12-2010

Enhancing Out-of-Season Production of Tomatoes and Lettuce Using High Tunnels

Britney L. Hunter
Utah State University

Recommended Citation

Hunter, Britney L., "Enhancing Out-of-Season Production of Tomatoes and Lettuce Using High Tunnels" (2010). *All Graduate Theses and Dissertations*. 811.
https://digitalcommons.usu.edu/etd/811

ENHANCING OUT-OF-SEASON PRODUCTION OF TOMATOES AND LETTUCE USING HIGH TUNNELS

by

Britney L. Hunter

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Plant Science

Approved:

Dr. Brent Black Co-Major Adviser	Dr. Dan Drost Co-Major Adviser
Dr. Richard Beard Committee Member	Byron Burnham Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2010

ABSTRACT

Enhancing Out-of-Season Production of Tomatoes and Lettuce
Using High Tunnels

by

Britney L. Hunter, Master of Science

Utah State University, 2010

Co-Advisers: Dr. Brent Black and Dr. Dan Drost
Department: Plants, Soils, and Climate

The growing season for vegetable crops is limited by freezing temperatures in arid high elevation climates such as northern Utah. Logan, Utah (41.73 N, 111.83 W, 1382 m elevation) has a short, variable growing season with an average frost-free period of 135 days. Extending the growing season provides growers with an opportunity to extend revenue into a normally unproductive period and benefit from out-of-season price premiums. High tunnels have been used to effectively extend the growing season for numerous crops by providing cold temperature protection. However, limited high tunnel research has been performed in arid high elevation regions that experience extreme temperature fluctuations. The use of high tunnels was investigated in North Logan, Utah to extend the growing season for tomatoes and lettuce. In 2009 and 2010, supplemental heating under low tunnels within high tunnels was investigated to provide early season cold temperature protection for tomatoes. Sunbrite tomatoes were transplanted into four high tunnels over three planting dates. Tomatoes were subjected to supplemental heating treatments including soil warming cables alone or in conjunction with 40-watt incandescent lights for air heating. The highest early season and overall yield was achieved with the 17 Mar. planting date. Early season yield was significantly less for the latest planting date (7 Apr.) compared to the 17 Mar. and 30 Mar. planting dates. Early season yield was significantly greater for treatment plots with soil plus air heating, and soil heating alone significantly improved total yield. The use of a vertical structure within a high tunnel was investigated to improve productivity for lettuce. Parris Island Cos lettuce was consecutively transplanted from spring 2008 to spring 2010 in a high tunnel at the same site. The vertical growing system allowed for 31 plants$\cdot$m^{-2} in south oriented gutters, and 45 plants$\cdot$m^{-2} in east/west oriented gutters compared to 25 plants$\cdot$m^{-2} in the ground including space for maintenance. Root zone temperatures in the gutters fluctuated widely in response to air temperatures, and super-optimal soil temperatures impeded growth. Productivity (g$\cdot$m^{-2}) in the gutters was only significantly greater than productivity in the ground soil during the spring and fall months when soil and air temperatures were not frequently below 0 °C or above 24 °C. This thesis includes both research results and extension factsheets intended for growers interested in high tunnel production of tomato and lettuce.

(153 pages)

ACKNOWLEDGMENTS

I would like to thank the Sustainable Agriculture Research and Education (SARE) program for generously funding this research intended to benefit farmers and researchers. I would also like to thank my committee members Dr. Dan Drost, Dr. Brent Black, and Dr. Richard Beard for supporting me through the academic research process and helping me see beyond my previous perspective. A special thanks to our research technician James Frisby who served as an exceptional mentor for data collection and occasional disaster relief.

Britney Hunter

CONTENTS

Page

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The importance of sourcing fresh produce on a local level is becoming a widespread consideration for people concerned with the character of their food. Progressive media sources portray a state of emergency regarding fossil fuel dependency and industrialized agriculture practices that exploit animals and natural resources. John Cloud pointed out in a recent article featured in TIME magazine that organic farming is becoming industrial-sized and remarkably similar to conventional agribusiness (Cloud, 2007). Organic or not, the fuel needed to transport our food over long distances is as environmentally significant as reducing chemical inputs on the farm. “Locavore” was designated word of the year for 2007 by the Oxford University Press. The word describes a person concerned with the ecological impacts of growing and transporting food, and strives to eat seasonally using only locally grown ingredients (OUP, 2007). One restaurant in California has catered to the locavores and created a 100 mile radius dining experience. This is a prime example of new niche market opportunities being created in response to the sustainable food crisis. It is easy for activists in California to commit to this idea, but there are fewer options for northern climates with a limited growing season.

Extending the growing season by protecting plants from cold temperatures can drastically improve productivity in the early and late season. High tunnels are one way that has been shown to effectively and profitably extend the growing season for warm and cool season crops in certain climates (Wells and Loy, 1993). Crops grown out of season command a price premium when sold in direct markets (Foord, 2004). High tunnels look and operate like greenhouses, but the temperature is maintained only by passive heating and cooling unlike standard greenhouses. As the high tunnel traps heat created by incoming solar radiation, optimal temperatures are maintained by manually opening and closing the doors and sides to provide cross ventilation. Beyond raising the temperature, high tunnels contribute to the production of improved quality and higher yielding small fruits and vegetables. By sheltering plants from rain and snow, high tunnels may decrease disease pressure that reduces yield. High tunnels also allow for controlled irrigation that maintains quality of fruits and vegetables. Insect pests and animals that damage crops and transmit diseases may also be deterred by high tunnels. Reducing the need for fungicide and pesticide application contributes to a more sustainable production system.

The decision to utilize high tunnels to extend the growing season is based on a number of factors that present advantages and disadvantages. The primary advantage to high tunnel production is profitability. High tunnels increase net returns per acre by protecting quality, increasing yields, and providing the opportunity to obtain off season price premiums. This allows a farmer to profit significantly without turning into an oversized operation. High tunnel growers may also find it easier to meet the market demands of restaurants and other direct markets that favor purchasing from growers who can provide produce over a longer period of time. The disadvantages of high tunnel production are increased fixed costs associated with the construction, and labor requirements associated with the management of the facility. Despite greater fixed costs and labor requirements, growing early season tomatoes in a simple PVC high tunnel can produce positive returns in small area. The success of a high tunnel operation will depend on the crop and the ability to obtain a premium price for the produce.

While the benefits of growing in high tunnels have been explored in other states, their use should be further exploited by growers in the arid high elevation climates of the intermountain west. The unique climate of the intermountain west presents benefits and challenges with regard to high tunnel production. Important factors to consider regarding a high tunnel venture include: Marketing and economics, temperature requirements, and pest management.

Crop Protection

Protecting crops from harsh weather to enhance off season production and improve quality is an increasingly common strategy used by modern vegetable growers. More growers are using protective structures as agricultural plastics become less expensive and more specialized. Protective structures for plants have been used for centuries all over the world in an attempt to improve production (Dalrymple, 1973; Wells and Loy, 1985). Early protective structures included wood frames covered in paper, paper domes, glass domes or “cloches,” and glass greenhouses. Improved plastics technology drastically advanced crop protection by providing a lightweight, durable, and relatively inexpensive material compared to glass. Polyethylene, a common agricultural plastic, was first used as a greenhouse cover in the U.S. in 1948 by Professor Emery Myers Emmert at the University of Kentucky (Jensen, 2004). Now plastics are used for many agricultural products such as drip tape, plastic mulch, and row covers. Plasticulture is the name given to crop production that utilizes plastic products to enhance crop performance. The benefits realized by increase in yield, increase in quality, and improved water savings are often greater than the cost of agricultural plastics. For example, black plastic mulch helps raise the soil temperature, which promotes early yield of various crops and limits weed growth and water evaporation at the soil surface. This reduces herbicide and water costs, and also encourages the production of valuable out-of-season produce.

Row Covers

Row covers are thin plastic blankets designed to shelter crop plants from cold and wind, and raise day temperatures to promote growth. Polyethylene, polypropylene, and polyvinyl chloride are common plastics used to make row covers. Thin polyethylene (1 to 4-mil thickness) is used for row covers or "low tunnels" placed low to the ground over a crop, and are supported by a wire hoop structure to resemble a tunnel. Thin polyethylene row cover alone was shown to protect tomato plants from freezing when outside temperatures were -3.8 ºC (Emmert, 1956; Waggoner, 1958). The support hoop is typically made of heavy gauge wire or plastic pipe. Polyethylene row cover requires daily ventilation because the cover traps substantial heat that can damage crops. Research has demonstrated plastic row covers to improve productivity of certain crops (Gerber et al., 1988; Wells and Loy, 1993). Slitted plastic technology was developed in an attempt to mitigate heat buildup and eliminate the need for manual ventilation; however the slits in the plastic do not provide adequate ventilation to avoid flower and fruit abortion in tomato (Peterson and Taber, 1991) or bolting in lettuce. Plastics can now be spun-bonded to produce a lightweight fabric-like cover that allows air to pass through, making it more appropriate for cool season crop protection. Polypropylene is commonly used to make spun-bonded covers, and is sometimes referred to as floating row cover or row cover cloth. Polypropylene can also serve as an excellent method for pest exclusion (Ennis, 2010). Spun-bonded row cover may be placed directly on the crop or supported by a low tunnel; however, the cloth may cause injury to plant tissues if it flaps in the wind. These row covers typically provides 2 to 3 °C of cold protection when temperatures are near freezing, and are most effective when the soil is warm (Wells and Loy, 1985; Wells and Loy, 1993).

High Tunnels

High tunnels are larger protective structures designed to shelter plants from cold temperatures and other adverse climate conditions. They are also designed to accommodate the full height of a crop as well as people and machinery for soil tillage and crop management. The structural frame of a high tunnel is typically made of galvanized steel pipe or PVC pipe that is arched in a tunnel shape. High tunnels are covered with polyethylene greenhouse plastic, but do not include the heating and cooling equipment common to standard greenhouses. Thick polyethylene plastic (6 to 8 mil) is UV stabilized to slow deterioration.

High tunnels protect plants from the cold in several ways. When short wave radiation enters a high tunnel on a sunny day, the radiation is partly absorbed by the soil and plants inside. Latent heat dissipates from the surface of the soil and plants by convection, transpiration, and emitted long wave radiation. The plastic covering on the high tunnel traps the warm air and reflects some long wave radiation back toward the soil and plants after the outside temperature drops. During the night the temperature inside a high tunnel may approach the outside temperature, but the plants stay warmer due to the plastic cover which retains heat by limiting long wave radiation emitted by the plants.

Still air inside the high tunnel will not cool as rapidly as the air outside because the air inside cannot mix with cooler air. This phenomenon is similar to the protection provided by a wind break, which provides a protective boundary layer around the plants. The frost protection of a high tunnel is limited to 1 to 4 °C at night when outside temperatures are near freezing. The combination of low tunnels within a high tunnel further enhances the temperature protection by trapping warm air and long wave radiation closer to the plants. Soil temperatures are naturally warmer than the air in the winter and cooler than the air in the summer. The soil stays even warmer inside a high tunnel due to absorption of heat trapped by the high tunnel. The type of plastic on a high tunnel will effect temperature, relative humidity, light, and CO_2 reaching the plants inside. Plants in high tunnels must adapt to daily temperature swings from as high as 35 °C during the day to 5 °C at night. The altered environment of a high tunnel requires a different management perspective than managing plants in the open field.

Relative Humidity

Relative humidity is an important consideration with regard to high tunnel production. Relative humidity describes the amount of water vapor in the air at any time. The closed conditions of a high tunnel create an environment with higher relative humidity and little air movement until ventilated. These conditions can promote diseases that thrive in high humidity, creating a need to ventilate even when outside conditions are cooler than desired. However, high tunnels also protect plants from rainfall which decreases the likelihood that foliar diseases will develop. The management of temperature and relative humidity in a high tunnel is primarily controlled through ventilation. Cross ventilation can be achieved by orienting the high tunnel parallel to prevailing winds, and limiting the size. Heidenreich et al. (2007) suggested that high tunnels should not be longer than 29.3 m or wider than 9.1 m to achieve adequate ventilation. The daily manual ventilation required for high tunnel production would only be feasible for tunnels that do not require extensive travel to reach. Installing automatic roll up sidewalls increases the construction cost, but greatly reduces the need for daily labor. The arid Utah climate is ideal for high tunnel production because the outside air lowers the relative humidity inside when ventilated.

Light

Covering a crop with plastic reduces the amount of photosynthetically active radiation (PAR) that a plant receives. In a high tunnel with a single layer of 6 mil greenhouse plastic, the accumulated light integral was decreased by 437 mol m^{-2} (24%) on average compared to outside (Both et al., 2007). Row covers further decrease light transmission to plants. Clean polypropylene row cover cloth allows for 80% light transmission while plastic row cover has approximately 75% light transmission (Wells and Loy, 1993). Light transmission through row cover cloth is greater than through plastic because it allows specks of direct sunlight to pass through. Light levels are also reduced as the sun angle changes in the fall in the northern hemisphere. The changing light angle will cause the southern exposure of a high tunnel to receive more direct light in the winter and early spring and fall. During the summer months, the east and west exposures will receive direct sun exposure for part of the day. The high tunnel should be located where it is not shaded by surrounding structures when the sun angle is at its lowest point if winter production is desired.

Limitations

Construction and labor costs are some of the limitations to high tunnel production; however construction costs for high tunnels are far less than that of traditional greenhouses. The cost of a high tunnel structure depends on the design. Galvanized steel high tunnel kits are available in a range of sizes. Steel-framed structures are generally more costly than PVC structures; however, steel structures have a longer life expectancy and may withstand high winds and large snow loads in extreme climates. Wind can tear plastic off of a high tunnel if it gets inside. Securing the plastic tightly and keeping high tunnels closed during storms is a key step in preventing structural damage. Snow load will cause a PVC high tunnel to collapse under the weight unless there is some support inside; however, PVC that is not broken can return to shape after the snow is brushed off. Utah State University offers detailed instructions on how to build a PVC high tunnel and the specific costs involved. Based on Utah State University's design, a 29.3 m by 4.3 m PVC high tunnel costs approximately $700 to build ($5.60 per m^2) excluding labor (Black et al., 2008). A similar sized steel structure would cost approximately $2,775 or $29.60 to $32.30 per m^2 to build (Reiss et al., 2004). The difference in price between the structures can make growing inside a PVC high tunnel more affordable to an individual grower.

In addition to the cost of growing a crop, more labor hours are required for high tunnel production, including hours to construct the tunnel, maintain the structure, and manually ventilate the tunnel daily. Based on the experience of the Utah State University high tunnel project, manual ventilation for a 29.3 m by 4.3 m high tunnel takes approximately 5 minutes per day for 60 days in the spring and fall. When low tunnels are built within the high tunnel, daily ventilation will take approximately 20 minutes. Construction labor for a 29.3 m by 4.3 m PVC high tunnel is estimated to be 25 hours (Black et al., 2008). Maintenance labor will depend on the structure.

Another limitation to high tunnel production is cropping space. Since high tunnels increase production costs, the crop grown inside should be valuable enough to offset the cost of construction. Space utilization using vertical structures has been explored for hydroponic systems in both the greenhouse and outdoor environments (Hochmuth et al., 1998; Jensen, 1991; Ozeker et al., 1999), and may be beneficial for high tunnels. Space utilization for hydroponic systems is achieved by stacking plants vertically with troughs or bags to achieve a greater number of plants per ground area. Common growing media for vertical grow systems and hydroponics include pumice, perlite, peat, and coconut coir. The composition of growing media can effect water holding capacity, but does not significantly impact crop growth (Hochmuth et al., 1998; Ozeker et al., 1999).

Diversification in Utah

High tunnels can contribute to the financial sustainability of a farm by providing a means to grow high quality produce at a time when a price premium can be obtained due to a shortage of the product. Product diversification is a strategy that is implemented to decrease economic risk to the grower and reduce the negative environmental impacts of monoculture. By having multiple crops in production, the income of the operation is not reliant on any one crop. The U.S. Census Bureau reported a 4% increase in the number of farms in the U.S. and a 9% increase in Utah. Most of the new farms are small operations with no specific commodity accounting for more than 50% of total production

(U.S. Department of Agriculture, 2007). An added benefit of a diversified operation includes the opportunity to capture profitable niche markets, and support of the local economy by growing crops that are otherwise imported. Markets and restaurants want to deal with suppliers who have a steady supply. Growers producing through the off season would have an advantage over growers who supply for a shorter season. A fresh marketing strategy might be necessary for expanding business; however, many growers with the potential to adopt a high tunnel system will already have an established market for their produce (Adam et al., 2007).

Northern Utah's high elevation (1382 m) desert presents unique benefits and challenges with regard to high tunnel production. Northern Utah has an average growing season of 135 frost free days (Table 1.1). Growing season is measured in frost free days, or the number of days between the last spring frost and the first fall frost. Sporadic frosts make planting early more risky for northern Utah compared to climates with more frost free days such as Missouri (Table 1.1). In arid climates like northern Utah, day time temperatures can be very warm even when night time temperatures are below freezing. This extreme temperature fluctuation is referred to as diurnal temperature variation. While cold temperatures limit the growing season, warm temperatures during the day and sunny skies could be advantageous to high tunnel production. Utah gets more solar radiation on average than other parts of the U.S. that are conducting high tunnel tomato research such as Missouri, New York, Pennsylvania, and New Jersey. Figure 1.1 shows Utah receives an average of 6 to 7 $kWh \cdot m^{-2}$ per day in May, whereas Missouri receives 5 to 6 $kWh \cdot m^{-2}$ per day based on data collected from a horizontal solar collector (Wilcox, 1994). More solar radiation should result in more accumulated growing degree hours in a high tunnel compared to climates with more cloudy conditions. Utah also has the advantage of dry air that limits the opportunity for diseases and pathogens to develop.

One strategy for helping plants survive freezing temperatures in a high tunnel early in the season is to have a back up heat source such as a propane heater. This can be very effective, but also costly when used on a large scale. Root zone heating is more energy efficient and has been shown to offset the negative effects of low air temperature (Diver, 2002; Gosselin and Trudel, 1985; Janes and Mcavoy, 1983). If a heat source could protect plants from sporadic freezing temperatures at night, the average frost free period would increase drastically.

Challenging climate conditions unique to Utah's high elevation desert warrant additional research concerning the adaptation of high tunnel vegetable production. The hypothesis for this research project is that tomatoes and lettuce can be successfully and economically grown in Utah with high tunnels. The following thesis chapters will discuss 1) experiments that have been conducted to optimize management systems for a high elevation climate, 2) economic evaluations of these management systems, and 3) extension publications that outline the specifics of these systems to serve as a resource for use in commercial production.

References

Adam, K. L., R. Balasubrahmanyam, and H. Born. 2007. Direct marketing. ATTRA. 10 June 2010. <http://attra.ncat.org/attra-pub/directmkt.html>.

Black, B., D. Drost, D. Rowley, and R. Heflebower. 2008. Constructing a low-cost high tunnel. Utah State Univ. Coop. Ext. 21 November 2010. <http://extension.usu.edu/files/publications/publication/HG_High_Tunnels_2008-01photos.pdf>.

Both, A. J., E. Reiss, J. F. Sudal, K. E. Holmstrom, C. A. Wyenandt, W. L. Kline, and S. A. Garrison. 2007. Evaluation of a manual energy curtain for tomato production in high tunnels. HortTech. 17(4): 467-472.

Cloud, J. 2007. Eating better than organic. TIME. 2 March 2010. <http://www.time.com/time/magazine/article/0,9171,1595245,00.html>.

Dalrymple, D. G. 1973. Controlled environment agriculture: A global review of greenhouse food production. U.S. Dept. Agr. Foreign Agr. Econ. Rpt. 89.

Diver, S. 2002. Root zone heating for greenhouse crops. ATTRA. 21 November 2010. <http://attra.ncat.org/attra-pub/rootzone.html>.

Emmert, E. M. 1956. Plastic row covering for producing extra-early vegetables outdoors. University of Kentucky Agr. Ext. Serv. Leaflet 167.

Ennis, B. 2010. Organic pest controls that work in the vegetable garden. Colorado State Univ. Coop. Ext. 21 November 2010. <http://www.coopext.colostate.edu/4DMG/PHC/organic.htm>.

Foord, K. 2004. High tunnel marketing and economics. Regents of the Univ. of Minnesota. 21 November 2010. <http://www.extension.umn.edu/distribution/horticulture/components/M1218-12.pdf>.

Gerber, J. M., I. Mohdkhir, and W. E. Splittstoesser. 1988. Row tunnel effects on growth, yield and fruit-quality of bell pepper. Scientia Horticulturae 36(3-4): 191-197.

Gosselin, A. and M. J. Trudel. 1985. Influence of root-zone temperature on growth, development and yield of cucumber plants cv. Toska. Plant and Soil 85: 327-336.

Heidenreich, C., M. Pritts, M. J. Kelly, and K. Demchak. 2007. High tunnel raspberries and blackberries. Cornell Univ. Dept. Hort. No.47.

Hochmuth, R. C., L. L. Leon, T. Crocker, D. Dinkins, and G. Hochmuth. 1998. Evaluation of two soilless growing media and three fertilizer programs in outdoor bag culture for strawberry in north florida. (Proc. Fl. Hort. Soc.) 111: 341-344.

Janes, H. W. and R. Mcavoy. 1983. Deleterious effects of cool air temperature reversed by root-zone warming in poinsettia. HortScience 18(3): 363-364.

Jensen, M. H. 1991. Hydroponic culture for the tropics: Opportunities and alternatives. Food and Fertilizer Technology Center for the Asian and Pacific Region. 21 Novemeber 2010. <http://www.agnet.org/library/eb/329/>.

Jensen, M. H. 2004. Plasticulture in the global community - View of the past and future. American Society for Plasticulture. 20 April 2009. <http://www.plasticulture.org/history_global_community.htm>.

Moller, A.L. and R. Gillies. 2008. Utah climate. 2nd ed. Utah Climate Center, Logan, U.T.

OUP. 2007. Oxford word of the year: Locavore. Oxford University Press Blog. 21 November 2010. <http://blog.oup.com/2007/11/locavore/>.

Ozeker, E., R. Z. Eltez, Y. Tuzel, A. Gul, K. Onal, and A. Tanrisever. 1999. Investigations on the effects of different growing media on the yield and quality of strawberries grown in vertical bags. Acta Horticulturae 491: 409-414.

Peterson, R. H. and H. G. Taber. 1991. Tomato flowering and early yield response to heat buildup under rowcovers. J. Amer. Soc. Hort. Sci. 116(2): 206-209.

Reiss, E., A. J. Both, S. Carrison, W. Kline, and J. Sudal. 2004. Season extension for tomato production using high tunnels. Acta Horticulturae 659: 153-160.

U.S.Department of Agriculture. 2007. 2007 Census of agriculture: Farm numbers. Natl. Agr. Stat. Serv.

Waggoner, P. E. 1958. Protecting plants from the cold. New Haven, Connecticut Agr. Expt. Sta. Issue 614.

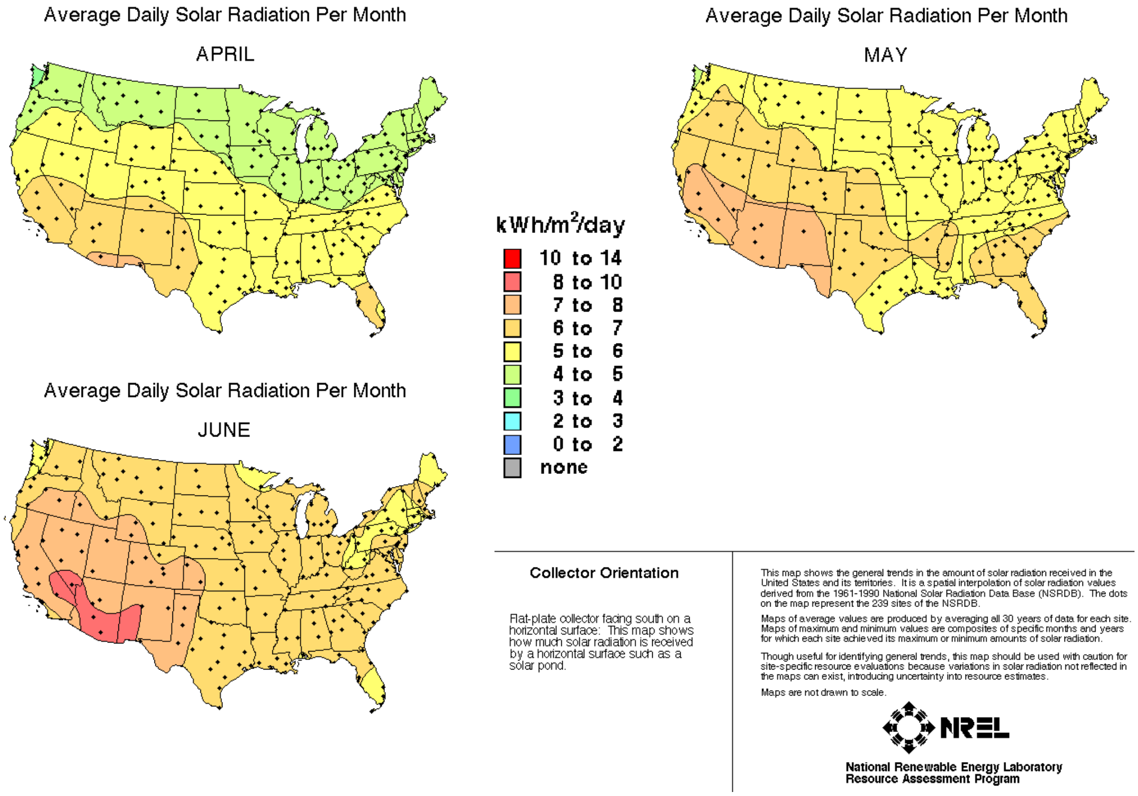
Wells, O. S. and J. B. Loy. 1985. Intensive vegetable production with row covers. HortScience 20(5): 822-826.

Wells, O. S. and J. B. Loy. 1993. Rowcovers and high tunnels enhance crop production in the northeastern united states. HortTech. 3(1): 92-95.

Wilcox, S. and W. Marion. 1994. Atlas for the solar radiation data manual for flat-plate and concentrating collectors. NREL. 4 August 2010. <http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/>.

Table 1.1. Average frost free days for four cities involved in high tunnel tomato research (Moller and Gillies, 2008).

	Logan, UT	Columbia, MO	Rock Springs, PA	Ithaca, NY
Frost Free Days	135	195	124	144



Collector Orientation

Flat-plate collector facing south on a horizontal surface: This map shows how much solar radiation is received by a horizontal surface such as a solar pond.

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

National Renewable Energy Laboratory
Resource Assessment Program

Figure 1.1 Average solar energy (kWh·m-2·day) in the United States for April, May, and June (Wilcox, 1994).

CHAPTER 2

IMPROVED COLD TEMPERATURE PROTECTION FOR EARLY SEASON HIGH TUNNEL TOMATOES

Abstract. The growing season for tomato is limited by freezing temperatures in arid high elevation climates such as northern Utah. In northern climates, high tunnels make it possible to plant earlier in the spring and produce tomatoes approximately one month earlier than in the field. However, limited high tunnel research has been performed in arid high elevation regions that experience extreme temperature fluctuations. High tunnels are designed to be passively heated; therefore additional protection from frost may be warranted if growers wish to plant significantly earlier than normal. Low tunnels built within a high tunnel reduce the energy requirement by concentrating heat around the plants when a heat source is placed inside the low tunnel. Sunbrite tomatoes were transplanted through black plastic mulch in four high tunnels on the Greenville Research Farm in North Logan, Utah (41.73 N, 111.83 W, 1382 m elevation) on 17 Mar., 30 Mar., and 7 Apr. in 2009, and on 19 Mar., 30 Mar., and 9 Apr. in 2010. In addition, three supplemental heating treatments (unheated (Control), soil warming cables (Soil), and soil warming cables plus 40-watt incandescent lights (Soil plus Air)) were tested to improve plant performance. Incandescent lights were selected due to their accessibility, ease of multiplication, and low energy requirement. Soil cables were buried 2.5 cm below soil and plastic mulch. Data collection and monitoring included soil and air temperatures, pruning biomass, plant growth, fruit production and quality. The highest yield was achieved for the 17 Mar. planting date in 2009. Early season and overall yield was significantly lower for the last planting date, 7 Apr. 2009.

Early season yield was significantly greater for treatment plots with soil plus air heat, however, this effect was only significant for the 17 Mar. planting date. Soil heating alone improved total marketable and total yield for the 17 Mar. planting date. Information gathered in this study about planting dates, yield, and energy costs will be valuable to growers in arid high elevation climates who want to utilize the benefits of growing early season tomatoes with high tunnels.

Introduction

Tomatoes are the most commonly grown high tunnel crop because early, local, high quality tomatoes have a high value in the produce market. Tomatoes have a higher value in the early season because low outdoor temperatures limit field tomato production. For climates near zone 5 on the USDA hardiness scale, growing in a high tunnel makes it possible to plant and produce tomatoes more than one month earlier than outdoors (Wells and Loy, 1993). Producing tomatoes before outdoor field production begins extends revenue into a normally unproductive period, and allows growers to benefit from out-of-season price premiums. The common consensus of spring tomato trials is that growing in high tunnels equates to earlier yields and higher quality fruit. By providing optimal temperatures for growth, high tunnels improve quality by preventing disorders associated with poor pollination such as cat-facing and puffiness (Dorais et al., 2001). By protecting plants from rainfall, high tunnels allow for controlled irrigation that prevents disorders such as fruit cracking, blossom end rot, and many foliar diseases. High tunnels have also been reported to improve fruit taste and texture, though literature discussing the role of high tunnels in improving taste and texture is limited**.** Krizek et al. (2006) showed that high tunnel-grown tomatoes had a higher sensory score for sweetness, flavor, texture, taste, and overall eating quality when compared to field grown fruit**.**

The benefits of high tunnel production such as earlier yield and improved quality have been explored in other states (Chism, 2002; Gent, 1992; Reiss et al., 2004) and should be further exploited in arid high elevation climates. In arid high elevation climates like Utah, day time temperatures can be very warm even when night time temperatures are below freezing. This extreme temperature fluctuation is referred to as diurnal temperature variation. While cold night temperatures limit the length of the growing season, warm temperatures during the day and sunny skies could be used advantageously when high tunnels are incorporated into a farms production system. For example, Utah gets more solar radiation on average than other parts of the U.S. that are conducting high tunnel tomato research such as Missouri, New York, Pennsylvania, and New Jersey. Figure 2.1 shows Utah receives an average of 6 to 7 $kWh{\cdot}m^{-2}$ per day in May, whereas Missouri receives 5 to 6 $kWh{\cdot}m^{-2}$ per day based on data collected from a horizontal solar collector (Wilcox, 1994). More solar radiation should result in more accumulated growing degree days in a high tunnel compared to climates with more cloudy conditions. Arid climates also have the advantage of low relative humidity that limits the opportunity for diseases and pathogens to develop.

