12-2013

Optimizing Systems for Cold-Climate Strawberry Production

Tiffany L. Maughan
Utah State University

Recommended Citation

Maughan, Tiffany L., "Optimizing Systems for Cold-Climate Strawberry Production" (2013). *All Graduate Theses and Dissertations*. 2034.
https://digitalcommons.usu.edu/etd/2034

OPTIMIZING SYSTEMS FOR COLD-CLIMATE STRAWBERRY PRODUCTION

by

Tiffany L. Maughan

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

of

MASTER OF SCIENCE

in

Plant Science

Approved:

Brent L. Black, Ph.D. Major Professor	Dan Drost, Ph.D. Committee Member
Kynda Curtis, Ph.D. Committee Member	Mark R. McLellan, Ph.D. Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2013

ABSTRACT

Optimizing Systems for Cold-Climate Strawberry Production

by

Tiffany L. Maughan, Master of Science

Utah State University, 2013

Major Professor: Dr. Brent Black
Department: Plants, Soils, and Climate

The Intermountain West region of the United States traditionally has not had large-scale strawberry production. This is primarily due to climatic challenges of harsh winters, frequent spring frosts and a short growing season. However, there is increasing demand for locally produced goods as well as an increasing consumer base as urban populations expand. Protected cultivation may allow growers to supply more produce to this expanding market for an extended season. To determine the effect on strawberry growth and fruit production of three protection methods (high tunnels, low tunnels and supplemental heating) annual hill strawberry trials were conducted over three years at the Greenville Research Farm in North Logan, UT (lat. 41.735 N, elevation 1455 m). For each system, multiple cultivars and nursery plant types (plug, bare-root dormant and bare-root fresh dug) were evaluated. Two supplemental soil heating temperatures were compared to unheated controls (7 and 15 °C). As plants under these protection systems are frequently exposed to sub-optimal air temperatures, a companion study to investigate the critical temperature for cold injury of strawberry leaves was executed. Low tunnels did not increase yield per plant above unprotected field plants (control). High tunnels, as well as high tunnels combined with low tunnels, had significantly higher early and total yield per plant than field production for both cultivars tested. There was no significant difference in yield between high tunnels and high tunnels combined with low tunnels. Targeted, in-ground supplemental heating also increased early and total yield per plant for both cultivars and all plant types, but these differences were not statistically significantly for ‘Chandler’ or ‘Seascape’ plug. There was no significant difference in total yield per plant between the two heating temperatures 7 and 15 °C. However, 15 °C heat treatment resulted in a 6.5 week earlier harvest than the 7 °C heated and unheated treatments. The LT_{50} for strawberry leaf photosynthesis was -5.3 °C. Leaves exposed to -3 °C did not have a significant decrease in net CO_2 assimilation rate from those held at 10 °C day/5 °C night (control). Once damaged, (exposed to -5 °C and -7 °C) leaves did not exhibit significant recovery over a 14 or 28 day period. Strawberry production in the Intermountain West can be extended and yield increased through the use of high tunnels, high tunnels plus low tunnels, or high tunnels plus low tunnels with supplemental heating. These environmental control strategies should be used to keep leaf temperatures above -3 °C, and to maintain optimum growing temperatures earlier in the spring and later in the fall. Direct market sales over these longer production periods can increase grower profits sufficiently to justify these additional inputs.

(137 pages)

PUBLIC ABSTRACT

Optimizing Systems for Cold-Climate Strawberry Production

By: Tiffany Maughan

Producing fruits and vegetables in the Intermountain West can be challenging due a short growing season, extreme temperatures, and limited availability of irrigation water. This is particularly true of strawberries, where commercial production is limited due to late fall and early spring frosts that shorten the growing season. With the increasing demand for local produce as urban populations grow and as consumer buying habits change, growers are looking for ways to overcome these climatic challenges. High tunnels are one option growers can use. High tunnels are similar to greenhouses, but less expensive to construct and to maintain. Another way to protect crops against adverse climatic conditions is with low tunnels. As the name implies, they are a smaller version of a high tunnel, usually only tall enough to cover the canopy of the plant. Low tunnels can be used by themselves or in conjunction with (inside) a high tunnel. Adding heat is another option. However, heating can be expensive and may not be profitable. Targeting heat additions in the root zone may decrease cost of heat but still provide protection to the plant.

These protection methods were evaluated in Cache Valley, Utah for effectiveness of increasing strawberry yield. High tunnels increased total yield, as did high tunnels used in conjunction with low tunnels. However, low tunnels by themselves were not able to increase yield in comparison to unprotected plants in the field. Targeted root zone heating was evaluated in both high and low tunnel with two target temperatures: 7 and 15 °C. There was no difference in total yield between the two temperatures, but both increased yield above the high tunnel alone and the 15 °C heating treatment moved the harvest season approximately 6.5 weeks earlier than unheated tunnels and approximately 12 weeks earlier than field production. The additional cost associated with using supplemental heat was offset by the increased yields and the higher value of early fruit.

Separate experiments were carried out to determine susceptibility of strawberry leaves to damage from cold temperatures, which can then be used to provide guidelines for temperature management in high tunnels. Strawberry leaves were not significantly damaged when exposed to -3 °C, but significant damage occurred once leaves were exposed to -5 °C. To maximize the advantages of protected cultivation, growers should manage tunnels and heating to keep leaf temperatures above -3 °C. These results provide improved guidelines for growers interested in using protected cultivation strategies to provide fruit for local consumption in the Intermountain West.

ACKNOWLEDGMENTS

Primarily and resoundingly I thank my husband, Spencer, for his prolonged and substantial support through countless late night runs to check on my plants, early morning departures to the farm, and mid-day lunches full of encouragement. Also, to my son for being the most patient and convenient baby I could have hoped for. Very special thanks to Dr. Brent Black for his constant and long-term advice, guidance, and help as I moved through my graduate project. Thanks to my other committee members, Dr. Dan Drost and Dr. Kynda Curtis, for speedy edits and welcome advice. I appreciate the funding from the Utah Department of Agriculture and Food, the Utah Agricultural Experiment Station, USU Cooperative Extension, and the North American Strawberry Growers Association. Finally, thank you to all employees and fellow graduate students who have helped me, specifically: James Frisby, Taunya Ernst, and Sam Day.

Tiffany Maughan

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Agricultural producers in Utah are faced with several challenges: shrinking agricultural land, harsh climactic conditions, and significant out-of-state competition. Combating these challenges is important to maintaining viability. Utah agricultural land is very limited, with only 2.3% of the state in irrigated agriculture (Hutson et al., 2005) and only a small portion of irrigated agriculture being dedicated to fruit production. Utah's population has steadily increased, with the last decade experiencing an annual growth rate of approximately 2.48%. As population has increased, prime fruit growing acreage has been lost to urban and suburban growth, pushing Utah to become a net importer of most fruits (Ernst et al., 2012).

Climate is a second major challenge to Utah fruit production, limiting both the type of fruit crops grown and the length of the growing season. Due to high elevation and arid conditions, large diurnal temperature fluctuations during spring and fall limit fruit production in many parts of the state. Additionally, Utah is primarily a semi-arid state, limiting water availability. Finding ways to combat these climatic challenges may increase yield and profitability for Utah fruit producers.

Lastly, out-of-state competition can limit financial success of produce growers in Utah. With the increased ability to ship produce long distances, year round supply to grocery stores is possible for most fruits. These out of state producers often do not have the climatic challenges Utah growers are faced with and may be able to sell their commodity at lower prices than Utah growers.

The production window for field-grown strawberries in Northern Utah is from late May to early July. This period directly overlaps peak national production and the lowest annual wholesale prices of approximately $1.32 per kg (USDA, NASS, 2009). This, combined with sub-optimal weather conditions, makes it unlikely Utah will ever be a significant exporter of strawberries. It is important that growers in Utah sell via direct local markets such as farmer's markets, community supported agriculture (CSAs), or roadside stands in order to avoid competing with national wholesale prices.

As urban development encroaches on agricultural land, farms are often in close proximity to high population centers. This can be exploited by direct selling to consumers. The recent locavore movement has resulted in a market of consumers interested in buying local products. Demand for fresh, locally produced food year-round has increased (Martinez et al., 2010). The number of farmer's markets in Utah increased by 40% between 2008 and 2010 (Utah's Own, 2012). Utah producers have the opportunity to increase production to meet this demand. Ideally, growers could produce fruits and vegetables year round to provide a constant supply to the consumer. However, as previously discussed due to climatic challenges, 4-season fresh produce production is difficult and often requires additional inputs.

Utah strawberry production is minimal, with acreage too low to justify reporting by the USDA. In 2009, per capita consumption of strawberry was 6.3 kg per year (USDA-ERS, 2011). Assuming Utah consumption is comparable to national averages, Utah growers would need to produce approximately 18 million kg of strawberries per year (350,000 kg per week) to meet in-state demand. Assuming Utah's field production season is approximately 6 weeks, and that per capita consumption remains relatively constant throughout the year, a conservative estimate for local demand for Utah strawberries would be 2.1 million kg, during the peak season. Of course, it is unlikely that consumption does not vary with season, making this a relatively conservative estimate of local demand. Production in Utah falls far short of providing enough strawberries to meet the demand in this relatively short market window. Rowley et al. (2010a) reported that high tunnels can increase total yields and advance the season by approximately 4 weeks in comparison to field-grown plants in the Intermountain West (Rowley et al., 2010a). This allows growers to provide strawberries for a longer period of the year and potentially increase profits as crops produced out of season command a price premium when sold in direct markets (Foord, 2004).

Strawberry growth is affected by many climatic and horticultural factors. This chapter provides a brief introduction of crop growth as influenced by temperature, light, cultivar, and plant type. Understanding plant responses to environmental stimuli and physiological characteristics is an important part of a successful management plan, particularly when environmental manipulation is economically feasible through the use of protected cultivation.

Plant growth: temperature.

Temperature is one of the most important limiting factors in temperate-zone strawberry production, with ideal temperatures for strawberry growth being between 20 and 26 ˚C (Darrow and Waldo, 1934). Growth of many crop plants responds predictably to temperature, following the growth/temperature relationship illustrated in Figure 1.1. This relationship is defined by critical minimum, optimum and maximum temperatures.

For strawberry, the minimum critical temperature is just above freezing (Galletta and Himmelrick, 1990), with growth rates increasing as temperature increases. Although there is some variation due to acclimation and cultivar differences, generally maximum growth rate occurs at 22 ˚C, and then steeply declines as temperatures approach the maximum limit. Growth slows dramatically at 30˚C with damage occurring above 35 ˚C (Arney, 1953; Carlen et al., 2009). In plants heat treated to kill virus, Converse (1987) found that growth stops at 35-38 ˚C. Temperatures in Utah meet these ideal growing conditions for only a short period each year, being either sub-optimal or super-optimal for most of the year.

Adequate fall development is important for high spring yields to occur. Vigorous crown growth and development occurs when temperatures are above 10˚C (Fernandez, 2001). In June-bearing cultivars, flower bud initiation and differentiation begin during the fall. Flower buds are formed when days are shorter than 14 hours or when temperatures are below 15 ˚C (Darrow and Waldo, 1934; Larson, 1994; Strand, 1994). Day-neutral cultivars produce flowers and fruit throughout the year, provided temperatures are between 7 and 15 ˚C (Strand, 1994).

Blossoms are susceptible to damage at temperatures below -1˚C (Hummel and Moore, 1997; Maas, 1998). Frost injury kills pistils and the associated receptacle tissue, resulting in an easily recognized blackened center. Depending on the extent of injury and stage of development, either no fruit will form or misshapen, unmarketable fruit develop. Primary flowers are the first to open on the inflorescence, and therefore are often the blossoms that are damaged. Primary flowers have the potential to produce larger fruit than secondary and tertiary flowers. Boyce et al. (1985) found that when primary or primary and secondary blossoms were removed, no weight compensation was made by remaining fruit. A removal of primary blossoms resulted in a 30% decrease in overall yield as the secondary and tertiary flowers did not compensate for the loss of yield from primary flowers.

During bloom, spring frosts are common in Utah. Thus, temperature modifications are needed to protect these first blossoms. In addition to the need for spring frost protection, improved temperature management in the fall allows for increased plant development before winter temperatures limit growth. There are several methods used for manipulating growing temperatures to stay within the optimum temperature range. Some notable methods are high tunnels, low tunnels, floating row covers and soil heating.

Protective system: high tunnels. High tunnels operate and look like greenhouses, but are passively heated and cooled, which significantly reduces operating costs as compared to greenhouses. They are temporary structures constructed with either galvanized steel or PVC pipe framing, and covered with greenhouse grade plastic (Fig. 1.2a). High tunnels are used to modify the growing environment for plants and are heated as short wave radiation from the sun enters the high tunnel and is absorbed by the soil and plants. The plastic traps the heat that dissipates from the covered plants and soil in the form of conduction and convection, as well as emitted long wave radiation, and the tunnel air temperature increases. This can result in as much as a 30 ˚C increase in air temperature above the ambient outside air temperature during the day (Wien et al., 2008). Much of the accumulated heat dissipates after the sun sets, but the air within the high tunnels can still remain 1 to 3 ˚C warmer than the surrounding environment during the night. The daily temperature increase extends the growing season earlier into the spring and later in the fall. Areas where the growing season is limited by extreme diurnal temperature fluctuations are particularly well suited for high tunnel use as energy accumulated during the day can maintain tunnel temperatures above freezing during the night. Utah's high elevation arid valleys are particularly prone to these spring and fall temperature fluctuations. In the Intermountain West, high tunnels can effectively extend the growing season for strawberries by approximately 4 weeks, making commercial production economically viable through higher prices in the extended season (Hancock and Simpson, 1995) and through higher yields by protecting the blossoms from spring frosts (Chapter 2 of Rowley, 2010).

Protected system: low tunnels. Low tunnels can also be used to increase temperature around the plant. Low tunnels are much smaller than high tunnels, usually only large enough to cover the strawberry bed and plant canopy. Clear plastic is suspended over plants using either sturdy wire or pipe. Low tunnels can be used in conjunction with a high tunnel (Fig. 1.2b), providing an additional 3 to 5 ˚C increase in night temperature (Wien et al., 2008). Temperature elevation during the day is significantly higher depending on light levels. Low tunnels are also used alone (Fig. 1.2c), providing less temperature increase, but reduced cost in comparison to the high tunnel/low tunnel combination. Although low tunnels are less expensive to construct than high tunnels, they are more difficult to ventilate, cool off much faster at night, and may not sufficiently extend the spring season (Hancock and Simpson, 1995). In Spain, Ariza et al. (2012) found no significant difference in early marketable fruit yield and total seasonal yield between high tunnels and low tunnel systems. Additionally, fruit quality was similar from one system to the next. In northeastern India, low tunnels are the most commonly used protected cultivation method and have been successful in providing protection from rain (Singh et al., 2012). In this region, high temperatures are of concern and low tunnels are used in combination with shade net to combat high temperatures that coincide with fruiting periods. Under these conditions low tunnels have been used successfully to increase yield and extend the season (Singh et al., 2012). Low tunnels may have some season extending effects similar to high tunnels, but research is needed to determine the effectiveness of low tunnels in the Intermountain West where the winters are much harsher and spring frosts more common than in Spain and northeast India. If an adequate level of spring frost protection could be achieved using low tunnels, the cost of frost protection might be much more feasible for Utah growers.

