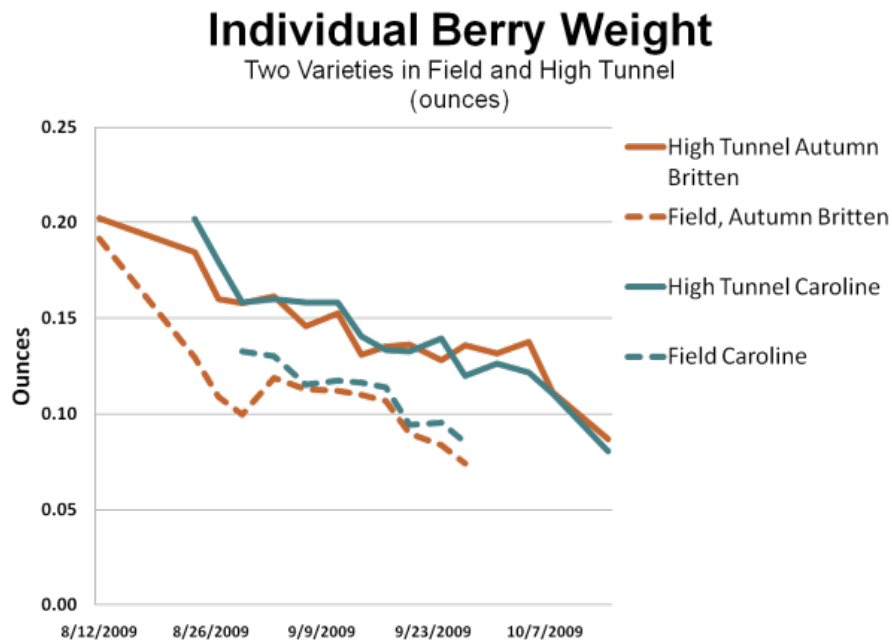
Two Varieties in Field and High Tunnel
(Pounds/36 linear foot of row)



Cumulative Yield

Two Varieties in Field and High Tunnel
(Pounds/36 linear feet of row)





Current Research on High Tunnel Fruit Production

Terry Nennich, University of Minnesota

In 2012, U of M researchers and Extension personnel began working in cooperation with growers in the Crookston, MN area to further study high tunnel fruit production. Three tunnels on grower-cooperator farms were planted with tree fruits including apple, cherry and plum. One tunnel was planted with a variety of small fruits: blueberry, honeyberry, strawberry, raspberry and blackberry. An additional tunnel has been built for planting in 2013 of high-risk tree fruits including peach, apricot and pear.

As of publication no data has been collected on these plantings; therefore no conclusions have been made on the success of these fruits in high tunnels. Information will be posted on our website, <http://hightunnels.cfans.umn.edu/>, when it becomes available.

High Tunnel Marketing & Economics

Karl Foord, Regional Extension Educator, University of Minnesota

Introduction

High tunnels have the potential to greatly increase the range of crops that can be grown in much of Minnesota. As growers research high tunnel production, they will find that tunnels can increase profitability by:

- Extending the production season or allowing production of crops not winter-hardy enough for field production,
- Increasing the quality and shelf life of the product,
- Minimizing the use of pesticides, and
- Ensuring a continuous flow of produce even when the outside environment is not favorable for field production.

But any new technology should be analyzed from a business perspective to determine if that technology can be a good investment for the owner. Getting started in high tunnel production requires a significant capital investment, and many growers will want to seek credit for this new venture. Lenders will want to know if a high tunnel can be profitable, so devising a business plan that realistically accounts for both the greater expense and the greater potential profit will be necessary.

To determine whether adopting this technology is the best path for a business, consider these questions:

- Does this technology fit with the goals and strategy of my operation?
- Is this technology the best path, or are there alternatives that would be a better investment of my time and energies?
- Can I project the financial impact of this technology? Will it meet my financial goals?
- What are the critical parts of this technology, the things that must be done right for this project to be a success?
- Can I also improve my chances for success by performing a sensitivity analysis that addresses the risks I may encounter: economic, scheduling, market competitive, and regulatory?
- How do I need to modify my management systems to improve success?
- How will I measure success?
- What assumptions am I making about yield and pricing, and is there a way to quantify and verify these assumptions?
- Is there someone who could review my plan and verify strengths and point out weaknesses?
- Do I have a financial advisor who could verify the financial projections?