In areas near zone 5 on the USDA hardiness map, tomatoes are typically transplanted outdoors in early May and begin to ripen in early August. High tunnel tomatoes can be planted four to six weeks earlier to advance ripening. Choosing an appropriate planting date is an important decision for growers in arid high elevation climates who want to use high tunnels to grow early season tomatoes. A two week delay in planting date was shown to delay ripening by two weeks for early high tunnel tomatoes transplanted in Connecticut (Gent, 1992). However, early season cold weather makes planting risky during March and April even when grown in high tunnels. Row covers and low tunnels have been shown to increase frost protection for tomatoes at night (Emmert, 1956; Waggoner, 1958), and could be used in combination with high tunnels though we could find no reports of this in existing literature. Research conducted on a local level will provide valuable information to growers about the effect of cold temperatures on early planting dates.

Typical outdoor early spring temperatures (March and April) in northern Utah are 10 to 20 °C during the day and -5 to 16 °C at night. Tomato plants are susceptible to chilling injury when exposed to temperatures below 10 °C. At the same time, day temperatures inside a high tunnel are normally 20 to 30 °C (Figure 2.2). Tomatoes grow best when temperatures are 25 to 30 °C during the day and 16 to 20 °C at night (Csizinszky, 2005). While temperatures may be optimal for tomato plants during the day, the high tunnel environment is still susceptible to freezing or chilling conditions at night. Night time temperatures in a high tunnel are typically only 1 to 4 °C warmer than the outside temperature. Row covers can offer an additional 2 to 6 °C of temperature protection. Thin polyethylene row cover alone was shown to protect tomato plants from freezing when outside temperatures were -3.8 ºC (Emmert, 1956; Waggoner, 1958). Low tunnels within an unheated glasshouse have been shown to promote early harvest, and increase total yield (Ankara, 2001). From 29 Mar. to 16 May in central and southern New Jersey, the use of a polyester energy curtain inside a high tunnel was found to increase the inside night time air temperature by 2.3 °C on average compared to the outside air temperature (Both et al., 2007). An energy curtain is a thick woven plastic cover that is typically pulled over the entire crop inside the high tunnel. The temperature inside without the energy curtain was 0.9 °C warmer. In the arid high elevation climate of northern Utah, temperatures below -7 °C occur from mid March to late April when growers would be transplanting tomatoes into high tunnels (Moller and Gillies, 2008). Temperatures below -7 °C would likely be devastating to an early high tunnel tomato crop due to the limited protection provided by row covers and high tunnels. Supplemental heating is therefore of interest to aid in cold temperature protection during the early season.

High tunnels typically do not have electricity service; however some backup heating could provide the frost protection necessary to keep valuable plants alive in the early spring. Supplemental heating is expensive for a large space, but low tunnels could reduce the energy requirement by concentrating heat around the plants when the heat source is placed inside the low tunnel. A similar approach was successful for greenhouse tomato, where the amount of fuel needed to run the heating system was significantly reduced by targeting the heat at plant level using convection tubes (Hanna and Henderson, 2008). Soil warming has been shown to increase biomass accumulation and nutrient uptake for many crops in the greenhouse environment (Gosselin and Trudel, 1985; Hurewitz et al., 1984; Shedlosky and White, 1987). Root zone heating has also been shown to partly offset the adverse effect of low night air temperatures on plants (Gosselin and Trudel, 1985; Janes and Mcavoy, 1983); however no studies assess the effectiveness of root zone heating when air temperatures are near freezing.

Objectives

In order to evaluate whether constructing and maintaining high tunnels to grow off season tomatoes could be a profitable implement for Utah growers, a study was conducted at the Greenville Research Farm in Logan, Utah. The study had three primary objectives. The first objective was to identify appropriate planting dates that provide early fruits. The second objective was to determine the ability of supplemental heat sources to provide low temperature protection for early-planted tomato plants by comparing yield (kg/plant), pruning biomass, fruit number, fruit size, and fruit quality between heating treatments. The third objective was to determine whether high tunnel production of tomatoes was economically viable for this region.

Materials and Methods

Experiments were conducted in four identical high tunnels on the Greenville Research Farm in North Logan, Utah (41.77 N and 111.81 W, 1382 m elevation, 135 frost-free days). The four tunnels measured 12.8 m by 4.3 m and were built with PVC hoops covered with a single layer of 6-mil greenhouse plastic (Black et al., 2008a). The study was conducted in 2009 and 2010.

Site preparation. Each high tunnel was prepared prior to transplanting by tilling the soil, adding fertilizer to the soil, burying soil heat cables where appropriate, and laying drip irrigation tape and black plastic mulch over the planting rows. The 1.5-meter doorway was large enough to allow a small tractor mounted tiller inside the tunnels. The three planting rows inside the high tunnel were 0.91 m wide with 0.61 m between the rows. Each 12 m long row was divided into three sections (4 m) making nine plots per high tunnel. The plants were spaced 46 cm apart for a total of 8 plants per plot. The experimental design was a randomized split plot with planting date as the whole-plot factor and heating treatment as the sub-plot factor. The four high tunnels served as replications. Figures A.1 and A.2 show plot maps for 2009 and 2010. Two houses used in the trial were managed organically and two were grown using conventional cropping approaches. The fertilizer regimen was a continuation of a nutrition study conducted during the previous three years. The fertilizer for the conventionally managed tunnel was applied at a rate of 402 g 42N-0P-0K, 120 grams 11N-52P-0K, and 150 g 0N-0P-60K per row. The organic tunnels were fertilized at a rate of 12.4 kg of composted chicken manure per row. Fertilizer was incorporated using a small tractor mounted roto tiller.

Drip tape with four inch emitter spacing was installed for irrigation. Watermark® sensors (Irrometer Company, Riverside, CA) were used to monitor soil moisture and schedule irrigations. Watermark® sensors were placed at 15.2 cm and 30.5 cm soil depth. Soil water content was maintained between 20 and 45 centibars as recommended for a clay loam soil (Creswell et al., 2010). Therefore, the plants were irrigated more frequently as the season progressed with irrigation occurring three to four times per week late in the season. Black plastic mulch was applied after the fertilizer, soil warming cable, and drip irrigation was installed. The mulch was secured by hand digging a furrow on each side of the row, then filling it in after the plastic was laid over the row and furrow.

Supplemental heating. Soil warming cables were installed following the fertilizer application. Non-automatic heavy duty soil warming cables (Wrap-On Company Inc., Bedford Park, IL) measuring 42.7 m were coiled on the soil surface in each high tunnel as directed by the product instructions. The cables made three passes within each plot and were covered with approximately 2.5 cm of soil (Figure A.3). The cables were attached to a thermostat with a remote soil sensor that was set to run only at night and when the soil temperature dropped below 21 °C. Each cable used 700 watts of electricity when running. The cable treatments were randomly assigned to six of the nine plots in each tunnel. To heat the air around the plants, three rubber weatherproof pigtail sockets were spliced into 12-gauge extension cords to create a light socket every 1.2 m (Figure A.4). Sockets contained 40-watt incandescent light bulbs, and the lights were programmed to turn on when the air temperature dropped below 16 °C.

The incandescent lights were used in conjunction with soil warming cables. This created three heating treatments (unheated (control), soil heat, soil plus air heat) which served as the sub-plot factor in the randomized split plot design (Figures A.1 and A.2). Thermostat temperatures were set to allow the soil heat cable and lights to run for a similar duration of time. Electrical use monitors (P3 International, New York, NY) were used to record the amount of electricity being used by the heat cables and lights separately. The cost of electricity was calculated by multiplying the kWh used in the high tunnels by the current cost of electricity in Logan, Utah ($0.04622 per kWh for general service).

Transplant production. Sun Brite (Seminis Seeds, Saint Louis, MO) tomato plants were grown for 8 weeks in a heated glass greenhouse before being transplanted to the high tunnels. 50-cell flats were direct seeded on 23 Jan., 5 Feb., and 18 Feb. 2009, and on 15 Jan., 27 Jan., and 9 Feb. 2010. Extra seedlings were thinned after the cotyledons had emerged. The soil mix used was one part peat moss, one part vermiculite, and one part perlite, and the plants were fertilized at a rate of 100 ppm with 20N-10P-20K after emergence. Greenhouse temperatures were maintained at 21 ºC during the day and 18 ºC at night, and the day length was extended to 16 hours using sodium halide lights. Plug plants were brushed lightly by hand daily to strengthen the stems.

Low tunnel covering. To increase the frost protection and retain heat within each respective plot, plastic row covers (low tunnels) were selected for this study. Low tunnels were constructed using 1.3 cm wide conduit pipe. Each 3 m section of conduit was bent in two places to make a 1 m tall by 1 m wide square arch (Figure A.5). The arches were secured by fitting them over a 61 cm section of rebar inserted in the soil. One arch was installed every 3.6 m to divide the plots. The arches were covered in two layers of plastic to separate the respective heating treatments. The low tunnels were covered in 3 m by 15 m sheets of 2-mil construction grade plastic, and all plants inside the high tunnel were under the low tunnels. The covering was removed each morning and replaced at the end of each day as needed to avoid excessive heat build up.

Planting dates. Tomatoes were transplanted in the four tunnels on 17 Mar., 30 Mar., and 7 Apr. 2009, and on 19 Mar., 30 Mar., and 9 Apr. 2010. Planting date served as the whole-plot factor in the randomized split plot design (Figures A.1 and A.2). Data pertaining to individual planting dates were also analyzed separately for some factors, making the experimental design completely randomized.

Tunnel and plant maintenance. The tunnels were cross ventilated by opening the doors and lifting the sides of the plastic as needed each day to maintain optimal temperatures inside (Figure A.6). When night time temperatures stayed above 12 °C in mid June, the plastic covering the tunnels was removed and a 40% shade cloth was applied to cover the house to prevent sun scald. Plants were irrigated for one hour, based on soil moisture monitoring, one to four times per week.

Plant growth and yield. Tomato plants from all planting dates were pruned on 12 May 2009. Therefore, the 2009 data was not equally representative of differences between heating treatments because plants from the 17 Mar. planting date were larger than plants from subsequent planting dates. The difference in dry mass between heating treatments was of primary interest, while the difference in dry mass between planting dates was expected and of less interest. To more accurately measure the effect of planting date and heating treatment on pruning biomass, pruning took place exactly 38 days after transplanting for each planting date in 2010. Pruning consisted of removing the three suckers closest to the ground from each plant in the respective plot. Suckers from each plot were bagged, weighed fresh, and then dried at 54 °C for one week prior to determining dry weight.

To further assess plant growth, digital photos of six tomato plants were taken weekly in 2009 to record the changes in plant size between planting dates. Two plants were photographed from each planting date which was assigned to one of the three treatments. This was an initial trial to support a more thorough data collection approach in 2010. In 2010, one plant from each plot in all four high tunnels was photographed every 10 days from 19 Apr. to 24 May. The images were edited using Adobe Photoshop to show only green pixels. The green pixels were then counted using a custom program developed at the Utah State University Crop Physiology Lab. The change in pixel number over time was used to represent growth and relative plant size.

Tomato harvest began on 7 July 2009 and continued two times each week (Tuesday and Friday) until 14 Aug. The "early" harvest period was considered 7 July through 24 July. In 2010, tomato harvest began on 13 July and was terminated on 26 Aug. Additional data from 2010 will be added to the study as it becomes available. Tomatoes were harvested at the light red to red stage according to the United States standard for color classification (U.S. Department of Agriculture, 1991). Tomatoes were separated into No. 1 and No. 2 grades according to the United States standards, and any other tomatoes were classified as cull. Tomato diameter was measured and placed in to four categories; >7.6 cm (3 inches), 6.4 to 7.6 cm (2.5 to 3 inches), 5.1 to 6.4 cm (2 to 2.5 inches), and <5.1 cm (2 inches). No. 1 and No. 2 quality tomatoes were placed in boxes approximately three layers deep after the stems were removed from the fruits. Tomatoes were sold by size category for approximately $5.50/kg ($2.50/lb) at the Cache Valley Gardener's Market.

Data collection and analysis. Soil and air temperatures inside the high tunnel were recorded with a CR1000 data logger linked to an AM16/32 multiplexer (Campbell Scientific, Logan, Utah). The multiplexor connected 24 gauge type-T thermocouple wire (Omega Engineering, Inc. Stamford, CT), and was programmed to read temperatures every 30 seconds. The air thermocouples were shielded, placed 0.3 m above the soil surface, and supported by a PVC pipe. The ends of the soil thermocouples were enclosed in glass and positioned 5 cm below the soil surface. Each plot had one air sensor and one soil sensor for a total of 18 thermocouple sensors in each high tunnel house. Average, high, and low temperatures were recorded hourly for the air and soil inside the high tunnel. Outside temperature and relative humidity data were collected with a sheltered

HMP50 probe (Vaisala Helsinki, Finland). Temperature data were used to calculate growing degree hours based on the modified ASYMCUR heat unit model (Black et al., 2008b).

A laboratory experiment was performed to gauge the heat exerting capability of the light bulbs within a low tunnel using a copper plate painted black. A 3.6 m low tunnel was set up in the laboratory similar to those used in the tunnel experiment. A copper plate outfitted with five thermistor temperature probes was placed in the low tunnel and connected to a CR10 data logger (Campbell Scientific, Logan, Utah). The plate was positioned approximately 33 cm from the light bulb. A sheltered type-E thermocouple sensor was used to monitor air temperature. The data logger was set up to record temperatures every 5 seconds from the copper plate. Lights were turned on and left on for 30 minutes before being turned off for 30 minutes. This process was repeated two times.

Labor hours were recorded in a daily journal, and supply costs were noted to generate enterprise budgets for the study. Yield data were collected at the time of harvest. Analysis of variance within SAS Statistical Software was used to compare mean yield differences between treatments and planting dates. Orthogonal analysis was used to separate differences between treatment pairs. Significant differences in means between treatments and planting dates were identified for: early yield (7 July through 24 July), marketable yield, overall yield, fruit size, fruit number, growing degree hours, chilling hours, pruning biomass, and plant size.

Results and Discussion

Low tunnels used within a high tunnel provided a 96% tomato plant survival rate when outside temperatures reached 16 ºC on 28 Mar. 2009 regardless of heat treatment. Temperature data collected from the unheated, soil heated, and soil plus air heated treatments were used to calculate accumulated growing degree hours. Growing degree hours are used to quantify accumulated heat as it relates to plant growth. For example, a Sun Brite tomato matures approximately 75 days after germination (Harris®, 2010), and no progress toward maturity is realized when temperatures stay below the base temperature for growth (10 ºC). Tomatoes incur cold temperature injury when temperatures are below 10 ºC. Growing degree hours accumulated most quickly when temperatures were close to optimal (25 ºC) based on the modified ASYMCUR model (Black et al., 2008b). Each planting date was analyzed separately due to uneven data collection intervals (Table 2.1). For example, the first planting date accumulated growing degree hours from 17 Mar. to 15 May while for the last planting date, growing degree hours were accumulated from 7 Apr. to 15 May.

Both soil heating alone and soil plus air heating increased accumulated growing degree hours under the low tunnel (Table 2.1). However, the increase in accumulated growing degree hours was not statistically significant due to substantial temperature variability between plots. The temperature data may have also underestimated the effect of the heat from the lights due to the location of the temperature sensors. The thermocouple temperature sensors were located in the lower canopy of the plants and shielded from the sun to maintain accuracy. The sensors likely could not pick up the heat radiating from the incandescent lights.

Inside a low tunnel in the laboratory, 40-watt incandescent lights increased the temperature of a black copper plate 2 ºC above ambient temperature (24 ºC) in approximately 15 minutes when the lights were switched on. The temperature of the copper plate returned to ambient temperature approximately 20 minutes after the lights turned off. This temperature change was observed over 2 hours turning the lights on and off 2 times while air temperature stayed constant. The plate was approximately the same distance away from the light bulb as the plants in the high tunnel. It was assumed that the infrared absorbtivity of the flat black surface of the plate was similar to the absorbtivity of the surface of a leaf because the albedo is similar for each surface. Albedo describes the fraction of incident radiation reflected by a surface. Therefore, the effect of the incandescent lights was likely greater on leaf temperature than on air temperature.

Temperature data below 10 ºC were also used to calculate accumulated chilling hours for the three heating treatments. Chilling hours represent the number of hours when the minimum air temperature fell between freezing and the base temperature for growth (10 ºC). Table 2.2 shows soil plus air heating resulted in a significant reduction in accumulated chilling hours for plants from the 17 Mar. planting date (PD 1) when compared to soil heating only. The decrease in accumulated chilling hours provided by soil plus air heating was not significant for the 30 Mar. or the 7 Apr. planting dates due to fewer instances of temperatures below 10 °C.

Figures 2.3 to 2.5 show how the heating treatments affected the air temperature by 0.5 to 1 ºC on cold spring nights. Figure 2.3 shows the daily temperature fluctuation where the soil plus air heat treatment kept the air slightly warmer at night. This 0.5 to 1 ºC difference each night lead to less accumulated chilling hours over time. The air temperature was not always higher for the soil plus air heat treatment (Figure 2.5). However, the plants also received radiant heat from the light bulbs that is not accurately expressed in the temperature data. Figure 2.4 shows the plot with soil plus air heating stayed warmer at night than the unheated and soil heat alone treatment plots when the night time low temperature was approximately 4 °C. On average, the air temperature was 0.5 °C warmer than either the unheated or soil heated treatments.

Plant Growth

Pruning biomass (Table 2.3) data were analyzed separately for 2009 because of differences in timing. In 2009, all plants were pruned on the same date (12 May), which affected the results since plants from PD 1 were significantly larger than plants from the other two planting dates at the time of pruning. The effect of soil plus air heating significantly increased pruning biomass for plants from PD 1 (Table 2.3). Soil plus air heating also noticeably (not statistically significant) increased pruning biomass for PD 3, but pruning biomass was statistically similar between both heating treatments for plants from PD 2 and PD 3 in 2009 (Table 2.3). This was due to variability among samples expressed in the standard error in Table 2.3.

In 2010, a more uniform sample time (38 days after transplanting) provided a more accurate comparison of pruning biomass between heating treatments and planting dates. Pruning biomass was significantly different among the three planting dates (Table 2.4). Heating significantly increased pruning biomass, and plants with the largest biomass were found in plots with soil plus air heating. Orthogonal contrast analysis indicated that biomass was similar between plots with soil heating alone and plots with soil plus air heating (Table 2.4). This suggests that either heating treatment provided a similar increase in pruning biomass compared to the unheated control. Although there was no significant interaction between planting date and heating treatment, planting dates were also analyzed separately to assess the effect of heating within the individual planting dates. For PD 1 and 2, while pruning biomass apparently was larger in treatments with soil plus air heating compared to the soil heating or unheated treatments, the difference was not statistically significant due to high variability which is reflected in the standard error (Table 2.5). Either heating treatment significantly increased pruning biomass for PD 3 only, and the increase in biomass was similar between soil and soil plus air heating (Table 2.5). This suggests that root zone heating alone significantly increased growth of tomato plants from PD 3, and is verified by the standard error values given in Table 2.5.

Canopy growth among treatments was quantified by comparing the number of green pixels in the photographs of the tomato plants taken over time. Data from individual planting dates were analyzed separately in order to compare values to 2010 pruning biomass data. Figure 2.6 shows how the soil and soil plus air heat treatment influenced pixel accumulation for the three planting dates. The soil plus air treatment had consistently greater average area based on pixel counts than the other treatments (Table 2.6). For all planting dates, canopy area in the soil and soil plus air treatments increased faster than the unheated treatment (Figure 2.6). However, this relationship was not always statistically significant due to variability among samples expressed in the standard error (Figure 2.6). For photographs taken on 26 Apr. and 3 May, heating significantly increased pixel counts for plants from PD 3, and the effect of heating was not significantly different between the soil and soil plus air treatments (Table 2.6). The same significant effect of heating is seen for PD 3 in the 2010 pruning data when the plants were pruned on 15 May. This suggests pixel number can accurately reflect an increase in biomass for tomato plants. Pixel count taken on 19 Apr. for PD 2 was significantly greater for soil plus air compared to soil heating only when compared to the unheated control (Table 2.6). This is not the case for the 7 Apr. planting date which suggests air heating had a greater effect for earlier planting dates. Figure 2.6 shows how the effects of the heating treatments overlap on PD 3, and remain separate for PD 1 and 2.

Tomato Productivity

The combination of soil and air heating resulted in significantly higher early season yield in 2009 when compared to the unheated and soil warming treatments (Table 2.7). Furthermore, supplemental heating increased marketable and total yield, but the effect was not statistically significant. This is due to high sample variability which is reflected by large standard error given in Table 2.7. Planting date 1 had significantly greater early market yield as well as total marketable yield when compared to later planting dates (Table 2.7). There was a significant interaction between planting date and heating for early yield because heating significantly increased yield for plants from PD 1, but did not affect yield for plants from PD 2 and PD 3 (Table 2.8). A closer evaluation of heating on PD 1 indicated that only the soil plus air heating treatment significantly increased early marketable yield, but both the soil and soil plus air heating treatments significantly increased overall and marketable yield (Table 2.9). Similarly, soil plus air heating increased pruning biomass for PD 1 (Tables 2.3 and 2.5), and decreased accumulated chilling hours (Table 2. 2). Therefore, air heating improved early season yield for PD 1.

Since overall yield was shown to respond positively to heat additions, the percentage of yield that fell into a given size or quality category was most relevant to the interpretation of the data. Both heating treatments had a positive effect on fruit size distribution for early marketable yield and increased the weight and number of fruits in the largest size class (≥ 7.6 cm) (Table 2.10 and 2.11). The unheated treatment had the highest weight and number of medium sized fruits (6.4 to 7.6 cm) when compared to the heated treatments. Weight and number of small fruits (< 6.4 cm) was similar among the heating treatments (Table 2.10 and 2.11). Large and medium sized fruits are the most desirable based on weight and marketability. The absence of supplemental heating did not significantly impact the weight of early large and medium sized fruits (Table 2.10). Supplemental heating had no apparent affect on No. 1 fruit quality of the total yield (Table 2.12), while the treatments with soil heating alone had the highest percentage of cull fruit. There is no apparent explanation for an increase in cull fruits for this treatment.

Plants from PD 1 produced the highest weight of early large marketable fruits (≥ 7.6 cm) while PD 3 had the lowest weight of large fruits (Table 2.10). However, PD 2 had the highest percentage of large and medium sized fruits together (91%) compared to the PD 1 (88%) and PD 3 (88%). PD 2 also had the highest percentage of No. 1 quality fruits compared to the other two planting dates (Table 2.12). This increase in quality may be attributed to more optimal temperatures during flower and fruit set. Disorders attributed to temperature stress during flower set such as zippering and misshapen fruit were noted during the 2009 season. However, the exact time of flower and fruit set was not recorded.

For the range of planting dates used in this study, there were significant benefits to planting early. Total and marketable yields for PD 1 were significantly higher than those measured for PD 2 and 3 (Table 2.7). Early marketable yield was significantly different among the three planting dates; however the difference between PD 1 and PD 2 was not as great. PD 3 had significantly less early season yield compared to PD 1 and PD 2. Figure 2.7 further illustrates how productivity separates drastically between planting dates from 14 July to 28 July. Figure 2.8 accentuates this effect and reveals PD 3 was slower to start producing, but produced more than PD 1 and PD 2 later in the season. For this reason, growers could benefit from planting over multiple dates. A similar result was seen for early-planted high tunnel tomatoes in Connecticut, which found a mid April planting date to be most appropriate since earlier plantings suffered from nutrient deficiency (Gent, 1992). The effect of heating on plant growth and yield in this study suggests supplemental soil and air heating were responsible for improved productivity of earlier planting dates.

Potassium deficiency is known to reduce fruit quality, and in this study it increased the number of cull fruits for all plants. Leaf tissue samples collected on 16 July indicated a low level of potassium in the tunnels. Tissue samples from the conventionally fertilized tunnel had lower potassium levels (1.04%) than plants grown in the organic tunnel (2.54%). Soil testing at the end of the season also indicated that tunnels previously fertilized and managed conventionally were deficient in potassium. The conventional tunnels averaged of 87 ppm of potassium in the soil while the organic tunnels had an average of 128 ppm. The recommended soil test level for potassium is between 130 and 150 ppm (Univ. of California, 2008). Additional potassium was incorporated before planting and as a side dressing for tomatoes planted in 2010. The organically fertilized houses had less instance of potassium deficiency, more No.1 fruits, and less cull fruits.

The heat cables used an average of 10.5 kilowatt-hours per night for each 12.8 m by 4.3 m high tunnel ($0.48/night), while the addition of lights used an extra 11.5 kilowatt-hours per day/night ($0.53/night). The heating treatments were activated on the first planting date (17 Mar.) and deactivated on 10 May when overnight low temperatures were consistently above 5 ºC. For very early spring planting, growers should consider using both soil and air heating because this was shown to have a positive affect on yield for PD 1 (17 Mar.). These heating treatments would be significantly beneficial only for very early plantings, and would be most critical for the first few weeks after transplanting to reduce chilling injury and increase nutrient uptake. However, supplemental heating could continue to benefit growth if used for a longer duration as seen by greater amounts of biomass accumulation on later planting dates which could improve late season productivity.

Summary

In this study, low tunnels within a high tunnel provided a 96% survival rate even when outside temperatures reached -8 ºC on 28 Mar. regardless of heat treatment. This is an exceptional demonstration of frost protection compared to an earlier study in which low tunnels alone protected tomato plants from freezing down to -3.8 ºC (Emmert, 1956). The high tunnel provided an additional 4 ºC of frost protection compared to low tunnels alone. However, survival is not the only important factor in early season tomato production. Harvest began on 7 July for all planting dates, approximately 5 weeks before outdoor production. The 17 Mar. planting date had the highest early season yield. Early season yield was significantly different among the three planting dates (Table 2.7), indicating the 10 to 13 day delay in planting significantly reduced early season yield. This result agrees with a previous study where a two week delay in planting date was shown to delay ripening by two weeks for early high tunnel tomatoes transplanted in Connecticut (Gent, 1992). The earliness achieved in this study was comparable to the earliness achieved in previous years using row cover cloth instead of low tunnels, and was similar to the earliness achieved with a high tunnel alone in New Hampshire (Wells and Loy, 1993). However, tomatoes in this trial began to ripen approximately one month earlier than indeterminate tomatoes under a low tunnel within an unheated glasshouse at a similar latitude to Logan, UT (41°N) (Ankara, 2001).

High early season and overall yields were achieved with a mid-March planting date (PD 1) in combination with supplemental soil and air heating. Supplemental heating did not significantly improve yield for the late March planting (PD 2) which provided similar early season yields to the mid March planting. However, the effect of supplemental heating may be significant for a late March planting date in the future depending on the extremity of cold temperatures in the first few weeks after transplanting. When supplemental heating was used, both root zone and air heating were beneficial for tomato transplants in early spring. Soil plus air heating showed a significant improvement in early season yield for PD 1 (Table 2.7), which coincided with a reduction in chilling injury to the plant tissue (Table 2.2) and an increase in biomass (Table 2.5). Root zone heating alone did not significantly improve early season yield, which implies the air heating element was responsible for the improvement in early season yield for PD 1. However, the effect of air heating alone was not tested in this study.

Soil heating alone significantly improved marketable and total yield for PD 1 (Table 2.9), which coincided with an increase in biomass (Table 2.5). This response was expected since root zone heating has been shown to increase growth by improving water and nutrient uptake for tomatoes (Hurewitz et al., 1984). Nutrient deficiency has been reported for earlier planted tomatoes in high tunnels, which was also seen in our study (Gent, 1992). While heating the air was critical for early season yield, it is likely that root zone heating also contributed to the increase in biomass and early season yield for PD 1 by improving water and nutrient uptake. Growers in northern Utah who want to maximize early season yield in a high tunnel tomato crop should transplant mid to late March using supplemental soil and air heating for the first two to six weeks after transplanting to increase water and nutrient uptake and minimize cold injury. Supplemental heating was not significantly beneficial for tomatoes transplanted in mid-April.

This study demonstrates planting tomatoes 10 to 20 days earlier can result in higher early season yields, and that using supplemental heating improves yield further. The added cost of energy associated with supplemental heating would be approximately $2.00 per night for a 29.3 m by 4.3 m high tunnel. Heating is most valuable early in the season, when planting on 17 Mar. could increase early season yield up to 1.32 kg per plant compared to later planting dates (7 Apr). This would equate to an additional 238 kg per 29.3 m by 4.3 m high tunnel (180 plants). A sale price of $5.50 per kg is would result in an additional $1,310 income for tomatoes planted on 17 Mar compared to planting on

7 Apr. While the risk of freezing temperatures is always present, added returns and an increase in out-of-season produce could be appealing for growers who are willing to plant earlier in the season.