Protective system: row covers. Floating row covers are also used in strawberry production (see Fig. 1.2d). Row covers are typically a spun-bonded or nonwoven fabric available in varying thickness. They are laid directly on top of the plant canopy. For strawberry production, row covers are typically used during the fall and spring to increase soil and air temperature and slow heat loss at night (Himmelrick et al., 2001). Lightweight (17 g/m^2) row covers can provide frost protection down to -2˚C (Himmelrick et al., 2001). Gast and Pollard (1991) found that with an early autumn row cover application, leaf growth continued longer in the fall and resumed earlier in spring. Row cover application in the fall also resulted in increased branch and flower formation compared to non-cover trials, thereby increasing yield (Gast and Pollard, 1991; Nestby et al., 2000).

Plant growth: light.

Leaf light interception is critical for photosynthesis. In general, higher levels of light translate into higher CO_2 assimilation or photosynthetic rates, up to the light saturation point (Ferree and Stang, 1988; Larson, 1994). Light levels are reduced in the fall as sun angles decrease. With the temperature protection provided by the tunnels, growth is possible into late fall and early spring provided there is sufficient available light.

Each of the three methods mentioned above, (high tunnel, low tunnel, and row cover) increase soil and air temperatures but result in some shading. In a high tunnel covered with a single layer of 6 mil greenhouse plastic, accumulated daily light integral was decreased by 437 mol m^{-2} (24%) compared to outside light levels (Both et al., 2007). Additional shading occurs when low tunnels are erected within the high tunnel, with the amount of shading varying with the type of plastic. Thin, clear plastic may only slightly increase shading whereas a thicker opaque plastic could contribute an additional 25% light reduction (Hunter, 2010). Depending on the type of plastic used, low tunnels used without a high tunnel may have minimal reduction in light transmission.

Spunbound and nonwoven row covers also reduce light reaching the canopy, which may outweigh potential temperature benefits. Depending on row cover weight, shading levels can be from 25-70%. Rubeiz et al. (1997) found that in a Mediterranean climate, temperature increase provided by the fall-applied floating row covers did not offset the shading effects (20% shade), and row cover treatment resulted in lower yields, even when row covers were removed at bloom. When used in conjunction with high tunnels, Hunter (2010) found low tunnels to be more effective at raising temperatures than floating row covers.

Once temperatures are above the maximum critical temperature, covering (high tunnel, low tunnel or row cover) is often removed. Shade cloth may then be suspended over the plants to attempt to keep the temperatures in the optimum range for a longer period. While a temperature reduction is gained from this practice, light levels are reduced. In a mild maritime climate, Wright and Sandrang (1995) saw no reduction in biomass accumulation of strawberry when a 25% shade cloth was applied on 1 May. However, as shade percentage increase to 70%, biomass accumulation decreased.

Photosynthetic or CO_2 assimilation rates of strawberry are similar to other fruit crops and are in the range of 15-25 µmol $m^{-1}s^{-2}$ (Hancock et al., 1989; Larson, 1994). However, these rates are significantly affected by light, as well as temperature and nutrient availability. In general, higher levels of light translate into higher assimilation rates. The light saturation point in strawberries is between 1000 and 1400 µmol $m^{-1}s^{-2}$ (495 W m^{-2} to 690 W m^{-2}) (Carlen et al., 2009; Ferree and Stang, 1988; Larson, 1994). During the winter in Logan, Utah the zenith angle of the sun is approximately 56° lower than during the summer (USDA-NREL, 2013). Due to these lower sun angles, typical winter light levels in Logan, Utah can be much lower than light saturation for strawberry, resulting in a reduction in photosynthesis during that time. Table 1.1 shows monthly average, and minimum and maximum values for total daily incoming solar radiation for 2012. January had the lowest daily average and June the highest, 3.3 and 32.2 MJ m^{-2} respectively (Utah Climate Center, 2013).

Ventilation is critical in both high and low tunnels, even during the winter when outside temperatures are low. On 30 November, 2010, Ernst (2012) recorded air temperatures of 21 ˚C in a high tunnel when the outside air temperature was -4 ˚C (Greenville Research Farm, North Logan, Utah). High tunnel air temperature was within the optimal temperature range for strawberry growth. However, under the low tunnel covering, temperatures can climb an additional 10 ˚C. This would be super-optimal for strawberry, resulting in decreased plant growth. High temperatures (40 ˚C day/35 ˚C night) have been found to be more detrimental to strawberry plant growth than cool (20 ˚C day/15 ˚C night) temperatures (Kadir et al., 2006). Pollen viability is also affected by high temperatures. Ledesma and Sugiyama (2005) exposed a non-heat tolerant strawberry cultivar to 30 ˚C day/25 ˚C night from the time inflorescence were visible until full bloom. Under these high temperature conditions, primary blossom pollen had a 62% reduction in viability. To avoid pollen viability reduction and other heat stress responses, ventilation is needed in both high and low tunnels.

Ventilation in a high tunnel can be achieved by opening a small door vent, opening one or both end doors, or lifting the sides of the tunnel during very warm weather. Low tunnels are vented by lifting the plastic partially or completely off the frame. As the season progresses, increased ventilation is needed. By late spring, high tunnel temperatures can remain above the optimal temperature range even with side wall ventilation. When night temperatures consistently stay above 10˚C, high tunnel plastic can be completely removed, to help keep day temperatures cooler.

Humidity is another important factor to consider with high and low tunnel strawberry production. The closed environment of high and low tunnels results in little air movement and increased relative humidity. High relative humidity can increase some insect problems, as well as provide ideal environments for many pathogens (Agrios, 2005). Humidity levels can be controlled by ventilation and tunnel size. Opening the tunnels for ventilation increases air movement and will lower relative humidity. Unfortunately, if temperatures are too low for ventilation, little can be done to lower humidity in the tunnel, except judicious irrigation to minimize soil surface evaporation. It is important to give attention to the structural design and dimensions of the high tunnel to not only optimize heat retention, but also enhance natural ventilation and reduce humidity. As the distance from the center of the high tunnel to the nearest ventilation opening increases, the potential for adequate ventilation decreases (Giacomelli, 2009).

Plant growth: soil temperature.

Soil temperature is also important for strawberry growth. Root growth continues in the fall until the soil is frozen, long after leaf growth has ceased. Root growth follows the same temperature relationship displayed in Figure 1.1, but is defined by slightly different critical temperatures. The minimum temperature for active root growth is 5 ˚C and the maximum is 31 ˚C (Bowen, 1991) with an optimum temperature range of 10 to 23 ˚C (Larson, 1994; McMichael and Burke, 1996). Wang and Camp (2000) reported the optimum root temperature to be 18 ˚C day/12 ˚C night. Soil temperatures have an effect on root length, branching, respiration, nutrient uptake, and water uptake. Roots grown in soils with sub-optimal temperatures are smaller and less branched, effecting plant growth throughout the season. If temperatures drop below the minimum, root tissue necrosis can occur. Additionally, low temperatures retard the uptake of nutrients.

During the winter, fall-planted strawberries are regularly exposed to sub-optimal soil temperatures, even in a high tunnel. Buried electric soil heating cables or hot water lines have been used successfully to heat soils. A study done in Oregon's Willamette Valley by Rykbost et al. (1975) used hot water pumped through buried pipes to heat soil in a matted row strawberry field. Water temperatures ranged from 25 to 40 ˚C. Soil warming in an open field did not result in earlier maturity of fruit, but plants had more foliage and 35% higher yields than non-heated plots. In a study investigating the effect of root-zone temperature in hydroponic production (nutrient film technique), strawberry roots were exposed to no heating, 20 ˚C, or 25 ˚C nutrient solutions (Economakis and Krulj, 2001). Total yield was increased from 145.5 g/plant (control) to 325.3 g/plant (25 ˚C nutrient solution). Early yield was also significantly increased by both heated-solution treatments.

With both buried heating cables and heated water treatments, additional material costs must be considered. Heating cables cost approximately $12.00 per row meter (More Electric Heating, Comstock Park, MI, 2012) and heated water treatments can vary in cost depending on size and material type used. Cost of instillation and energy use for heating also effect cost of production. Although some benefits of strawberry root zone heating have been observed in both field production and hydroponic culture, potential benefits in low-input protected cultivation such as high tunnel systems, have yet to be evaluated. Economic evaluation is needed to determine if the additional costs of targeted root-zone heating are justified.

Plant Type: June Bearing, Day Neutral.

Commercially, June-bearing (short-day) and day-neutral strawberry plants are the two plant types of primary importance. Ever-bearing (long-day) type plants are typically grown only in the home garden. June-bearing plants are facultative short-day plants, meaning they will initiate flower buds either under short-day conditions (less than 14 hours) or when temperatures are less than 15 ˚C. When temperatures are above 15 ˚C, the critical photoperiod for flower bud initiation is 8-12 hours (Darrow, 1939; Larson, 1994). In areas with cold winters, like most of Utah, flower buds are initiated in the late summer and fall for June-bearing plants. These buds then break when temperatures become warm enough after the winter dormant period (Darrow and Waldo, 1934; Strik, 1984).

Day-neutral plants produce crowns and flower buds about 3 months after planting. This is because they initiate flower buds throughout the growing season regardless of the day length, as long as temperatures are below 22 ˚C (Bringhurst and Voth, 1975; Durner et al., 1984.) Floral induction for ever-bearing types occurs when the day length exceeds 12 hours and if temperatures are moderate.

Due to complex interactions between genotype, temperature, and photoperiod, some cultivars of strawberry do not fall directly into either June-bearing or day-neutral classifications. Darrow (1966) and others suggest that there is gradient of flowering types ranging from obligate short-day to facultative short-day to completely day neutral (Nicoll and Galletta, 1987; Yanagi and Oda, 1993).

Nursery Plant Type: Dormant, Fresh Dug, and Plug Plants.

Nursery plant type can influence plant physiology and growth. Optimal planting date, runner and crown formation, and yield vary with plant type. Annual hill strawberry plantings are established using either dormant, fresh dug, or plug plants, depending on the production region. Both dormant and fresh dug plant types are relatively inexpensive per plant, but both have challenges for use in a high tunnel system in Utah. Dormant plants (Fig. 1.3a) are generally available only in the spring. Field grown nursery plants are dug in the late fall and stored over winter, then shipped in the spring. This poses a problem for fall planting systems such as those used in high tunnels in the Intermountain West. Some nurseries will hold dormant stock for late summer plantings, but orders need to be placed well in advance. Another option is receiving the plants in the spring and storing them throughout the summer, but providing correct storage conditions can be difficult. Dormant plants are stored at -1.5 ˚C and need to be moist, but not too wet (Durner et al., 2002). Fall planted dormant plants have been stored for at least 9 months by planting time, which can increase plant cost (additional storage) and dramatically decrease plant survival.

Fresh-dug bare-root plants (Fig. 1.3b) usually become commercially available in mid to late October. They are field grown nursery plants that are dug and shipped for immediate transplanting. For fall plantings in Utah, late October does not allow sufficient time for establishment before cold winter temperatures limit growth. High tunnels provide season extension into the fall, but may not provide adequate pre-dormant growth of roots and crowns.

Plug plants, also known as tray plants, (Fig. 1.3c) are a third option. Initially plug plants are more expensive than dormant or fresh dug plants, but those costs may be recouped with higher yields and increased plant survival rates. Although growing in popularity (Durner et al., 2002), plug plants are currently not commercially available in the Intermountain West. However, plug plants are fairly easy to produce and can be grown in a small greenhouse or cold frame (Rowley et al., 2010b) either on farm or by a local nursery. Despite the limited availability, plug plants may have several advantages over dormant and fresh dug plants: less time to produce transplants, no exposure to soil-borne pathogens, greater control over transplanting dates (Durner et al., 2002) and reduced runners (Rowley, 2010).

Low temperature effect on physiology. Exposure to temperatures below 4 ˚C and above freezing results in a decreased growth rate, although strawberry leaves continue to photosynthesize (Galletta and Himmelrick, 1990). Low temperatures negatively affect cell membranes, increasing rigidity (Ruelland et al., 2009). Freezing temperatures (below 0 ˚C) have even more detrimental effects than low temperatures. Freezing temperatures may result in ice crystal formation within the cell membrane, causing the cell to rupture (Ruelland et al., 2009). During cold winter months in temperate climates, leaves often remain green even when exposed to freezing temperatures. However, it is not clear if these leaves remain photosynthetically active. Most research on cold temperature damage in leaves has been conducted on detached leaves or excised leaf disks. Detached leaves sustain significant damage, as assessed by solute leakage, from temperatures between -5 and -12 ˚C (O’Neill et al., 1981; Owens et al., 2002).

Strawberry plants can adapt to different climates. Being able to acclimate and develop freezing tolerance is vital to survival over cold winters. Exposure to low, non-freezing temperatures induces biochemical and physiological modifications which allow the plant to withstand subsequent freezing temperatures (Ndong et al., 1997). Strawberry plants acclimate to low temperatures and can survive sub-freezing temperatures by tolerating extra-cellular ice formation in crown tissues. This is accomplished by water moving from within the cell to outside the cell to form extracellular ice. When this occurs, injury to strawberry crowns is due to dehydration when too much of the water has migrated out of cells (Warmund, 1993). Additionally, strawberry plants survive freezing by accumulating protective proteins in overwintering crowns through changes in gene expression, and by increasing cell wall integrity (Koehler et al., 2012). For most cultivars, cold-temperature acclimation is achieved after 7 days. Acclimation rate is affected by cultivar, drought and temperature exposure (Darrow, 1966). Strawberry leaves under protected cultivation in Utah are frequently exposed to sub-optimal or freezing temperatures, thus acclimation is still necessary for plant survival.

Summary

The overall aim of this thesis is to investigate methods for optimizing strawberry production for a high-elevation arid temperate climate. Specific objectives for this include: determine the optimal planting date for bare-root dormant nursery plants of June-bearing strawberries, and compare multiple cultivars of both nursery plant types planted on their respective optimized date (Chapters 2 and 3); determine whether a low tunnel only system is as effective as high tunnels for spring frost protection and evaluate the horticultural prospects of targeted supplemental heat on high tunnel strawberry production (Chapter 3); develop partial budgets of high tunnel plus low tunnel and high tunnel plus low tunnel combined with supplemental heating, and compare the costs and returns of each system (Chapter 4); summarize pest and disease management strategies for high elevation high tunnel strawberry production (Chapter 5); and determine minimum critical temperature for strawberry leaves in order to develop physiologically based temperature management recommendations for fall and winter high tunnel management (Chapter 6).

Literature Cited

Agrios, G.N. 2005. Parasitisim and disease development. p. 72-102. In: Plant pathology. 5th Edition. Elsevier Academic Press, Burlington, MA.

Arney, S.E. 1953. Studies of growth and development in the genus *Fragaria*. I. factors affecting the rate of leaf production in Royal Sovereign strawberry. J. Hort. Sci. 28: 73-84.

Ariza M.T., C. Soria, J.J. Medina-Minguez, and El Martinez-Ferri. 2012. Incidence of misshapen fruits in strawberry plants grown under tunnels is affected by cultivar, planting date, pollination, and low temperatures. HortScience 47(11): 1569-1573.

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

Bowen, G.D. 1991. Soil temperature, root growth, and plant function. p. 309-330. In: Y. Waisel, A. Eshel and U. Kafkafi (eds.). Plant roots: the hidden half. 1st Edition. Marcel Dekker, Inc., New York, NY.