Marketing: Planning for Profit

Producers must achieve a profit level that compensates them for their efforts and the risk they have assumed in production. People who have survived in the horticulture business will

tell you, if there isn't a market for something, don't grow it! All of your assets, including your new high tunnel, are liabilities—until your customer shows up with money and turns them into assets. If the customer does not show up, the assets remain liabilities. An analysis of the suitability of high tunnels for your operation is incomplete unless you have a good understanding of how your efforts will be received in the marketplace.

Marketing is sometimes an afterthought for growers who love the processes of production. But the success of high tunnels as a sustainable part of your business will depend heavily on your success in marketing.

The possibilities for high tunnel profitability are great, but capturing those profits is not a given. Can you evaluate the market and assess the premium people may be willing to pay for the value you bring? How much would your customers pay for fresh, local produce that is:

- *First to market ahead of the regular season, and last at market after killing frosts.* This is the primary advantage of high tunnels.
- *Higher quality.* Because your market is local, you can bring to market a product freshly picked at peak ripeness, and compared to the produce that comes from your fields, high tunnel produce is likely to be even better! Keeping rain off the foliage and fruit, eliminating mud-splash, keeping temperatures warm, preventing damage from wind storms, easily providing water and nutrients as needed by plants: these all lead to bigger harvests of significantly better produce.
- *Not readily available.* In Minnesota, these include tomatoes, peppers, and garlic in the north, and fall-bearing raspberries in much of the state.
- *Certified organic or produced with very little pesticide.* In high tunnels, disease pressure is greatly reduced, and the use of beneficial insects for pest control is easier than in the field.
- *Luxury priced.* Higher prices imply higher quality; lower prices low quality. Some consumers are willing to buy more expensive produce simply because it is more expensive. Know your market!

Grow what the market values

The true challenge for fruit and vegetable growers operating on a smaller scale is to find those markets that place high value on their products. Wanting a product and valuing it are different. Customers demonstrate their assessment of value by exchanging money for satisfaction. (When asked directly, people may underestimate or overestimate what they are truly willing to pay.)

It's important to understand how your customer values the product. One challenge is to select the market channel that best fits with your goals and situation. Price sensitivities and your profit margins will vary by channel.

Wholesale Channels

Wholesale channels involve customers who are not the end product consumer, including professional chefs or restaurant owners, wholesale produce brokers, produce managers at local grocery stores, or cooperative organizations. Your product is now part of their product. How does your product impact the value that they deliver to their customers?

What is the value to a restaurateur to have a tomato in a salad that is more than just a piece of pink in a sea of green? What if the tomato actually tasted good? Would this help to create customer loyalty for the restaurateur? The more your product is a key component of your customer's offering, the greater the value it will be assigned by your customer.

Understanding and delivering this kind of value is critical to developing a competitive product, and *capturing your share* of the value delivered is critical to maintaining a sustainable business operation.

For wholesale customers, focus on the total value delivered to their operation. More than just product quality, value can include reliability, trustworthiness, timeliness, and an ability to position oneself as a critical cog in their operation. The position to avoid is to be perceived as just another part of their cost structure—the definition of a vulnerable business relationship is one where your customer views you only as an input cost, which should be reduced as much as possible.

The importance of customer relations cannot be overemphasized. People want quality, but quality without reliability is of little use to the wholesale buyer. If your product is an important part of their offering, they have to know that you can deliver. The last thing a chef wants is to prepare a menu and then not be able to deliver because of the lack of an ingredient. Communication about the status of supply and delivery schedules is part of reliability.

Retail Channels

Retail channels involve customers who are the end product consumer. The interface point varies: a roadside or on-farm stand, a pick-your-own operation, a farmers' market, or a subscription arrangement such as Community Supported Agriculture (CSA).

The risks associated with retail markets can be reduced by a better understanding of your customers, especially their behavior patterns. Market analysis identifies customers in two ways: who they are and what they do. The first is called demographic and might identify where people live, how old they are, and how much money they make. These are good things to know about your customers to help you formulate the best win-win deal between what they want and what you have to offer.

Even more important than the demographic data is the behavioral data. How do they purchase their produce? How important is taste, presentation, location of purchase, philosophy of production? For some people one or more of these is irrelevant. For others these features are very important. The key is to identify those people who value your unique offerings.