References

Ankara, L. A. 2001. Effect of low-tunnel, mulch and pruning on the yield and earliness of tomato in an unheated glasshouse. J. Appl. Hort. 3(1): 23-27.

Black, B., D. Drost, D. Rowley, and R. Heflebower. 2008a. Constructing a low-cost high tunnel. Utah State Univ. Coop. Ext. 21 November 2010. <http://extension.usu.edu/files/publications/publication/HG_High_Tunnels_2008-01photos.pdf>.

Black, B., J. Frisby, K. Lewers, F. Takeda, and C. Finn. 2008b. Heat unit model for predicting bloom dates in rubus. HortScience 43(7): 2000-2004.

Both, A. J., E. Reiss, J. F. Sudal, K. E. Holmstrom, C. A. Wyenandt, W. L. Kline and S. A. Garrison. 2007. Evaluation of a manual energy curtain for tomato production in high tunnels. HortTech. 17(4): 467-472.

Chism, J. 2002. Warm-season vegetable production in high tunnels. The Kerr Center for Sustainable Agriculture. 1 December 2010. <http://www.kerrcenter.com/publications/2002_proceedings/warm-season_veggies.pdf>.

Creswell, T., G. Ruhl, J. Faghihi, S. Weller, B. Aly, and J. Masiunas. 2010. Midwest vegetable production guide for commercial growers. 21 November 2010. <http://www.btny.purdue.edu/Pubs/ID/ID-56/>.

Csizinszky, A. A. 2005. Production in the open field, p. 237-252. In E. Heuvelink. Tomatoes. CABI Publishing, Oxfordshire, UK.

Dorais, M., A. P. Papadopoulos, and A. Gosselin. 2001. Greenhouse tomato fruit quality. HortScience 26: 236-319.

Emmert, E. M. 1956. Plastic row covering for producing extra-early vegetables outdoors. Univ. of Kentucky Agr. Ext. Serv. Leaflet 167.

Gent, M. P. N. 1992. Yield response to planting date and ventilation temperature of tomato grown in unheated high tunnels in the northeast USA. Acta Horticulturae 303: 53-60.

Gosselin, A. and M. J. Trudel. 1985. Influence of root-zone temperature on growth, development and yield of cucumber plants cv. Toska. Plant and Soil 85: 327-336.

Hanna, H. Y. and E. D. Henderson. 2008. Fuel type and releasing the heated air near plant roots reduced production cost of greenhouse tomatoes. HortTech. 18(2): 290-294.

Harris®. 2010. Harris® Seeds. 11 August 2010. <http://www.harrisseeds.com/storefront/p-231-tomato-sunbrite.aspx>.

Hurewitz, J., M. Maletta, and H. W. Janes. 1984. The effects of root-zone heating at normal and cool air temperatures on growth and photosynthetic rates of tomatoes. Acta horticulturae 148: 871-876.

Janes, H. W. and R. Mcavoy. 1983. Deleterious effects of cool air temperature reversed by root-zone warming in poinsettia. HortScience 18(3): 363-364.

Krizek, D.T, R. Saftner, E. Park, J. Abbott, M. Camp, and D. Clark. 2006. Yield data from 2005 and instrumental and sensory evaluation of tomato fruits from plants grown in high tunnels at Beltsville, MD, or obtained from commercial sources. HortScience 41: 967-1084.

Moller, A. L. and R. R. Gillies. 2008. Utah Climate. 2nd ed. Utah Climate Center, Logan, UT.

Reiss, E., A. J. Both, S. Carrison, W. Kline, and J. Sudal. 2004. Season extension for tomato production using high tunnels. Acta Horticulturae 659: 153-160.

Shedlosky, M. E. and J. W. White. 1987. Growth of bedding plants in response to root-zone heating and night temperature regimes. J. Amer. Soc. Hort. Sci. 112(2): 290-295.

U.S. Department of Agriculture. 1991. United States standards for grades of fresh tomatoes. Agr. Mktg. Serv. 15 March 2010. <http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050331>.

Univ. of California. 2008. UC pest management guidelines: Tomato fertilization. UC IPM Online. 3 March 2010. <http://www.ipm.ucdavis.edu/PMG/r783900711.html>.

Waggoner, P. E. 1958. Protecting plants from the cold. New Haven, Connecticut Agr. Expt. Sta. Issue 614.

Wells, O. S. and J. B. Loy. 1993. Rowcovers and high tunnels enhance crop production in the northeastern United States. HortTech. 3(1): 92-95.

Wilcox, S. and W. Marion. 1994. Atlas for the solar radiation data manual for flat-plate and concentrating collectors. NREL. 4 August 2010. <http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/>.

Table 2.1. The effect of heating treatments on accumulated growing degree hours in 2009 organized by planting date (2009).

Mar. 17		1-Apr	15-Apr	1-May	15-May
Unheated		704	1437	2859	4702
Soil		769	1548	2994	4818
Soil plus Air		953	1989	3573	5475
Mar. 30					
Unheated		82	745	2084	3930
Soil		107	915	2335	4129
Soil plus Air		97	958	2489	4320
Apr. 7					
Unheated			557	2082	3844
Soil			547	2278	4499
Soil plus Air			666	2295	4180
ANOVA					
Factor	df	P-value			
Mar. 17					
Heating Treatments	2	0.287	0.326	0.290	0.285
No Heat vs. Heat	1	0.261	0.319	0.297	0.314
Soil vs. Soil plus Air	1	0.255	0.261	0.231	0.215
Mar. 30					
Heating Treatments	2	0.246	0.117	0.211	0.441
No Heat vs. Heat	1	0.136	0.053	0.114	0.283
Soil vs. Soil plus Air	1	0.483	0.632	0.463	0.523
Apr. 7					
Heating Treatments	2		0.112	0.494	0.439
No Heat vs. Heat	1		0.286	0.264	0.281
Soil vs. Soil plus Air	1		0.064	0.930	0.525

Table 2.2. The effect of heating treatments on accumulated chilling hours organized by planting date (2009). One chilling hour was accumulated when hourly temperature was below 10 ºC.

Mar. 17	1-Apr	15-Apr	1-May	15-May
Unheated	206	367	530	643
Soil	209	371	530	631
Soil plus Air	183	315	442	529
Mar. 30				
Unheated	28	184	342	446
Soil	29	185	344	449
Soil plus Air	28	178	315	406
Apr. 7				
Unheated		84	247	361
Soil		84	246	351
Soil plus Air		66	204	300

ANOVA

Factor	df	P-value			
Mar. 17					
Heating Treatments	2	0.005	0.008	0.001	0.001
No Heat vs. Heat	1	0.030	0.034	0.004	0.004
Soil vs. Soil plus Air	1	0.003	0.005	0.001	0.001
Mar. 30					
Heating Treatments	2	0.629	0.567	0.590	0.457
No Heat vs. Heat	1	0.636	0.334	0.399	0.430
Soil vs. Soil plus Air	1	0.426	0.758	0.602	0.345
Apr. 7					
Heating Treatments	2		0.300	0.523	0.364
No Heat vs. Heat	1		0.415	0.287	0.187
Soil vs. Soil plus Air	1		0.191	0.897	0.766

Table 2.3. The effect of heating treatments on mean dry and fresh pruning biomass (± SE) for three planting dates in 2009. All plants were pruned on 12 May, and thus analyzed separately.

		2009	
		DW (g)	FW (g)
Mar. 17			
Unheated		57.7 ± 8.7	557.8 ± 83.0
Soil Heat		56.2 ± 13.9	628.3 ± 163.4
Soil plus Air Heat		118.2 ± 16.9	1208.5 ± 174.1
Mar. 30			
Unheated		53.4 ± 13.9	498.8 ± 151.6
Soil Heat		37.7 ± 1.8	422.0 ± 21.4
Soil plus Air Heat		45.0 ± 2.8	482.3 ± 35.5
Apr. 7			
Unheated		7.4 ± 1.5	59.5 ± 7.8
Soil Heat		6.2 ± 1.6	59.9 ± 16.5
Soil plus Air Heat		14.1 ± 5.1	123.5 ± 56.3
ANOVA			
Factor	df	P-value	
Mar. 17			
Heating Treatments	2	0.003	0.004
No Heat vs. Heat	1	0.027	0.016
Soil vs. Soil plus Air	1	0.002	0.003
Mar. 30			
Heating Treatments	2	0.422	0.806
No Heat vs. Heat	1	0.258	0.672
Soil vs. Soil plus Air	1	0.532	0.636
Apr. 7			
Heating Treatments	2	0.253	0.187
No Heat vs. Heat	1	0.503	0.327
Soil vs. Soil plus Air	1	0.135	0.117

Table 2.4. The effect of heating treatments and planting date on mean dry and fresh pruning biomass (± SE) in 2010. Plants pruned 38 days after transplanting.

		DW (g)			FW		
Planting Date							
March 17		27.9	±	6.0	282.6	±	63.2
March 30		30.7	±	5.1	*	±	*
April 7		54.6	±	7.1	568.6	±	79.3
Heating Treatments							
Unheated		23.5	±	4.5	237.0	±	41.8
Soil Heat		41.1	±	7.7	501.4	±	85.3
Soil plus Air Heat		48.5	±	6.6	538.3	±	88.5
ANOVA							
Factor	df	P-value					
Planting x Heating Treatments	4	0.313			0.334		
Planting Date	2	0.001			0.002		
PD 1 vs. PD 2 and 3	1	0.018			*		
PD2 vs. PD 3	1	0.002			*		
Heating Treatments	2	0.003			0.012		
Heat vs. Unheated	1	0.001			0.004		
Soil vs. Soil plus Air	1	0.281			0.701		

*Missing samples

Table 2.5. The effect of heating treatments on mean dry and fresh pruning biomass (± SE) for three planting dates in 2010. Plants pruned 38 days after transplanting.

		2010	
		DW (g)	FW
Mar. 17			
Unheated		16.4 ± 5.8	158.0 ± 59.3
Soil Heat		27.3 ± 5.5	279.5 ± 59.4
Soil plus Air Heat		39.9 ± 15.4	410.4 ± 161.9
Mar. 30			
Unheated		21.6 ± 10.2	missing
Soil Heat		26.2 ± 7.9	
Soil plus Air Heat		44.2 ± 5.3	
Apr. 7			
Unheated		32.5 ± 6.5	316.1 ± 67.2
Soil Heat		69.9 ± 11.8	723.3 ± 120.7
Soil plus Air Heat		61.5 ± 11.1	666.3 ± 133.0
ANOVA			
Factor	df	P-value	
Mar. 17			
Heating Treatments	2	0.263	0.243
No Heat vs. Heat	1	0.172	0.155
Soil vs. Soil plus Air	1	0.365	0.363
Mar. 30			
Heating Treatments	2	0.125	missing
No Heat vs. Heat	1	0.158	
Soil vs. Soil plus Air	1	0.114	
Apr. 7			
Heating Treatments	2	0.052	0.034
No Heat vs. Heat	1	0.021	0.013
Soil vs. Soil plus Air	1	0.526	0.663

Table 2.6. The effect of heating treatments on canopy growth represented by accumulated green pixels in pictures of tomato plants for three planting dates in 2010.

Mar. 17	19-Apr	26-Apr	3-May	10-May
Unheated	354038	840144	1820678	2454643
Soil	517542	1268481	2513949	4041686
Soil plus Air	1305368	1848830	2771649	Saturated[1]
Mar. 30				
Unheated	205957	572579	1225722	1784131
Soil	280860	885184	1889325	2469543
Soil plus Air	495094	1241971	2634838	Saturated
Apr. 7				
Unheated	140315	268193	635168	956326
Soil	171048	517782	1147242	1427206
Soil plus Air	154880	505120	1088130	Saturated

ANOVA

Factor	df	P-value			
Heat, Mar. 17	2	0.081	0.257	0.307	0.620
No Heat vs. Heat	1	0.102	0.179	0.152	
Soil vs. Soil plus Air	1	0.067	0.328	0.671	
Heat, Mar. 30	2	0.031	0.085	0.115	0.255
No Heat vs. Heat	1	0.045	0.058	0.076	
Soil vs. Soil plus Air	1	0.042	0.192	0.231	
Heat, Apr. 7	2	0.740	0.015	0.037	0.165
No Heat vs. Heat	1	0.523	0.005	0.014	
Soil vs. Soil plus Air	1	0.690	0.854	0.728	

---

[1] All plants for a given heating treatment were marked saturated when the leaves no longer fit within the picture frame for at least one photograph in that treatment`

Table 2.7. The effect of heating treatments and planting date (± SE) on mean yield (kg/plant) in 2009.

		Early Mkt.[1]	Mkt.[2]	Total
Unheated		1.20 ± 0.13	4.34 ± 0.21	5.01 ± 0.25
Soil Heat		1.39 ± 0.18	4.60 ± 0.30	5.51 ± 0.39
Soil plus Air Heat		1.87 ± 0.27	4.96 ± 0.37	5.83 ± 0.46
March 17th (PD 1)		2.04 ± 0.22	5.14 ± 0.37	6.05 ± 0.46
March 30th (PD 2)		1.71 ± 0.09	4.62 ± 0.29	5.24 ± 0.37
April 7th (PD 3)		0.72 ± 0.07	4.15 ± 0.15	5.05 ± 0.24
ANOVA				
Factor	df		P-value	
Planting x Treatment	4	0.012*	0.178	0.355
Heating Treatments	2	<0.001	0.235	0.285
No Heat vs. Heat	1	0.002	0.163	0.145
Soil vs. Soil plus Air	1	0.003	0.326	0.555
Planting Date	2	<0.001	0.035	0.134
PD 1 vs. PD 2 and 3	1	<0.001	0.022	0.051
PD 2 vs. PD 3	1	<0.001	0.196	0.722

[1] Early yield describes fruit picked from 7 July to 24 July

[2] Marketable describes No. 1 and No. 2 quality fruit and excludes cull fruit

[*] Interaction values found in Table 2.8

Table 2.8. The interaction of planting date and heating treatments (± SE) on early marketable yield (kg/plant) of tomatoes in 2009.

	Planting Date		
	17 Mar.	30 Mar.	7 Apr.
Unheated	1.48 ± 0.14	1.49 ± 0.09	0.64 ± 0.09
Soil Heat	1.76 ± 0.27	1.74 ± 0.22	0.68 ± 0.06
Soil plus Air Heat	2.87 ± 0.28	1.89 ± 0.11	0.84 ± 0.18

ANOVA

Factor	df	P-value		
Heating Treatments	2	0.014	0.232	0.528
No Heat vs. Heat	1	0.029	0.122	0.458
Soil vs. Soil plus Air	1	0.016	0.499	0.406

Table 2.9. The effect of heating treatments (± SE) on yield (kg/plant) from the 17 Mar. planting date (PD 1).

	Early Mkt	Mkt.	Total
Unheated	1.48 ± 0.14	4.17 ± 0.22	4.85 ± 0.07
Soil Heat	1.76 ± 0.27	5.24 ± 0.42	6.29 ± 0.54
Soil plus Air Heat	2.87 ± 0.28	5.99 ± 0.86	7.02 ± 1.09

ANOVA

Factor	df	P-value		
Heating Treatments	2	0.014	0.068	0.102
No Heat vs. Heat	1	0.029	0.036	0.048
Soil vs. Soil plus Air	1	0.016	0.273	0.415

Table 2.10. The effect of heating treatments and planting date on fruit size distribution for early marketable yield (kg/plant) in 2009.

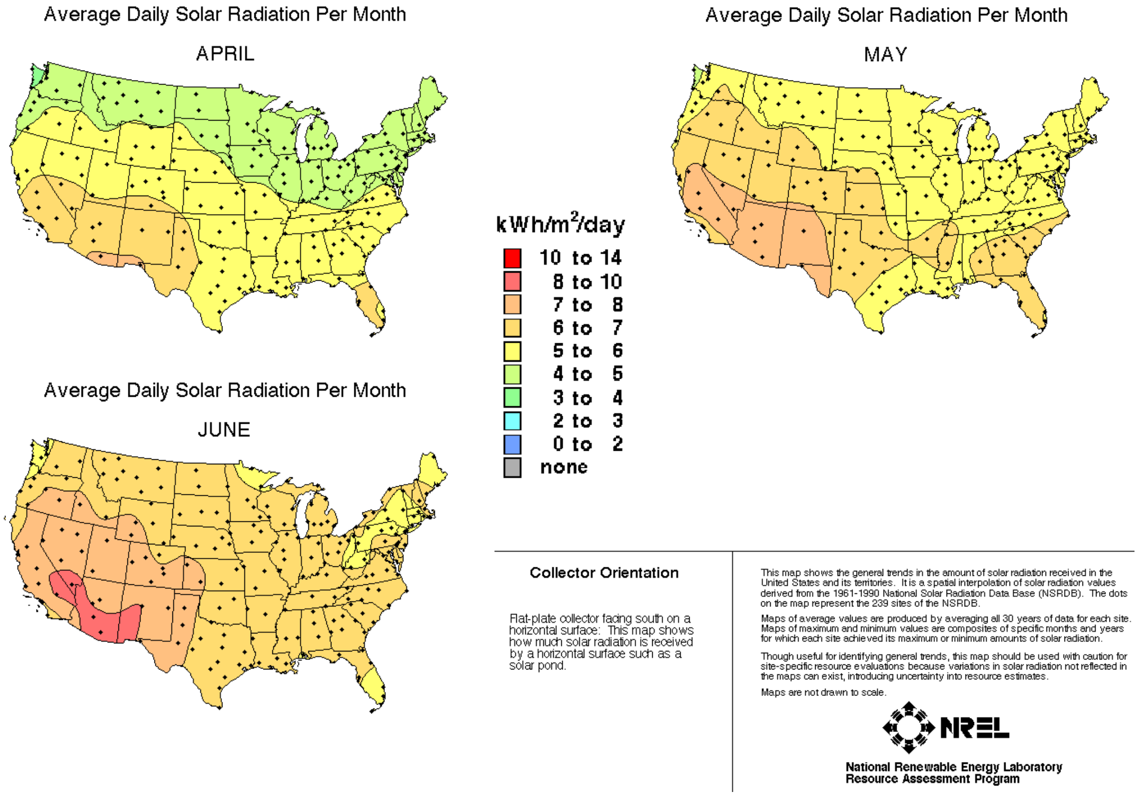
	≤ 2"	2 - 2.5"	2.5 - 3"	≥ 3"
Unheated	4%	9%	26%	61%
Soil Heat	4%	8%	22%	66%
Soil and Air Heat	3%	7%	21%	69%
March 17th	3%	9%	20%	68%
March 30th	3%	7%	25%	66%
April 7th	5%	7%	27%	61%

Table 2.11. The effect of heating treatments and planting date on fruit number of early marketable yield (fruits/plant) in 2009.

	≤ 2"	2 - 2.5"	2.5 - 3"	≥ 3"
Unheated	10%	19%	29%	42%
Soil Heat	13%	16%	25%	46%
Soil and Air Heat	11%	15%	25%	49%
March 17th	13%	18%	23%	46%
March 30th	9%	15%	29%	47%
April 7th	15%	13%	29%	43%

Table 2.12. The effect of heating treatments and planting date on fruit quality for total yield (kg/plant) in 2009.

	No. 1	No.2	Cull
Unheated	71%	16%	13%
Soil Heat	71%	13%	16%
Soil and Air Heat	70%	16%	14%
March 17th	68%	18%	14%
March 30th	74%	14%	12%
April 7th	69%	13%	18%



Collector Orientation

Flat-plate collector facing south on a horizontal surface: This map shows how much solar radiation is received by a horizontal surface such as a solar pond.

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

National Renewable Energy Laboratory
Resource Assessment Program

Figure 2.1. Average solar energy (kWh·m^{-2}/day) in the United States for April, May, and June (Wilcox, 1994).

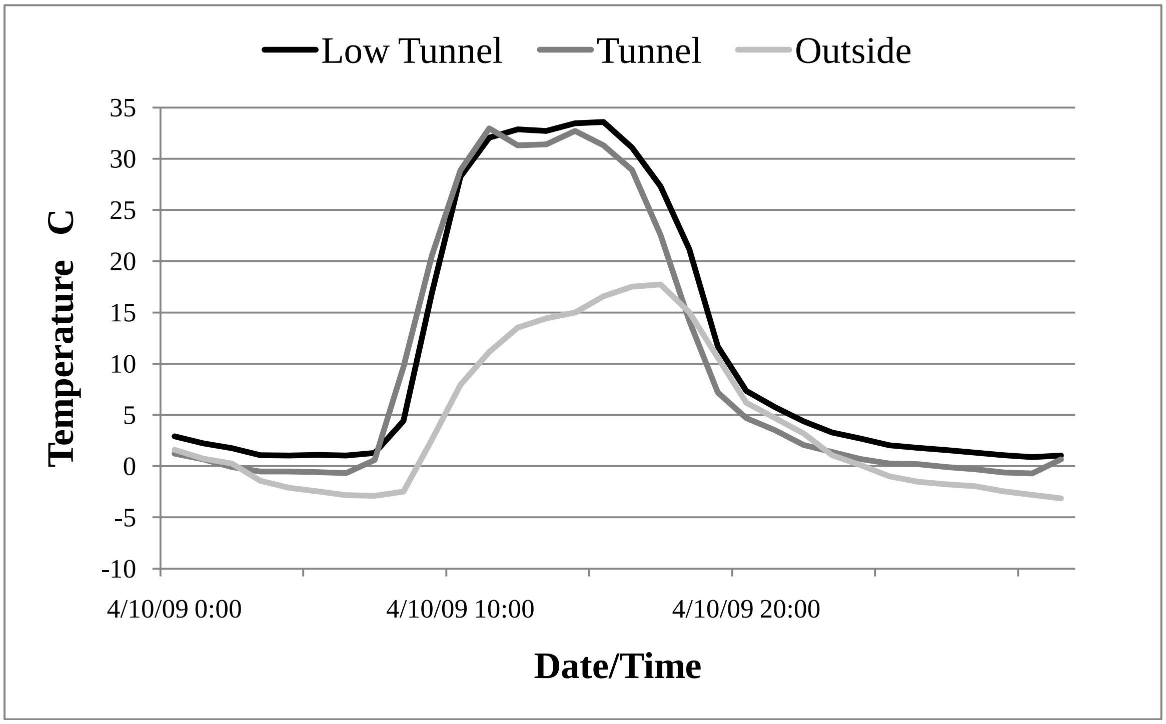


Figure 2.2. Inside and outside high tunnel temperatures for a sunny spring day when the tunnel and low tunnels were partially ventilated.

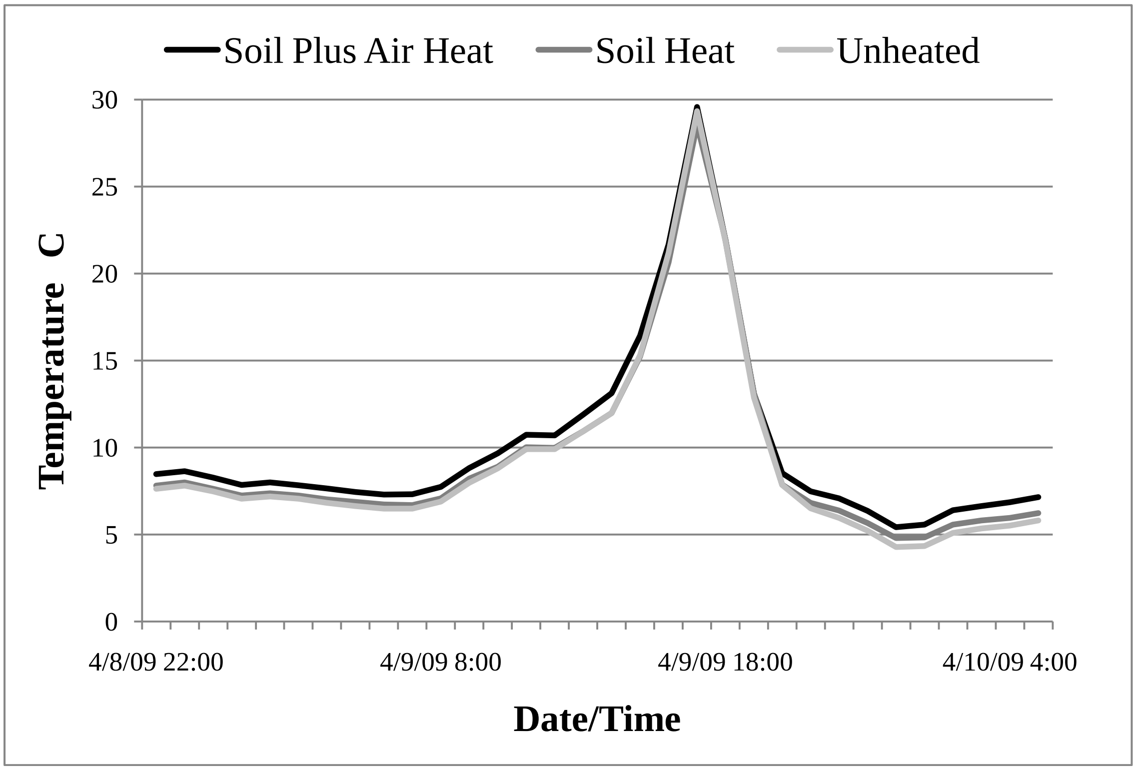


Figure 2.3. The effect of various heating treatments on air temperatures within the plant canopy under a low tunnel within a high tunnel.

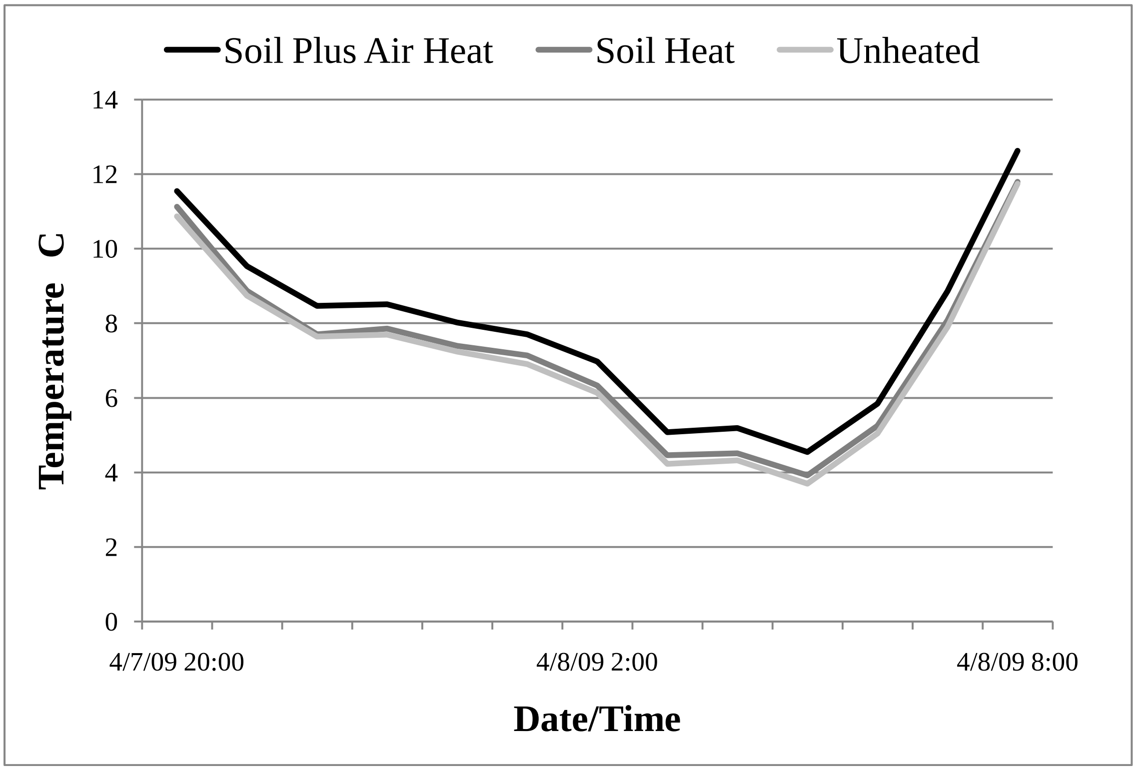


Figure 2.4. The effect of various heating treatments on air temperatures within the plant canopy under a low tunnel within a high tunnel on a night when outside temperatures were above freezing.

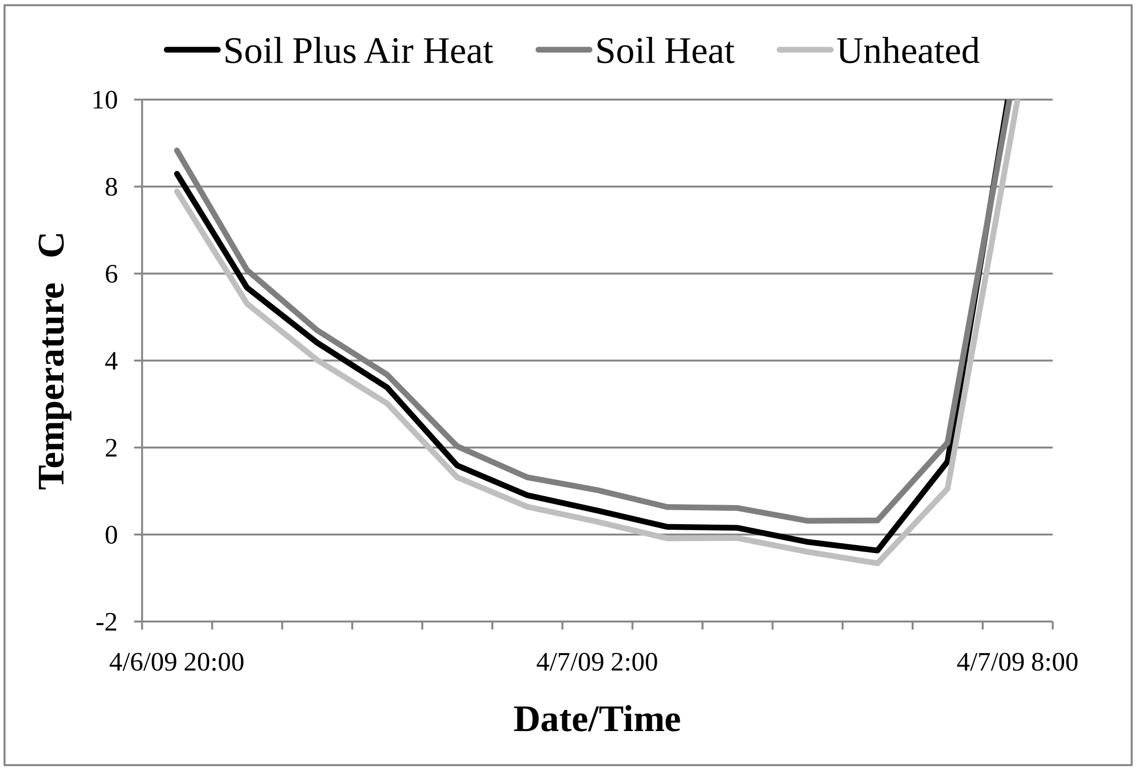


Figure 2.5. The effect of various heating treatments on air temperatures within the plant canopy under a low tunnel within a high tunnel on a night when temperatures outside were below freezing.