Boyce, B.R., A.L. Hazelrigg, and A.W. Linde. 1985. Field evaluation of loss of primary or primary and secondary blossoms on strawberry fruit weight and yield. Advances in Strawberry Production 4: 32-33.

Bringhurst, R.S. and V. Voth. 1975. Breeding and exploitation of day-neutral strawberries in subtropical environments. HortScience 10: 329.

Carlen, C., A.M. Potel, and A. Ancay. 2009. Photosynthetic response of strawberry leaves to changing temperatures. Acta Hort. 838: 73-76.

Converse, R. H. 1987. Detection and elimination of virus and virus-like diseases in strawberry. p. 2-10. In: Converse, R.H. (ed.). Virus diseases of small fruits. USDA/ARS Washington, DC.

Darrow, G. M. 1939. Interrelation of temperature and photoperiodism in the production of fruit-buds and runners in the strawberry. Proc. Amer. Soc. Hort. Sci. 34: 360-363.

Darrow, G.M. 1966. The Strawberry. History, breeding and physiology. Holt, Rinehart and Winston. New York, NY.

Darrow, G.M. and G.F. Waldo. 1934. Responses of strawberry varieties and species to duration of the daily light period. USDA Technical Bulletin 453, Washington, DC.

Durner, E.F., J.A. Barden, D.G. Himmelrick, and E.B. Poling. 1984. Photoperiod and temperature effects on flower and runner development in day-neutral, Junebearing, and everbearing strawberries. J. Amer. Soc. Hort. Sci.. 109(3): 396-400.

Durner, E.F., E.B. Poling, and J.L. Maas. 2002. Recent advances in strawberry plug transplant technology. HortTechnology 12(4): 545-550.

Economakis, C.D. and L. Krulj. 2001. Effect of root-zone warming on strawberry plants grown with nutrient film technique (NFT). Acta Hort. 548: 189-195.

Ernst, T. 2012. Optimizing winter spinach production in high tunnels. M.S. Thesis. Utah State University, Logan Utah.

Ernst, T., S.D. Rowley, B.L. Black, and T.R. Roper. 2012. Reviewing potential local fruit markets: a Utah case study. J. Amer. Pomol. Soc. 66(1): 16-22.

Fernandez, G.E. 2001. Fall-applied rowcovers enhance yield in plasticulture strawberries. HortTechnology 11(3): 440-444.

Ferree D.C. and E.J. Stang. 1988. Seasonal plant shading, growth, and fruiting in ‘Earliglow’ strawberry. J. Amer. Soc. Hort. Sci. 113(3): 322-327.

Foord, K. 2004. High tunnel marketing and economics. Regents of the University of Minnesota. M1218. June 13, 2012 <http://www.extension.umn.edu/distribution/horticulture/components/M1218-12.pdf>

Galletta, G.J. and D.G. Himmelrick. 1990. Small fruit crop management. Prentice Hall, Englewood Cliffs, NJ.

Gast, L.B. and J.E. Pollard. 1991. Rowcovers enhance reproductive and vegetative yield components in strawberries. HortScience 26(12): 1467-1469.

Giacomelli, G.A. 2009. Engineering principles impacting high-tunnel environments. HortTechnology 19(1): 30-33.

Hancock, J.F., J.A. Flore, and G.J. Galletta. 1989. Variation in leaf photosynthetic rates and yield in strawberries. J. Amer. Soc. Hort. Sci. 64: 449-454.

Hancock, J. and D. Simpson. 1995. Methods of extending the strawberry season in Europe. HortTechnology 5(4): 286-290.

Himmelrick, D.G., F.M. Woods, B.S. Wilkins, and J.A. Pitts. 2001. Use of floating row covers in annual hill plasticulture strawberries. Small Fruits Rev. 1(4): 63-71.

Hummel, R.L. and P.P. Moore. 1997. Freeze resistance of Pacific Northwest strawberry flowers. J. Amer. Soc. Hort. Sci. 122(2): 197-182.

Hunter, B.L. 2010. Enhancing out-of-season production of tomatoes and lettuce using high tunnels. M.S. Thesis. Utah State University, Logan, Utah.

Hutson, S.S., N.L. Barber, F.J. Kenny, K.S. Linsey, D.S. Lumia, and M.A. Maupin. 2005. United States Geological Survey estimated use of water in the United States in 2000. USGS Circular 1267. June 13, 2012 <http://water.usgs.gov/watuse/>

Kadir, S., G. Sidhu, and K. Al-Khatib. 2006. Strawberry (*Frangaria x ananassa* Duch.) growth and productivity as affected by temperature. HortScience 41(6): 1423-1430.

Koehler, G., R.C. Wilson, J.V. Goodpaster, A. Sonsteby, X. Lai, F.A. Witzmann, J. You, J. Rohloff, S.K. Randall, and M. Alsheikh. 2012. Proteomic study of low-temperature responses in strawberry cultivars (*Fragaria* x *ananassa*) that differ in cold tolerance. Plant Physiol. 159: 1787-1805.

Larson, K.D. 1994. Strawberry. p. 2-17. In: B. Schaffer, and P.C. Anderson. (eds.) Handbook of environmental physiology of fruit crops, Vol. 1, Temperate crops. CRC Press, Boca Raton, FL.

Ledesma, N. and N.Sugiyama. 2005. Pollen quality and performance in strawberry plants exposed to high-temperature stress. J. Amer. Soc. Hort. Sci. 130(3): 341-347.

Maas, J.L. 1998. Compendium of strawberry diseases. 2nd edition. The American Phytopathological Society. APS Press, St. Paul, MN.

Martinez, S., M. Hand, M. Da Pra, S. Pollack, K. Ralston, T. Smith, S. Vogel, S. Clark, L. Lohr, S. Low, and C. Newman. 2010. Local food systems: concepts, impacts, and issues. USDA, Economic Research Service. Report 97.

McMichael, B.L. and J.J. Burke. 1996. Temperature effects on root growth. p. 383-396. In: Y. Waisel, A. Eshel and U. Kafkafi (eds.). Plant roots: the hidden half. 2nd Edition. Marcel Dekker, Inc., New York.

Ndong, C., F. Ouellet, M. Houde, and F. Sarhan. 1997. Gene expression during cold acclimation in strawberry. Plant Cell Physiol. 38(7): 863-870.

Nicoll, M.F. and G. J. Galletta. 1987. Variation in growth and flowering habits of Junebearing and everbearing strawberries. J. Amer. Soc. Hort. Sci. 112: 872-880.

Nestby, R., R. Bjorgum, A. Nes, T. Wikdahl, and B. Hageberg. 2000. Winter cover affecting freezing injury in strawberry in a coastal and continental climate. J. Hort. Sci. & Biotechnol. 75(1): 119-125.

O’Neill, S.D., D.A. Priestley, and B.F. Chabot. 1981. Temperature and aging effects on leaf membranes of a cold hardy perennial, *Fragaria virginiana.* Plant Physiol. 68: 1409-1415.

Owens, C.L., M.F. Thomashow, J.F. Hancock, and A.F. Iezzoni. 2002. *CBF1* Orthologs in sour cherry and strawberry and the heterologous expression of *CBF1* in strawberry. J. Amer. Soc. Hort. Sci. 127(4): 489-494.

Rowley, D. R. 2010. Season extension of strawberry and raspberry production using high tunnels. M.S. Thesis. Utah State University. Logan, Utah.

Rowley, D., B.L. Black, and D. Drost. 2010a. Early-season extension using June-bearing 'Chandler' strawberry in high-elevation high tunnels. HortScience 45(10): 1464-1469.

Rowley, D., B.L. Black, and D. Drost. 2010b. Strawberry Plug plant production. USU Extension Factsheet #Horticulture/Fruit/2010-01pr.

Rubeiz, I.G., K.M. Nadi, M.T. Farran, and M.M. Freiwat. 1997. Rowcover effects on growth and yield of strawberry cultivars grown in a Mediterranean climate. Small Fruit and Viticult. 5(2): 47-56.

Ruelland, E., M.N. Vaultier, A. Zachowski, and V. Hurry. 2009. Cold signaling and cold acclimation in plants. Adv. in Botanical Res. 49: 36-150.

Rykbost, K.A., L. Boersma, H.J. Mack, and W.E. Schmisseur. 1975. Yield response to soil warming: Vegetable crops. Agron. J. 67: 738-743.

Singh A., A. Syndor, B.C. Deka, R.K. Singh, and R.K. Patel. 2012. The effect of microclimate inside low tunnels on off-season production of strawberry (*Fragaria* x *ananassa* Duch.). Scientia Hort. 144: 36-41.

Strand, L.L. 1994. Integrated pest management for strawberries. University of California, Statewide Integrated Pest Management Project: Publication 335.

Strik, B.C. 1984. Flower bud initiation in strawberry cultivars. Fruit Var. J. 39:5-9.

USDA-Economic Research Service. 2011. Food availability (per capita) data system. United States Department of Agriculture, Economic Research Service. May 9, 2012

<http://www.ers.usda.gov/Data/FoodConsumption/FoodAvailspreadsheets.htm#fruitfr>

USDA-National Agricultural Statistics Service. 2009. Monthly prices received by growers for fresh strawberries. National Agricultural Statistics Service, Agricultural Prices. May 5, 2012 <http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1381>

USDA- Natural Resource Ecology Laboratory. 2013. UV index. Colorado State University, Fort Collins, CO. August 15, 2013 <http://uvb.nrel.colostate.edu/UVB/uvb_dataAccess.jsf>

Utah Climate Center. 2013. Orchard weather network. River Heights – Zollinger fruit farm. September 27, 2013 <http://climate.usurf.usu.edu.>

Utah's Own. 2012. Utah farmers markets. Utah.gov services. June 14, 2012 <http://utahsown.utah.gov/farmersmarkets/index.php>

Wang, S.Y. and M.J. Camp. 2000. Temperatures after bloom affect plant growth and fruit quality of strawberry. Scientia Hort. 85(3): 183-199.

Warmund, M.R. 1993. Ice distribution in 'Earliglow' strawberry crowns and tissue recovery following extracellular freezing. J. Amer. Soc. Hort. Sci. 118(5): 644-648.

Wien, H.C., J.E. Reid, C. Rasmussen, and M.D. Orzolek. 2008. Use of low tunnels to improve plant growth in high tunnels. July 9, 2012 <http://www.hort.cornell.edu/hightunnel/about/research/general/USEOFLOWTUNNELSarticle2008.pdf >

Wright, C.J. and A.K. Sandrang. 1995. Efficiency of light utilization in the strawberry (Fragaria x ananassa) cv. Hapil. HortScience 70(5): 705-711.

Yanagi, T. and Y. Oda. 1993. Effects of photoperiod and chilling on floral formation of intermediate types between June- and everbearing strawberries. Acta Hort. 348: 339-346.

Table 1.1 Daily total incoming solar radiation (MJ/m^2) averaged by month in Cache County, Utah (Utah Climate Center, Zollinger Orchard, 2013).

	MJ/m^2		
Day	Daily Average	Min. of Month	Max. of Month
January	3.3	0.5	8.5
February	7.7	<0.01	17.6
March	15.8	5.3	24.5
April	21.8	8.4	29.3
May	26.5	9.9	32.8
June	32.2	18.7	35.2
July	28.1	6.0	34.1
August	25.1	11.2	31.2
September	20.0	3.2	25.5
October	13.6	1.5	19.7
November	8.3	1.9	13.4
December	3.4	0.9	9.7

Accessed via <http://climate.usurf.usu.edu>

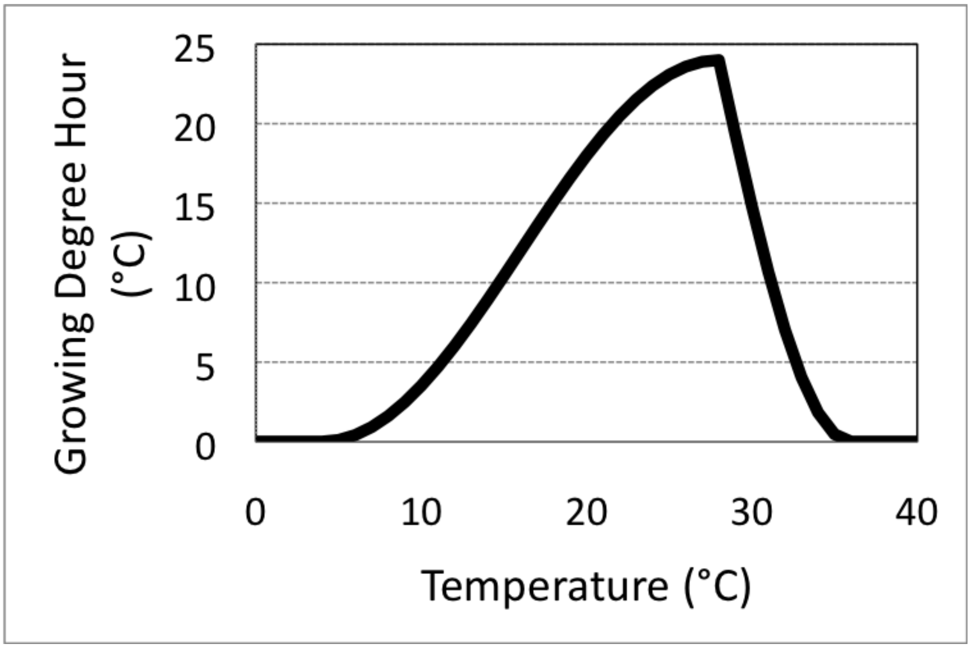

Figure. 1.1. Relationship between strawberry growth rate and temperature.

Figure. 1.2. High tunnel strawberry production (a), low tunnels with in high tunnel (b), low tunnel alone (c), floating row cover (d).

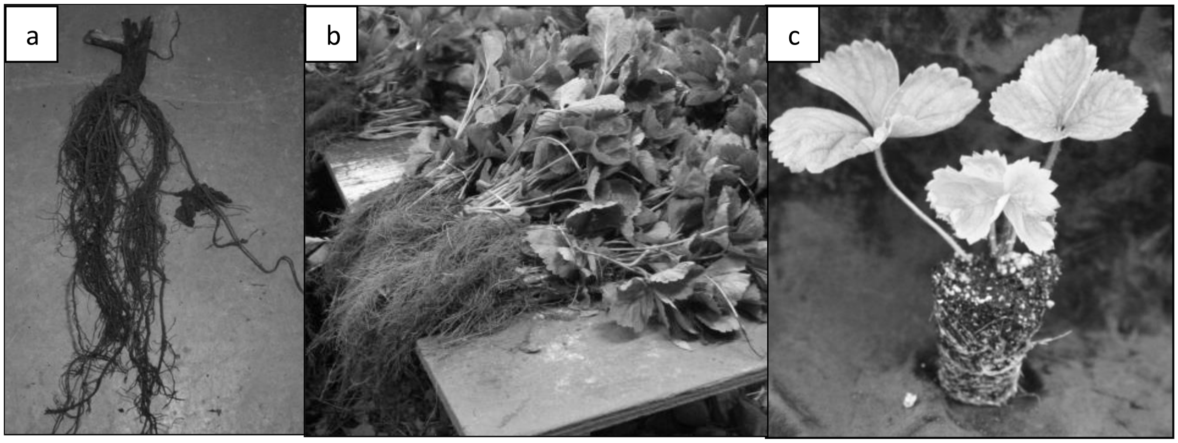

Figure. 1.3. Dormant cold-stored plant (a), fresh dug plant (b), plug plant (c).