If your retail customers value low price over high quality, investing in a high tunnel may be a bad idea!

Record Keeping

What is your system for capturing data? It is difficult to establish a win-win business relationship with customers if you don't know what constitutes a win for you.

Evaluate your financial tracking system. It needs to be simple, accurate, and focused on those numbers that will help you identify your best and most profitable crops, horticulture methods, and market channels. With this information, you can continue to eliminate inefficiencies and choose profitable pathways. Without it, you are left with hunches.

When times are great you may be able to prosper without good systems. But when times become challenging it is much more difficult. What do you think the probabilities are that you will not encounter challenging times?

Reasonably priced computer and barcode systems exist that can reduce tedium, improve accuracy, and give you good management data. It may be that food security issues will generate regulations requiring this level of data. Your customers may demand it before the law does.

Financial Analysis

This is what a lender will want to see, and what you will want for your own peace of mind as you go ahead with a substantial investment.

Establishment Costs

How are the costs associated with the establishment of high tunnels classified? Are there capital costs that will be depreciated? What part of the establishment of the tunnels can be expensed? What are the tax implications? Are there labor related costs? Are there any own or lease issues? Do you have a timeline for establishment and a finance plan that matches?

Table 1 estimates costs of establishing a 26' x 96' high tunnel. The cost estimate ranges from about \$7,000 to about \$11,000. Many tunnels will cost more, if they include heaters or more sophisticated environmental controls. Smaller tunnels could cost somewhat less. Another thing to consider is shipping. Obviously shipping from Ledgewood Farms in New Hampshire is going to be more than from Farmtek in Iowa. But there is no question that the construction of a tunnel is a significant capital project for any farm.

Table 1. High Tunnel Construction Costs (20' x 96') excluding site preparation and shipping (2012)											
Item										Cost Range	
										Low	High
Site Prep.	Site specific										
Gothic Frame Kit	Distributor	Base Kit		Upgrade Options					Shipping		
		6' Spacing	4' spacing	Door							
	Poly-Tex	\$5,467	\$6,734	\$264						\$5,731	\$6,998
Construction	Local Labor		114	man-hours	Where on the learning curve?			\$15	per hr.	\$1,710	
	Professional Construction		Per sq. ft. basis			Cost per tunnel		1920	sq. ft.		
	Estimate		\$0.50	to	\$1.00	\$960	to	\$1,920	\$		\$1,920
Non-kit Materials	Materials obtained locally for: baseboards, hipboards, rope (may want extra screws and metal banding)									\$300	\$500
Irrigation	Includes: set up, headers, drip tape									\$200	\$400
Misc.	Miscellaneous items not anticipated									\$100	\$200
Totals	Construction cost range based on above estimates									\$8,041	\$10,018
Note	There are many sizes available - please visit: http://www.poly-tex.com/high_tunnels.html for more details										