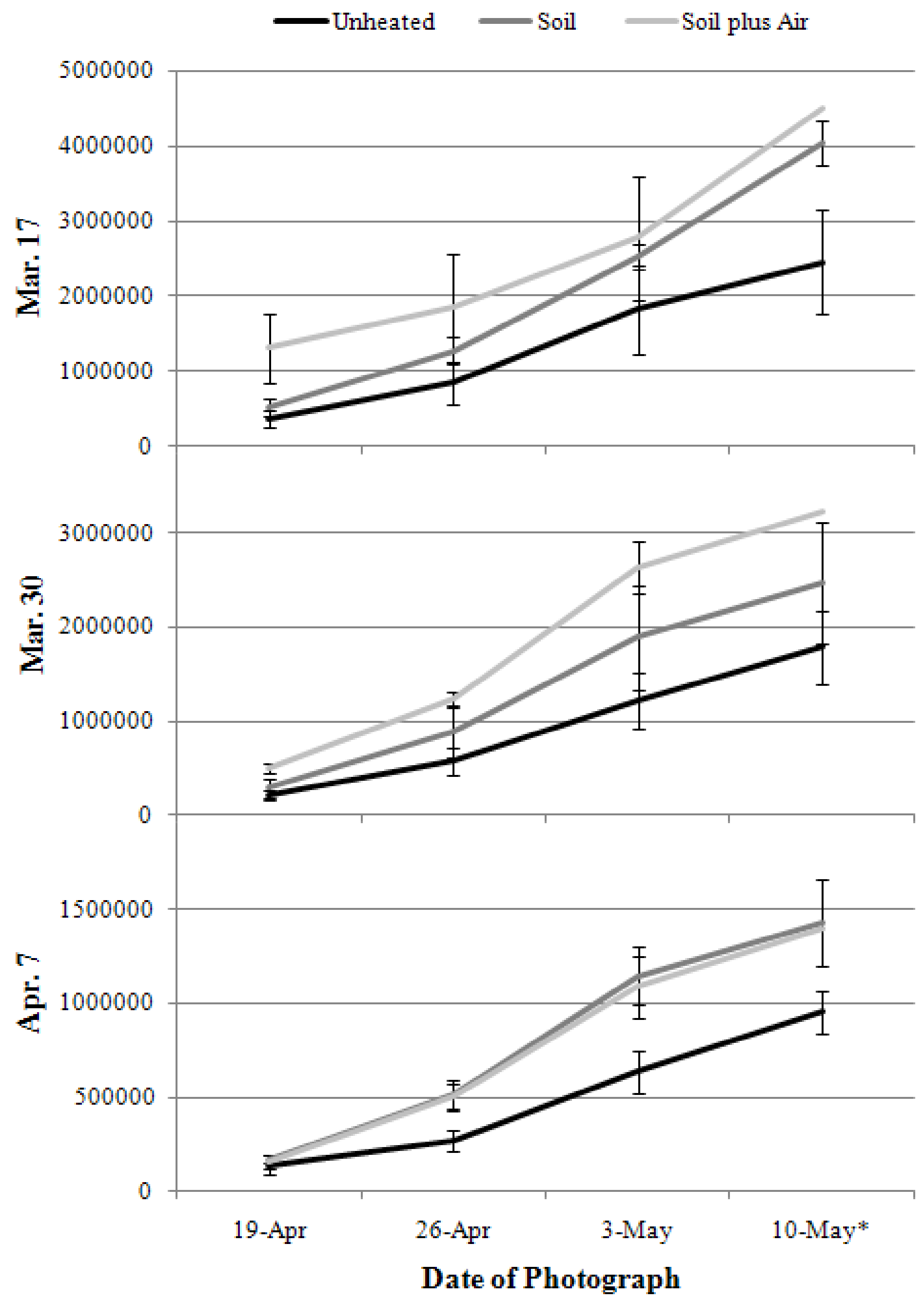


Figure 2.6. Effect of heating treatments on accumulated green pixels over time for three planting dates in spring 2009.

*Data value estimated for soil plus air treatment on May 10 because plant leaves had grown beyond the range of the camera lens and were labeled “saturated.”

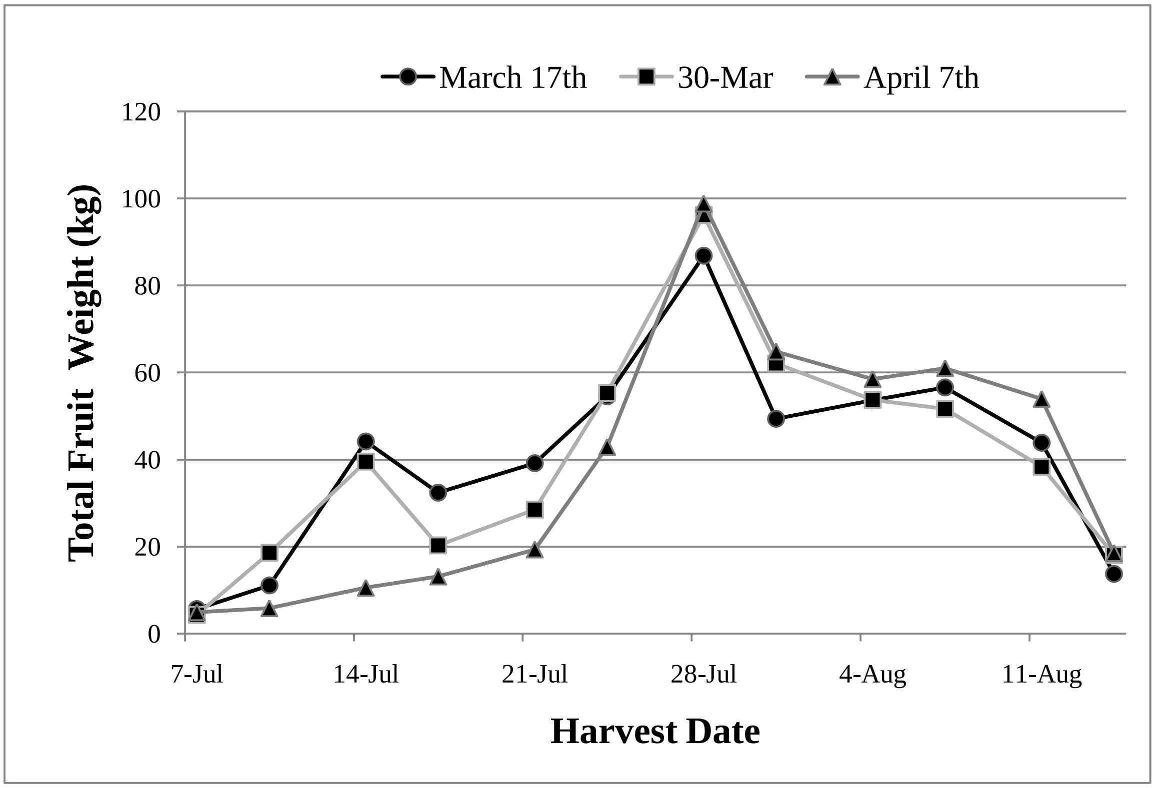


Figure 2.7. Seasonal change in fruit weight (kg) for three planting dates over the twelve week harvest period in 2009.

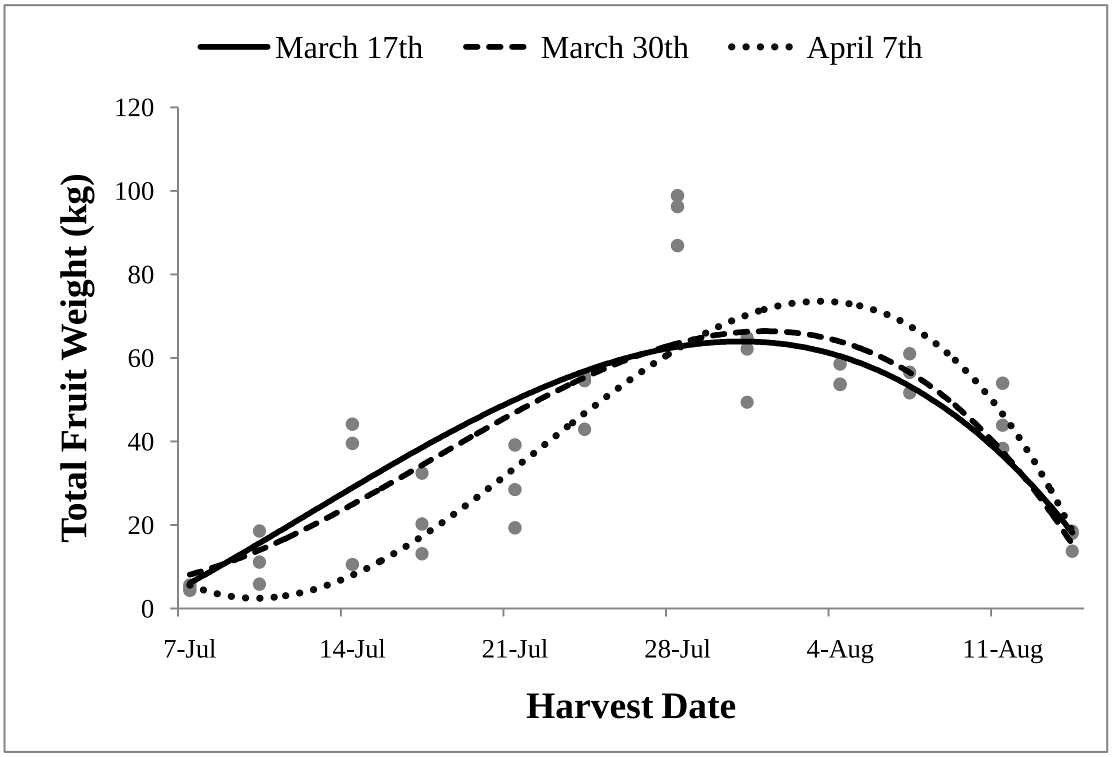


Figure 2.8. Polynomial regression curve (third order) for total fruit weight harvested (kg) for three planting dates over the 12-week harvest period in 2009.

CHAPTER 3

ENTERPRISE BUDGET FOR HIGH TUNNEL TOMATO PRODUCTION

Introduction

Tomato is not a primary agricultural crop in the Intermountain West region of the United States because the growing season is limited by cold temperatures. In the arid high elevation climate of the Intermountain West, temperatures in the spring are sub-optimal and include intermittent frost events that affect unprotected tomato plants. The last spring frost for northern Utah (Logan, UT) occurs anywhere between Apr. 25 and Jun. 21 with an average last frost date of May 7. The first fall frost occurs between Aug. 30 and Oct. 24 with an average first frost date of Sept. 26 (Moller and Gillies, 2008). In northern Utah, tomatoes are transplanted after the expected last frost date in mid May, and harvest begins in early August. This leaves a very short production season outdoors. Tomatoes have a higher value in the produce market particularly when they are early, local, and of high quality. High tunnels provide a way to protect an early planted tomato crop from cold spring temperatures, thus promoting early production. Research at Utah State University found it is possible to grow and produce ripe tomatoes approximately one month earlier than outdoor grown plants with the use of high tunnels. Early season tomatoes command a price premium, attract new customers to direct market produce stands, and are an enticing product offering for Community Supported Agriculture (CSA) shares.

This chapter includes an enterprise budget for high tunnel tomato production (Table 3.1), as well as a partial budget that compares high tunnel tomato production with and without the use of supplemental heating (Table 3.2). The high tunnel budget is based on a crop production system developed at the Utah State University Greenville Research Farm in North Logan, UT (Hunter et al., 2010; Ch. 2). Production for both budgets is accomplished with determinate type tomatoes which are transplanted into the tunnels after being raised in a heated greenhouse. Determinate type tomatoes are used to concentrate production in the early season before outdoor production begins, and before the wholesale price of tomatoes drops. This paper provides an explanation and discussion of some of the major costs involved in high tunnel tomato production. The prices in the budget were recorded as supplies were purchased from local retailers and online distributors.

The enterprise budget is broken into two parts. The first section includes yearly income and expenses from operations associated with growing high tunnel tomatoes. The second section describes the capital investment expenses and associated annual depreciation. Depreciation is an accounting tool used to match the portion of the capital expense to the period in which it was used. This budget uses the straight line depreciation method, and assumes no salvage value at the end of the useful life. The total cost of the capital investment is divided by the number of years in the investments useful life to find depreciation. Based on the experience from the Utah State University high tunnel project, the estimated useful life of a low-cost high tunnel is approximately 6 years (Black et al., 2008). The useful life of the irrigation system is assumed to be the same (Rowley et al., 2010).

Revenue

Production data are based on an average yields over three years of ‘Sun Brite’ tomatoes transplanted from mid March to early April. Yield data were collected in North

Logan, UT, with an average production of 10 lbs/plant. Sun Brite is a determinate variety which produces the bulk of its fruit in a 5-6 week period, and sufficiently early high tunnel tomatoes will typically finish as field crops begin to ripen. Price premiums for out of season tomatoes will depend on the local market options; however, direct market growers in Utah have been known to receive \$2.00 to \$4.00 per pound for early season fruit. In season field grown fruit typically sells for \$0.24 to \$0.50 per pound (Ward, 2003). However, some producers with good quality produce are able to maintain a higher selling price that loyal customers are willing to pay.

Supplies

Tomato transplants are not difficult to grow or to order from a local greenhouse; however it takes 6-8 weeks to grow a mature transplant. The majority of supplies necessary for the construction of a low-cost high tunnel can also be found locally (Black et al., 2008). Greenhouse supply companies will provide the plastic covering, mulch, and drip tape. PVC piping is readily available at local sprinkler stores, and other supplies can be found at any standard hardware store. One may find it hard to procure attractive market boxes locally. Plastic tubs or buckets may be used for harvesting, but produce boxes help protect the fruits during shipping and increase marketing appeal.

Labor

Most of the labor cost in high tunnel tomato production comes from temperature management of the high tunnel during the early spring, and from hand harvesting of the fruits. High tunnels must be ventilated (opened and closed) every day in the spring for approximately 10 weeks. For a 96 by 14 ft tunnel, ventilation takes roughly 20 minutes per day when low tunnels are used inside the high tunnel, but can take less than 5 minutes for a high tunnel alone. Harvest time for a 96 by 14 ft high tunnel is approximately two hours based on our experience at Utah State University. Harvest took place twice per week for six weeks in the Utah State high tunnel tomato studies.

Tunnel Construction

The initial cost of the high tunnel will vary depending on type (steel or PVC) and size. The price given in this enterprise budget is for a low cost PVC high tunnel developed at Utah State University (Black et al., 2008). Steel-framed structures are generally more costly than PVC structures; however, steel structures have a longer life expectancy and may be more rugged against wind and snow in extreme climates. Fixed costs will be greater when using a steel framed structure, but all other expenses will be comparable (Upson, 2010). If using or constructing a steel framed tunnel, adjust the costs accordingly in the budget.

Irrigation System

This enterprise budget assumes that a year-round water source is located in close proximity to the high tunnel(s). If this is not the case, installation of such a system will be required and needs to be accounted for. The irrigation system is also useful for fertilizer application with the use of a fertilizer injector. The fertilizer injector station is the largest cost associated with the irrigation system; however, with proper planning and minimal effort, a single injector station can serve multiple high tunnels and crops.

Additional Heating

After investing time and energy in transplanting tomatoes early, it could be devastating to lose plants to frost. Back up frost protection may be of interest to growers who would like some frost insurance. Low tunnels constructed within high tunnels create a smaller space that may be heated which can save on energy requirements. In a trial conducted during 2009 and 2010 in Logan, Utah we assessed the effectiveness of root zone heating with buried heat cables and air warming with incandescent lights for low energy cold temperature protection. The results showed that building a low tunnel within a high tunnel adds adequate frost protection to plants when planted in mid March in northern Utah without the use of additional heating. However, additional heat input with soil plus air heating showed promise in protecting plants from cold temperature stress and promoted earlier growth and higher yields (Hunter, et al. 2010; Ch. 2). Costs associated with several heating elements are included at the end of the budget, as well as in a partial budget comparing high tunnel tomato production with and without heating (Table 3.2). The lighting system is a temporary installation, and would cost approximately twice as much to meet regulations for a permanent installation.

Net Income

Based on the management system developed at the Utah State University high tunnel research facilities, net income for a 96 by 14 ft low-cost-high tunnel is estimated to be $2,692. This includes total sales of $4,250 less total expenses of $1,558. An average price of $2.50/lb was received for Utah State University high tunnel tomatoes at the Gardener’s Market in Logan, Utah. Expenses include annual operating expenses, or the expenses associated with yearly production; as well as the annual depreciation costs of the high tunnel and irrigation system.

References

Black, B., D. Drost, D. Rowley, and R. Heflebower. 2008. Constructing a low-cost high tunnel. Utah State Univ. Coop. Ext. 21 November 2010. <http://extension.usu.edu/files/publications/publication/HG_High_Tunnels_2008-01photos.pdf>.

Hunter, B., B. Black, and D. Drost. Improved cold temperature protection for early season high tunnel tomatoes, p.15-57. In: Enhancing out-of-season production of tomatoes and lettuce using high tunnels. Utah State Univ., Logan, MS Thesis.

Moller, A. L. and R. R. Gillies. 2008. Utah climate. 2nd ed. Utah Climate Center, Logan, UT.

Rowley, D., B. Black, and D. Drost. 2010. High tunnel strawberry production. Utah State Univ. Coop. Ext. 2 December 2010. <http://extension.usu.edu/files/publications/publication/Horticulture_HighTunnels_2010-01pr.pdf>

Upson, S. 2010. Economic feasibility of hoop house tomato production. 20 October 2009. <http://www.noble.org/ag/Horticulture/HoopTomato/Index.htm>.

Ward, R. 2003. Costs and returns per acre from growing tomatoes. Extension Economics. 9 January 2010. <http://extension.usu.edu/agribusiness/files/uploads/specialty/pdf/2003%20Tomato%20Budget.pdf>.

Table 3.1. Determinate tomato enterprise budget for 96’ by 14’ low-cost high tunnel.

	96' by 14' High Tunnel			
Sales	units	quantity	unit price	total
Early Tomatoes	lbs	1,700	$ 2.50	$ 4,250.00
Supplies				
Preplant and preparation costs				
Soil Test	each	1	$ 14.00	$ 14.00
Fuel	gal	1	$ 2.50	$ 2.50
Preplant fertilizers N-P-K	lbs	8	$ 1.00	$ 8.00
Compost	tons	0.45	$ 50.00	$ 22.50
Plastic mulch	ft	290	$ 0.05	$ 14.50
Drip tape	ft	290	$ 0.05	$ 14.50
Establishment				
Transplants	each	200	$ 0.25	$ 50.00
Plastic for low tunnels	ft	300	$ 0.20	$ 60.00
Wood stakes	ea	100	$ 0.45	$ 45.00
Baling twine	ft	2600	$ 0.01	$ 15.60
46-0-0 Urea	lbs	1.5	$ 0.33	$ 0.50
Tomato Harvest				
Harvest boxes	each	20	$ 1.00	$ 20.00
Market boxes	each	25	$ 2.40	$ 60.00
Total Supplies				$ 267.10
Labor				
Preplant and preparation costs				
Soil test	hours	0.5	$ 10.00	$ 5.00
Apply preplant fertilizers	hours	0.75	$ 10.00	$ 7.50
Tillage	hours	2	$ 10.00	$ 20.00
Install drip tape	hours	0.75	$ 10.00	$ 7.50
Install plastic mulch	hours	3.75	$ 10.00	$ 37.50
Establishment				
Planting labor	hours	2.5	$ 10.00	$ 25.00
Install low tunnels	hours	3	$ 10.00	$ 30.00
Install support stakes	hours	2	$ 10.00	$ 20.00
Prune and train/tie plants	hours	8	$ 10.00	$ 80.00
Weeding	hours	6	$ 10.00	$ 60.00
Install/remove plastic and shade	hours	12	$ 10.00	$ 120.00
Monitoring and ventilation	hours	26	$ 10.00	$ 260.00
Tomato Harvest				
Harvest and grading	hours	24	$ 10.00	$ 240.00
Post Harvest				
House clean out	hours	4.5	$ 10.00	$ 45.00
Total Labor				$ 957.50
Annual Operating Expenses (supplies and labor)				$ 1,224.60
Annual Cost of High and Low Tunnels				$ 274.50
Annual Cost of Irrigation System	* details on next page			$ 58.82
Total Expenses				$ 1,557.92
Net Income				$ 2,692.09

	units	quantity	unit cost	total
Tunnel Construction				
High Tunnel				
High Tunnel	each	1	$ 697.00	$ 697.00
HT Construction Labor	hours	25	$ 10.00	$ 250.00
Extra 6-mil Greenhouse film	24'x100'	1	$ 200.00	$ 200.00
Shade Cloth		1	$ 300.00	$ 300.00
High Tunnel Subtotal				$ 1,447.00
Low Tunnel				
conduit arches	10'	30	$ 1.65	$ 49.50
1/2" x 24" rebar	each	60	$ 1.66	$ 99.60
Low Tunnel Subtotal				$ 149.10
Total				$ 1,596.10
Annual Depreciation Cost of High and Low Tunnels				$ 266.02
Irrigation system				
3/4" poly pipe	ft	14	$ 0.42	$ 5.88
1" valve	each	1	$ 5.15	$ 5.15
misc fittings	each	10	$ 1.00	$ 10.00
drip hose adapter	each	6	$ 0.56	$ 3.36
*injector	each	1	$ 265.00	$ 265.00
* filter	each	1	$ 12.50	$ 12.50
* pressure regulator	each	1	$ 11.00	$ 11.00
*Instalation	hours	4	$ 10.00	$ 40.00
Total				$ 352.89
Annual Depreciation Cost of Irrigation System				$ 58.82
*can be used for multiple high tunnels				
Additional Heating				
Heat Cables				
Cables (250' H.D. GRO-QUICK)	each	3	$ 154.57	$ 463.71
Thermostat	each		$ 88.35	$ 88.35
Labor				
Installation	hours	1.5	$ 10.00	$ 15.00
Energy cost (approximate)	day	50	$ 0.96	$ 48.00
Cable Total				$ 615.06
Lights				
Extension cords (50 ft)	each	6	$ 32.82	$ 196.92
Pigtail sockets	each	60	$ 2.55	$ 153.00
suitcase splice connectors (brown)	each	120	$ 0.47	$ 56.40
electrical tape roll	each	6	$ 3.49	$ 20.94
40-Watt light bulbs	each	60	$ 0.50	$ 30.00
Thermostat	each	1	$ 49.95	$ 49.95
Labor				
splicing lights	hours	5	$ 10.00	$ 50.00
Installation	hours	1.5	$ 10.00	$ 15.00
Energy cost (approximate)	day	50	$ 1.06	$ 53.00
Light Total				$ 625.21

Table 3.2. Partial budget comparing high tunnel tomato production with and without the use of supplemental heating.

Added returns from supplimental heating	$	5,772.00
Reduced returns from absence of heating	$	4,250.00
Added costs of heating		
Supplies (Annual cost, 3 yr)		
Soil Heating	$	184.02
Air Heating (lights)	$	169.07
Labor		
Soil Heating	$	15.00
Air Heating (lights)	$	15.00
Energy Cost		
Soil Heating	$	48.00
Air Heating (Lights)	$	53.00
Total Soil	$	247.02
Total Air	$	237.07
Net income for Heating compared to Unheated		
Soil Heating	$	1,274.98
Air Heating (Lights)	$	1,284.93
Both	$	1,037.91

CHAPTER 4

HIGH TUNNEL TOMATO PRODUCTION FACTSHEET

Introduction

Tomato is a commonly grown high value vegetable crop that can add diversity to small scale and part time farming operations. Growing tomatoes in high tunnels makes it possible to produce the crop approximately one month earlier and 6 weeks later than field grown tomatoes. High tunnels increase marketing opportunities, improve early cash flow, and yields are often higher than outdoor grown tomatoes. High tunnels are relatively inexpensive to build, are passively heated and cooled, and allow planting as early as March in many locations in Utah. Tomatoes begin to ripen in June and can be harvested as late as November.

High tunnels are temporary structures covered with a single layer of greenhouse grade plastic which is supported by a galvanized steel or PVC frame. Frequent sunny days make growing in high tunnels logical in Utah because tunnels are passively heated using solar radiation. High tunnels help protect plants from cold injury at night and maintain optimal growing temperatures during the day. Daily ventilation may be necessary to prevent temperatures from exceeding the optimal range. A full list of construction details and photographs for a low-cost PVC-frame high tunnel can be found at: http://extension.usu.edu/files/publications/publication/HG_High_Tunnels_2008-01photos.pdf.

Variety Selection

Select tomato varieties based on fruit size, earliness, soluble solids (sweetness), growth habit (determinate or indeterminate), and disease resistance. Determinate varieties are a good choice for high tunnel production in Utah because they allow for early production in the tunnel with most fruits ripening prior to field-grown tomatoes. Vine growth is limited for determinate varieties making it easier to trellis the plants. Indeterminate varieties continue to grow, flower, and fruit throughout the season, so more robust trellising and a taller tunnel are required. Heirloom varieties, while popular at farmers markets, generally lack disease resistance, are more prone to cosmetic defects. High tunnels help protect plants from diseases and the weather that can cause cosmetic defects. All tomato varieties tend to perform better and have higher quality when grown in a high tunnel. Consult with your local nursery or garden center, seed salesman or any seed catalog for detailed information on tomato growth characteristics. While we have not conducted any tomato variety trials for high tunnels at Utah State University, some of the recommended varieties for high tunnels based on other universities variety trials can be found at: http://www.hightunnels.org/ForGrowers/WarmSeasonVegetables/warmseasonvegtomprod.htm.

Site Selection

Deep sandy to loamy soil with a pH of 6.5 to 7.5 is ideal for tomato production. Most Utah soils are good for tomato production as long as the soil is well drained, fertile, and there is no salt build up. Tomato plants are sensitive to herbicides in soil, so pay special attention to tunnel site selection if residual herbicides have been used in the past. The high tunnel should be located near a year-round water source in order to facilitate irrigation in the early spring and late fall when seasonal irrigation water is not available.

Site Preparation and Fertility Management

Prior to planting, have the soil tested to determine nutrient needs and deficiencies. It is a good idea to incorporate composted organic matter before planting to sustain soil fertility. An initial application of 5 tons per acre of high quality compost of known nutrient analysis is recommended. Specific fertilizer rates recommended for tomato production based on soil tests are listed in Tables 4.1 and 4.2. A common practice is to add half of the required nitrogen fertilizer and all the phosphorous and potassium prior to planting. The additional nitrogen is then added after fruit set. Table 4.2 describes an appropriate nitrogen fertility schedule if fertilizer is injected with drip irrigation. Spreading out the nitrogen fertilizer applications allows for less leaching and improves plant growth and yield.

High tunnel tomatoes can be grown with organic fertilizers which promote soil fertility, and yields are often equal to tomatoes grown using conventional fertilizers. Organically grown tomatoes tend to have a higher market value. Composted chicken manure has been used for tomato production due to its high mineralization capacity. The high tunnel study at Utah State found tomato yields were similar between composted chicken manure and conventional fertilizers, but fruit quality was higher when grown with compost. The organic-managed tomatoes produced 79% No.1 quality fruits while the conventionally fertilized tomatoes yielded only 60% No.1 quality fruits primarily due to potassium deficiency. The initial rate of compost application is quite high (15 tons per acre) and amounts are reduced as soil fertility increases in later years. It is advised that regular soil tests be conducted to ensure that nutrient balances in the soil are maintained, and salt accumulation is avoided, when growing tomatoes using organic methods. More detailed information about organic tomato production can be found at attra.ncat.org/attra-pub/tomato.html. After enriching the soil with nutrients, incorporate the fertilizers to a depth of 4-6 inches with a tractor mounted or hand operated tiller. High tunnels can be designed to accommodate small machinery for soil tillage and other operations.

Drip irrigation is well suited for tomato production in high tunnels and should be used in combination with black plastic mulch. Plastic mulches reduce water evaporation from the soil, blocks weeds, and warm the soil to promote early growth and fruiting (Images 2 & 3). Lay plastics at least one week prior to planting to help increase soil temperature. Bury 6 inches of the plastic edges in the soil to secure the mulch. This can be done by making small trench on both sides of the planting bed and filling in the trench after the plastic mulch is laid down. Be sure to place the drip tape under the plastic mulch and water the beds after installation.