CHAPTER 2

OPTIMIZING PLANTING DATE BY NURSERY PLANT TYPE FOR ‘CHANDLER’ AND ‘FESTIVAL’ STRAWBERRY IN INTERMOUNTAIN WEST HIGH TUNNEL PRODUCTION

Introduction

June-bearing cultivars are sensitive to and effected by photoperiod, and fall planting date has been shown to affect plant growth and yield (Albregts and Chandler, 1994; Galletta and Bringhurst, 1990; Rowley, 2010). To maximize early season fruit production, planting date optimization is necessary. Planting too early results in excessive vegetative growth, primarily unwanted runner production. Planting too late will not allow for adequate crown development. Yields are reduced with either early or late planting. Previous work by Rowley et al. (2010) determined that 1 September was the optimum planting date for fall-planted ‘Chandler’ plug plants in high elevation high tunnels in northern Utah. However, additional June-bearing cultivars were not evaluated. Nursery plant type also influences growth response. In this study we evaluated two plants types: bare-root dormant and plug plants. Cold-stored dormant plants are generally available in the spring after they are dug in the late fall and kept in cold storage over the winter. They are planted as bare-root plants and have no leaves when planted. Plug plants are rooted, have actively growing leaves, and have not been cold-stored when planted. Cold-stored bare-root transplants can have decreased success in plant establishment and plant vigor compared to rooted plug plants (Kokalis-Burelle, 2003). The research done by Rowley et al. (2010) only determined the optimum planting date for plug plant type. The optimal planting date for bare-root dormant plants is undetermined.

Our objectives were: (1) to determine if the optimum planting date for plug plants differs between selected June-bearing cultivars; (2) to determine an optimum planting date for dormant plants; and (3) compare the performance of plug and dormant plants of three June-bearing cultivars, all planted at their respective optimum dates.

Materials and Methods

Experiments were conducted in high tunnels located at the Greenville Research Farm in North Logan, Utah (41.73 N, 1382 m elevation, 119 frost free days). A 4.3 m wide by 27.4 m long high tunnel was used. The tunnel had an east/west orientation and was constructed with PVC pipe framing and covered with clear, 6 mil greenhouse grade plastic, according to the design of Black et al. (2008). This study was conducted from the fall of 2010 to spring 2011.

Site preparation. All plots were managed as a modified annual hill system. Raised beds, 60 cm wide and 20 cm high were spaced on 1.2 m centers with three beds in the tunnel. The beds were covered with 1 mil black plastic mulch. Two lines of drip tape with emitters every 10 cm (7.5 $L \cdot m^{-1} \cdot h^{-1}$) were used for irrigation and fertilization. Drip tape was placed on top of beds under the plastic mulch. Plants were spaced in 2 offset rows on the beds with 30 cm between plants in the row and between offset rows. Each row was divided into 21 six-plant plots.

Plant material. June bearing cultivars ‘Chandler’, ‘Festival’ and ‘Allstar’ were used. The plants were transplanted into the tunnels in the summer and fall of 2010 for harvest in 2011 (Table 2.1). For each of the cultivars, two plant types were evaluated:

dormant and plug. Cold-stored dormant plants were obtained from a commercial nursery (NorCal Nursery Inc., Red Bluff, CA) in the spring of 2010 and stored in a walk-in cooler at 5 ˚C until planting. Plants in cold storage were lightly watered as needed to keep roots from drying out. Planting of cold-stored dormant ‘Festival’ plants was initiated on 22 July and planting continued every 7 days until 19 August for a total of 5 planting dates. ‘Chandler’ dormant plants were planted on 29 July and 5 August (Table 2.1). A broader planting range was used for ‘Festival’ than ‘Chandler’ as the optimal planting date for ‘Chandler’ had previously been determined (Rowley, 2010) and space was limited.

Plug plants were produced as described by Rowley (2010). Briefly, cold-stored dormant plants were obtained from a commercial nursery (NorCal Nursery Inc., Red Bluff, CA) and planted into soilless media in PVC gutters placed in a greenhouse maintained at 22 °C day and 15.5 °C night. A day length of 14 hours was maintained with supplemental light from metal-halide lamps. The soilless media used was a mixture of 1:1:1 peat moss, vermiculite, and perlite. Dormant plants were allowed to establish and produce runners for approximately 10 weeks. Water soluble fertilizer (20N-10P-20K) was supplied 3 to 4 times per week at rate of 100 $mg \cdot L^{-1}$ N. Runner tips were removed from the mother plant when two trifoliate leaves were present and root initials were visible. Runner tips were immediately planted into50-cell plug trays (63 cm^3 per cell) and kept on a mist bench for 2 weeks. Plants were then removed from the mist bench and maintained under greenhouse conditions for an additional 2 to 3 weeks. Once plants had sufficient root development, they were planted in the high tunnels on the appropriate dates. Planting in the high tunnels began on 23 August and continued through 4 October, for a total of 7 planting date treatments (Table 2.1).

Fall/winter tunnel maintenance. High tunnels were covered with the plastic on 29 September, 2010. Tunnels were vented when high tunnel temperature exceeded 20 °C by either opening a small door vent in the end-walls, or completely opening one or both end doors, depending on temperature. Plots were irrigated twice each week in the fall and infrequently during the winter months, based on soil moisture. Resistance block soil moisture sensors (Watermark®, Irrometer Company, Riverside, CA) installed at 15 cm depth were used to monitor soil moisture. During the fall, 20N-20P-20K water soluble fertilizer was injected into irrigation water for a final concentration of 100 $\text{mg}\cdot\text{L}^{-2}$ N with each irrigation event. No fertilizer was applied during the winter. Wooden snow supports were used to strengthen the PVC tunnel frame against snow load, until snow could be swept off. Low tunnels were placed over individual rows within the high tunnels to provide addition frost protection during the winter months. The low tunnels were approximately 76 cm wide and 38 cm tall, and were set up in mid-November and removed around mid-May. The plastic used for low tunnels was 2 mil construction grade (non UV-stabilized). Low tunnels were vented by lifting one or both side(s) when necessary.

Spring tunnel maintenance. Tunnels were vented as described above. As temperatures increased in late May and early June, the plastic on the side of the tunnels was also lifted to allow for cross ventilation. When night temperatures consistently stayed above 5 °C (beginning of June), high tunnel plastic was removed and replaced with 40 percent light-reduction shade cloth. During the spring, 10N-30P-20K water soluble fertilizer was injected into irrigation water at a rate of 50 $\text{mg}\cdot\text{L}^{-2}$ N at every watering.

Data collection. Plants were evaluated for vegetative, as well as reproductive growth. Runners were removed as needed in the fall and weekly in the spring, with removed runners counted. The number of branch crowns per plant was recorded just before the beginning of harvest in the spring and again at the end of the production season. Ripe fruit was harvested twice weekly during the production season. Total mass of ripe fruit, average fruit size based on a 10-fruit sample, and a visual assessment of marketability were recorded. Yield data were classified as early (total mass of fruit per plant produced before the unprotected field control plants began producing) and total (total mass of fruit over the production season).

Statistical analysis. Experimental data were subjected to analysis of variance (ANOVA) by standard procedures using the PROC REGWQ in SAS (version 9.3, SAS Institute, Cary NC).

Results and Discussion

Cultivar comparison. Planting date treatment differences in early (first 5 weeks of harvest) and total (12 weeks of harvest) yields were not statistically significant at $P \leq 0.05$ for ‘Festival’ or ‘Chandler’. However, the general trend was similar to that previously reported (Rowley et al., 2010), where ‘Festival’ plugs planted on 30 August had the highest early and total yield of the 7 planting dates (Fig. 2.1). Total and early yields for ‘Chandler’ plugs were similar across all planting dates, with a slight decrease for the latest planting dates (Fig. 2.2). The 30 August ‘Festival’ planting date also had the highest crown number per plant of that cultivar (Table 2.2) although again, not statistically significantly. ‘Chandler’ plugs planted on 30 August (Table 2.1) also had the highest number of crowns per plant, but only differed statistically from the latest planting date, 4 October. For both ‘Festival’ and ‘Chandler’ there was no significant difference in number of fall runners produced per plant among planting dates. For both cultivars, the timing window was not as defined in the 2010-2011production cycle as was observed in previous years (Rowley et al., 2010), and this broader window appears to have been typical of the fall 2010 conditions. However, these results suggest that the optimum planting date of 1 September that was previously defined for Chandler plugs is consistent for a second June-bearing cultivar.

Dormant plant optimum planting date. Dormant planting dates ranged over 5 weeks, from 22 July to 19 August. These dates were selected relative to the plug planting dates, based on the assumption that bare-root dormant plants require a one-month longer establishment period than plug plants (N. Nourse, personal communication). Figure 2.3 compares the effect of planting date on early (first 5 weeks of harvest) and total yield (12 weeks of harvest) for dormant ‘Festival’ plants. The 29 July planting date resulted in significantly higher early and total yield than the other 4 planting dates ($P = 0.010$ and 0.012, respectively). The remaining 4 planting dates did not have significantly different early or total yields. 29 July had the highest final crown per plant and second lowest runners per plant of dormant planting dates (Table 2.3). These results confirm the recommendation that an optimum planting date for cold-stored dormant plants is approximately one month earlier than the plug plant optimum.

Plant types and cultivars. The three cultivars compared were ‘Chandler’, ‘Festival’ and ‘Allstar.’ Plug plants were planted on 30 August, and dormant plants were planted on 29 July. Each cultivar was from a different region of the United States. ‘Chandler’ was selected in California for adaptation to mild maritime climates, and is a major worldwide cultivar with high yields (Hancock, 1999). ‘Festival’ was selected in Florida for adaptation to low light winter production (Chandler et al., 2000). ‘Allstar’ was selected in Maryland for the mid-Atlantic and Midwestern US production. ‘Chandler’ had significantly higher total yield per plant (*P* = 0.028) than ‘Festival’ and ‘Allstar’ for dormant plant type and had significantly higher yield than ‘Allstar’ for plug plant types (*P* = 0.033). There was no significant difference among plant type or cultivars for final crown per plant (*P* = 0.75 and = 0.31 respectively, Table 2.4). For fall runners producer per plant there was no significant difference among cultivars (*P* = 0.62) but dormant plants produced significantly more runners than did plug plants (*P* = 0.003). However, there was a large difference in both runner number and plant survival among plant types. Plug plant type had slightly higher plant survival and total yield than dormant plants. ‘Chandler’ is recommended as it had the highest yields of the three cultivars tested and plug plant type maybe the best option due to high yield per plant, plant survival, and lack of runners.

Conclusion

‘Festival’ plug plants had the same optimal planting date as ‘Chandler’ plug plants, 30 August. This is in agreement with previously published results. Optimal planting date for dormant June-bearing strawberries is 29 July, approximately 4 weeks earlier than the optimal planting date for plug plants. Of the three cultivars planted, ‘Chandler’ had the highest total yield per plant and there was no difference in number of crowns per plant or runners produced.

Literature Cited

Albregts E.E. and C.K. Chandler. 1994. Effect of transplant chilling and planting date on fruiting response of 4 strawberry clones. Proc. Florida State Hort. Soc. 107: 323-325.

Black, B.L, D. Drost, D. Rowley, and R. Heflebower. 2008. Constructing a low-cost high tunnel. Utah State University Cooperative Extension. Publication 9739.

Chandler, C.K., D.E. Legard, D.D. Dunigan, T.E. Crocker, and C.A. Sims. 2000. ‘Strawberry Festival’ strawberry. HortScience 35: 1366-1367.

Galletta, G.J. and D.G. Himmelrick. 1990. Small fruit crop management. Prentice Hall, Englewood Cliffs, NJ.

Hancock, J.F. 1999. Chapter 6, Cultural systems. In: Strawberries. CABI Publishing, University Press. Cambridge, UK.

Kokalis-Burelle, N. 2003. Effects of transplant type, plant growth-promoting rhizobacteria, and soil treatment on growth and yield of strawberry in Florida. Plant and Soil 256: 273-280.

Rowley, D.R. 2010. Season extension of strawberry and raspberry production using high tunnels. M.S. Thesis. Utah State University. Logan, Utah.

Rowley, D., B.L. Black, D. Drost, and D. Feuz. 2010. Early-season extension using June-bearing ‘Chandler’ strawberry in high-elevation high tunnels. HortScience 45(10): 1464-1469.

Table 2.1 Treatment combinations included in the 2010-2011 comparison of cultivars, plant types and planting dates.

Cultivar	Type	Planting dates
Chandler	Dormant	29-Jul, 5-Aug
	Plug	23-Aug, 30-Aug, 6-Sept, 13-Sept, 20-Sept, 27-Sept, 4-Oct
Festival	Dormant	22-Jul, 29-Jul, 5-Aug, 12-Aug, 19-Aug
	Plug	23-Aug, 30-Aug, 6-Sept, 13-Sept, 20-Sept, 27-Sept, 4-Oct
Allstar	Dormant	29- Jul, 5-Aug
	Plug	30-Aug

Table 2.2 Effect of planting date on end of season crown number and fall runners for 'Festival' and 'Chandler' plug plants.

	Branch Crowns (#/plant)		Fall Runners (#/plant)	
Planting Date	Chandler	Festival	Chandler	Festival
23-Aug	6.2	5.2	0.7	0.4
30-Aug	6.9	6.2	0.6	0.6
6-Sep	6.6	4.4	0.2	0.2
13-Sep	5.9	5.3	0.0	0.1
20-Sep	5.2	4.2	0.0	0.2
27-Sep	5.0	3.3	0.0	0.3
4-Oct	4.4*	4.7	0.1	0.1
Analysis of Variance		*P*		
Planting date	0.013	0.198	0.445	0.264

* indicates significantly different from numbers within column at $P \leq 0.05$.

Table 2.3. Effect of planting date on end of season crown number and fall runners of 'Festival' dormant plants.

Planting date	Crown/plant	Fall Runner/plant
22-Jul	5.5	2.6
29-Jul	6.9	3.9
5-Aug	6.3	5.9
12-Aug	6.6	4.4
19-Aug	5.6	4.2

Number in same column not significantly different at $P \leq 0.05$.

Table 2.4. Comparison of total yield, final crown number, fall runners and plant survival for three June-bearing cultivars.

		Total yield (g/plant)	Final crowns (#/plant)	Fall runners (#/plant)	Survival (%)
Plug	Chandler	498a	6.9a	0.6a	99%a
	Festival	335a	6.2a	0.5a	97%a
	Allstar	200b	5.2a	0.3a	100%a
Dormant	Chandler	283a	5.1a	3.1b	92%a
	Festival	229b	6.9a	3.9b	71%b
	Allstar	207b	5.5a	2.3b	100%a
	Analysis of Variance			*P*	
	Plant Type	<0.073	0.748	0.618	0.045
	Cultivar	0.032	0.310	0.003	0.115

Numbers within a column followed by the same letter are not significantly different at P≤0.05.