Table 2. High Tunnel Crop Budget – Tomatoes (2012)					
	\$/Tunnel (20' x 96' - 5 rows - 320 plts/tunnel)				
Yield (lbs. per plant)	7	10	14	17	20
Yield (lbs. per tunnel)	2,240	3,200	4,480	5,440	6,400
VARIABLE COSTS					
Fertilizer	\$40	\$50	\$60	\$70	\$80
Pest Control	\$50	\$50	\$50	\$50	\$50
Black Plastic Mulch	\$20	\$20	\$20	\$20	\$20
IRRIGATION					
Dripline	\$25	\$25	\$25	\$25	\$25
Drip Irrigation Operation	\$25	\$25	\$25	\$25	\$25
Plant Maintenance (Stakes, Twine)	\$30	\$30	\$30	\$30	\$30
Fuel	\$30	\$30	\$30	\$30	\$30
Transplant Materials	\$48	\$48	\$48	\$48	\$48
Packaging - Boxes (@\$1.50)	\$105	\$150	\$210	\$255	\$300
Marketing (3% of ave. revenue)	\$50	\$75	\$100	\$150	\$200
LABOR					
Transplanting	\$66	\$66	\$66	\$66	\$66
Trellis - Staking, Training	\$110	\$110	\$110	\$110	\$110
Weeding	\$25	\$25	\$25	\$25	\$25
Ventilation & Monitoring	\$220	\$220	\$220	\$220	\$220
Machinery Operation	\$35	\$35	\$35	\$35	\$35
Harvest	\$263	\$315	\$350	\$438	\$525
Grading/Packing	\$68	\$81	\$90	\$113	\$135
Seasonal Cleanup	\$55	\$55	\$55	\$55	\$55
Land Preparation*	\$55	\$55	\$55	\$55	\$55
Interest Expense	\$36	\$40	\$44	\$50	\$56
TOTAL VARIABLE COSTS	\$1,355	\$1,505	\$1,648	\$1,869	\$2,090
FIXED COSTS					
Land (rent of .2 ac at \$150 per acre)	\$30	\$30	\$30	\$30	\$30
Depreciation	\$700	\$700	\$700	\$700	\$700
TOTAL FIXED COSTS	\$730	\$730	\$730	\$730	\$730
TOTAL COSTS	\$2,085	\$2,235	\$2,378	\$2,599	\$2,820
BREAKEVEN PRICE					
32# box	\$29.79	\$22.35	\$16.99	\$15.29	\$14.10
per pound	\$0.93	\$0.70	\$0.53	\$0.48	\$0.44
Assumptions:					
Planting rate - 64 plants per 96 ft					
Tunnel dimensions: 96' by 20'					
96 ft x 20 x 5 rows = 320 plants per tunnel	Yield		Variable Expenses		
Yield at 7 lbs. per plant =	2,240		\$1,214		
Yield at 10 lbs. per plant =	3,200		\$1,349		
Yield at 14 lbs. per plant =	4,480		\$1,475		
Yield at 17 lbs. per plant =	5,440		\$1,679		
Yield at 20 lbs. per plant =	6,400		\$1,882		
Land area = 1.2 x area of tunnel					
Interest expense = 4% loan 9 month term on: variable expenses					
* assigned a land preparation charge in lieu of machinery and equipment expenses					

Benefit Analysis

What kind of financial benefits will come from the high tunnel operation?

Benefits from increased revenues

It is critical to define the source of value and the justification for high premiums? Will the value come from products that the market recognizes, but that have a higher value due to timing and quality? Will the value come from features of production, such as organic or reduced use of pesticides? Will the products be new to the market and valued because of their scarcity? Perhaps yields will be higher and the marketing season longer, increasing revenues without increasing price.

Benefits from reduced costs

Will the benefits of this system come from a cost reduction? This could be a reduction in the cost of input materials, such as chemicals used for pest control. It's likely that growing crops in the high tunnel will cost more than field production in nearly every way, but there could be some savings: watch for them.

Table 3 shows that as both yield and price go up, the potential revenue for a high tunnel crop (in this case, tomato) can be very large.

Table 3. Price/Yield Matrix							
Yield		Price per pound					
(lb/plant)	(lb/tunnel)	\$1.00	\$1.50	\$2.00	\$3.00	\$3.50	\$4.00
7	2240	2,240	3,360	4,480	\$6,720	\$7,840	\$8,960
10	3200	3,200	4,800	6,400	\$9,600	\$11,200	\$12,800
14	4480	4,480	6,720	8,960	\$13,440	\$15,680	\$17,920
17	5440	5,440	8,160	10,880	\$16,320	\$19,040	\$21,760
20	6400	6,400	9,600	12,800	\$19,200	\$22,400	\$25,600

A grower wanting to take a more conservative view might figure on yield going up moderately and price being only slightly above the price for field-grown tomatoes. To see if a tunnel can be profitable with higher and lower yields and prices, conduct a *sensitivity analysis*.

Sensitivity Analysis

Whenever attempting to project the financial outcome of a project the answer should never be one number but rather a range of results. This is because there will be uncertainty or potential variation in inputs. In this case we do not know the exact yields or price received for produce. To address this we can specify a range of these input values and then determine the effects of these changes on the output projections.

This is called a **sensitivity analysis**, and it allows us to create a range of profit figures for the enterprise by varying the price and yield input values.

We do have to assign a time value to money. Most businesses like to earn money at a greater rate than what money presently costs them (the cost of capital). This rate could vary from inflation to a higher expectation linked to the bond or equity markets. At this point it is a factor in the spreadsheet. This spread sheet permits one to vary yields and prices and the value of money to arrive at a Net Present Value (NPV) of the high tunnel project. NPV has been described as the cost associated with tying up money in a project, when it could be invested with a financial firm, and earning dividends or interest.