Irrigation Management

Tomatoes require regular, uniform watering during the growing season. Inconsistent watering can cause blossom end rot, and during fruit sizing can cause cracking. A small decrease in water after fruits reach mature size can trigger plants to begin ripening. Soil water status should be monitored regularly to maintain consistent soil water. This is easily done with a resistance block sensor or a tensiometer. Place sensors at various locations and depths in the soil profile to get a more accurate measure of soil water content. Soil texture (clay, loam, sand) influences the soils ability to hold water (Table 4.3). Other low cost tools and methods to monitor soil water can be found at http://attra.ncat.org/attra-pub/soil_moisture.html.

Transplant Production

Transplanting is recommended for most growing areas of Utah. Many growers produce their own transplants, but plants can also be purchased from a local greenhouse supplier. Sow seeds into plastic plug trays with 50-72 cells per tray filled with a good soilless mix. Adequate light is essential to produce a quality plant. Cool white fluorescent lights positioned to stay 2 to 3 inches above the plants, lit for 14–16 hours per day will ensure plants grow big and healthy. Growth temperatures should be approximately 75°F during the day and 65°F at night. Water regularly and feed weekly with a soluble complete fertilizer diluted to 100 ppm. Gently brushing the plants each day or exposing them to wind helps make the plants stocky and strong. Condition or “hardened off” transplants for a short time each day by exposing them to cool temperatures (50-60°F) one week before transplanting to adapt the tomato for cold temperatures found in the tunnels. Allow 6-8 weeks for growing transplants depending on greenhouse growing temperatures. Transplants should have 5-7 mature leaves and a well developed root system. It is advised that transplants be covered with floating row cover or low tunnels during the first 4-6 weeks after establishment in the spring.

Planting, Pruning and Training

Tomato planting dates vary depending on location and climate conditions in Utah. Tomatoes in tunnels are often spaced 18-24 inches apart in row depending on the variety with rows spaced 36-48 inches apart. A 14’x 96’ high tunnel would accommodate 186 plants if there are three rows (48” apart) with plants spaced 18 inches apart. Once planted water well and cover with floating or low tunnel row covers (Figures 4.1 and 4.2). Ventilate tunnels whenever temperatures inside exceed 90°F (Figure 4.3).

High tunnel tomatoes are commonly trellised using a stake and weave system (Figure 4.4). Staking helps reduce sunscald and ground staining thus producing higher yields of #1 quality fruits. It involves driving 4 foot long wooden stakes 18” deep every other plant and weaving string horizontally between the stakes. Prior to applying the first string, the plants are pruned of secondary shoots (suckers). Suckers are the vigorous new growth found at the base of the leaves. Remove suckers from the bottom 3 leaves on determinate varieties when the suckers are 3-4 inches long. Suckering reduces vine growth but promotes earlier and larger fruit. After suckering attach the first string one foot above the ground and additional strings after every 8 inches of new growth. Generally plants are only suckered once and trellised 3-4 times. The most common method of trellising indeterminate varieties is a vertical wire system. Six foot tall support posts are placed every 5 to 10 feet with a 12-guage wire running between them. Plants are then tied to a vertical piece of twine attached to the overhead wire. Additional ties and/or clips are used to keep the vine attached to the twine.

High Tunnel Temperature Management

Tomatoes grow best at temperatures between 75 and 85°F and when night temperatures stay above 50°F. At temperatures between 50 and 60°F, ‘rough’, irregular fruit growth (cat-facing) occurs. Temperatures above 95°F can damage tomato blossoms causing flowers to fall off or develop misshapen fruit [1]. High tunnels can mitigate some of these temperature variations thus resulting in higher yields and more #1 quality fruits.

Utah has limited frost free days. Local freeze-free dates can be found at the Utah Climate Center website under climate reports (climate.usurf.usu.edu). Use the website to find the earliest, average, and latest recorded spring freeze dates for your production area. With this information, tomatoes can be planted from 4-6 weeks earlier which allows for earlier flowering and fruiting. Some frost protection is still needed when planting in high tunnels. When outside temperatures are between 20 and 35°F in early spring, the temperature will be 1-4°F warmer inside a high tunnel. Row cover cloth or Reemay® is a thin spun bonded fabric that can be laid directly on the plants and left on during establishment (Figure 4.1). The cloth helps keep the temperatures around the plants 2 – 4°F warmer than the surrounding air and limits heat lost during cold nights. Low tunnels inside high tunnels (Figure 4.2) will keep night temperatures slightly warmer than cloth covers, but plastic must be vented during the day to avoid excessive heat. The total cold temperature protection provided by different row covers within high tunnels is 3-10°F when outside temperatures are near freezing. Plants are further protected by the windbreak that the tunnel provides. Another strategy for avoiding frost inside the high tunnel early in the season is to have a back up heat source such as a propane heater. This can be very effective, but also costly when used on a large scale. Root zone heating is more energy efficient and has been shown to offset the negative effects of low air temperature [2]. Results from the Utah State University high tunnel tomato trial, including an assessment of back up heat sources, can be found near the end of the bulletin.

Daily ventilation may be required to ensure temperatures inside do not exceed 90°F. Ventilation may entail opening a single door in April, or both sides and doors in May when day temperatures are warm (Figure 4.4). When night temperatures stay above 50°F, the plastic on the high tunnel should be removed and replaced with a 30-50% shade cloth. This is important to avoid excessive heat buildup in the tunnel and to prevent sunscald on the fruits.

Pest Management

Pests can reduce yield and threaten fruit quality. Healthy plants grown in a clean environment are less likely to have pest outbreaks that require chemical treatments. Application of chemicals in tunnels is more hazardous than in the open field due to the closed environment. Chemicals used inside a closed high tunnel should be labeled for greenhouse use. If using chemicals in tunnels, follow the directions on the label closely and always wear appropriate personal protective equipment. If you are having trouble diagnosing a pest problem, contact your county Extension agent or other knowledgeable individual. Some of the common insects found in high tunnels include aphids, various worms, beetles and grasshoppers.

Aphids: Aphids are tiny insects that feed on plants by sucking sap out of stems and leaves. Aphids can also transmit viruses and diseases. Symptoms include stunting and distortion of plant growth and sticky sap on the leaves. Prevent aphids from becoming a problem by making sure transplants are free of aphids before planting, and controlling weeds in and around the tunnels. Insecticidal soaps and horticultural oils are effective at controlling aphids, are safe to use inside a tunnel, and often come in organic formulations.

Hornworms and Fruitworms: Hornworms are large green caterpillars with white v-shaped or dashed markings on their sides and a black or red hook/horn on the back end of the worm. The worms develop into moths which emerge in the late spring to lay eggs. Worms devour foliage quickly and also feed on the fruit. Hand removal is the recommended control for light infestations. Biological (naturally occurring) insecticide is available for hornworm control, and hornworms may also be controlled with other common chemical insecticides. Fruitworms (also called corn earworms) are foliage feeding caterpillars that often bore into green or ripening fruits. The same control methods can be used for fruitworms as hornworms.

Flea Beetles: Flea beetles are small black or brown beetles that jump when disturbed. Adult flea beetles chew holes in leaves which can make plants more susceptible to disease. Seedlings and transplants are particularly susceptible. Most plants eventually outgrow flea beetle damage. For heavy infestations a chemical insecticide may be required.

Grasshoppers: Grasshoppers emerge in spring with an appetite for foliage and fruit that lasts all summer. Eliminating weeds near the high tunnel will deter grasshoppers from feeding there and finding a way into the tunnel. It is a good idea to scout regularly for grasshoppers before they become a problem. Removing tomato plants promptly after the harvest and controlling weeds in the fall will discourage female grasshoppers from laying eggs near the tunnels. Biological baits are available for grasshopper control as well as baits containing chemical insecticide for fast control in severe infestations.

Disease Control: High tunnels trap warm humid air which can promote disease. Disease resistant varieties, proper soil drainage, good ventilation, and crop rotation aid in disease prevention. Most hybrid varieties are disease resistant or tolerant. Specific resistances are abbreviated on the seed packet or plant label and may include *Verticillium* wilt (V), *Fusarium* wilt races 1 & 2 (F or FW), Nematodes (N), *Alternaria* stem canker

(A), and/or Tobacco mosaic virus (T). Common diseases noted in high tunnels include mold and mildews, various wilts and viruses.

Mold and Mildew: Grey mold is a common disease of tunnel house tomatoes caused by the fungus *Botrytis cinerea*. Grey mold looks like light grey colored fuzzy growth on the stems and leaves. White fuzzy patches on leaves are powdery mildew. Fungal diseases also cause leaf spots that can be yellow, brown, or black. Common leaf spot diseases include early blight and *Septoria* leaf spot. These diseases reduce leaf cover which can decrease yield and cause sunscald. Good ventilation and air circulation will help reduce excess moisture in the tunnels thus preventing most diseases. Placing drip irrigation below plastic mulch will also help to maintain dry foliage. Fungicide can be applied when diseases are first noticed.

Wilts: *Fusarium* wilt is a common tomato disease. Plants with *fusarium* wilt appear to be under water stress (wilting) because the disease attacks tissue responsible for water transport to the leaves. The stem will appear brown inside if cut open. Infected plants should be destroyed and no susceptible tomato varieties should be planted in the area. *Verticillium* wilt attacks many species of plants including potato, pepper, watermelon, strawberry, and radish. Symptoms are similar to *fusarium* wilt but lower leaves have yellow blotches on them that progress upward as the disease progresses. Plants are stunted and yield is greatly reduced. No varieties susceptible to *verticillium* wilt should be planted in the area.

Viruses: Viruses can be spread by insects, contact with other infected plants, and from tobacco products through human contact. Tobacco mosaic virus, cucumber mosaic virus, and spotted wilt are common viruses that affect tomato. Plants infected with a virus tend to have dwarfed light green leaves that may be twisted or cupped. Yellow ring spots can be seen on the fruits of plants infected with a spotted wilt virus. Plants should be removed and destroyed immediately to prevent the spread of virus.

Physiological Disorders: Tomatoes are susceptible to several physiological and environmental disorders that limit production or affect fruit quality. Most of the disorders are poorly understood and can be induced by many conditions related to nutrition, environments, or cultural practices.

Blossom end rot and fruit cracking are two disorders associated with irregular watering. Blossom end rot (Figure 4.5) looks like a sunken brown to black spot on the bottom of the fruit and is caused by a localized calcium deficiency. Fruit cracking takes place when rapid changes occur in the movement of water or solutes into the fruit during fruit growth or ripening. Cracks may be radiating outward from the stem scar (radial cracks) or encircling (concentric cracks) the fruit. “Russetting” are minute, hair-line cracks which give the fruit a rough feel but are not always visible. Most hybrid varieties are more resistant to cracking while heirloom types are quite susceptible.

Cat-facing is misshapen fruits with leathery protruding tissue at the blossom end of the fruit. Cat-facing (Figure 4.5) is caused by cold temperatures and low light conditions during flowering and early fruit growth. Sunscald (Figure 4.5) occurs when green fruits are exposed to intense sun light which bleaches the flesh of the tomato and cause them to ripen unevenly. The affected tissue may be leathery, have yellow skin and white flesh extending into the core, and is firmer than surrounding tissues. Plants grown with low nitrogen levels are more likely to experience sunscald as leaf growth does not shade the fruits. Use shade cloth over the tunnel to reduce sunscald. Blotchy ripening

(Figure 4.5) can be caused by sunscald or nutrient deficiency. While the cause of blotchy ripening is not completely understood, soils with potassium and nitrogen deficiency are more likely to express the symptoms. The symptoms cannot be seen on immature fruits and generally show as greenish, yellowish or white areas near the calyx of otherwise normal red tomato fruits. Large fruited varieties are more susceptible. Management strategies include maintaining high soil potassium levels, keeping air temperatures below 90°F, and minimizing soil water stress.

Weed Management: Weeds promote pests and compete with tomatoes for water, nutrients, and light, especially when tomato plants are small. Weeding is simplified in a high tunnel with the use of plastic mulch. The edges of the high tunnel (inside and out) are the only problem weed areas since foot traffic keeps weeds down in the walkways and water is only being applied under plastic mulch. Weeding should be shallow near the plants to avoid damaging the roots. Chemical weed control should be avoided at all costs. Herbicides labeled for field tomatoes may not be appropriate for use in tunnels due to the risk of accumulating fumes in the closed environment.

Harvesting and Handling

Fruits can be picked when they are light green to pink but picking when tomatoes are approaching full ripeness will result in better flavor and market appeal. Harvesting should take place frequently (2-3 times per week) if tomatoes are vine ripened. Some growers remove the calyx (Image 8) which can puncture other fruits and thus reduce fruit quality. If the calyx is left on the fruit, more care is needed during picking and packaging to minimize damage to other fruits. Before marketing, tomatoes should be graded into U.S. size (small, medium, large or extra large) and grade categories (#1, #2 or culls).

Specific tomato grading guidelines can be found at http://www.ams.usda.gov under a search for tomato grades. Fruits graded as #1 are mature, well shaped, firm, and free of decay, injuries or sunscald. Fruits graded as #2 may have some minor defects such as russetting or radial cracks, but must be mature, firm and free of broken skin. Mature red tomatoes are best when stored at approximately 50°F [3].

Utah State High Tunnel Tomato Trials

Sunbrite (determinate) tomatoes have been used for all tomato trials conducted at Utah State University. From 2005-2008, we compared the production of tomatoes when grown using organic or conventional based fertilizers. In 2009, tomatoes were planted on three dates (March 17, March 30, and April 7) and additional low tunnels made of 2-mil construction grade plastic were used inside the tunnels for added plant protection early in the season. Electric soil heat cables (Figure 4.6) and 40 watt incandescent light bulbs (Figure 4.2) were evaluated in the early season to provide supplemental heat. In all studies, tomatoes were transplanted through black plastic mulch and drip irrigation was used for watering. The plastic covering the high tunnel was removed in early to mid-June and replaced with 40% shade cloth (Figure 4.7) during the 2008-2009 studies to prevent sunscald. Replicated, randomized experimental design was used for all trials, and yield relationships were derived through statistical analysis.

Red ripe tomatoes were harvested two times per week starting in early July and ending in early to mid-August and graded according to U.S. standards (Figure 4.8). In most years, harvest was completed before the onset of full production of locally grown field tomatoes. Cull fruits were affected by potassium deficiencies, sunscald, grasshopper feeding, and cat-facing. The overall yield suggests that it is possible to produce more than 2,000 lbs (11 lbs per plant) of tomatoes per 14'x 96'high tunnel. An enterprise budget for high tunnel tomato production will be available on the Utah State University Extension website in summer 2010.

Marketable yield of organically grown tomatoes was lower than those grown with conventional fertilizers in 2005 during the first year of the nutrient study. However, by 2006, marketable yield was only slightly lower when grown organically compared to conventional approaches. By 2007 and 2008, marketable tomato fruit yields were higher when using organic production approaches than if conventional fertilizers were used (Table 4.4). The addition of shade cloth in 2008 increased the quality of all the tomatoes by protecting the fruit from sunscald.

The combination of soil and air heating (incandescent lights) resulted in significantly higher early season yield, but was similar to the other treatments in overall yield (Table 4.5). There was no difference in yield between unheated plots and those heated with cables only. The effect of the lighted treatment was only significant for plants from the March 17 planting date. The results indicate that light bulbs offer some cold protection in the very early season, and that root zone heating does not increase cold protection for high tunnel tomatoes.

Fruits began to ripen in late June for all plantings and picking commenced on July 7. Early season and overall marketable yield was significantly lower for the April 7 planting date (Table 4.6). The results indicate that planting in late March leads to earlier and greater yields for high tunnel tomatoes compared to planting in early April. On March 28 the outside low temperature was recorded at 16°F while the low temperature recorded inside the tunnels was 25°F. 4% of plants from the first planting date were lost to cold during this time regardless of heating treatment. Excellent plant survival implies that low tunnels within high tunnels are adequate to help tomato plants survive early season frost events.

Summary

Early tomatoes can provide local farmers additional product to sell at farmers' markets and other local retail outlets at a time when outdoor production is not yet available. High tunnels allow 4-6 week earlier production, high yields, and better quality and thus are an economically attractive product in marginal production areas of Utah. High tunnel tomatoes should not be thought of as an alternative to outdoor production. Rather they are an early season compliment to other products, thus allowing farmers to supply local tomatoes to the public for a longer period of time, and during a time when local tomatoes command a price premium.

Literature Cited

1. Marr, C. 2009. *Commercial Vegetable Production: Tomatoes.* Available at: http://www.ksre.ksu.edu/library/hort2/mf312.pdf.

2. Diver, S. 2002. *Root Zone Heating for Greenhouse Crops*. Available at: http://www.attra.org/attra-pub/PDF/ghrootzone.pdf.

3. Orzolek, M., et al. 2009. *Tomato Production*. Agricultural Alternatives. Available at: http://pubs.cas.psu.edu/freepubs/pdfs/ua291.pdf.

4. Peet, M. M. 2005. *Irrigation and Fertilization*. In: *Tomatoes*. A. Heuvelink (editor) pg. 181.

5. Egel, D. et al. 2009. *Midwest Vegetable Production Guide for Commercial Growers.* Available at: http://www.btny.purdue.edu/Pubs/ID/id-56/irrigation.pdf

6. Jett, L. 2009. *Production of Tomatoes Within a High Tunnel*. Available at: http://www.hightunnels.org/ForGrowers/WarmSeasonVegetables/warmseasonvegtomprod.htm.

Table 4.1. Fertilizer rates based on pre-plant soil test results for tomato grown in bare soil [4].

Nitrogen (lb/acre)	P_2O_5 (lb/acre)[1] Soil Phosphorous level[2]			Potassium (lb/acre)[1] Soil Potassium level[3]			Application Time
	Low[2]	Medium	High	Low[3]	Medium	High	
50	150	100	50	180	120	60	Incorporate prior to planting
50	0	0	0	0	0	0	When 1st fruits 1” in diameter
100	150	100	60	180	120	60	Total recommended

[1] A 14’x 96’ high tunnel is 1,344 square feet (.03 acres). One acre equals 43,560 square feet.

[2] <15 ppm is considered low, and >25 ppm is considered high phosphorous for soil test results.

[3] <130 ppm is considered low, and > 250 ppm is considered high potassium for soil test results.

Table 4.2. Fertilizer rates based on pre-plant soil test results for transplants in plastic mulch [4].

Nitrogen (lb/acre)	P_2O_5 (lb/acre) [1] Soil Phosphorous level[2]			K_2O (lb/acre) [1] Soil Potassium level[3]			Application Time
	Low[2]	Medium	High	Low[3]	Medium	High	
40	90	40	0	120	60	0	Incorporate prior to planting
20	20	20	20	20	20	20	2 weeks after transplanting
20	20	20	20	20	20	20	When 1st fruits 1” in diameter
20	20	20	20	20	20	20	When 1st fruits turns color
100	150	100	60	180	120	60	Total recommended

[1] A 14’x 96’ high tunnel is 1,344 square feet (.03 acres). One acre equals 43,560 square feet.
[2] <15 ppm is considered low, and >25 ppm is considered high phosphorous for soil test results.
[3] <130 ppm is considered low, and >250 ppm is considered high potassium for soil test results.

Table 4.3. Soil tension values for different soil textures for use in scheduling drip irrigation as listed by the Midwest Vegetable Production Guide [5]

	0% Depletion of Available Water (Field Capacity)[1]	**20-25% Depletion of Available Water [2]**
Soil Texture	Soil Tension Values (in centibars)	
Sand, loamy sand	5-10	17-22
Sandy loam	10-20	22-27
Loam, silt loam	15-25	25-30
Clay loam, clay	20-40	35-45

[1] At field capacity a soil contains 100 percent of available water holding capacity; any excess water in the root zone has drained away.
[2] Start trickle irrigation for shallow-rooted crops at this point.
Adapted from New Jersey Commercial Vegetable Production Guide, New Jersey Ag Expt. Station, Rutgers; and Water Management in Drip-irrigated Vegetable Production by T.K. Hartz, UC-Davis, Calif., Vegetable Research and Information Center.

Table 4.4. Effect of organic and conventional fertility on tomato yield in 2007 and 2008.

	Yield (lbs/plant)			
Grade	Organic ‘07	Organic ‘08	Conventional ‘07	Conventional ‘08
Marketable	8.9	7.5	8.1	6.9
#1	5.4	5.6	4.7	5.2
#2	3.5	1.9	3.4	1.7
Culls	3.2*	0.2	3.1*	0.3

*excessive sunscald damage
Harvest Periods: 2007 – 3 July to 10 August; 2008 – 21 July to 28 August
#1 and #2 grades are considered marketable

Table 4.5. The effect of supplemental heat on tomato yields in 2009.

	Yield (lbs/plant)		
Grade	Unheated	Soil Heat Cables	Soil Heat and Lights
Marketable	9.6	9.9	10.7
#1	7.8	8.3	8.7
#2	1.8	1.6	2.0
Culls	1.5	1.9	1.8

Table 4.6. Effect of planting date on tomato yield in 2009.

	Yield (lbs/plant)		
Grade	March 17	March 30	April 7
Marketable	10.8	10.6	8.8
#1	8.6	8.9	7.4
#2	2.2	1.7	1.4
Culls	2.0	1.8	1.4

Figure 4.1 (left) Row cover cloth over tomato plants inside a high tunnel in early spring. Figure 4.2 (center) Opened low tunnels over tomato plants inside a high tunnel with experimental lights for frost protection. Figure 4.3 (right) Staked tomatoes inside a ventilated high tunnel in summer.

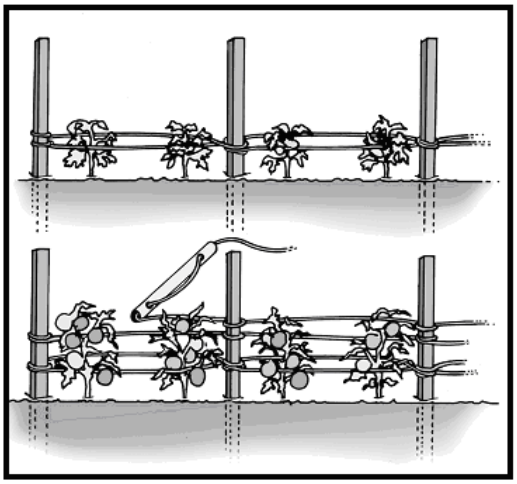


Figure 4.4. Tomato trellis system [6]

Figure 4.5. Common tomato disorders include blossom end rot (left), cat-facing (center-left), sunscald (center-right), and blotchy ripening (right).

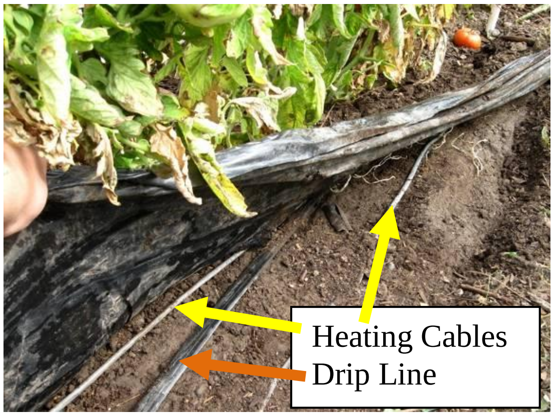


Figure 4.6. Soil heat cables under plastic mulch

Figure 4.7. Shade cloth

Figure 4.8. Harvested tomatoes before grading

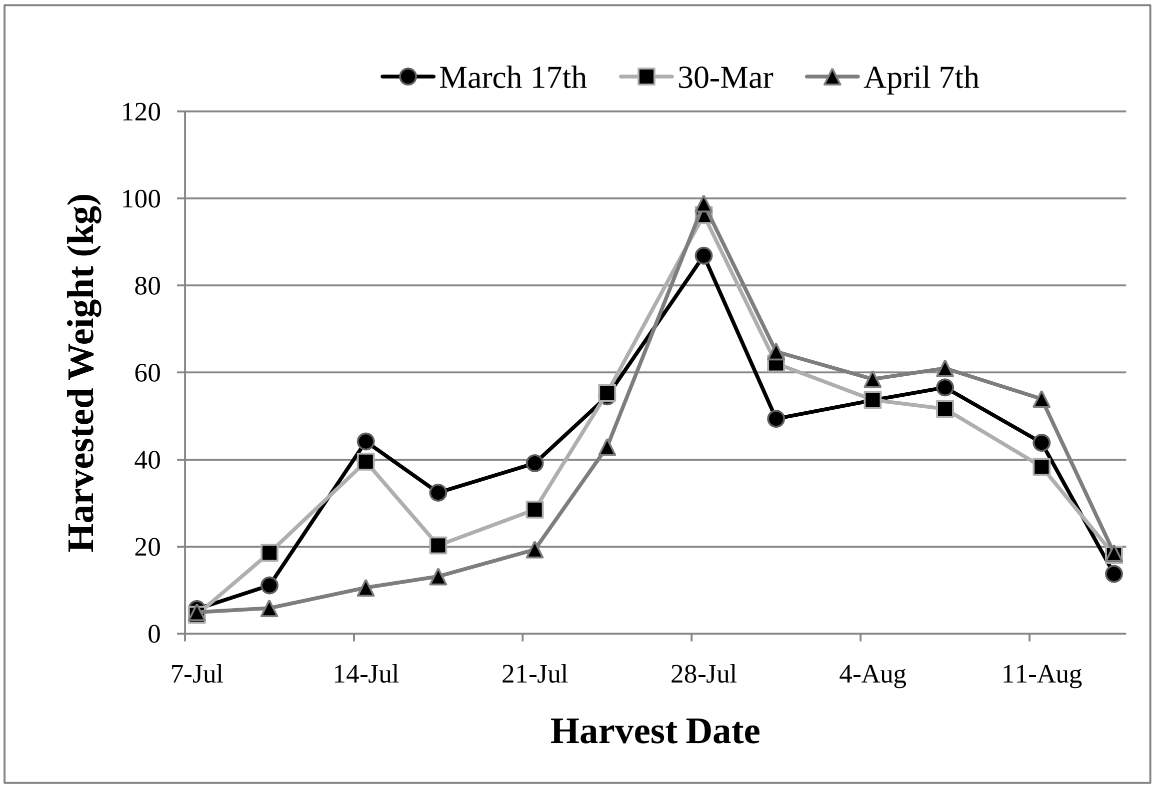


Figure 4.9. 2009 tomato yield by planting date for a 96’ by 14’ high tunnel.

CHAPTER 5

USING A VERTICAL GROWING SYSTEM TO OPTIMIZE PRODUCTIVITY FOR HIGH TUNNEL LETTUCE

Abstract. High tunnels make it possible to plant and crop lettuce nearly year round for climates near USDA hardiness zone 5. High tunnel crops should be valuable enough to offset the costs associated with high tunnel production; therefore increasing plant density without compromising optimal plant spacing could be used to increase productivity. Vertical growing techniques have been utilized in the greenhouse environment and for outdoor hydroponic strawberry and could be adapted to high tunnel lettuce production. Root zone heating has been shown to enhance growth and nutrient uptake for various greenhouse crops and could be useful for high tunnel production. Plants of Parris Island Cos lettuce were consecutively transplanted from spring 2008 to spring 2010 in a high tunnel on the Utah State University campus. Plants grown vertically in rain gutters achieved 45 plants$\cdot$m^{-2} compared to 25 plants$\cdot$m^{-2} in the ground system, including walkways and maintenance areas. Root zone heating was added in 2009 to overcome winter conditions that limited productivity. Despite a higher plant population, productivity was not consistently better in the gutter system. Soil media temperatures in the gutters fluctuated widely in response to air temperature. In 2008, fresh weight$\cdot$m^{-2} was only higher in the gutter system during spring and fall when soil temperatures were not frequently above 24 °C. While root zone heating compensated for low air temperatures in the early spring and late fall, warmer than optimal soil temperatures continued to impede growth. Further research should be performed to explore growing vertically with a larger rooting volume that may stabilize soil media

temperatures. Ways of improving production in the ground soil should be further explored due to its superior performance in this study without the use of supplemental heating.

Introduction

Lettuce is a popular crop for high tunnel production because there is consistent market demand, and it can be grown in the normally unproductive off-season. High tunnels make it possible to plant and crop lettuce nearly year round in climates near USDA hardiness zone 5 (Coleman, 2009). This is possible because the plastic covering on a high tunnel traps substantial heat that provides favorable temperatures when outside temperatures are below optimal. Outdoor growers must wait to plant until the soil is not frozen, while the soil in a high tunnel will not generally freeze if the high tunnel stays closed and free of snow cover. Lettuce is typically direct seeded when soil temperatures are optimal for germination (15 to 18 ºC), and transplanted when temperatures are below 15 ºC. The high tunnel environment can be unfavorable for lettuce production when temperatures exceed the optimal range for growth (18 to 25 ºC), which can lead to premature bolting and buildup of bitter compounds in the leaf (Zhao and Carey, 2009). However, use of shade cloth helps reduce leaf temperature in the summer months to minimize bolting and bitterness. The plastic covering also excludes rain that leads to soil splashing on the leaves, and harsh weather conditions such as hail that damage plants and reduce quality. Many insect and animal pests may also be excluded by the high tunnel; however, common greenhouse pests such as aphid tend to accumulate rapidly when humidity builds up within the high tunnel. Rodents may also be a problem as they are attracted to the warm high tunnel environment when outside temperatures are cold and food is scarce.

Days to maturity (seed to harvest) of lettuce varies with temperature and light. In Maine, lettuce planted in a high tunnel in early March took 65 days to mature compared to 100 days when planted in early October due to lower temperature and light in the fall (Coleman, 2009). Light levels are not as favorable from October through March when high tunnel lettuce is normally produced. However, solar radiation levels in sunny desert climates such as Utah will mature lettuce in about half the time required compared to areas with cloudy conditions (Glenn, 1984). Figure 5.1 illustrates how the intermountain west region surrounding Utah receives more solar radiation than other regions of the United States at similar latitudes. The changing light angle will cause the southern exposure of a high tunnel to receive more direct light in the winter and early spring and fall. During the summer months, the east and west exposures will receive direct light for half of the day. Because fluctuating light and temperatures vary depending on geographic location, localized information about seasonal productivity would be extremely useful for growers in arid high elevation regions similar to Logan, UT (41.77 N and 111.81 W, 1382 m elevation).