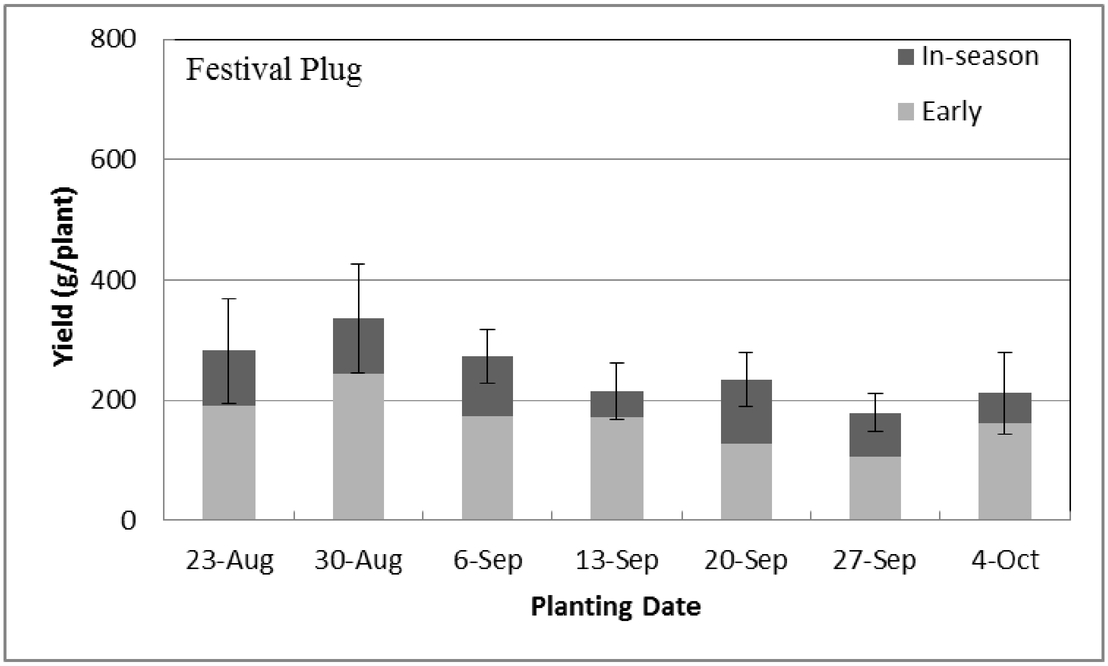

Figure 2.1. Effect of planting date on early (first 5 weeks of harvest) and in-season (last 7 weeks of harvest) yield of 'Festival' plug plants. Vertical bars represent standard error of the mean.

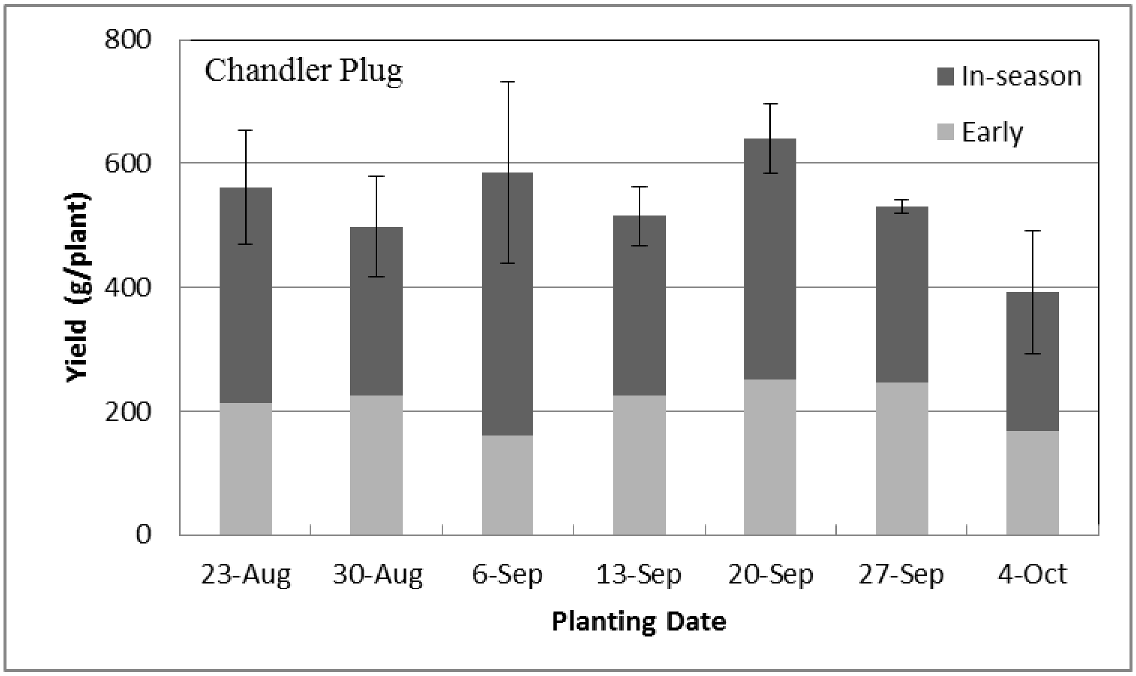

Figure 2.2. Effect of planting date on early (first 5 weeks of harvest) and in-season (last 7 weeks of harvest) yield for ‘Chandler’ plug plants. Vertical bars represent standard error of the mean.

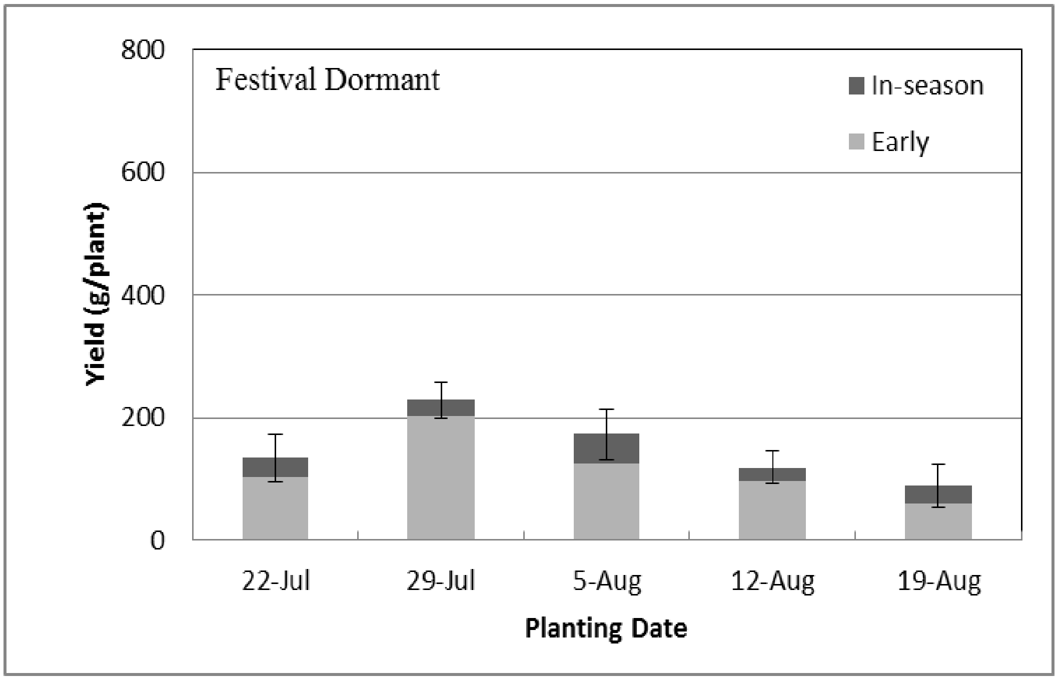

Figure. 2.3. Effect of planting date on early (first 5 weeks of harvest) and in-season (last 7 weeks of harvest) yield for ‘Festival’ dormant plants. Vertical bars represent standard error of the mean.

CHAPTER 3

HIGH TUNNELS, LOW TUNNELS AND ROOT ZONE HEATING FOR ENVIRIONMENTAL MANIPULATION OF COLD-CLIMATE STRAWBERRY PRODUCTION

Abstract. Spring strawberry production in the Intermountain West region of the United States is limited by harsh climatic conditions, with frequent spring frosts that kill blossoms, super-optimal summer temperatures and short falls. Unlike production in northeastern North America, overhead irrigation for frost protection is not an option due to limited water availability. Tunnels can be used to provide frost protection and extend the growing season. Research was conducted to evaluate and compare the effectiveness of low tunnels, high tunnels and supplemental root zone heating for cold protection of ‘Chandler’ and ‘Seascape’ strawberries. Three nursery plant types, dormant, fresh dug and plug were also evaluated. Low tunnels were not able to increase early or total yield above unprotected field production. High tunnel and low tunnels inside high tunnels had significantly higher early and total yields than field production, but there was no significant difference between high tunnel only and low tunnels inside high tunnels. There was no difference in early or total yield per plant between the two temperatures tested for in-ground supplemental heating (7 and 15 °C), but heat treatments had significantly higher early and total yield than the high tunnel only treatment for both dormant and fresh dug plant types. For the 15 °C heating treatment, the first day of harvest was earlier than high tunnel production by 6.8 and 6.2 weeks in 2012 and 2013 respectively. The higher potential profits from early season direct-market strawberries

may justify the added inputs of tunnels and root zone heating to protect blossoms and advance fruit harvest.

Introduction

Strawberry production in Utah is limited by harsh climatic conditions. High elevations and semi-arid conditions result in large diurnal temperature fluctuations during spring and fall that limit fruit production in many parts of the state. The optimal temperature for strawberry growth is between 20 and 26 ˚C (Darrow and Waldo, 1934). Temperatures in many parts of Utah do not stay in this optimal range for very long, and are either sub- or super-optimal for most of the year. Additionally, spring frost events are common in Utah. As strawberry blossoms are susceptible to damage below -1 ˚C (Hummel and Moore, 1997; Maas, 1998), frost protection is often needed to maintain viability of early flowers. Primary blossoms are the first to open on the inflorescence and therefore have the highest risk of frost damage. Primary blossoms also produce the largest, highest quality fruit (Galletta and Himmelrick, 1990). Once the primary blossom is lost, the remaining fruit do not grow large enough to compensate for the lost fruit and there is a reduction in yield (Boyce et al., 1985). In order to maximize yield in the Intermountain West these blossoms need to be protected.

High tunnels have been used successfully to extend the growing season and protect against frost events in the Intermountain West (Rowley, 2010). High tunnels are relatively inexpensive greenhouse-like structures constructed with PVC pipe or galvanized steel and covered with plastic. They are heated as short wave radiation from the sun enters the high tunnel and is absorbed by the soil and plants. The plastic traps the heat that dissipates from the covered plants and soil in the form of conduction and convection, as well as emitted long wave radiation, and the tunnel air temperature increases. In this way, high tunnels are able to increase air temperature above ambient by as much as 30 °C during the day and 1 to 3 °C at night (Wien et al., 2008).

Low tunnels, as the name implies, are a smaller version of a high tunnel and are usually only large enough to cover the strawberry bed and plant canopy. Clear plastic is suspended over plants using either sturdy wire or pipe. Low tunnels can be used singly or in conjunction with a high tunnel. When combined with a high tunnel, they can provide an additional 3 to 5 ˚C increase in night temperature (Wien et al, 2008). When low tunnels are used alone, they are less expensive compared to the high tunnel/low tunnel combination, but provide less day/night increase above ambient air temperature. Ariza et al. (2012) found no significant difference in early or total yield, nor in fruit quality of strawberry between high tunnel and low tunnel protection systems in a Mediterranean climate in Spain.

Strawberry plants need adequate fall crown development for high spring yields. High tunnels both protect from fall frosts and extend optimum growing conditions to improve crown development prior to winter dormancy. Low tunnels are not sturdy enough to support a snow load and are not installed until early spring. As a result, plants grown under a low tunnel system may not have as well developed branch crowns as plants under a high tunnel. Although this may result in lower total yield per plant, the reduction in material costs between the systems may justify the comparatively lower-input low tunnel system. This would particularly be true if spring frost protection is adequate.

High tunnels are typically not heated, a major distinguishing factor between tunnels and greenhouses. However, targeted supplemental heating has been used in tunnel production of spinach and tomato to further extend the season and increase yield (Ernst, 2012; Hunter, 2010). Soil temperature is an important factor of strawberry growth. The minimum temperature for active root growth is 5 ˚C and the maximum is 31 ˚C (Bowen, 1991) with an optimum temperature range of 10 to 23 ˚C (Larson, 1994). Soil heating has been successfully used in unprotected field strawberry production to increase yield over unheated treatments (Rykbost et al., 1975) but we are not aware of any studies evaluating soil heating for high tunnel strawberry production.

Using the appropriate nursery plant type and planting date is also critical to obtaining adequate fall crown development. There are three nursery plant types that can be used for strawberry production: bare-root dormant, fresh dug and plug plants. Each plant type has some advantages and disadvantages. Bare-root dormant plants are widely available and fairly inexpensive, but have been in storage for approximately 9 months by the time they are planted in the late summer. This long storage period may reduce plant survival. Fresh dug plants are also widely available but not until late October, which may be past the optimal planting date for the Intermountain West. Both dormant and fresh dug types are shipped as bare root plants. Plug plants are not widely available commercially, and may need to be produced on site (Rowley et al., 2010b), or production contracted through a local nursery. Of the three types, plug plants are also the most expensive. However, as actively growing rooted plantlets, they are vigorous and high yielding (Durner et al., 2002).

The objectives of this study were: (1) to determine whether a low tunnel only system is as effective as low tunnels plus high tunnels for alleviating spring frost damage in the Intermountain West region of the United States; (2) to evaluate the effectiveness of targeted supplemental heat on strawberry early and total yield; and (3) to determine an optimum nursery plant type among plug, dormant and fresh dug; for both June-bearing (‘Chandler’) and a day-neutral (‘Seascape’) cultivar.

Materials and Methods

This study was conducted in North Logan, Utah at the Greenville Research Farm (41.73 N, 1382 m elevation, 119 frost free days). Two 4.3 m wide by 27.4 m long tunnels were used. They were covered with clear, 6 mil, greenhouse grade plastic according to the design of Black et al. (2008). A field area adjacent to the high tunnels was used for low tunnel treatments and field production comparisons. Treatments were planted in fall 2011 for harvest in the spring and summer of 2012. The treatments were replanted in the fall of 2012 for harvest in 2013.

Site preparation. All plots were managed as a modified annual hill system. Raised beds, 60 cm wide and 20 cm high were spaced on 1.2 m centers. The beds were covered with 1 mil black plastic mulch. Two lines of drip tape with emitters every 10 cm (7.5 $L \cdot m^{-1} \cdot h^{-1}$) were used for irrigation and fertilization. Drip tape was placed on top of beds under the plastic mulch. Plants were spaced in 2 offset rows on the beds with 30 cm between plants in the row and between offset rows.