Having identified our anticipated costs for both the establishment and operation of the high tunnel, we can see how various yield and price values impact the potential value of the project. Note that the following scenarios assume a tunnel whose costs are at the low end of the range established for construction of a high tunnel.

High Tunnel Production System Sensitivity Analysis Profitability Scenarios. (5-year tunnel life expectancy)

High Tunnel Production System – Sensitivity Analysis						
Profitability Scenarios (5 year life expectancy of tunnel)						
Scenario # 1 - Low Price (\$1.50) Low Yield (7 lbs./plant)						
	Year					
Year	0	1	2	3	4	5
Average Yield (lbs. per tunnel)	-	2240	2240	2240	2240	2240
Average Price (per pound)	-	\$1.50	\$1.50	\$1.50	\$1.50	\$1.50
Revenues		\$3,360	\$3,360	\$3,360	\$3,360	\$3,360
Expenses		\$2,085	\$2,085	\$2,085	\$2,085	\$2,085
Profit/Cash Flow		\$1,275	\$1,275	\$1,275	\$1,275	\$1,275
PV of Cash Flow @ 4.00 %		(\$9,500)	\$1,226	\$1,179	\$1,133	\$1,090
NPV @ 4.00 %		\$5,676				
		(\$3,824)				

High Tunnel Production System – Sensitivity Analysis						
Profitability Scenarios (5 year life expectancy of tunnel)						
Scenario # 2 - Medium Price (\$2.50) Medium Yield (14 lbs./plant)						
	Year					
Year	0	1	2	3	4	5
Average Yield (lbs. per tunnel)		4480	4480	4480	4480	4480
Average Price (per pound)		\$2.50	\$2.50	\$2.50	\$2.50	\$2.50
Revenues		\$11,200	\$11,200	\$11,200	\$11,200	\$11,200
Expenses		\$2,378	\$2,378	\$2,378	\$2,378	\$2,378
Profit/Cash Flow		\$8,822	\$8,822	\$8,822	\$8,822	\$8,822
PV of Cash Flow @ 4.00 %		(\$9,500)	\$8,483	\$8,156	\$7,843	\$7,541
NPV @ 4.00 %		\$39,274				
		\$29,774				

High Tunnel Production System – Sensitivity Analysis						
Profitability Scenarios (5 year life expectancy of tunnel)						
Scenario # 3 - High Price (\$4.00) High Yield (20 lbs./plant)						
	Year					
Year	0	1	2	3	4	5
Average Yield (lbs. per tunnel)		6400	6400	6400	6400	6400
Average Price (per pound)		\$4.00	\$4.00	\$4.00	\$4.00	\$4.00
Revenues		\$25,600	\$25,600	\$25,600	\$25,600	\$25,600
Expenses		\$2,820	\$2,820	\$2,820	\$2,820	\$2,820
Profit/Cash Flow		\$22,780	\$22,780	\$22,780	\$22,780	\$22,780
PV of Cash Flow @ 4.00 %		(\$9,500)	\$21,904	\$21,061	\$20,251	\$19,472
NPV @ 4.00 %		\$101,413				
		\$91,913				

The worst-case outcome is Scenario 1, where we have assumed a low yield and low price received. The investment has not been recouped, even after the fifth season. If you thought that these results were the best that you could achieve, you would not start the project.

Scenario 2 assumes an average yield and average price received, the tunnel breaks even in the second growing season, and returns a profit to the grower. If you thought you could achieve these results, you would want to give serious consideration to this project. If you performed a net present value analysis on another potential project, you could compare the two projects to see which might be more profitable. You could also change the rate of the cost of capital from 10% to a value more appropriate to your operation, if you could borrow money for an interest rate less than ten percent.

Scenario 3 is the best case scenario, and assumes that you can produce better than average yields and obtain a significant price premium. In this case the venture would be very profitable.

These are just three of a large number of possible values that could be entered into the spreadsheet. The spreadsheet will be posted on the high tunnel web site, so that you can download the file and change the values as you wish, to reflect actual yields and prices, actual interest rates, and actual cost of construction and crop production.

References

1. High Tunnel Production Manual, Department of Horticulture, Pennsylvania State University. <http://plasticulture.psu.edu/node/115>
2. Gregory, Patrick J., *Maximum Return—The Ultimate On-Time, On-Budget, Results-Driven Project Planning Guide*, Living Spirit Press, 2003.

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