High tunnels can increase production costs, so the crop grown inside should be valuable enough to offset these costs. Lettuce plants are spaced depending on the variety to allow for each plant to mature without inhibiting the growth of adjacent plants. Net profit increases when yield per area increases, thus optimizing plant density will maximize yield and profit. Space utilization using vertical structures has been explored in the greenhouse environment and for outdoor production using hydroponic systems (

Hochmuth et al., 1998; Jensen, 1991; Ozeker et al., 1999), and may be beneficial for high tunnels. Space utilization for hydroponic systems is achieved by stacking plants vertically with troughs or bags to achieve a greater number of plants per ground area. Common soil media for vertical grow systems and hydroponics include pumice, perlite, peat, and coconut coir. The composition of growing media can effect water holding capacity, but does not significantly impact crop growth (Hochmuth et al., 1998; Ozeker et al., 1999). Research regarding outdoor hydroponic systems is currently most prevalent for strawberry and other high value crops. Lettuce is not commonly regarded as a high value crop, but the consistent demand for fresh greens makes lettuce a promising opportunity to utilize a vertical growing system to achieve greater yields within a high tunnel.

High tunnels typically do not have electrical service in conjunction with a reduced energy production method; however targeted root zone heating could enhance productivity with minimal energy addition. Root temperature is commonly known to be a major contributing factor for plant growth (Ikeda and Osawa, 1984). Root zone heating has been shown to offset the detrimental effect of cold air temperatures (<16 °C) for bedding plants raised in a greenhouse (Shedlosky and White, 1987), and to increase biomass accumulation and nutrient uptake for hydroponic greenhouse lettuce (Economakis, 1997; Moorby and Graves, 1980). The increase in biomass associated with root zone heating is attributed to increased water uptake, which leads to greater leaf area and increased light interception (Moorby and Graves, 1980). Thompson et al. (1998) noted that maintaining optimal root zone temperatures is essential for hydroponic systems. Optimal solution temperature is approximately 24 ºC and there is an increase in root damage at 31 ºC (Thompson et al., 1998). Root damage at 31 ºC was likely caused by the development of root disease that subsided when root zone temperature decreased. Root zone heating also affects root biomass. Moorby and Graves (1980) note differences in root structure at different solution temperatures in a hydroponic system. Lettuce roots developed at cooler solution temperatures (<16 ºC) were short, thick, and slow growing, and roots developed at warmer solution temperatures (>23 ºC) were long and fine. An increase in root surface area promotes nutrient uptake by creating more sites for nutrients to enter the roots (Mengel, 1995). Most hydroponic culture is contained in a controlled environment with automated heating and cooling, whereas high tunnels rely on passive heating and cooling. No studies are known that assess the effectiveness of root zone heating in lettuce when air temperatures are near freezing.

There is some concern regarding the accumulation of nitrate in lettuce leaves with respect to health risks associated with dietary intake of nitrates as well as ground water pollution from nitrate runoff (Byrne et al., 2001). The increase in growth resulting from root zone heating raises the demand for nutrients within the plant, therefore increasing nutrient uptake. However, increasing nutrient uptake does not necessarily lead to a higher proportion of nitrate within lettuce leaves (Economakis, 1997). The primary factors affecting nitrate accumulation are soil nitrogen content, form (e.g. nitrate, ammonium, or urea), and irrigation frequency (Abu-Rayyan et al., 2004; Byrne et al., 2001; Thompson and Doerge, 1996).

Objectives

In order to evaluate whether constructing and maintaining high tunnels to grow off season lettuce could be profitably implemented by Utah growers, a study was conducted at the Greenville Research Farm in Logan, Utah. The study had three primary objectives. The first objective was to evaluate vertical growing systems built to face different directions (south, east, and west) for space efficient high tunnel lettuce production in an arid high elevation climate. The purpose of using different orientations was to test the effect of light interception on plant growth. The second objective was to address the productivity of consecutive planting dates throughout the year to identify productive planting intervals for growers. The third objective was to evaluate the effectiveness of root zone heating to increase productivity of romaine lettuce in a vertical growing system when environmental conditions were less than ideal.

Materials and Methods

"Parris Island Cos" lettuce (*Latuca sativa*) was consecutively transplanted into raised gutters filled with growing media inside a high tunnel starting in the spring of 2008 on the Greenville Research Farm in North Logan, Utah (41.77 N and 111.81 W, 1382 m elevation). The low-cost high tunnel measured 4.3 m by 12.8 m and was built with PVC hoops covered with a single layer of 6-mil greenhouse plastic (Black et al., 2008).

Site Preparation

The high tunnel was prepared prior to transplanting by laying weed barrier cloth, constructing the vertical growing towers, filling the towers with soilless media, turning the ground soil for the control plots, and laying drip irrigation tape in the gutters and planting rows. The vertical grow system was constructed using PVC rain gutters fastened to triangular wooden towers (Figure A.7). The gutters measured approximately 10 cm wide and 8 cm deep. The bottom gutter was approximately 6 cm above ground level.

The gutters were spaced 23 cm apart vertically with a horizontal offset of 12 cm, resulting in a sloped configuration. Two designs accommodated placing the towers at different orientations within the high tunnel to study the effect of light interception on yield. The east/west facing gutter system (Figure A.8, design A) consisted of two towers that were 1 m tall and contained six 2.44 m long gutters on each side of the tower, for a total of twelve gutters per tower. The ground based control for the east/west gutter system consisted of six 1.2 m by 1.4 m blocks. The south facing gutter system (Figure A.8, design B) consisted of two towers that were 1.5 m tall and contained nine 3.05 m long gutters on each tower. The ground based control for the south facing gutter consisted of six 1.8 m by 1.2 m blocks. Space for maintenance (e.g. harvesting) was considered in the calculation of productivity between tower designs (Figure A.9).

The gutters were filled with soilless media consisting of a 1:1:1 mixture of perlite, vermiculite, and peat moss. The media was used to grow no more than two successive plantings before being replaced with new media. The ground soil for the control treatment was turned over manually using a spading fork, and raked smooth. The soil in the tunnel had a silt loam texture. The drip irrigation tape used had a 10.2 cm emitter spacing and was placed in the center of the gutter, or 2.5 cm from the lettuce crown on the ground.

Transplant Production

Lettuce plants were grown for 4 weeks in a heated glass greenhouse before being transplanted in the high tunnel. Seeds were planted approximately every 2 weeks. Three seeds per cell were placed just below the soil surface in 128-cell flats. The extra seedlings were thinned after the cotyledons had emerged. The soilless media used was the same as described above. The plants were fertilized at a rate of 100 ppm 20N-10P-20K mix. The greenhouse temperatures were maintained at 21 ºC during the day and 18 ºC at night, and the day length was extended to 16 hours using sodium halide lights.

Planting Dates

Consecutive planting began on 17 Mar. 2008 and continued through 1 May 2009. Planting began again on 4 Sept. 2009 and continued through 5 Apr. 2010. Three planting dates were grown in the high tunnel at a time. On each planting date, 6 south facing gutters were planted with 22 plants per gutter, and 8 east or west oriented gutters were planted with 18 plants per gutter. There were two ground beds planted with 54 plants each that served as the control for the south oriented gutters, and two ground beds planted with 42 plants each that served as the control for the east/west gutters. All the plants in the gutters and ground were spaced 15 cm apart. Plants growing in the vertical system had a greater plant density with 31 plants m^2 in the south oriented gutters, and 45 plants plants m^2 in the east/west oriented gutters compared to 25 plants m^2 in the ground based system. Planting dates were analyzed separately because significant differences between planting dates were not of interest, while seasonal patterns in productivity were of interest.

Tunnel Maintenance

The tunnel was cross ventilated by opening the doors and lifting the sides of the plastic as needed to maintain optimal temperatures (15 to 25 °C). In mid June, when night time temperatures stayed above 10 °C, the plastic was removed and a 40% shade cloth was used to cover the house to reduce day time temperatures. In the winter months, spun bonded polypropylene row cover was used for frost protection when night time temperatures were below 0 °C. The row cover was removed during the day except on extremely cold and cloudy days.

Irrigation and Fertilization

All plants were irrigated using drip tape with 10.2 cm emitter spacing. All plants were liquid fertilized during each watering with Peters® Professional 20N-20P-20K fertilizer (Scotts, CA Geldermalsen, The Netherlands) at 100 ppm using a fertilizer injector. Raised gutters were irrigated twice daily for 4 minutes, and the ground beds were irrigated every third day for 20 minutes during the peak of the summer. Irrigation frequency was cut in half during the cooler months.

Supplemental Heating

Gro-Quick 24' (Wrap-On, Bedford Park, IL) electric soil heating cables were used to heat the raised gutters. The heat cables were intended to prevent the growing media from freezing, but could also promote plant growth. The built in thermostat was set to turn on when the root zone temperature dropped below 21 °C (Figure A.10). Energy use data were collected using an electricity meter. Eight of the 18 south facing gutters were heated with cables. Six of 12 east facing, and six of 12 west facing gutters were heated.

Data Collection

Growth data were collected with a destructive harvest every 10 days after transplanting. Four harvests were taken from each treatment plot (gutter) with a final harvest at 40 days. Three plants from each treatment plot were taken at each harvest.

Leaf number, leaf area, and fresh weight were recorded for each individual plant. The three plants from each treatment plot were then placed in one bag, dried at 80 ºC, and one dry weight was recorded for each plot.

Soil and air temperatures inside the high tunnel were recorded with a CR1000 data logger linked to an AM16/32 multiplexer (Campbell Scientific, Logan, Utah). In 2008, data were collected using six thermocouples to record air temperature at various heights in the high tunnel as well as eight HOBO (Onset®, Cape Cod, MA) sensors to record ground soil and gutter soil temperatures. In 2009, air temperature was recorded at three heights within the high tunnel, ground temperatures at four locations within the tunnel, and root zone temperatures were recorded using 12 glass covered thermocouples. The ends of the soil thermocouples were enclosed in glass and positioned 5 cm below the surface of the soil or growing media. In 2009, the multiplexor connected 19 type-T thermocouples (Omega Engineering, Inc. Stamford, CT), and were programmed to read temperatures every 30 seconds. The air thermocouples were shielded and placed at varying heights within the tunnel. Average, high, and low temperatures were recorded hourly for the air, ground, and gutter root zone inside the high tunnel. Outside temperature and relative humidity data were collected with a sheltered HMP50 probe (Vaisala Helsinki, Finland).

Data Analysis

Analysis of variance (ANOVA) within SAS Statistical Software was used to compare mean yield differences among treatments. Data from each planting date were analyzed separately because significant differences between planting dates were not of interest, while seasonal patterns in productivity were of interest. Orthogonal contrasts were used to separate differences between treatment pairs. Two experimental designs were used in the analysis. A nested factorial design with three factors was used to identify differences in fresh weight per plant among the three orientations (east, west, south), and also between gutters located low on the tower and gutters located high on the tower. This allowed for accurate evaluation of the effect of light interception on fresh productivity between the three orientations for data collected in 2008. The three factors were orientation (3 levels), replication (2 levels), and height (2 levels) where orientation was nested within two replications. A completely randomized design with two replications was used to compare productivity among gutter designs (east/west, south, and ground control) for data collected in 2008. Fresh and dry weight per m^2, leaf area index, and leaf number per plant were analyzed. A completely randomized design was also used to analyze data collected in 2009 to assess the effect of root zone heating on fresh and dry weight productivity. Maintenance space required (e.g. walkways) varied between the three designs and was included in the calculation of productivity per m^2 (Figure A.9). Electricity usage data were collected with an electricity meter and were used to calculate the cost of electricity for the root zone heating.

Results and Discussion

2008 Production. Plant density in the vertical growing systems was 31 plants·m^{-2} in the south oriented gutters, and 45 plants·m^{-2} in the east/west oriented gutters compared to 25 plants·m^{-2} for the ground grown plants, including space for maintenance. Fresh weight per plant after 40 days was not consistently greater for any particular gutter orientation (Table 5.1). The effect of orientation was only significant for the 18 Nov. 2008 planting date, where plants grown in the south oriented gutters had a significantly greater fresh weight per plant. This effect was likely caused by the shift of the sun to a far south position in November and December. The east/west facing gutters do not receive as much direct light during this time, which was believed to be responsible for the lower levels of production.

Extreme high and low air temperatures were ongoing within the high tunnel (Table 5.2). Soilless media in the gutters had smaller rooting volumes, and was susceptible to greater temperature fluctuation compared to the ground soil. The media became cooler than the ground soil on cold nights and warmer than the ground on warm days (Table 5.2). Media temperature in the gutters fluctuated similarly to the air temperature in late October in 2009 (Figure 5.2). Since hot air rises, it was assumed that plants may respond differently depending on the vertical height of the gutter. Fresh weight yield values for the gutter heights are given in Table 5.1. The gutters lower to the ground appeared to have higher fresh weight yields than gutters located higher on the tower, but differences were only statistically significant in early April and October (Table 5.1). Occasional drought stress was observed for plants in the highest gutters. The drip tape in the gutters higher on the tower was always last to fill with water during irrigation, and may have received slightly less water than the lower gutters. This may also explain the improved yield in the lower positions on the towers.

Gutter orientation and height are not addressed for productivity ($g \cdot m^{-2}$) data because there was no significant difference among the gutter orientations and heights in 2008 (Table 5.1). Fresh weight productivity differed greatly among seasons (Figure 5.3). Despite a higher plant population, the raised gutter system did not increase fresh weight$\cdot m^{-2}$ after 40 days during the winter and summer seasons compared to production in the ground. The raised gutter system did however increase fresh weight yield after 40 days during the spring and fall months compared to production in the ground (Figure 5.3). This seasonal pattern was likely due to extreme soil and air temperatures.

Table 5.3 compares frequency of temperature extremes between two production periods, 19 Mar. to 16 Apr. and 7 May to 4 Jun 2008. These periods are associated with two planting dates in the study (17 Mar and 13 May), and were selected based on the available temperature data. The values in Table 5.3 represent hours that air temperature and gutter soil temperature stayed above 24 °C or below 0 °C in the high tunnel. Both the air and gutter soil temperatures were recorded above 24 °C and below 0 °C during the 19 Mar. to 16 Apr. period, with air and gutter soil temperatures frequently dropping below 0 °C. Even though temperatures varied widely, lettuce grown in the gutter system had significantly greater fresh weight ($g \cdot m^{-2}$) than the ground based control during this period (Table 5.4), which illustrates the benefits to growing vertically. However, during the 7 May to 4 Jun. period, air and gutter soil temperatures were frequently above 24 °C and did not drop below 0 °C (Table 5.3). Lettuce fresh weight in the gutters during the 7 May to 4 Jun. period was significantly lower than in the ground grown lettuce system (Table 5.4). Productivity for the ground grown lettuce was greater for subsequent planting dates as both air and soil temperatures continued to increase. These comparisons imply that warmer than optimal soil and air temperatures are more detrimental to lettuce growth in the gutters than below freezing temperatures.

The seasonal pattern of growth differences reflected in Figure 5.3 is more clearly displayed in Table 5.4. Spring represents planting dates that occur from the beginning of March to the end of April, and fall represents planting dates from the beginning of

September to the end of October 2008. During the spring and fall seasons, the mean yield ($g \cdot m^{-2}$) was consistently greater in the gutter system than for plants grown in the ground production system (Table 5.4). This pattern suggests that growing in the unheated vertical gutter system in 2008 was only beneficial for transplanting Mar. to Apr. and Sept. to Oct. Despite the use of shade cloth, the majority of plants from the 2 July planting date in 2008 bolted after growing 40 days in the high tunnel (Table 5.4). The large biomass values in the gutters are indicative of bolted plants with more stem and leaf mass from the 2 July planting date. Bolting can be attributed to super optimal soil temperatures and possibly water stress.

Leaf area index and leaf number generally coincided with an increase in fresh weight yield. Leaf area index in the gutters increased during the spring and fall with the highest values seen for the 25 Apr. and 15 Sept. planting dates (Table 5.5). However, leaf area index was very high for the 2 July planting date (Table 5.5) which can be attributed to bolted plants which produce additional leaves on a tall stalk. Table 5.5 shows that LAI for the plants in the ground did not fluctuate as widely. Figure 5.4 also shows fresh weight per plant was more consistent for plants grown in the ground than for plants in the gutters. This variability in the gutters reflects the effect of extreme soil temperatures, and may also be an indication that the media in the gutters was more favorable for the development of root rot seen in the transplants growing in this system.

2009 soil heating case study. Gutter orientation and height are not addressed for the 2009 data because there was no significant effect of gutter orientation or height on average plant productivity in 2008 (Table 5.1). However, we attempted to address the concern that cold root zone temperature in the gutters significantly limited plant productivity. Inserting heating cables into the gutters prevented the soil from freezing and allowed for improved lettuce growth when air temperatures in the tunnel were below freezing (Figure 5.5). Soil heating increased fresh weight·m^{-2} after 40 days in the gutter system enough to exceed fresh weight production in the ground during the fall 2009 and spring 2010. Voles were responsible for destroying all plants in the ground treatment for the 3 Mar. planting date in 2010. Similarly to the pattern seen in 2008, there are some planting dates (Sept. 4 and Mar. 19 for example) where root zone heating is not necessary to obtain greater yield per area in the gutters compared to the ground (Table 5.6). Future work is needed to assess the role of soil heating on productivity.

Production considerations. The fresh weight of lettuce heads in this study rarely reached what is considered marketable size. Commercially grown romaine lettuce is packaged in boxes of two dozen plants that must weigh 42 to 50 lb (19 to 23 kg) to meet the requirements of standard weight (U.S. Department of Agriculture, 2006). Therefore, individual plants would weigh 800 to 900 grams at maturity, which also implies commercial lettuce is grown 1.5 to 3 times longer (60 to 120 days) than the lettuce in this study. Other guidelines simply state lettuce should be uniform in size and free of damage. For farmers with small operations that sell product via direct markets, size may not be as big of an issue. Small plants and leaves tend to be more tender, and smaller leaves are desirable for salad mixes. Figure 5.4 reflects a possible market weight set point (60 g) for lettuce in this study. This weight was selected because leaves are tender at this stage of development and the size and weight of the head is large enough to make two small salads. Because we used a uniform sampling time, it is difficult to estimate the actual days to maturity for Parris Island Cos in this study. If the soil needed to be warmed, the cost of electricity for the soil heating would be approximately $0.79 per day per 12.8 m by 4.3 m high tunnel when temperatures are below freezing. The cost of soil heating may be worthwhile to growers who wish to continue production later in the season using a vertical growing system. However, further economic analysis is needed and at this time the vertical production system cannot be recommended.

Summary

Parris Island Cos lettuce grown in vertical gutters did not perform well in this study when compared to growing in ground soil. Plants grown in the ground soil were generally larger (Figure 5.4) and fresh weight yield·m^{-2} was higher for plants grown in the ground soil most of the year. The most significant factor contributing to poor plant size in the gutter system was extreme soil temperature. Seedling root rot was also noted and may have contributed to an overall decrease in plant growth in the gutters. This relationship is demonstrated by Thompson et al. (1998) who noted a solution temperature of 31 ºC promoted pathogens and contributed to root damage. In the same study, plants grown at a 31 ºC air temperature maintained high-quality growth when grown with a cooler root temperature of 24 ºC. We also noted that soilless media in the gutters had higher maximum temperatures (Table 5.2) and more hours at higher temperatures (Table 5.3).

Air and gutter soil temperatures frequently dropped below 0 °C during 19 Mar. to 16 Apr. 2008 period (Table 5.3). However, the gutter system had a significantly greater productivity (g·m^{-2}) than the ground during this period (Table 5.4). As the season progressed (7 May to 4 Jun. period), air and gutter soil temperatures were frequently above 24 °C and did not drop below 0 °C (Table 5.3). Productivity in the gutters became significantly lower than in the ground during this time frame. Ground grown lettuce productivity was greater at subsequent planting dates when soil and air temperatures were often in excess of 24 °C. This suggests warmer than optimal soil and air temperatures were more detrimental to lettuce growth than experiencing some freezing temperatures. As weather conditions improved in autumn, differences in productivity between the gutters and the ground based system were not as dramatic.

According to the literature, warmer root zone temperatures positively affected growth until a certain point. Moorby and Graves (1980) note a positive effect on growth when the root zone is heated between 20 and 26 ºC. In our study, root zone heating (to 21 ºC) improved productivity in the vertical gutter system. Gutters with root zone heating had a consistently greater yield ($g{\cdot}m^{-2}$), leaf number, and LAI (Tables 5.4 and 5.5). This increase in growth is comparable to previous literature with regard to root zone heating (Economakis, 1997; Shedlosky and White, 1987). Table 5.6 shows root zone heating contributed to a statistically significant increase in fresh and dry weight in fall 2009 and spring 2010. However, this increase in growth was not significant for the 5 Apr. planting date when temperatures were more favorable, and when the heating cable would turn on less frequently. This implies root zone heating is only beneficial when air temperatures are cooler than optimal.

The cost of electricity would be approximately $0.79 per day for a similarly designed 12.8 m by 4.3 m high tunnel based on the energy use data collected. Heating increased fresh weight by 0.3 kg to 2 kg per m^2. Depending on the sale price, the increase in yield may offset the cost of energy. Though no true economic data were collected to determine the value of this system, growing in a vertical gutter system may be beneficial for growers with poor soil conditions. However, the vertical gutter system is inferior for warm season lettuce production. A larger rooting volume such as that seen for outdoor hydroponic strawberry (Ozeker et al., 1999) may experience less extreme temperature fluctuations, and should be explored in future experiments. With regard to early and late season production, ways of improving production in the ground soil should be further explored due to its superior performance in this study.

References

Abu-Rayyan, A., B. H. Kharawish, and K. Al-Ismail. 2004. Nitrate content in lettuce (Lactuca sativa L) heads in relation to plant spacing, nitrogen form and irrigation level. J. Sci. Food Agr. 84(9): 931-936.

Black, B., D. Drost, D. Rowley, and R. Heflebower. 2008. Constructing a low-cost high tunnel. Utah State Coop. Ext. 21 November 2010. <http://extension.usu.edu /files/publications/publication/HG_High_Tunnels_2008-01photos.pdf>.

Byrne, C., M. J. Maher, M. J. Hennerty, M. J. Mahon, and P. A. Walshe. 2001. Reducing the nitrate content of protected lettuce. Dept. Crop Sci., Hort., and For., Univ. College, Dublin. 3 October 2010. <http://www.teagasc.ie/research/reports/ horticulture/4561/eopr-4561.pdf>.

Coleman, E. 2009. The winter harvest handbook :Year-round vegetable production using deep-organic techniques and unheated greenhouses. Chelsea Green Publishing, White River Jct., VT.

Economakis, C. D. 1997. Effect of root-zone temperature on growth and water uptake by lettuce plants in solution culture. Acta Horticulturae 449(1): 199-203.

Glenn, E. P. 1984. Seasonal effects of radiation and temperature on growth of greenhouse lettuce in a high insolation desert environment. Scientia Horticulturae 22(1-2): 9-21.

Hochmuth, R. C., L. L. Leon, T. Crocker, D. Dinkins, and G. Hochmuth. 1998. Evaluation of two soilless growing media and three fertilizer programs in outdoor bag culture for strawberry in north Florida. (Proc. Fl. Hort. Soc.) 111: 341-344.

Ikeda, H. and T. Osawa. 1984. Lettuce growth as influenced by N source and temperature of the nutrient solution. (Proc. Intl. Congr. Soil. Cult.) 273-281.

Jensen, M. H. 1991. Hydroponic culture for the tropics: Opportunities and alternatives. Food and Fertilizer Technology Center for the Asian and Pacific Region. 21 Novemeber 2010. <http://www.agnet.org/library/eb/329/>.

Mengel, D. 1995. Roots, growth, and nutrient uptake. Perdue Ext. 21 November 2010. <http://www.agry.purdue.edu/ext/pubs/AGRY-95-08.pdf>.

Moorby, J. and C. J. Graves. 1980. Root and air temperature effects on growth and yield of tomatoes and lettuce. Acta horticulturae 98: 29-44.

Ozeker, E., R. Z. Eltez, Y. Tuzel, A. Gul, K. Onal, and A. Tanrisever. 1999. Investigations on the effects of different growing media on the yield and quality of strawberries grown in vertical bags. Acta Horticulturae 491: 409-414.

Shedlosky, M. E. and J. W. White. 1987. Growth of bedding plants in response to root-zone heating and night temperature regimes. J. Amer. Soc. Hort. Sci. 112(2): 290-295.

Thompson, H. C., R. W. Langhans, A. J. Both, and L. D. Albright. 1998. Shoot and root temperature effects on lettuce growth in a floating hydroponic system. J. Amer. Soc. Hort. Sci. 123(3): 361-364.

Thompson, T. L. and T. A. Doerge. 1996. Nitrogen and water interactions in subsurface trickle-irrigated leaf lettuce: I. Plant response. Soil Sci. Soc. Amer. J. 60: 163-168.

U.S. Department of Agriculture. 2006. United States standards for grades of field grown leaf lettuce. Agr. Mktg. Serv.

Zhao, X. and E. E. Carey. 2009. Summer production of lettuce, and microclimate in high tunnel and open field plots in Kansas. HortTech. 19(1): 113-119.

Wilcox, S. and W. Marion. 1994. Atlas for the solar radiation data manual for flat-plate and concentrating collectors. NREL. 4 August 2010. <http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/>.

Table 5.1. The effect of gutter orientation on average plant fresh weight of lettuce plants grown in a vertical system in 2008. Data represent harvest 40 days after transplanting.

		Planting Date										
Fresh weight (g/plant)		Mar-17	Apr-7	Apr-25	May-18	July-2	July-25	Aug-20	Sept-15	Oct-3	Oct-27	Nov-18
South		27.9	55.4	140.9	43.9	134.4	24.3	35.5	66.1	17.0	11.9	4.8
East		18.3	*	121.5	30.9	141.9	21.5	30.7	61.1	23.4	6.9	3.6
West		34.1	71.6	128.2	40.4	162.9	16.3	20.9	56.6	15.2	8.3	4.3
Gutter High		25.6	51.5	125.3	36.1	159.5	17.7	26.2	63.7	15.4	8.5	4.0
Gutter Low		29.5	82.0	128.0	41.5	131.8	26.0	32.7	56.8	19.2	10.6	4.5
ANOVA												
Factor	df	p-value										
Orientation x Height	2	0.306	0.288	0.373	0.431	0.334	0.553	0.121	0.315	0.012	0.843	0.012
Height	1	0.756	0.027	0.625	0.631	0.242	0.178	0.620	0.506	0.034	0.847	0.313
Orientation	2	0.129	0.394	0.650	0.381	0.522	0.368	0.342	0.773	0.790	0.065	0.044
South vs. East/West	1	0.907	*	0.417	0.368	0.393	0.483	0.358	0.564	0.981	*	0.045
East vs. West	1	0.051	*	0.690	0.293	0.464	0.263	0.255	0.694	0.508	*	0.080

*Missing values due to accidental harvest or pests

Table 5.2. 2008 monthly minimum and maximum root zone and air temperatures in the high tunnel without root zone heating.

	Minimum Temperatures (ºC)			Maximum Temperatures (ºC)		
	Soil	Gutter Media	Air	Soil	Gutter Media	Air
February	2	-5	-10	10	26	33
March	5	0	-9	13	28	40
April	7	0	-6	16	35	38
May	10	0	-2	20	31	35

Table 5.3. Hours above 24 °C and below 0 °C for two time periods in spring and summer 2008.

	19 Mar. to 16 Apr.		7 May to 4 June	
	Gutter Media	Air	Gutter Media	Air
Hours above 24°C	39	64	60	93
Hours below 0°C	35	95	0	0

Table 5.4. The effect of two vertical growing systems on fresh and dry weight productivity ($g \cdot m^{-2}$) of lettuce plants in 2008. Data represent harvest 40 days after transplanting.