Plant Material. Two cultivars were used for all plantings: ‘Chandler’ a June-bearing type and ‘Seascape’ a day-neutral type. Three nursery plant types were evaluated:

cold-stored dormant plants, fresh dug plants, and plug plants. Bare root, cold-stored dormant plants were obtained from a commercial nursery (NorCal Nursery Inc., Red Bluff, CA) in spring 2011 and 2012, and stored in a walk-in cooler at 5 ˚C until planting. Plants in storage were lightly watered as needed to keep roots from drying out. Fresh dug plants were purchased from two commercial nurseries (NorCal Nursery Inc., Red Bluff, CA in 2011; Lassen Canyon Nursery, Redding, CA in 2012) as soon as they became available in the fall. Plug plants were produced as described by Rowley et al. (2010b). Briefly, cold-stored dormant plants were obtained from two commercial nurseries and planted into soilless media in PVC gutters placed in a greenhouse maintained at 22 °C day and 15.5 °C night. The soilless media used was a mixture of 1:1:1 peat moss, vermiculite, and perlite. Dormant plants were allowed to establish and produce runners for approximately 10 weeks. Water soluble fertilizer (20N-10P-20K) was supplied in the irrigation water 3 to 4 times per week at a rate of 100 $mg \cdot L^{-1}$ N. Runner tips were removed from the mother plant when two trifoliate leaves were present and root initials were visible. Runner tips were immediately planted into 62.5 cm^3 plug trays and kept on a mist bench for 2 weeks. Plants were then removed from the mist bench and maintained under greenhouse conditions for an additional 2 to 3 weeks. Once plants had sufficient root development, they were planted in the high tunnels.

Low tunnel construction. The outdoor low tunnels (Fig. 3.1a) were constructed in the early spring (approximately 1 May) with hoops made from 8 gauge high tensile trellis wire (Wilson Irrigation, Yakima, WA) and covered with clear, 1 mil UV-stabilized plastic (Trickl-Eez Company, Biglerville, PA). Low tunnels within the high tunnels were constructed approximately 1 November using 1.3 cm diameter conduit pipe. The conduit was bent in two places to form a square arch and placed over the strawberry beds approximately 76 cm wide and 38 cm tall. Clear, 2 mil construction grade plastic was placed over the conduit to form the low tunnels (Fig. 3.1b).

In-ground supplemental heating. In selected treatment plots, heavy duty electric heating cables (Wrap-On Company Inc., Bedford Pak, IL) were buried approximately 3 cm below the soil surface of the raised bed in a serpentine pattern with 3 cables per plot, and secured with landscape fabric pins. Strawberry plants were placed in between heat cable so the heat cable ran along both sides of the plant, 5 cm (approximately) away from the crown. The cable in each plot was attached to a thermostat with a remote soil sensor that was positioned at 3 cm depth, 4 to 5 cm from the nearest cable. Cables were activated to heat when soil temperature dropped below 7 or 15 °C, depending on the plot. To monitor electrical use, thermostats were attached to a watt meter (Kill-a-Watt, P3 International, New York, NY). Each heated plot (whether 7 or 15 °C) was covered with a high tunnel plus low tunnel.

Data collection. Plants were evaluated for vegetative, as well as reproductive growth. Runners were removed and counted weekly each spring, and as needed in the fall. In the spring and again at the end of the production season, the number of branch crowns per plant was recorded. Ripe fruit was harvested twice weekly during the production season. Total mass of ripe fruit, average fruit size based on a 10-fruit sample, and a visual assessment of marketability was recorded. Yield data were categorized as ‘early’ (total fruit mass produced per plant before the beginning of production in the unprotected field plots) and ‘total’ (total fruit mass produced over the entire season).

The amount of labor hours needed to perform individual tasks related to strawberry production was recorded daily. Labor hours and material costs were used to update an existing high tunnel enterprise budget and develop partial budgets comparing protection systems (Chapter 4).

Statistical design. The high tunnel experiment was conducted using a split-plot design with the presence or absence of a low tunnel, and the presence or absence of heating cables as the main plot treatments. Strawberry cultivar (‘Chandler’ and ‘Seascape’) and plant type (dormant, fresh dug, and plug) were sub-plot treatments. The adjacent outside field area was configured as a split plot design with the presence or absence of a low tunnel as the main plot treatment and the strawberry cultivars (‘Chandler’ and ‘Seascape’) and plant types (dormant and plug) as the sub-plot treatments. No fresh dug plants were planted in the outside field area due to late availability.

Data analysis. Data were analyzed using the PROC GLM procedure of the SAS statistical analysis software (version 9.3, SAS Institute, Cary NC) with a statistical significance threshold of $P \leq 0.05$. The REGWQ method was used to make multiple comparisons.

Results and Discussion

Yields in 2013 were extremely low, likely due to extreme temperature events occurring on 14 January, 31 March, and 14 April 2013 (Table 3.1). In January 2013 outside air temperature was below -20 °C for 7 consecutive nights (17 to 23 January). Even with tunnel protection, plants were exposed to temperatures below -10 °C every night. Strawberry crowns are damaged at about -6 °C and killed at -12 °C (Galletta and Himmelrick, 1990). Leaf photosynthetic activity is lost when temperatures drop below -5 °C (Chapter 6). On 31 March, temperatures were abnormally high for that time of year (20 °C), accompanied by high light levels (peak flux of 14.8 MJ m^2). Unfortunately, this corresponded with a failure to ventilate the high tunnel and low tunnels within the high tunnel. Air temperature in the high tunnel (HT) and under the low tunnel in the high tunnel (HT+LT) reached 49 °C and 59 °C, respectively. Damage to strawberry tissue occurs at 35 °C (Arney, 1953; Carlen et al., 2009). Finally, a late spring freeze on 14 April resulted in air temperature inside the HT of -4.7 °C and -0.4 °C under the HT+LT, killing many of the open blossoms that had survived the previous heat event. The combination of these events reduced the yield in 2013 across all high tunnel treatments to about 10% of that observed in previous years. As a result, the following discussion primarily focuses on the 2012 production season.

High and low tunnel. Low tunnel only (LT) did not provide any benefit above the unprotected field control (UFC) in either 2012 or 2013. In 2012, there was no statistically significant difference in total yield per plant between the two treatments or plant types (P = 0.56 and 0.94 respectively) for ether cultivar tested (Table 3.2). There was a significant interaction (P = 0.006) between cultivar and plant type with 'Chandler' dormant having significantly lower total yield per plant than 'Chandler' plug and 'Seascape' dormant having significantly higher total yield per plant than 'Seascape' plug (Table 3.2). The lack of increase of yield under LT may be due to the low tunnel design used (Fig. 3.1a). Low tunnel plastic was tightly stretched over wire hoops to keep the plastic in place in the wind. However, the tightly stretched plastic did not remain in contact with the soil along the edges, and could be blown up above the raised bed on windy nights, losing accumulated heat and exposing the plants to ambient air temperature. In 2013, the low tunnels in the field were modified to alleviate this problem, but low tunnels still did not have significantly higher total yield per plant (Table 3.2)

For both ‘Chandler’ and ‘Seascape’ there was no significant difference between high tunnel only (HT) and high tunnel plus low tunnel (HT+LT) for early or total yield ($P = 0.23$ and $P = 0.11$, respectively). The lack of yield increase under the HT+LT treatment was surprising, as a temperature benefit above that of the HT was observed under the HT+LT treatment on most nights (Fig. 3.2), which was in agreement with observations by Wien et al. (2008). Low tunnels were ventilated during the day to avoid excess heat accumulation. However, a lack of significant benefit of HT+LT could be due the relatively mild spring in 2012 where the air temperature within the high tunnel only went below -2 °C twice from 1 March to 31 April (data not shown). Without severe frosts, the high tunnels were able to provide the needed frost protection and the low tunnels were not necessary on most nights. However, in a more extreme year (such as 2013), low tunnels may be more vital for additional frost protection.

In 2012, both ‘Chandler’ and ‘Seascape’ high tunnel treatments had higher total yield than unprotected field control (UFC) and low tunnel treatments (‘Chandler’ HT plug and dormant were 670 and 389 g/plant higher than UFC, respectively. A similar increase was seen with ‘Seascape’). These yield data are included only for reference, as the high tunnel treatments were run as separate experiments and therefore statistical comparison between HT to UFC is not possible. Previous work by Rowley et al. (2010a) also found a significant benefit of high tunnels over field production. Hancock and

Simpson (1995) found low tunnels cool off much faster at night than high tunnels, which has also been observed at this location (Ernst, 2012). This may have contributed to the lower yields seen under the LT treatment. Ariza et al. (2012) saw no difference between low and high tunnels when used in a Mediterranean climate. Similarly, low tunnels have been found to be effective in northeastern India (Singh et al., 2012). Our findings differ from these and suggest that low tunnels alone may not be suited for strawberry production in areas with more extreme weather conditions such as the Intermountain West.

In-ground supplemental heating. Soil heating was used in conjunction with high tunnel plus low tunnel at two temperature set points: 7 and 15 °C. Overall main treatment (presence or absence of heating) was significant ($P = 0.005$), but there was no significant difference between the two heating treatments for total yield (Table 3.3) among all plant types and cultivars tested ($P = 0.068$ and $P = 0.74$, respectively). For ‘Seascape,’ there was a significant increase of total yield over HT with the addition of soil heating for each plant type. However, ‘Chandler’ only had a significant increase in total yield for dormant and fresh dug plant types. The lack of significance in the plug plant type was due to an abnormally high total yield for the ‘Chandler’ HT plots (Table 3.3).

There was no significant difference among heating treatments ($P = 0.85$) or cultivar ($P = 0.13$) in spring crown number per plant (Table 3.4). There was a significant difference among plant types ($P < 0.0001$). The lack of significance between heating temperatures was somewhat surprising. Wang and Camp (2000) saw the best root growth under an 18 °C day/12 °C night temperature regime. Rykbost et al. (1975) used heated water at temperatures ranging from 25 to 40 °C to warm field soil, and they saw a significant increase in yield and plant canopy growth. The 7 °C set point used here is much lower than these temperatures and below the optimum temperature range for root growth of 10 to 23 °C (Larson, 1994). The similar performance between 7 and 15 °C heating treatments in total and early yield per plant suggest that the benefits of increasing root zone temperature can be achieved with a lower level of input. The 7 °C heating treatments used 82% less energy than the 15°C heating treatments (290 kWh vs 1592 kWh) over approximately 5 months of heating.

Early and total yield per plant are indicators of overall season performance. Time course analysis allows for a closer look at in-season performance. Figure 3.3 shows a yield time course for the heating treatments for each plant type in 2012. Interestingly, although there was no significant difference between the two heating treatments for early or total yield, the 15 °C heating treatment moved the first day of harvest forward for plug, dormant and fresh dug plant types compared to the 7 °C heating treatment (Table 3.5). The 15 °C heating treatment advanced ‘Chandler’ by an average across plant types of 3.1 weeks and advanced ‘Seascape’ by 3.4 weeks earlier than 7 °C heating treatment (Table 3.5). The first day of harvest was moved forward similarly in 2013, where 15 °C heating treatment advanced ‘Chandler’ plug and fresh dug harvests by 4.9 and 3.7 weeks, compared to the 7 °C heating treatment, respectively. The 15 °C heating treatment of ‘Seascape’ plug and fresh dug were 4.5 and 4.2 weeks earlier than 7 °C heating treatment, respectively. Averaged across all nursery plant types, the 15 °C heating treatment moved the first day of harvest earlier than the high tunnel-only treatments by 6.8 weeks in 2012 and by 6.2 weeks in 2013.

Plant type and cultivar. In 2012, there was a significant difference between total yield (Tables 3.2 and 3.3) for ‘Chandler’ and ‘Seascape’ ($P = 0.034$) with Seascape having a higher mean by 87.8 g/plant, or 20% percent. As expected for day-neutral cultivars, ‘Seascape’ produced fruit later into the summer than the June-bearing cultivar ‘Chandler’. However, a major objective of protected cultivation is early production, as early strawberries can be sold at a higher price, and may be more important to profitability than total yield. Production season can be compared based on early yields (Table 3.5), defined as production that occurs before outside strawberry production begins (on 22 May), or based on the date of first harvest. ‘Chandler’ had slightly higher early yields than ‘Seascape’, although differences were not statistically significant ($P = 0.18$). In 2012, ‘Seascape’ had earlier first day of harvest than ‘Chandler’ by an average of 1.5 week, with some variability among treatments (Table 3.5). Similarly, in 2013 ‘Seascape’ had an average first day of harvest 1 week earlier than ‘Chandler’ (data not shown). Crown number is an indicator of plant establishment. As with early and total yield, ‘Chandler’ had significantly more crowns per plant at the beginning of the season (counted 1 May) than ‘Seascape’ ($P = 0.003$).

Dormant and plug plant types did not differ in early or total yield per plant in 2012, but both were significantly higher than fresh dug plants ($P < 0.0001$). This was also seen with crown number per plant. Although dormant and plug plant types performed similarly in yield per plant, yield per planted area differed due to plant survival effects that altered final plant density (Fig. 3.1). ‘Chandler’ dormant treatments only had 40% survival, compared to 95% for ‘Chandler’ plug plants. If survival rate is considered, high tunnel ‘Chandler’ dormant plants produce 1.14 $kg \cdot m^{-2}$ and plug plants produce 3.23 $kg \cdot m^{-2}$ (Table 3.6), when averaged across presence or absence of low tunnel treatments. When plant survival is taken into account, it is clear that dormant plants have much lower yield per tunnel area than plug plants. This agrees with findings by Kokalis-Burelle (2003) who noted decreased stand establishment and plant vigor with dormant bare-root plant types. Survival of bare-root fresh dug plants was still very high for both cultivars, although the first day of harvest was delayed relative to plug (Table 3.5). Dormant plants produced significantly more fall runners per plant than the plug or fresh dug plant types for both cultivars ($P = 0.0001$). These runners need to be removed to promote crown development (Galletta and Himmelrick, 1990), representing an additional labor cost for the dormant plant system.

Conclusion

Low tunnels alone did not increase yield or vegetative development for either cultivar tested. High tunnel significantly increased both early and total yield compared to unprotected field control and low tunnel systems. Low tunnels combined with a high tunnel did not significantly increase yield over high tunnel protection but this may have been due to a mild spring in 2012. ‘Chandler’ had higher early yields than ‘Seascape,’ but did not have significantly different total yield. Plug and dormant plant types did not have significantly different per plant yields, but when plant survival was considered, plug plant plots yielded 183% more than dormant plant plots. Dormant plants also produced more fall runners than plug plants. The lower cost for dormant plants could only be justified if initial plant survival and establishment could be significantly improved, and runners could be efficiently removed or controlled. For the Intermountain West, it is recommended to use ‘Chandler’ plug plants under high tunnel or high tunnel combined with a low tunnel system.

In-ground supplemental heating significantly increased early yields above HT alone for ‘Chandler’ and ‘Seascape’ dormant and fresh dug plant types, but not significantly for plug plant type. Total yield was increased significantly for ‘Chandler’ dormant and fresh dug and all three plant types for ‘Seascape’. There was no significant difference for early or total yield per plant between 7 and 15 °C heating treatments. Harvest of 15 °C heating treatments was an average of 3.8 weeks earlier than for 7 °C heating, and 6.3 week earlier than the unheated high tunnel treatment. Without a significant difference between heating levels, the lower (7 °C) heating treatment is recommended. However, to meet a very early market demand, the use of 15 °C heating may be warranted.

Literature Cited

Ariza M.T., C. Soria, J.J. Medina-Minguez, and E. Martinez-Ferri. 2012. Incidence of misshapen fruits in strawberry plants grown under tunnels is affected by cultivar, planting date, pollination, and low temperatures. HortScience 47(11): 1569-1573.

Arney, S.E. 1953. Studies of growth and development in the genus *Fragaria*. I. Factors affecting the rate of leaf production in Royal Sovereign strawberry. HortScience 28: 73-84.

Black, B.L, D. Drost, D. Rowley, and R. Heflebower. 2008. Constructing a low-cost high tunnel. Utah State University Cooperative Extension. Publication 9739.

Bowen, G.D. 1991. Soil temperature, root growth, and plant function. p. 309-330. In: Y. Waisel, A. Eshel and U. Kafkafi (eds.). Plant roots: the hidden half. 1st Edition. Marcel Dekker, Inc. New York, NY.

Boyce, B.R., A.L. Hazelrigg, and A.W. Linde. 1985. Field evaluation of loss of primary or primary and secondary blossoms on strawberry fruit weight and yield. Adv. Strawberry Production 4: 32-33.

Carlen, C., A.M. Potel and A. Ancay. 2009. Photosynthetic response of strawberry leaves to changing temperatures. Acta Hort. 838: 73-76.

Darrow, G.M. and G.F. Waldo. 1934. Responses of strawberry varieties and species to duration of the daily light period. USDA Technical Bulletin 453, Washington DC.

Durner, E.F., E.B. Poling, and J.L. Maas. 2002. Recent advances in strawberry plug transplant technology. HortTechnology 12(4): 545-550.

Durner, E.F., J.A. Barden, D.G. Himmelrick and E.B. Poling. 1984. Photoperiod and temperature effects on flower and runner development in day-neutral, junebearing, and everbearing strawberries. J. Amer. Soc. Hort. Sci. 109(3): 396-400.

Ernst, T. 2012. Optimizing winter spinach production in high tunnels. M.S. Thesis. Utah State University, Logan Utah.

Galletta, G.J. and D.G. Himmelrick. 1990. Small fruit crop management. Prentice Hall, Englewood Cliffs, New Jersey.

Hancock, J. and D. Simpson. 1995. Methods of extending the strawberry season in Europe. HortTechnology 5(4): 286-290.

Hummel, R.L. and P.P. Moore. 1997. Freeze resistance of Pacific Northwest strawberry flowers. J. Amer. Soc. Hort. Sci. 122(2): 197-182.

Hunter, B.L. 2010. Enhancing out-of-season production of tomatoes and lettuce using high tunnels. M.S. Thesis. Utah State University, Logan Utah.

Kokalis-Burelle, N. 2003. Effects of transplant type, plant growth-promoting rhizobacteria, and soil treatment on growth and yield of strawberry in Florida. Plant and Soil 256: 273-280.

Larson, K.D. 1994. Strawberry. In: B. Schaffer and P.C. Anderson, (eds.). Handbook of environmental physiology of fruit crops, Vol. 1, Temperate Crops. CRC Press, Boca Raton, FL.

Maas, J.L. 1998. Compendium of strawberry diseases. 2nd edition. The American Phytopathological Society. APS Press, St. Paul, MN.

Rowley, D. R. 2010. Season extension of strawberry and raspberry production using high tunnels. M.S. Thesis. Utah State University. Logan, Utah.

Rowley, D., B.L. Black, and D. Drost. 2010a. Early-season extension using June-bearing ‘Chandler’ strawberry in high-elevation high tunnels. HortScience 45(10): 1464-1469.

Rowley, D., B.L. Black, and D. Drost. 2010b. Strawberry plug plant production. USU Extension Factsheet #Horticulture/Fruit/2010-01pr.

Rykbost, K.A., L. Boersma, H.J. Mack, and W.E. Schmisseur. 1975. Yield response to soil warming: Vegetable crops. Agronomy J. 67: 738-743.

Singh A., A. Syndor, G.C. Deka, R.K. Singh, and R.K. Patel. 2012. The effect of microclimate inside low tunnels on off-season production of strawberry (*Fragaria* x *ananassa* Duch.). Scientia Hort. 144: 36-41.

Wang, S.Y. and M.J. Camp. 2000. Temperatures after bloom affect plant growth and fruit quality of strawberry. Scientia Hort. 85(3): 183-199.

Wien, H.C., J.E. Reid, C. Rasmussen, and M.D. Orzolek. 2008. Use of low tunnels to improve plant growth in high tunnels. July 9, 2012 <http://www.hort.cornell.edu/hightunnel/about/research/general/USE%20OF%20LOW%20TUNNELS%20article%202008.pdf.>

Table 3.1. Temperature extremes (°C) on three dates in 2013 for the outside ambient air temperature at 0.9 m above ground level (Outside), high tunnel air temperature at canopy level (HT) and air temperature at canopy level under high tunnel and low tunnel (HT+LT).

	Outside	HT	HT+LT
14-Jan	-28.03	-13.82	-11.1
31-Mar	20.06	49.21	59.1
14-Apr	-7.01	-4.73	-0.425

Temperature was monitored using thermocouples connected to a CR 1000 data logger (Campbell Scientific, Logan, UT).

Table 3.2. Effect of low tunnel only (LT) on total per plant yield (g/plant) for 'Chandler' and 'Seascape' in 2012 and 2013.

		Treatment	Plug	Dormant
2012	Chandler	UFC	101*	26.3
		LT	91.6*	66.3
	Seascape	UFC	105	154*
		LT	110	157*
	Analysis of variance	*P*		
	Low Tunnel	0.565		
	Cultivar	0.001		
	Type	0.937		
	Cultivar*Type Interaction	0.006		
2013	Chandler	UFC	105	
		LT	66.7	
	Seascape	UFC	84.3	
		LT	33.0	
	Analysis of variance	*P*		
	Low Tunnel	0.066		
	Cultivar	0.457		
	LT*Cultivar Interaction	0.951		

*indicates significant difference from values within the same row.

Table 3.3. Effect of low tunnels and supplemental heating on total yield in 2012, expressed as g/plant.

		Plug	Dormant	Fresh Dug
			(g/plant)	
Chandler	HT only	771a	643b	41c
	HT+LT	628b	730b	120b
	7°C+HT+LT	901a	862a	166a
	15°C+HT+LT	924a	963a	240a
Seascape	HT only	495c	725b	173b
	HT+LT	710b	1014a	326a
	7°C+HT+LT	587b	1064a	255a
	15°C+HT+LT	628b	940a	295a

Analysis of variance	*P*
LT & Heating	0.005
Cultivar	0.402
Type	<0.001
Cultivar*Type Interaction	0.031

Numbers within a column followed by same letter are not significantly different at $P \leq 0.05$.

Table 3.4. Effect of supplemental heating on spring crown number in 2012. Crown counts were collected in early May.

		2012		
	Treatment	Plug	Dormant	Fresh Dug
Chandler	HT only	6.6	6.6	2.1*
	LT+HT	6.2	5.6	2.4*
	LT+HT+45	7.2	6.1	2.7*
	LT+HT+60	6.1	5.9	2.3*
Seascape	HT only	4.6	5.1	1.9*
	LT+HT	4.2	7	2.5*
	LT+HT+45	4.2	6	2.3*
	LT+HT+60	4.2	5.6	2.1*

Analysis of variance	*P*
LT & Heating	0.851
Cultivar	0.129
Type	<0.001

* indicates number is significantly different within row at $P \leq 0.05$.

Table 3.5. Effect of supplemental heating on early yield (g/plant prior to 22 May) and first day of harvest in 2012.

		Plug		**Dormant**		**Fresh Dug**	
Year	Treatment	Early Yield (g/plant)	First day of harvest	Early Yield (g/plant)	First day of harvest	Early Yield (g/plant)	First day of harvest
Chandler	HT	410.8a	20-Apr	310.3b	1-May	32.7b	20-Apr
	HT+LT	294.7b	10-Apr	288.5b	17-Apr	54.9b	13-Apr
	HT+LT+7°C	431.9a	8-Mar	396.9a	3-Apr	77.1a	28-Mar
	HT+LT+15°C	493.2a	17-Feb	543.0a	2-Mar	130.3a	19-Mar
Seascape	HT	183.0b	28-Mar	249.7b	17-Apr	52.1b	17-Apr
	HT+LT	246.5b	23-Mar	384.1a	19-Mar	83.4a	28-Mar
	HT+LT+7 °C	187.3b	24-Feb	366.6a	19-Mar	79.1a	23-Mar
	HT+LT+15°C	245.0b	17-Feb	445.0a	24-Feb	90.8a	24-Feb

Analysis of variance	*P*
LT & Heating	<0.001
Cultivar	0.006
Type	<0.001

Numbers within a column followed by same letter are not significantly different at $P \leq 0.05$.

Table 3.6. Effect of low tunnels and supplemental heating on total yield in 2012. Values are expressed as kg/m^2.

		Plug	**Dormant**	**Fresh Dug**
		kg/m^2	kg/m^2	kg/m^2
Chandler	HT only	3.28a	1.52b	0.17c
	HT+LT	2.77a	1.42b	0.56c
	7°C+HT+LT	4.01a	2.15b	0.74c
	15°C+HT+LT	3.55a	2.59b	1.09c
Seascape	HT only	2.66a	1.74b	0.91c
	HT+LT	3.02a	2.91b	1.53c
	7°C+HT+LT	3.14a	2.04b	1.19c
	15°C+HT+LT	3.25a	2.41b	1.37c

Analysis of variance	*P*
LT & Heating	0.008
Cultivar	0.155
Type	<0.001

Numbers within a row followed by same letter are not significantly different at $P \leq 0.05$.

Figure 3.1 Unprotected field control and low tunnels suspended above raised beds (a), and low tunnels inside a high tunnel (b). Outside low tunnels were constructed using UV-stabilized plastic, and tensioned against the wind. Low tunnels inside the high tunnels were constructed using non UV-stabilized construction grade plastic and were draped loosely across supports.

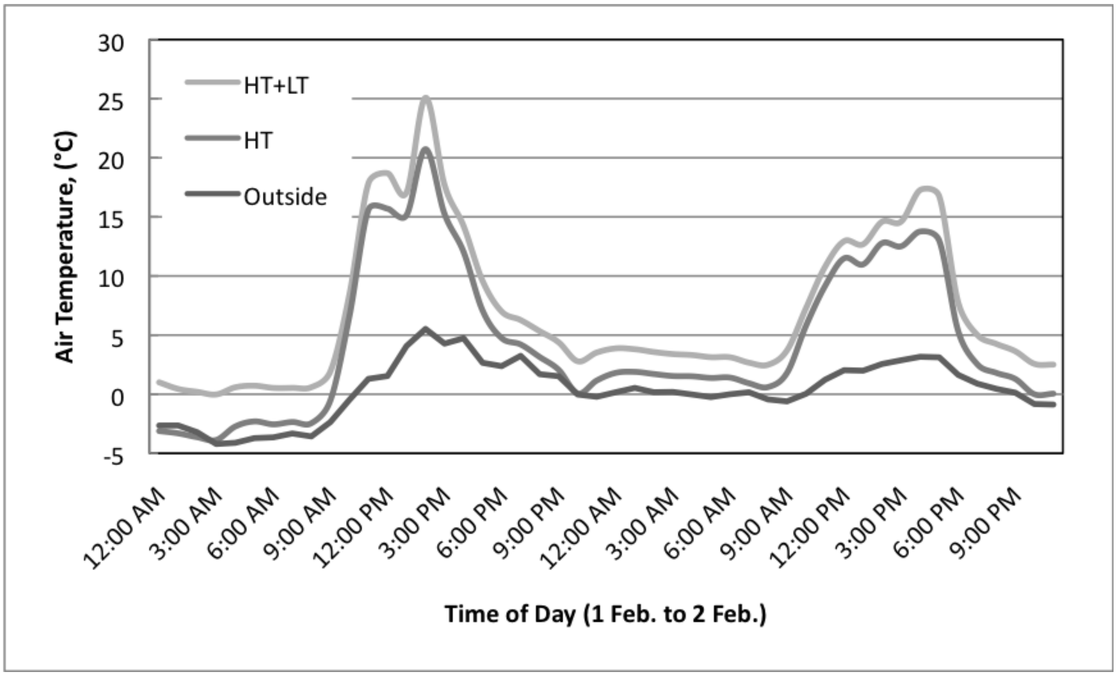

Figure 3.2. Effect of high tunnel (HT) and high tunnel plus low tunnel (HT+LT) on air temperature at canopy level compared to outside ambient air temperature 0.9 m above the ground (Outside) in 2012.

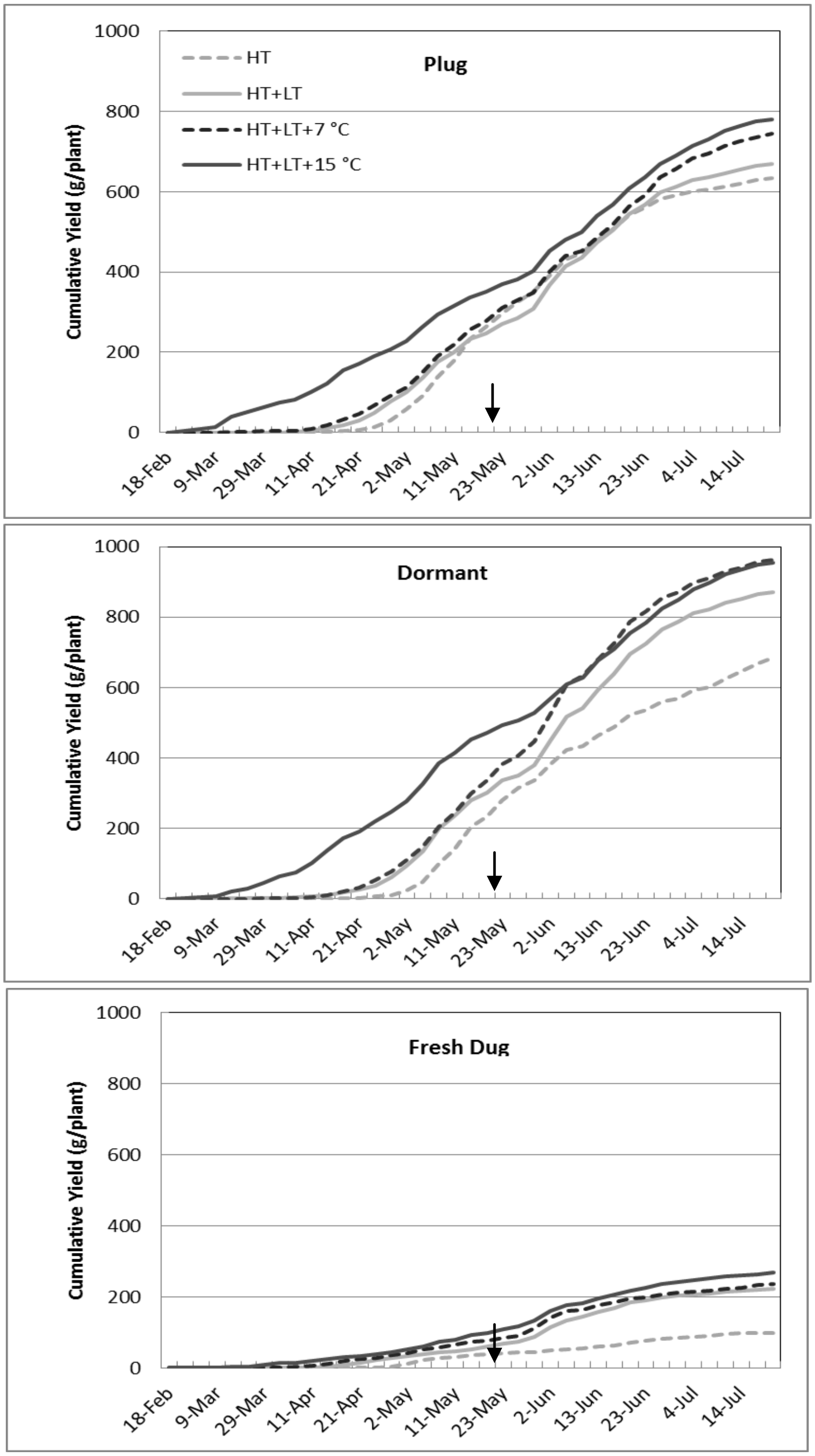

Figure 3.3. Effect of supplemental heating on cumulative yield by plant type, averaged across cultivars in 2012. Arrow represents beginning of production in unprotected field plots.