		Planting Date										
		Mar-17	Apr-7	Apr-25	May-13	July-2	July-25	Aug-20	Sept-15	Oct-3	Oct-27	Nov-18
Fresh Weight												
East/ West Gutter		1179	3221	6197	1603	6860	851	1160	2648	906	342	178
South Gutter		876	1736	4420	1376	4216	763	1114	2074	533	375	151
Ground		311	992	4295	3030	3740	3075	2646	1838	801	173	210
Dry Weight												
East/ West Gutter		146	293	443	143	486	123	105	291	48	38	32
South Gutter		124	169	305	100	303	96	140	232	36	36	26
Ground		54	88	196	153	218	198	225	166	53	22	28
ANOVA												
Factor	df	p-value										
System												
Fresh Weight	2	0.022	0.043	0.428	0.001	0.013	<0.001	0.001	0.207	0.216	0.027	0.603
Ground vs. Gutters	1	0.010	0.025	0.593	<0.001	0.078	<0.001	<0.001	0.107	0.212	0.010	0.038
East/ West vs. South	1	0.322	0.057	0.232	0.396	0.013	0.458	0.867	0.468	0.185	0.363	0.173
Dry Weight	2	0.015	0.004	0.001	0.017	0.003	0.002	0.001	0.012	0.029	0.040	0.140
Ground vs. Gutters	1	0.005	0.002	0.001	0.044	0.013	0.001	<0.001	0.007	0.052	0.017	0.781
East/ West vs. South	1	0.599	0.011	0.047	0.019	0.008	0.280	0.101	0.158	0.034	0.816	0.057

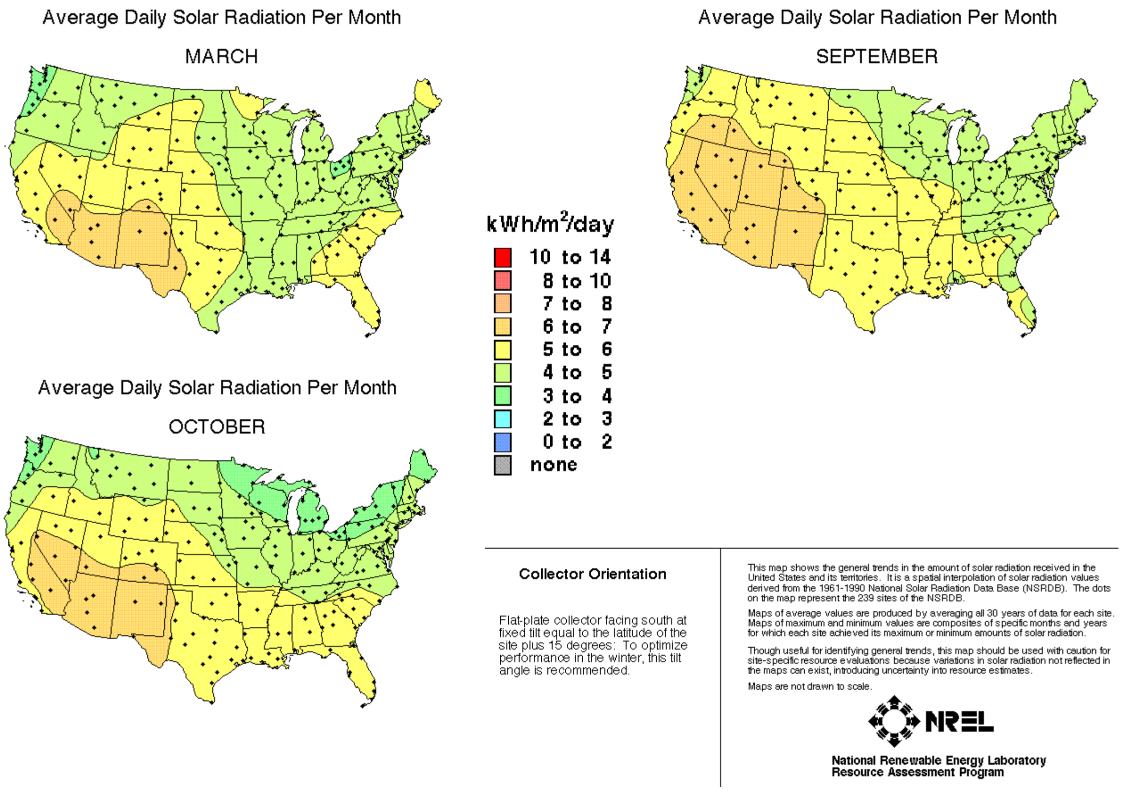
Table 5.5. The effect of growing vertically in gutters on leaf number and leaf area index of lettuce plants in 2008. Data represent harvest 40 days after transplanting.

		Planting Date										
		Mar-17	Apr-7	Apr-25	May-13	July-2	July-25	Aug-20	Sept-15	Oct-3	Oct-27	Nov-18
Leaf number (#/plant)												
East/ West Gutter		16.0	26.6	26.9	18.4	28.1	14.5	13.5	19.3	15.3	10.9	7.0
South Gutter		17.3	27.7	28.8	19.3	27.3	15.5	16.7	21.9	16.7	12.3	7.9
Ground		11.5	20.0	25.7	19.7	23.9	20.8	18.0	19.7	17.2	10.3	10.1
LAI (m2 leaf area/m2 ground)												
East/ West Gutter		1.97	5.10	8.68	3.03	11.89	1.83	1.84	4.42	1.37	0.69	0.35
South Gutter		1.52	2.83	6.68	2.60	7.04	1.39	1.91	3.39	1.03	0.69	0.29
Ground		0.54	1.76	7.30	4.64	5.41	4.86	3.83	2.67	1.29	0.33	0.41
ANOVA												
Factor	df	p-value										
System												
Leaf number	2	0.041	0.030	0.120	0.265	0.162	0.007	0.004	0.150	0.168	0.197	<0.001
Ground vs. Gutters	1	0.016	0.015	0.132	0.457	0.071	0.002	0.018	0.471	0.233	0.124	<0.001
East/ West vs. South	1	0.036	0.775	0.123	0.152	0.687	0.477	0.009	0.067	0.151	0.513	0.044
LAI	2	0.015	0.034	0.079	0.006	0.002	<0.001	0.001	0.085	0.291	0.024	0.056
Ground vs. Gutters	1	0.006	0.020	0.665	0.002	0.014	<0.001	<0.001	0.039	0.669	0.009	0.042
East/ West vs. South	1	0.380	0.043	0.032	0.320	0.004	0.571	0.849	0.407	0.132	0.712	0.121

Table 5.6. The effect of growing lettuce vertically in gutters with additional root zone heating heating on dry weight and fresh weights in fall 2009 and spring 2010.

		Planting Date						
		4-Sep	9-Oct	23-Oct	17-Nov	3-Mar	19-Mar	5-Apr
Dry Weight (g/m2)								
unheated gutter		197	120	97	38	186	0	492
heated gutter		231	149	152	70	263	0	439
ground		156	95	72	35		0	266
Fresh weight (g/m2)								
unheated gutter		2756	1364	640	157	2277	4705	5487
heated gutter		3624	2150	1253	453	3094	6733	7235
ground		2999	1778	785	191		2781	4779
ANOVA								
Factor	df	p-value						
Root Heating								
Dry weight	2	0.013	0.004	0.001	0.002	<0.001		0.004
Ground vs. Gutters	1	0.007	0.004	0.005	0.023	*		0.001
Heated vs. Unheated	1	0.082	0.021	0.003	0.001	*		0.294
Fresh weight	2	0.119	0.007	0.002	<0.001	0.082	0.012	0.001
Ground vs. Gutters	1	0.619	0.973	0.152	0.037	*	0.012	<0.001
Heated vs. Unheated	1	0.045	0.002	0.001	<0.001	*	0.044	0.057

*Vole damage



Collector Orientation

Flat-plate collector facing south at fixed tilt equal to the latitude of the site plus 15 degrees. To optimize performance in the winter, this tilt angle is recommended.

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

Figure 5.1. Average solar energy (kWh·m-2·day) in the United States for March, September, and October (Wilcox, 1994).

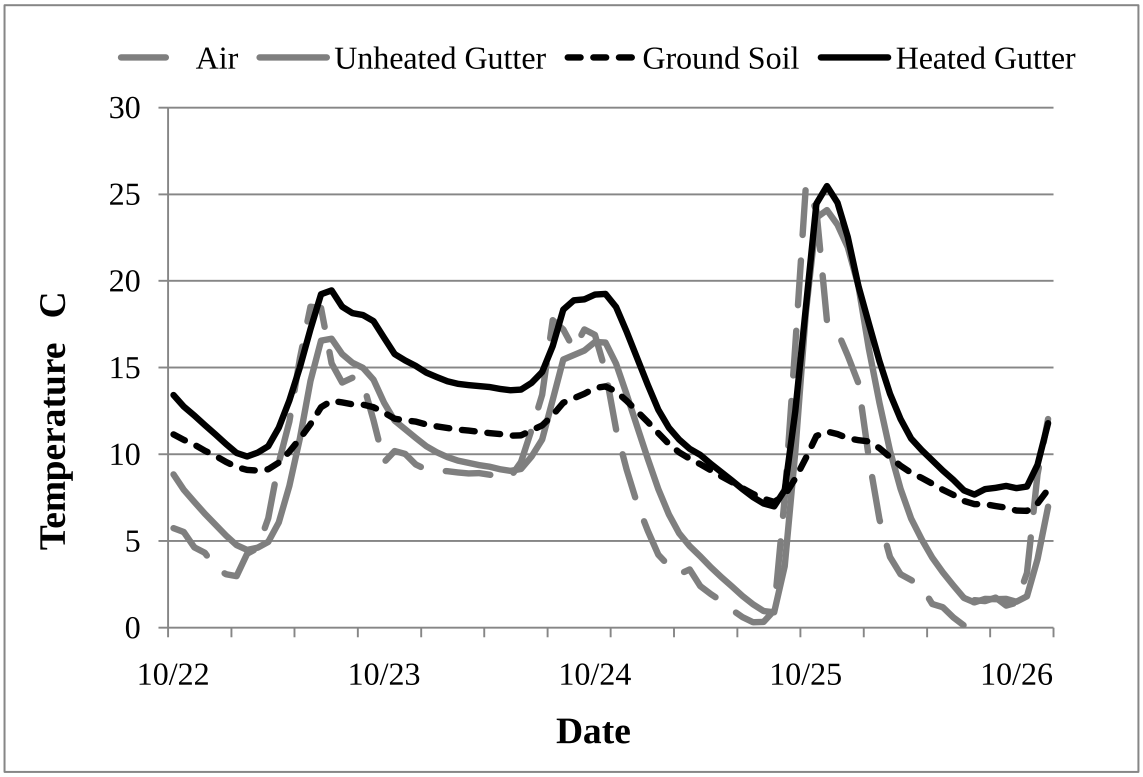


Figure 5.2. Effect of vertical growing system on daily soil and air temperatures 22 to 26 Oct. 2009.

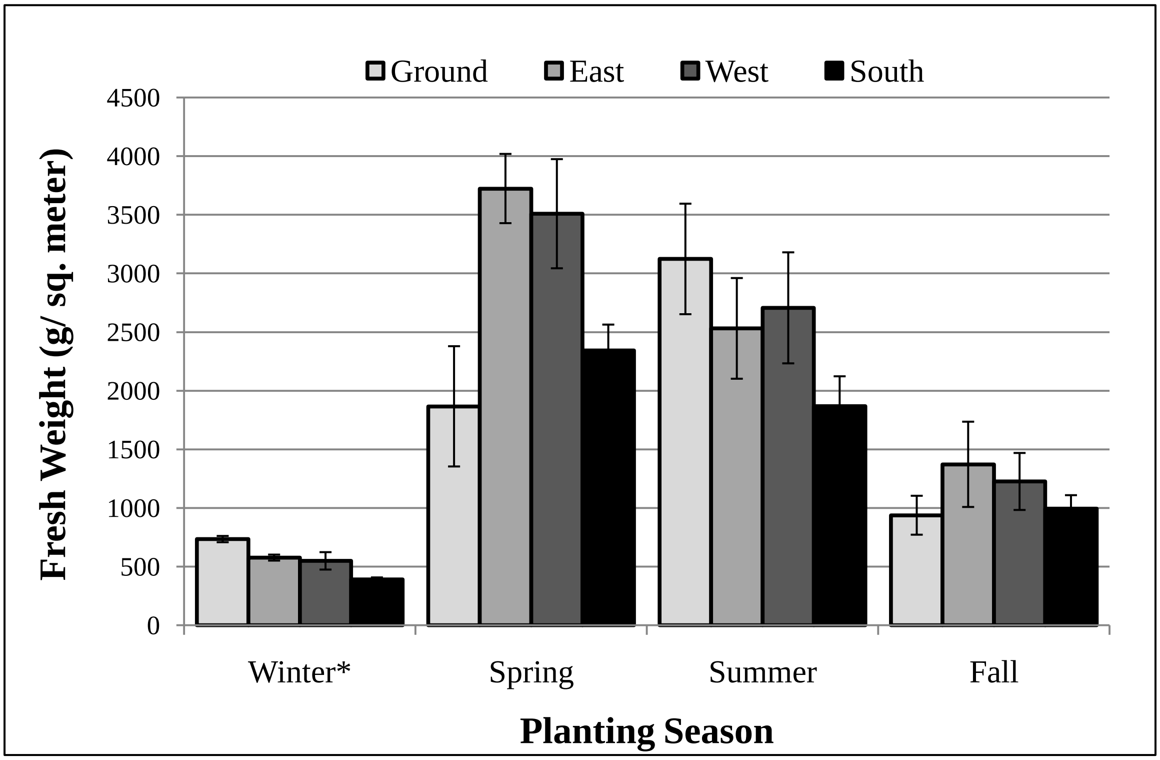


Figure 5.3. Effect of vertical production on seasonal average lettuce fresh weight (g·m-2) after 40 days in 2008. Error bars represent the Standard Error for each category.

* Winter November - February; spring March - April; summer May – August; fall September –October. Values reflect average production without soil heating.

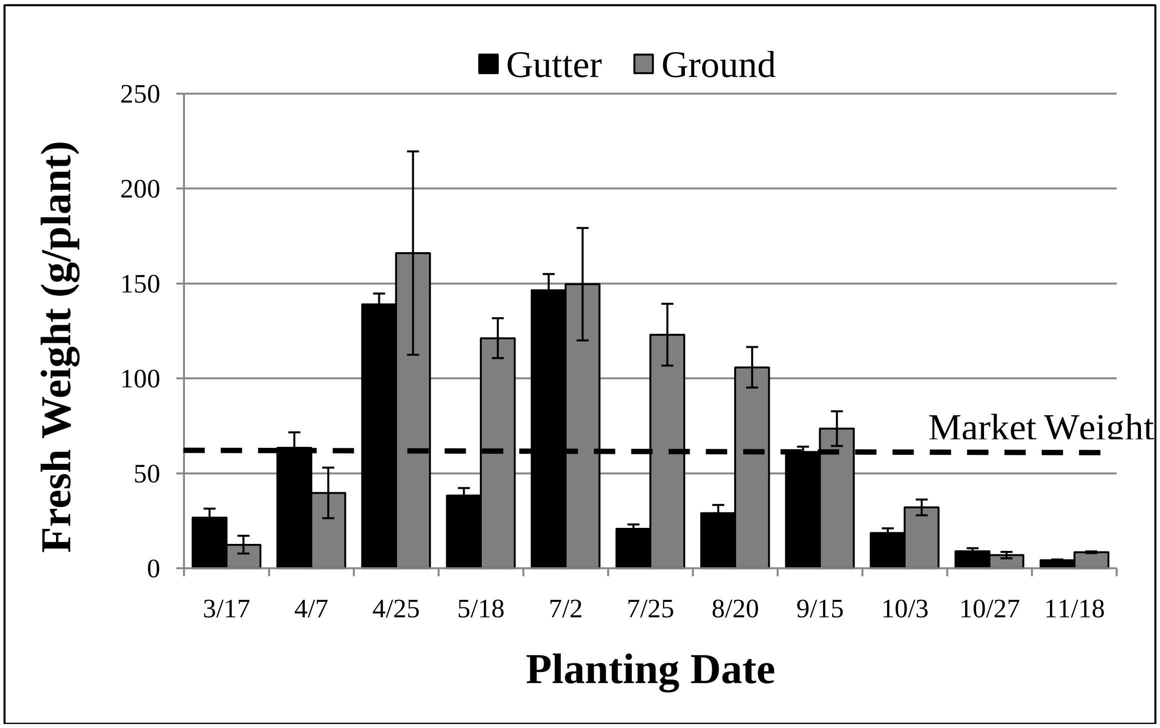


Figure 5.4. Average lettuce fresh weight per plant after 40 days over 11 planting dates in 2008. Fresh weight of 60 g deemed large enough for sale in local markets.

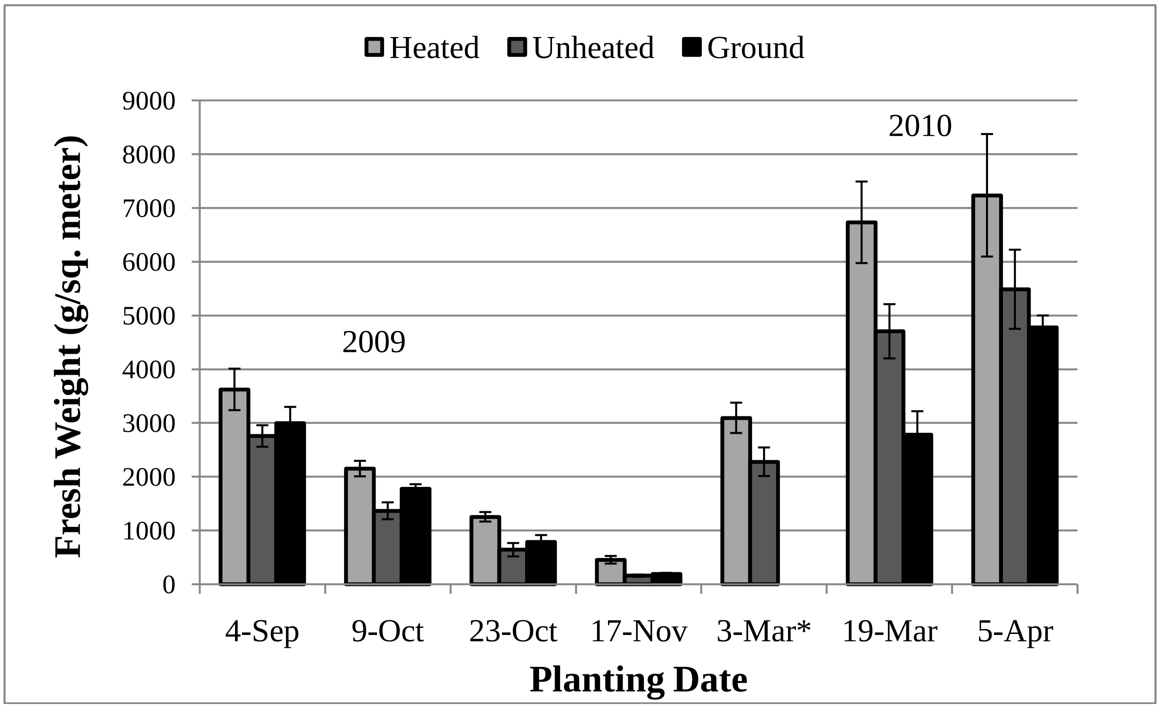


Figure 5.5. Effect of root zone heating on productivity (g·m-2) of lettuce planted in fall 2009 and spring 2010. Data represents plants harvested 40 days after transplanting. Error bars represent the Standard Error for each category. * Voles destroyed all plants in the ground plots for the Mar. 3 2010 planting date

CHAPTER 6

HIGH TUNNEL LETTUCE PRODUCTION FACTSHEET

Introduction

The demand for fresh locally produced lettuce is on the increase. A high tunnel makes it possible to grow lettuce 6-8 weeks before and after outside production has ended. In addition, season round production may be possible in some situations. High tunnels increase marketing opportunities, improve early cash flow, and yields are often higher than outdoor grown lettuce. High tunnels are relatively inexpensive to build, are not heated, and allow planting as early as February in many locations in Utah.

High tunnels are temporary structures covered with a single layer of greenhouse grade plastic which is supported by a galvanized steel or PVC frame. Frequent sunny days make growing in high tunnels logical in Utah because tunnels are passively heated using solar radiation. High tunnels can help protect plants from cold injury at night and maintain optimal growing temperatures during the day. Daily ventilation may be necessary to prevent temperatures from exceeding the optimal growth range. A full list of construction details and photographs for a low-cost PVC-frame high tunnel can be found at: extension.usu.edu/files/publications/publication/HG_High_Tunnels_2008-01photos.pdf.

Variety Selection

Many types of lettuce grow well in high tunnels including: romaine, bibb, oakleaf, butterhead, batavia, and baby lettuce mixtures. Heading lettuce such as Iceberg is not suited for high tunnel production. Select varieties based on market demand, cold or heat tolerance, and disease resistance. Lettuce takes 35-65 days to mature depending on the variety and climate conditions. Baby lettuces may be ready to harvest 20-30 days after seeding. Customers expect a variety of greens in a salad mix with varying colors, textures, and leaf sizes. Herbs and other specialty greens add pleasant flavors and textures to a salad. Arugula, radicchio, and mustards are specialty greens common to a mesclun mix. Some customers like the specialty greens with a spicy or strong flavor while others prefer mild, sweet flavors. Consult with your seed salesman or any seed catalog for detailed information on lettuce growth characteristics. All leaf lettuce varieties tend to have a better performance and higher quality when grown in a high tunnel. A list of suggested varieties and desirable characteristics can be found at the Penn State Extension website in the publication “Growing Leafy Vegetables” (http://pubs.cas.psu.edu/FreePubs/pdfs/uj226.pdf).

Site Selection

Lettuce grows best in sandy loam to light clay soils with a pH of 6.5 to 7.5. Utah soils are good for lettuce production as long as the soil is well drained and there is not a build up of salts, as measured by the soil electrical conductivity (EC). The high tunnel should be located near a year-round water source in order to facilitate irrigation in the early spring and late fall when seasonal irrigation water is not available. Shifting sun angle can cause buildings and trees that do not shade a high tunnel in the summer to shade a tunnel in the winter months. Be sure to position the high tunnel so it is not shaded for early season production.

Site Preparation and Fertility Management

Prior to planting, have the soil tested to determine nutrient deficiencies and soil electrical conductivity. A conventional fertilizer that includes nitrogen, phosphorous, and potassium should be incorporated before planting. Phosphorous is essential for early growth particularly when plants are grown in cold or cool environments. For crops grown for approximately 60 days in spring and fall, apply a total of 10-15 lbs/acre of nitrogen (Example: 10 lbs of 5-3-3 fertilizer per 14 x 96' high tunnel). Apply 20-30 lbs/acre for summer crops. Nitrogen should be added two or three times throughout the growing cycle starting about two weeks after planting. Spreading out the nitrogen applications allows for less leaching and improves plant growth and yield. Injecting soluble fertilizer in the irrigation system is an efficient and effective application method.

Lettuce can be grown with organic fertilizers which promote soil quality. Organically grown lettuce may have a higher market value. Incorporate well composted organic matter before planting to sustain soil fertility. An initial application of 5 tons per acre of high quality compost of known nutrient analysis is recommended. This is equal to 300 lbs per 14' by 96' high tunnel. Repeat this process between crop cycles to build up soil fertility. Be sure to test soil regularly as nutrient and salt levels can build up quickly when compost is constantly added to the high tunnel. More information about organic lettuce production can be found at http://attra.ncat.org/attra-pub/lettuce.html.

Incorporate the compost or fertilizers to a depth of 4-6 inches with a tractor mounted or hand operated tiller. High tunnels can be designed to accommodate small machinery for soil tillage and other operations. Plant residue from previous plantings should be removed completely before re-planting to create a clean seed bed and avoid disease carryover.

Irrigation Management

Lettuce plants require a constant supply of moisture. Drip irrigation is well suited for lettuce production in high tunnels. Drip tape should have emitters every 4 inches to water closely spaced lettuce plants, and should be located 1 to 2 inches away from the plants. Watering should be frequent enough to prevent the leaves from wilting. Soil water monitoring is easily done with a resistance block such as the Irrometer® Watermark sensor. Place one sensor 6 inches deep and another sensor 1 foot deep. The meter will give a reading in centibars, which reflects the force required for a plant to extract water from the soil, so a higher reading means drier soil. Soil texture (clay, loam, sand) influences the soils ability to hold on to water. An example of threshold readings for different soil textures are listed in Table 6.1. Irrigation should occur when 20-25% of the available water is depleted. A reading of less than 5 centibars indicates excessive water. A comparison of other low cost tools and methods to monitor soil water can be found at attra.ncat.org/attra-pub/soil_moisture.html.

Seeding vs. Transplanting

Lettuce plants can be direct seeded or transplanted into the high tunnel. Transplanting is recommended when temperatures outside are not favorable for germination. Lettuce seeds germinate best when soil temperatures are between 60 and 65 °F. Lettuce seeds can germinate when soil temperatures are near 40 °F, but emergence is slow. Seeds become dormant at soil temperatures above 75 °F, so germination is poor when soils are too warm. Lettuce leaves that are cut and sold as baby greens are generally direct seeded while lettuce sold as a head is typically transplanted. Seeding tools are available to spread seed uniformly into rows along the soil. Pelleted (coated) seed that is uniform in size and shape must be used with seeders. Some thinning may be required after seeding.

For transplants, sow seed into 128 cell flats and allowed to grow for 3 to 4 weeks before planting outside. Plant seeds ¼ inch deep and water gently so seeds do not wash to the surface. Use sterile flats and soil media to avoid transmitting root diseases. Seeds can also carry root diseases and may be treated before purchasing. Root disease may appear as poor germination and stunted growth of seedlings (Figure 6.1). Water and feed daily with a soluble complete fertilizer diluted to 100 ppm after emergence. Condition or "hardened off" transplants by exposing them to cool temperatures one week before transplanting to prepare the plants for the colder temperatures they may experience in the tunnel.

Planting Dates and Spacing

High tunnels make it possible to plant 6-8 weeks earlier in the spring compared to planting outside. The lettuce trials at Utah State University found Parris Island Cos did well when transplanted and grown in a high tunnel from mid February through early June. Warmer temperatures in July and August caused lettuce to bolt, even when grown under a 40% shade cloth cover. Parris Island Cos also performed well when transplanted from late August through early October in a high tunnel. The trials took place in Logan, Utah which is a zone 4-5 on the USDA cold hardiness scale. The number of days from planting to harvest is increased when temperatures are cool and sun angle is low. Lettuce takes about 15 days longer to mature when planted at the end of February than it does when planted at the end of March [1]. Seeds can be sown once per week to ensure a continual harvest.

Plant spacing depends on variety and growing period. Seed rows of baby leaf lettuces 2-3 inches apart with a seeder [1]. This equates to 12 rows on an 18 inch bed. Within-row spacing can be as close as 1 inch. Transplant lettuce 4-6 inches apart (4-9 plants/ft^2) in beds 2-3 foot wide to give the plant adequate space to mature. Harvesting smaller plants is beneficial in several ways. A smaller plant requires less space, so plants can be sown closer together to increase yield in a given area. The longer a plant is in the ground, the more opportunities there are for pests to invade the plant. More frequent seeding and harvesting will be required to keep up with growth. When leaves are cut just above the base of the plant, new leaves may grow from the same plant. The quality of re-growth varies by variety.

High Tunnel Temperature Management

Lettuce grows best at temperatures between 60 and 75°F. The best growing seasons for high tunnel lettuce in Utah is in spring and fall. Hot temperatures in the summer cause lettuce to bolt, or flower prematurely though some varieties are less prone to bolting. Shading with a 40-50% shade cloth can help cool the plants so they continue to grow in hot temperatures. Lettuce plants are susceptible to chilling injury when temperatures are near freezing. Plants may not show immediate signs of injury, but growth may not be as vigorous. The cold protection of a high tunnel is limited to 2 to 3 °F when outside temperatures are near freezing. Row cover cloth or Reemay® (a thin spun bonded fabric) can be laid directly on the plants to protect them from chilling injury

(Figure 6.2). The row cover cloth helps keeps night temperatures around the plants 2 to 4 °F warmer than the surrounding high tunnel temperature, thus limiting heat lost during cold clear nights. Low tunnels support a layer of plastic over the plants that will keep night temperatures slightly warmer, but plastic must be removed during the day to avoid excessive heat. Low tunnels should be used in the very early spring and late fall when outside temperatures are below or near freezing (Figure 6.2).

Daily ventilation of the high tunnel is needed to ensure temperatures inside do not exceed 75°F. Ventilation may entail opening a single door in March, or both sides and doors in April when day temperatures are warm. The plastic on the tunnel is generally removed when outdoor temperatures stay above 50ºF.

Pest Management

Pests can reduce yield and threaten plant quality. Lettuce is expected to be free of pests before it is sold at the market. Healthy plants grown in a clean environment are less likely to have pest outbreaks that require management. Application of chemicals in tunnels is more hazardous than in the open field due to the closed environment. If using chemicals in tunnels, determine if the material is registered for greenhouse use, and if so follow the directions on the label closely and always wear appropriate personal protective equipment. If you are having trouble diagnosing a pest problem, contact your county extension agent or other knowledgeable individual. Some of the common insects found in high tunnels include aphids, slugs, and grasshoppers.

Aphids: Aphids are tiny insects that feed on plants by sucking sap out of stems and leaves. Aphids can also transmit plant viruses and diseases. Symptoms include stunting and distortion of plant growth and sticky sap on the leaves. Prevent aphids from becoming a problem by making sure transplants are free of aphids before planting and controlling weeds in and around the tunnels. Insecticidal soaps and horticultural oils are effective at controlling aphids and often come in organic formulations. Natural predators can also help suppress aphids. Natural predators of aphids include green lacewings, parasitic wasps, aphid midges, and lady beetles. More information about aphid control can be found at http://attra.ncat.org/attra-pub/gh-aphid.html.

Slugs: Slugs are a common lettuce pest. Diatomaceous earth is a naturally occurring fine rock powder that slugs will not crawl over because it dries them out. The efficacy of diatomaceous earth in tunnels may be marginal when air humidity is high. Copper stripping is an effective barrier because it causes a chemical reaction that repels slugs. Place a 2-6 inch thick (depending on how big your slugs are) strip of copper around the outer edge of the high tunnel. Many home gardeners find success using a shallow dish of beer to attract and drown slugs. Chemical slug baits are also very effective, but can be toxic to wildlife and animals. Chemical slug baits must not come in contact with the plants, so it is recommended to apply outside the high tunnel only.

Grasshoppers: Grasshoppers emerge in spring with an appetite for foliage and fruit that lasts all summer. Eliminating weeds near the high tunnel will deter grasshoppers from feeding there and finding a way into the tunnel. It is a good idea to scout regularly for grasshoppers before they become a problem. Removing tomato plants promptly after the harvest and controlling weeds in the fall will discourage female grasshoppers from laying eggs near the tunnels. Biological baits are available for grasshopper control as well as baits containing chemical insecticide for fast control in severe infestations.

Disease Control: High tunnels trap warm humid air which can promote disease. Disease resistant varieties, proper irrigation and soil drainage, good ventilation, and crop rotation aid in disease prevention. Plants in the cabbage family (kale, radish), beet family (chard, spinach), or carrot family are examples of plants that could be rotated with lettuce in high tunnels. Limit opportunities for disease growth by removing dead plant residue, and managing weeds and insects in the tunnel and surrounding area. Diseased plant materials should be destroyed and kept out of compost used for future plantings. Remove plants carefully to avoid distributing spores. The most common diseases found in high tunnels are leaf drop, damping-off, and downy mildew. Controlling disease with fungicides must be done at the proper life stage of the disease to be effective. Guidelines for use can be found on the label.

Leaf Drop: Leaf drop (*Sclerotinia minor*) infects the stem and leaves that come into contact with the soil. A soft brown decay can be seen on the base of the plant which eventually kills the crown tissue and causes all the leaves to drop. The fungus thrives in cool wet conditions, and can live in the soil for 2 -3 years. Avoid excessively wet soils with careful irrigation. Fungicide can be used to protect the crop and must be directed toward the base of the plant to be effective.

Damping off: Damping off (*Rhizoctonia solani*) lives in the soil and attacks young seedlings. Seedlings may be infected before they emerge from the soil surface resulting in uneven stands. Infected seedlings have decayed roots and brown legions on the stem. Avoid excessively wet soils with careful irrigation. Several fungicides are effective at controlling *Rhizoctonia*.

Downy Mildew: Downy mildew (*Bremia lactucae*) appears as light green to yellow spots on the upper leaf surface with white fluffy growth on the underside of the spots. Older leaves are attacked first. Downy mildew can also kill seedlings if the cotyledons are infected, but many varieties are resistant to *Bremia*. Apply fungicides before the development of the disease if the disease has been a problem in the past.

Weed Control: Weeds harbor insect and disease pests and compete with lettuce for water, nutrients, and light, especially when plants are small. Plants spaced close together prevent weeds from growing and becoming a problem. Collinear, diamond, and stirrup shaped hoes are easy to use and small enough to drag in-between rows of plants. They do a good job of severing small weed seedlings at the soil surface. Weeds taller than 2 inches are harder to remove without digging up the soil which may damage the roots of the lettuce. Hand weeding is required for larger weeds.

Harvesting and Marketing

Harvest whole lettuce plants by cutting the stem with a sharp knife at the soil surface or for repeated harvests at the base of the leaf. After cutting, place lettuce in cool water to keep it hydrated. Lettuce greens must be washed thoroughly and dried before packaging. Commercial salad spinners are available for drying, but many growers build their own. A mixer is helpful in combining lettuce varieties to make a salad mix. Washing and mixing must be done carefully to avoid bruising or breaking the leaves.

Growing high tunnel lettuce is a good idea for farmers that already have a customer base that wish to add salad greens to their product offering. During the winter months when direct marketing through farmers markets may not be available, local restaurants, caterers, or small food service providers may be new markets for lettuce. For existing community supported agriculture (CSA) farms, off season production can allow for extended subscriptions when few local produce options are available.

Utah State High Tunnel Lettuce Trials

Parris Island Cos lettuce has been used for lettuce trials at Utah State University since spring 2008. Transplants were raised in a heated greenhouse for four weeks before being transplanted into the high tunnel. The trials evaluated a vertical growing technique to utilize space inside a high tunnel as well as root zone heating in 2009. Plants were grown in ground beds for comparison. In the vertical growing system, plants were grown in PVC gutters attached to wood frames and positioned at south, east, and west orientations (Figure 6.3). Plants were grown in potting soil (soilless media) consisting of equal parts peat moss, vermiculite, and perlite. All plants were spaced 6" apart. Drip irrigation was used for watering and all fertilizer application. A cloth row cover was placed over the plants when temperatures were below freezing. In mid June 2008 the plastic covering the tunnel was removed and replaced with a 40% shade cloth to maintain more favorable temperatures for growth. In 2009, soil heating cables were installed in half of the gutters to prevent the soil media from freezing and to promote plant growth. The cables included an automatic thermostat set at 70°F (Figure 6.4).

Vertical vs. Ground Production Case Study

The vertical growing system allowed for 6 plants per square foot compared to 4 plants per square foot in the ground. New plants were transplanted approximately once per month and harvested at 10 day intervals with the final harvest occurring after 40 days. The vertical system had higher fresh weight yield after 40 days compared to the ground system in the spring and fall only (Figure 6.5). Lower production in gutters during the summer months (June-August) was due to excessively hot root zone temperatures which were unfavorable for growth (Table 6.2). Table 6.2 also shows the media in the gutters froze while the ground soil did not during the early spring. Gutter orientation (E, W, S) did not influence lettuce production.

Root Zone Heating Case Study

Inserting heating cables into the gutters prevented the soil media from freezing and allowed for continued growth when temperatures in the tunnel were below freezing (Figure 6.6). Figure 6.6 shows root zone heating increased productivity (lb/ft^2) in the gutter system enough to exceed production in the ground during the October and November planting periods. Freezing root zone temperatures restricted productivity in the unheated gutters by limiting water and nutrient uptake (Table 5.2). Each cable covered 20 feet of gutter and had an output of 80 watts. The cost of electricity for the soil heating would be approximately $4.00 per day per 14’ by 96’ high tunnel when temperatures are below freezing.

Summary

Early and late season lettuce can provide local farmers with produce to sell at farmers’ markets and other local retail outlets at a time when outdoor production is not available. High tunnels allow for year round production, high yields, and better quality. High tunnel lettuce should not be thought of as an alternative to outdoor production. Rather greens are a compliment to other products, thus allowing farmers to supply local produce to the public for a longer period of time.

References

1. Coleman, E. 2009. *The Winter Harvest Handbook :Year-Round Vegetable Production Using Deep-Organic Techniques and Unheated Greenhouses*. Chelsea Green Publishing, White River Jct., VT.

2. Egel, D. et al. 2009. *Midwest Vegetable Production Guide for Commercial Growers.* Available at: http://www.btny.purdue.edu/Pubs/ID/id-56/irrigation.pdf

Table 6.1. Soil tension values for different soil textures for use in scheduling drip irrigation as listed by the Midwest Vegetable Production Guide [2].

	0% Depletion of Available Water (Field Capacity)[1]	**20-25% Depletion of Available Water [2]**
Soil Texture	Soil Tension Values (in centibars)	
Sand, loamy sand	5-10	17-22
Sandy loam	10-20	22-27
Loam, silt loam	15-25	25-30
Clay loam, clay	20-40	35-45

[1] At field capacity a soil contains 100 percent of available water holding capacity; any excess water in the root zone has drained away.

[2] Start trickle irrigation for shallow-rooted crops at this point.

Adapted from New Jersey Commercial Vegetable Production Guide, New Jersey Ag Expt. Station, Rutgers; and Water Management in Drip-irrigated Vegetable Production by T.K. Hartz, UC-Davis, Calif., Vegetable Research and Information Center.

Figure 6.1. Variable transplant size due to root rots & poor sowing depth.

Figure 6.2. Low tunnel (left) and row cover cloth (right) covering spinach in late winter.

Figure 6.3. Lettuce grown in PVC gutters

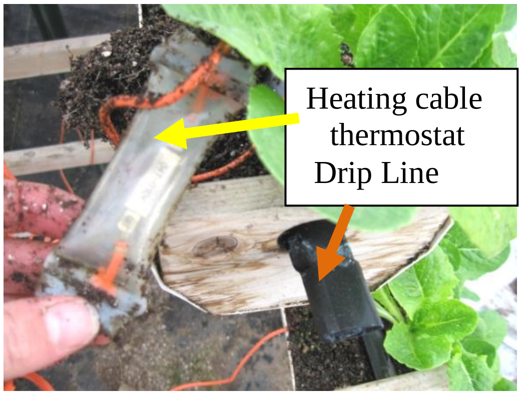


Figure 6.4. Soil heating cable in gutter

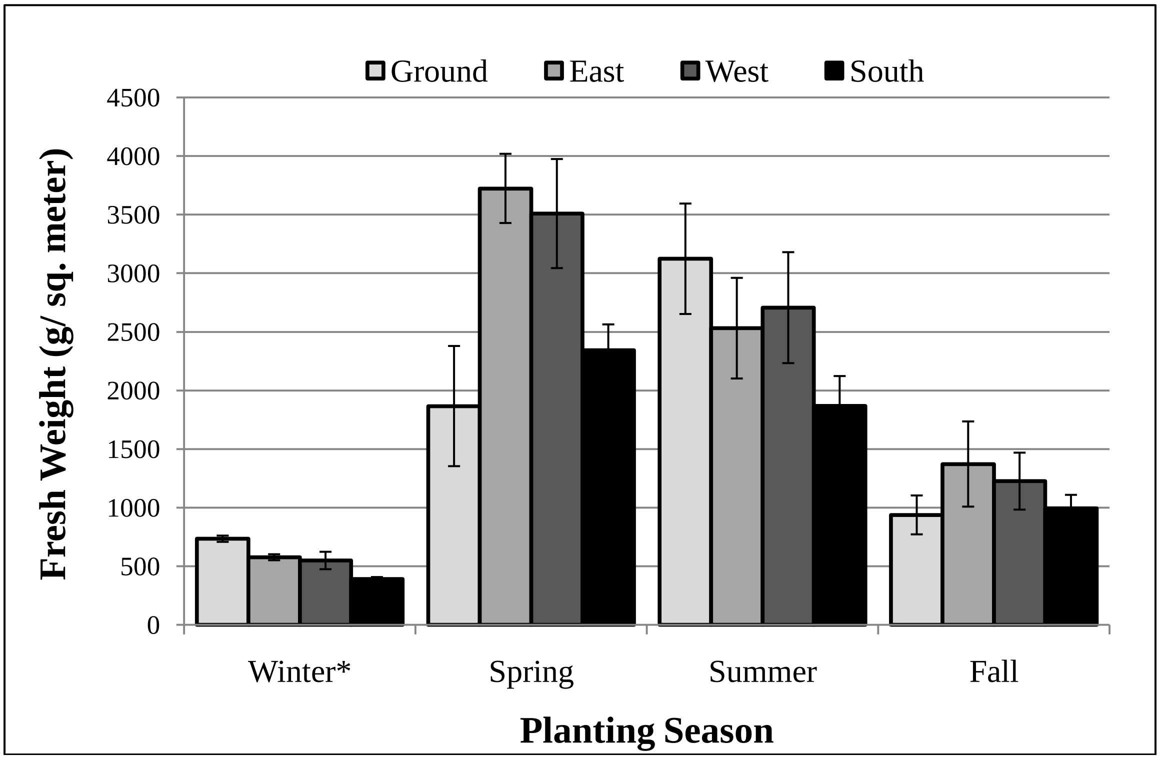


Figure 6.5. Vertical production of several orientations compared to ground production based on fresh weight per square foot after 40 days in 2008. Bars represent the Standard Error for each category. *Winter (November – February), spring (March - May), summer (June – August), fall (September –October).

Table 6.2. Monthly soil and air temperature extremes in the high tunnel in 2008.

	Minimum Temperatures (ºF)			Maximum Temperatures (ºF)		
	Soil	Gutter Soil	Air	Soil	Gutter Soil	Air
February	32	23	14	50	80	95
March	41	31	16	55	82	104
April	45	31	20	61	94	100
May	50	32	28	68	88	95

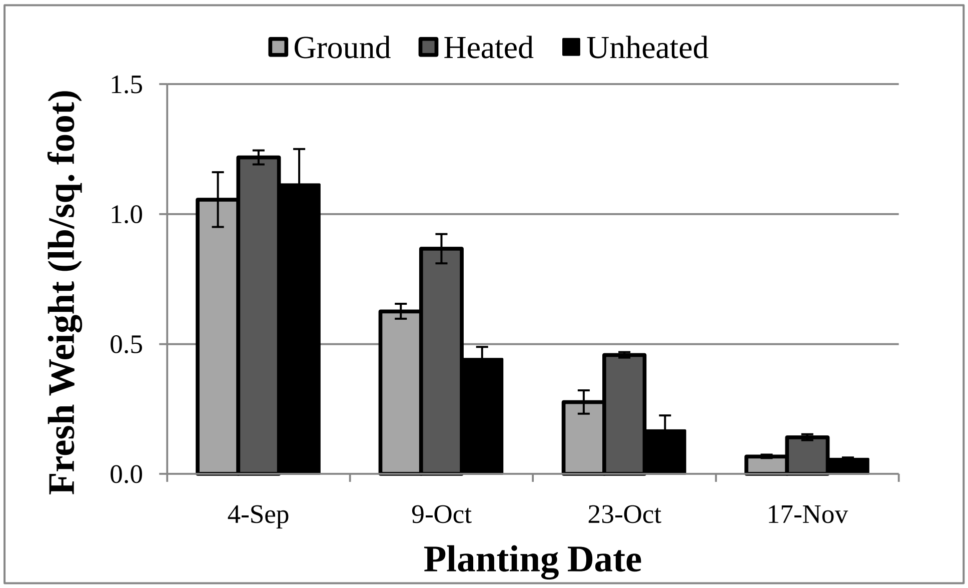


Figure 6.6. Heated gutter production compared to unheated gutter and ground production based on fresh weight per square foot after 40 days for four fall planting dates in 2009. Bars represent the Standard Error for each category.

CHAPTER 7

SUMMARY AND CONCLUSION

Low tunnels within high tunnels were shown to provide adequate frost protection for early season high tunnel tomatoes in this study. Plants experienced a 96% survival rate when temperatures reached -8 °C on 28 Mar. 2009 regardless if soil or soil plus air heating treatments were utilized. The combination of root zone heating and air heating with incandescent lights improved early season yield of tomatoes transplanted on 17 Mar., but did not significantly improve yield for subsequent planting dates. Root zone heating alone did not improve early season yield for the 17 Mar. planting date, but did improve total marketable (No.1 plus No. 2) and overall yield. The improvement in early and total yield coincided with an increase in plant biomass as well as a decrease in accumulated chilling hours. Early season yield was high for the 17 Mar. and 30 Mar. planting dates while early yield was significantly lower for the 7 Apr. planting. Planting tomatoes on 17 Mar. produced the highest overall yield, while the 7 Apr. planting date had significantly lower yield.

Growers in northern Utah who want to maximize early season yield for a high tunnel tomato crop should transplant from mid to late March using a crop cover in combination with supplemental soil and air heating. Plastic low tunnels and spun-bonded row cover cloth are practical crop cover choices. Plastic low tunnels trap more heat around the plants and provide slightly better frost protection, but spun-bonded row covers do not need to be ventilated daily. Supplemental heating will only be significantly beneficial for the first 2 to 3 weeks after transplanting to increase water and nutrient uptake and minimize cold injury. However, supplemental heating could continue to benefit growth if used for a longer duration. High tunnel tomatoes should not be thought of as an alternative to outdoor production. Rather they are an off season compliment to other products, thus allowing farmers to supply local tomatoes to the public for a longer period of time, and during a time when local tomatoes command a price premium.

Off season lettuce can provide local farmers with produce to sell at farmers' markets and other local retail outlets at a time when outdoor production is not available. Parris Island Cos lettuce grown in vertical gutters did not have a greater mean plant weight in this study when compared to growing in the ground soil. Growth of plants grown in the gutters was stunted by extreme soil temperatures. Root rot was also prevalent in the lettuce seedlings throughout the study, and may have been correlated with high root zone temperature. Growth of plants in the gutters suffered the most when soil temperatures were above 24 °C. However, when accounting for the higher plant densities in the gutters, productivity ($g \cdot m^{-2}$) was significantly greater than productivity in the ground soil during the spring and fall months, but significantly less in the winter and summer months. Root zone heating evaluated in 2009 and 2010 significantly increased productivity in the late fall and early spring. However, even with root zone heating the window of time where productivity in the gutters exceeded ground productivity was short. A vertical growing system may be useful to a grower with poor soil conditions, but further design alterations must be made. A larger rooting volume may experience less temperature fluctuation, and improved water management may reduce root rot problems. Ways of improving production in the ground soil should be further explored due to its superior performance in this study.

Growing and consuming fresh locally grown vegetables can be thought of as a move toward environmental and economic sustainability. Supporting local farmers by paying the true cost associated with raising high quality food supports local business and strengthens the community. Local food is attractive to customers who realize locally harvested produce is fresher, and that less fuel was required to transport the produce to market. This idea of sustainably can serve as an excellent marketing tool for Utah growers trying to expand their direct markets. High tunnels are advantageous to production despite the extreme temperature fluctuations common to arid high elevation regions, and could be used to increase local food production in the intermountain west.

APPENDIX

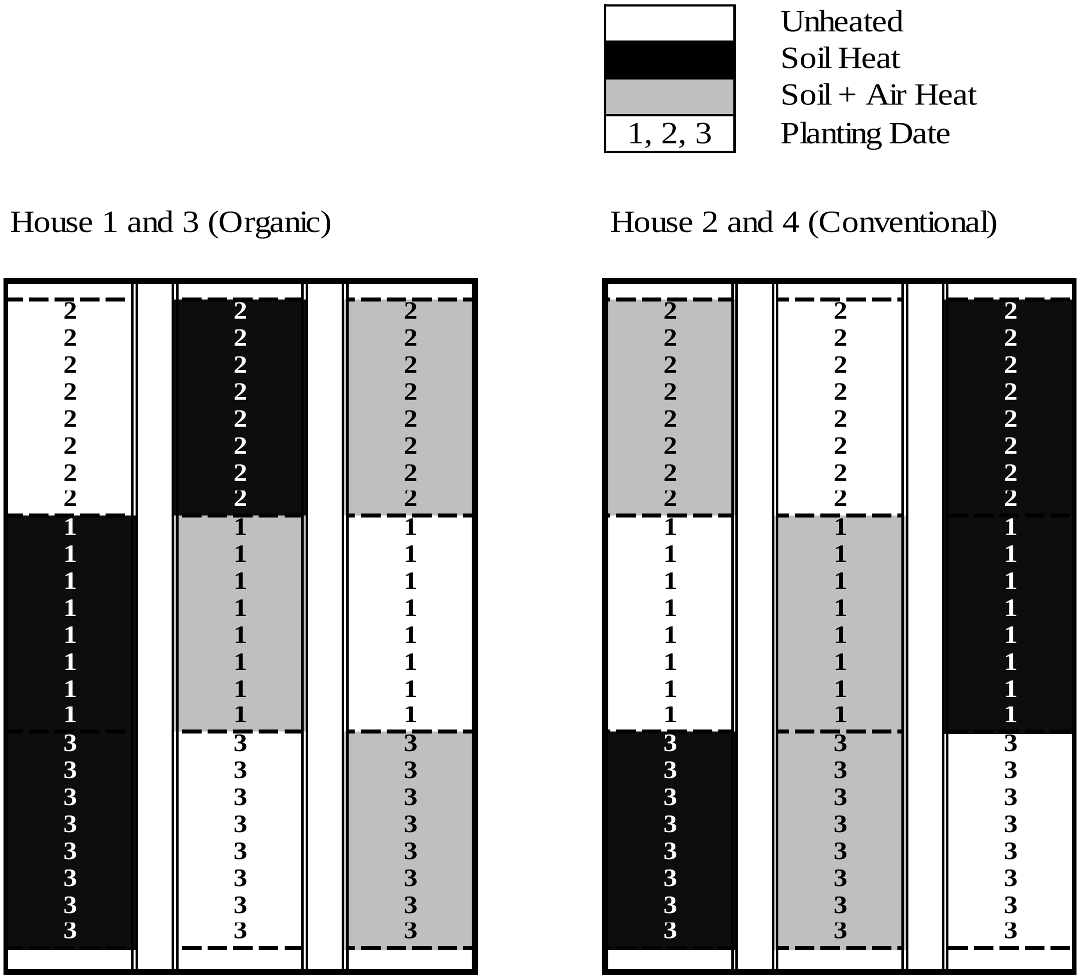


Figure A.1. Tomato high tunnel plot map 2009.

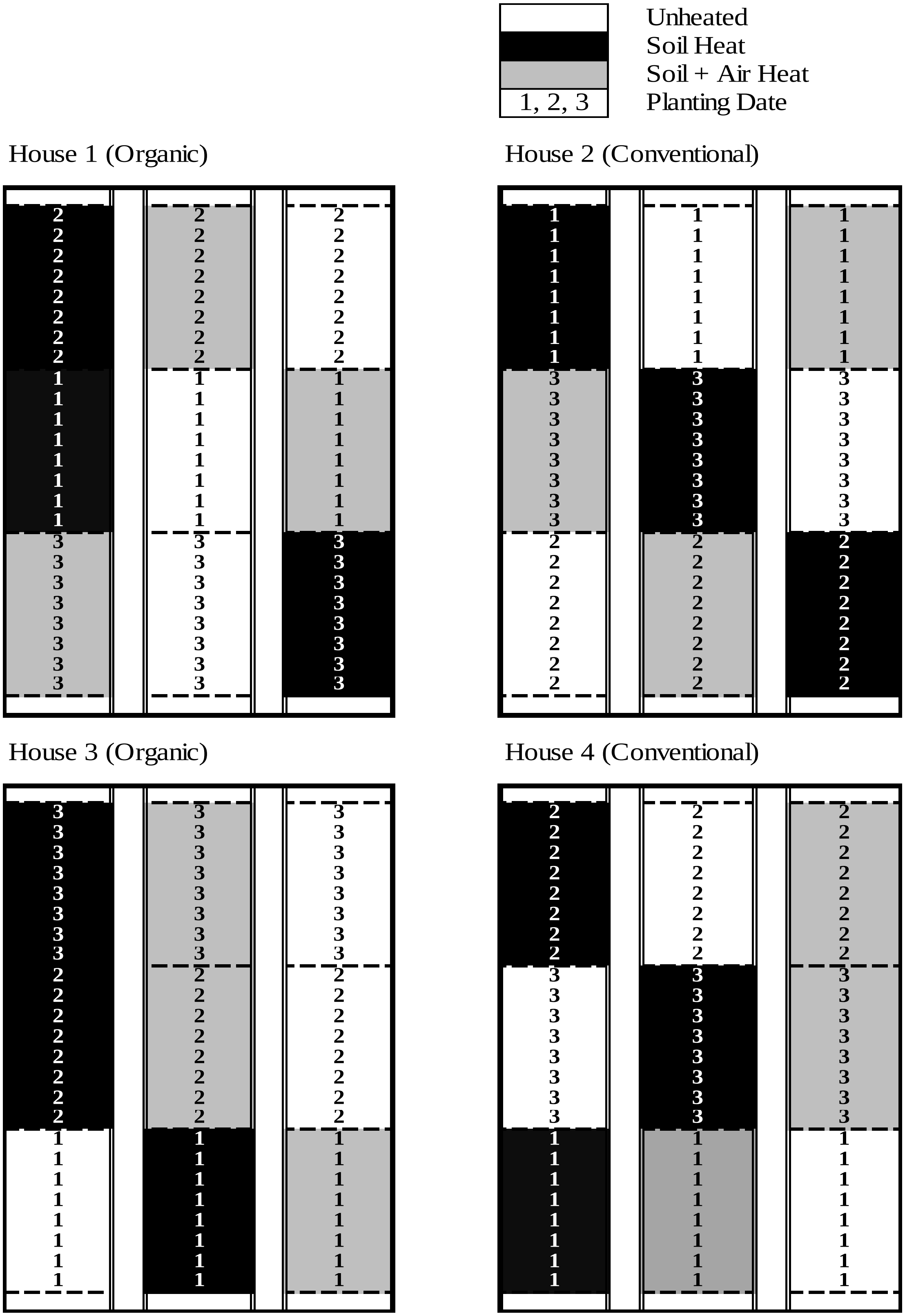


Figure A.2. Tomato high tunnel plot map 2010

Figure A.3. Picture of soil heat cable under plastic mulch

Figure A.4. Picture of lights under the low tunnel

Figure A.5. Picture of tomatoes and under low tunnel within high tunnel

Figure A.6. Picture of ventilated high tunnel

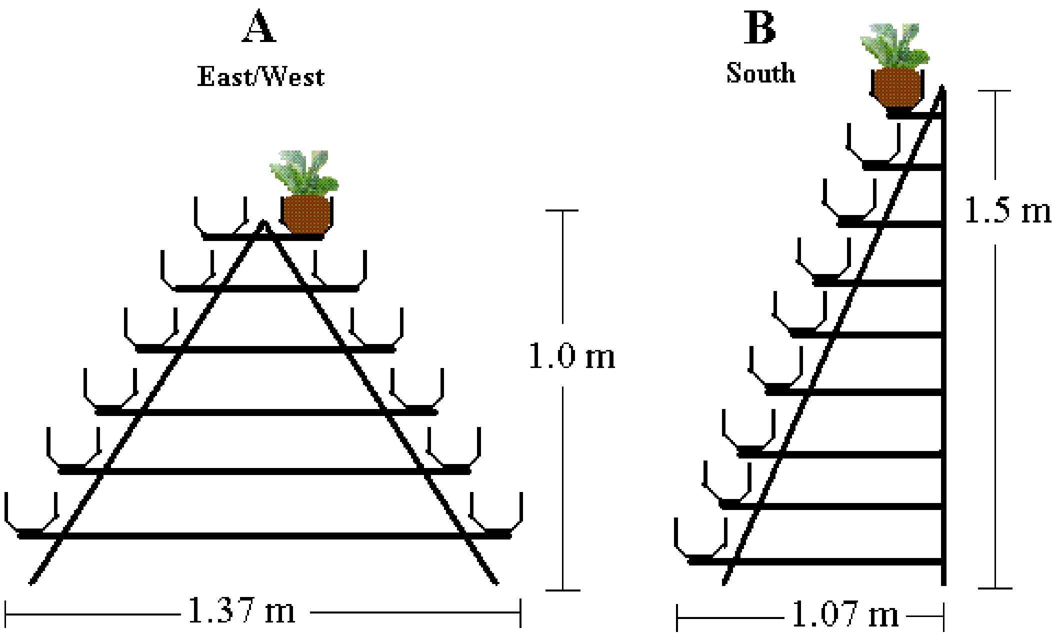


Figure A.7. Gutter design. PVC rain gutters screwed on to the wood shelves.

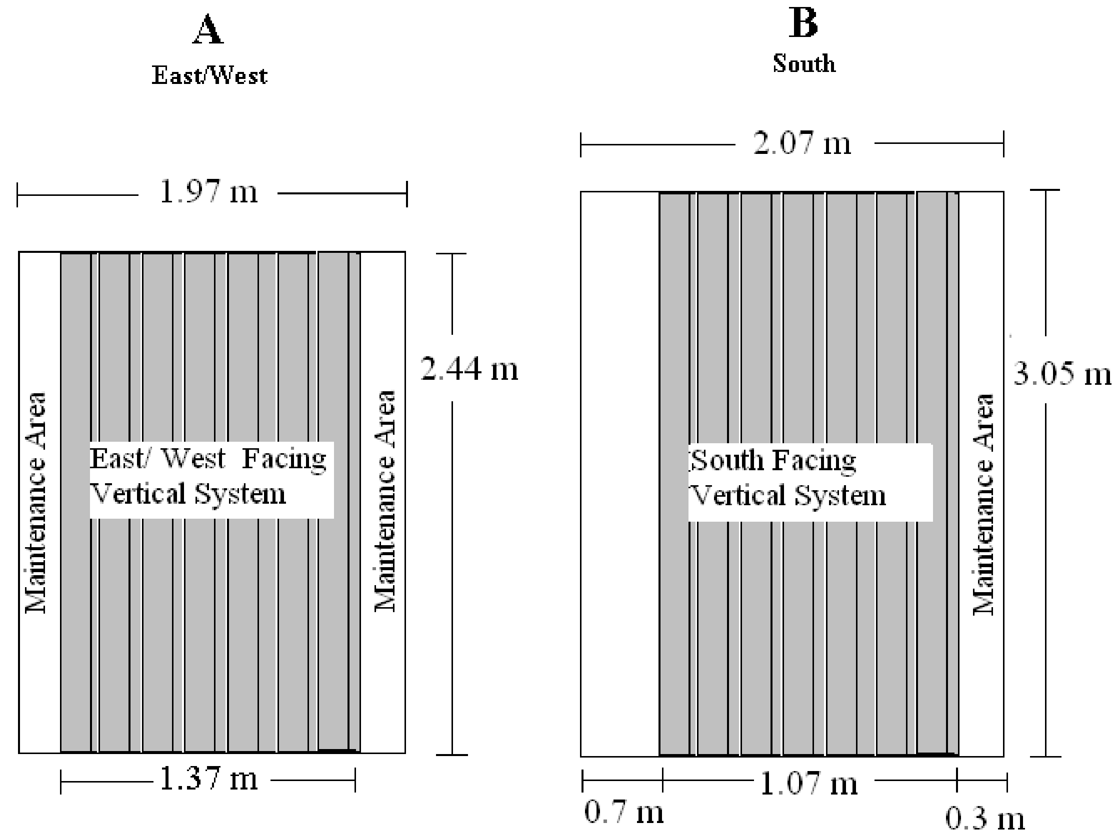


Figure A.8. Vertical growing system dimensions including maintenance area.

Figure A.9. Picture of lettuce grown in PVC gutters

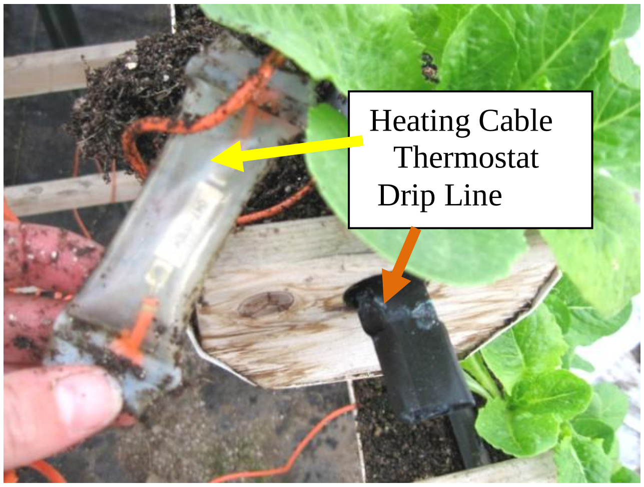


Figure A.10. Picture of soil heating cable in gutter