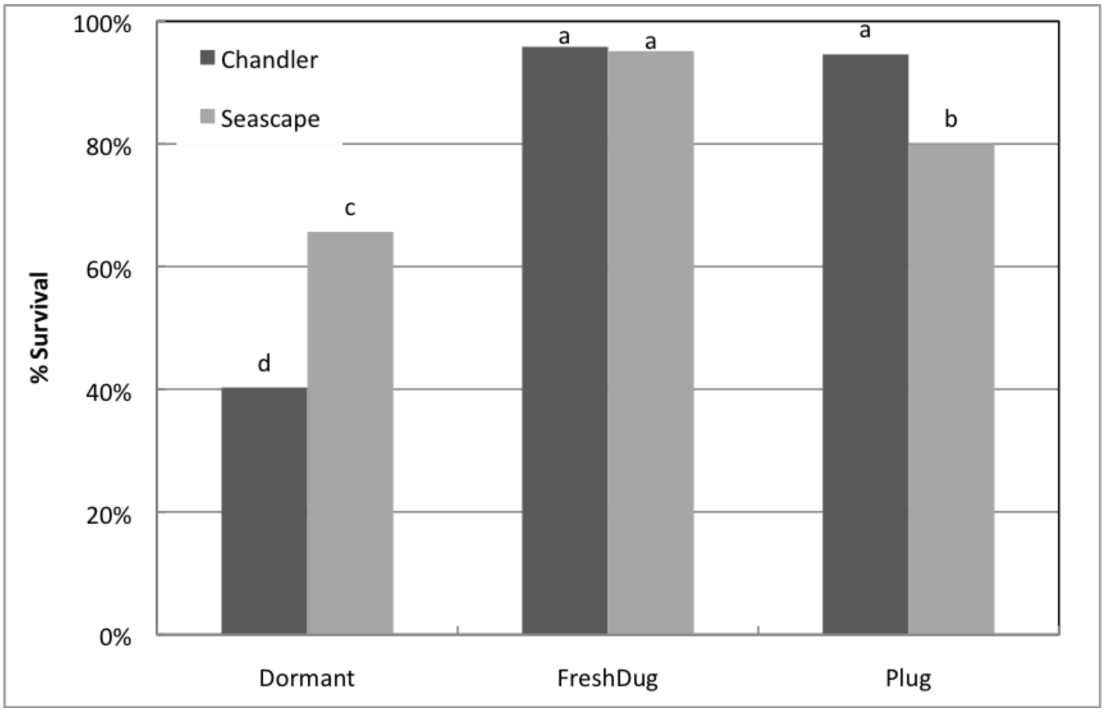

Figure 3.4. Comparison of plant survival among 2 cultivars with 3 plant types: dormant, fresh dug, and plug. Survival rates based on plants alive per 6-plant plot on 22 July, 2012 and were averaged across heating and low tunnel treatments.

CHAPTER 4

ECONOMIC EVALUATION OF ADDED HIGH TUNNEL PROTECTION SYSTEMS: LOW TUNNEL AND IN-GROUND SUPPLIMENTAL HEATING

Introduction

The Intermountain West region has not historically been a major producer of strawberries. However, increased consumer demand for local products, as evidenced by the growing locavore movement (Martinez et al., 2010), will likely provide an expanding market for locally produced strawberries. The existence of a local market may encourage increased commercial production of strawberries. However, the region’s harsh semi-arid climate and relatively short growing season limit strawberry production to only about 6 weeks in the spring. Consumer interest in buying local foods has spurred research on methods to successfully supply produce for longer periods of the year in areas with climate limitations. One method used is a high tunnel a plastic covered, unheated greenhouse-like structure that can be inexpensively constructed (Wells and Loy, 1993). The use of a high tunnel has successfully provided frost protection and increased the normal 6 week strawberry production window in the Intermountain West by approximately 4 weeks (Rowley et al., 2010a). This season extension method provides growers with a longer period to sell fruit, but also may increase profits. Consumers are willing to pay a price premium for out of season produce when sold in direct markets such as farmer’s markets and road-side stands (Foord, 2004). Previous research conducted in the Intermountain West found strawberry production in high tunnels to be economically viable (Rowley, 2010).

Low tunnels are similar to high tunnels and provide another method of providing frost protection (Chapter 3; Ernst, 2012). Low tunnels are also covered with plastic, but are smaller than high tunnels, with plastic suspended just above the canopy of the plant and commonly only cover one row. Low tunnels can be used in conjunction with a high tunnel, providing an additional 3 to 5 ˚C increase in night temperature (Wien et al., 2008). During the day, temperature elevation may be significantly more depending on light levels and without proper ventilation can cause excessive temperatures that can be damaging. A third option is to provide supplemental heat in the soil. This can be accomplished through buried hot water lines or electric soil heating cables. Heating the soil to optimal soil temperatures moves the harvest earlier in the year and may increase yields (Chapter 3; Rykbost et al., 1975).

Each of the above methods (high tunnel, low tunnel and supplemental heating) has an addition cost above unprotected field production. This chapter includes an enterprise budget for high tunnel strawberry production (Table 4.1) which is revised and updated from a previously published budget for the region (Rowley, 2010). Also included are partial budgets (an economic tool used to calculate the effect on profits of a change in the operation) comparing high tunnel production with a high tunnel plus low tunnel system (Tables 4.3 and 4.4), and unheated high tunnel production with in-ground supplemental heating used in conjunction with a high tunnel plus low tunnel system (Tables 4.5 and 4.6). The high tunnel budget is based on an annual hill strawberry production system at the USU Greenville Research Farm in North Logan, UT. Plants are fall planted into raised beds covered with plastic mulch, cared for over the winter, and the plants produce in the spring and removed in mid-July.

Budget sections. Revenues were divided into two sections: early out-of season strawberries, and in-season strawberries. Early yield was calculated as the total mass yield produced before non-protected field production begins. Early strawberries typically command price premiums over in-season production. When the field (unprotected) strawberries begin yielding, local supply increases and the total price per pound is lowered. In limited test marketing in Logan Utah, a $1.50 per pound premium was common for the early, out of season early strawberries. Based on interviews with some strawberry growers in Utah, budgets were calculated at $4.50 per pound for in season and $6.00/pound for early season strawberries (Day, personal communication, 2013; Meikle, personal communication, 2013; Weeks, personal communication, 2013). Price per pound will vary by market and geographical area, thus users of this information should use these numbers as an approximate guide. Yield data (quantity of one pound clamshells) from productivity data were collected in North Logan, UT and averaged over a three year period for the enterprise budget and all ‘Chandler’ partial budgets. Over the three seasons, the field production season began between 1 May and 12 May. Early production ranged from 0.5 to 0.9 pounds per plant.

Production supplies were priced based on costs in Logan, UT and may vary across regions. Plug plants are not commercially available in the Intermountain West and are not amenable to shipping over long distances so must be either produced on site (Rowley, 2010b) or production contracted through a local nursery. Supplies ordered from online sources will have an additional shipping cost. The enterprise budget is calculated for one

14’x96’ high tunnel. However, prices listed on per acre basis are calculated assuming 20 tunnels per acre (Ward et al., 2011).

Labor was priced at $10.00 per hour, though this may vary among operations. Quantity of hours needed per activity was recorded and averaged over a two year period, although depending on tools and experience time needed may vary.

Asset depreciation (high tunnel, low tunnel and heat cables) was calculated using straight line depreciation and assumed no salvage value at the end of the useful life (Tables 4.2 and 4.7). Total cost of investment was divided by number of years the asset is assumed to be useful resulting in the annual depreciation cost. High tunnel useful life is 6 years and the initial cost of the high tunnel was based on the low-cost high tunnel design used at Utah State University (Black et al., 2008). High tunnel cost will vary depending on design and materials used. Low tunnel and in-ground supplemental heating cost was also calculated based on low tunnels and heat cables used at the Greenville Research Farm (Chapter 3). As seen in the enterprise budget (Table 4.1), net income was estimated at $1,944.27 per 96’ high tunnel (or $38,885.38 per acre) when quantity of one pound clamshells was averaged over three years.

High tunnels vs. high tunnel+low tunnel

A partial budget comparing the costs and returns of a high tunnel only system (HT) and a high tunnel plus low tunnel system (HT+LT) was prepared for two cultivars: ‘Seascape’ (Table 4.3) and ‘Chandler’ (Table 4.4). Yield per plant for HT was a three year average and yield per plant for HT+LT was based off of 2012 data only as 2013 yields were severely limited due to environmental factors (Chapter 3). For ‘Seascape’ plug plantings the HT+LT had a $1,144.11 per 96’ high tunnel higher net income than HT (Table 4.3). However, ‘Chandler’ HT+LT did not have a higher yield than the HT and actually had $537.84 less return than the high tunnel only system (Table 4.4). This was only seen in that year and may be an anomaly in the data.

Unheated vs heated high tunnel+low tunnel

A partial budget comparing an unheated high tunnel (HT+none) to a high tunnel plus low tunnel with in-ground supplemental heating was prepared. Two temperatures, 7 and 15 °C (HT+LT+7 and HT+LT+15 respectively), were evaluated and can be seen in Table 4.5 (‘Chandler’) and Table 4.6 (‘Seascape’). Again, yield per plant for HT+none averaged over three years (2011-2012) and yield per plant for heated treatments was based on 2012 data. For both cultivars and both heating levels (7 and 15 °C), net income was increased with the application of supplemental heating over HT+none. The increase over HT+none was more dramatic for ‘Chandler’ than ‘Seascape,’ but for both cultivars the difference between supplemental heating temperatures was fairly small, a $133.15 higher net income for HT+LT+15 over HT+LT+7 for ‘Chandler’ (Table 4.5) and a $255.15 higher net income for ‘Seascape’ (Table 4.6) per 96’ tunnel. These findings may justify the use of supplemental heating in high tunnel strawberry production in the Intermountain West.

Price per pound was based on an equal price throughout the early season. However, heating cables shifted the production season earlier than the HT+none production (Chapter 3). Earlier fruit could potentially command even higher price premiums depending on market conditions and further increase the profitability of using supplemental heating.

Conclusions

High tunnels are a profitable method of producing strawberries in the Intermountain West when sold through direct market outlets. Additionally, adding low tunnels and supplemental heating at both 7 and 15 °C can further increase net income. The use of a high tunnel plus low tunnel combination may be justified, depending on cultivar and year. These frost protection methods (high tunnel, high tunnel plus low tunnel, and supplemental heating) should be considered for extending the season, increasing yields and therefore, net income for strawberry growers in the Intermountain West region.

Literature Cited

Black, B., D. Drost, D. Rowley, and R. Heflebower. 2008. Constructing a low-cost high tunnel. Utah State University Extension bulletin # HG/High Tunnels/2008-01pr. Utah State University, Logan UT. <http://extension.usu.edu/files/publications/publication>

Ernst, T. 2012. Optimizing winter spinach production in high tunnels. M.S. Thesis. Utah State University, Logan Utah.

Foord, K. 2004. High tunnel marketing and economics. Regents of the University of Minnesota. M1218. June 13, 2012 <http://www.extension.umn.edu/distribution/horticulture/components/M1218-12.pdf>

Martinez, S., M. Hand, M. Da Pra, S. Pollack, K.Ralston, T. Smith, S. Vogel, S. Clark, L. Lohr, S. Low, and C. Newman. 2010. Local food systems: concepts, impacts, and issues. USDA, Economic Research Service. Report 97.

Rowley, D.R. 2010. Season extension of strawberry and raspberry production using high tunnels. M.S. Thesis. Utah State University, Logan, Utah.

Rowley, D., B.L. Black, and D. Drost. 2010a. Early-season extension using June-bearing ‘Chandler’ strawberry in high-elevation high tunnels. HortScience 45(10): 1464-1469.

Rowley, D., B.L. Black and D. Drost. 2010b. Strawberry plug plant production. USU Extension Factsheet #Horticulture/Fruit/2010-01pr. Utah State University, Logan UT. <http://extension.usu.edu/files/publications/publication>

Rykbost, K.A., L. Boersma, H.J. Mack, and W.E. Schmisseur. 1975. Yield response to soil warming: Vegetable crops. Agronomy Journal 67: 738-743.

Ward, R., D. Drost, and A. Whyte. 2011. Assessing profitability of selected specialty crops grown in high tunnels. Journal of Agribusiness 29(1):41-58.

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

Wien, H.C., J.E. Reid, C. Rasmussen and M.D. Orzolek. 2008. Use of low tunnels to improve plant growth in high tunnels. July 9, 2012 <http://www.hort.cornell.edu/hightunnel/about/research/general/USEOFLOWTUNNELSarticle2008.pdf>

Table 4.1. High tunnel June-bearing strawberry enterprise budget for a 14' x 96' tunnel.

		1- 96 ft tunnel		
Revenues	Units	Quantity	unit Price	Total
Early Out-of Season Strawberries	1 lb clamshells	373	$6.00	$2,238.70
In-Season Strawberries	1 lb clamshells	472	$4.50	$2,122.61
Total Revenues				$4,361.31
Operating Expenses				
Supplies				
Preplant and preparation costs				
Soil test	Each	1	$14.00	$14.00
Fuel	Gal	0.38	$3.50	$1.31
Preplant fertilizers and soil amendments	Lbs	2.25	$15.00	$33.75
Plastic mulch	Ft	281	$0.05	$14.06
Drip tape	Ft	576	$0.05	$28.80
Strawberry establishment and growth				
Plug plants	Each	743	$0.26	$193.05
20-20-20 water soluable fertilizer mix	Lbs	11.34	$1.23	$13.95
10-30-20 water soluable fertilizer mix	Lbs	2.84	$1.49	$4.22
Captan	Lbs	0.43	$9.82	$4.20
Thionex 50 W	Lbs	0.03	$7.51	$0.20
Strawberry harvest				
1 lb clamshells	Each	1033	$0.25	$258.19
Total Supplies				**$565.73**
Labor				
Preplant and preperation costs				
Soil test	Hours	0.5	$10.00	$5.00
Apply preplant fertilizers	Hours	0.75	$10.00	$7.50
Tillage	Hours	7.5	$10.00	$75.00
Form raised beds	Hours	13	$10.00	$130.00
Install drip tape	Hours	0.75	$10.00	$7.50
Cover with plastic mulch	Hours	1	$10.00	$10.00
Strawberry establishment and growth				
Planting labor	Hours	6	$10.00	$60.00
Fertigation	Hours	2	$10.00	$20.00
Pesticide applications	Hours	4.5	$10.00	$45.00
Hand weeding	Hours	4	$10.00	$40.00
Plastic and shade cloth install/removal	Hours	12	$10.00	$120.00
Monitoring and ventilation	Hours	30	$10.00	$300.00
Strawberry harvest				
Hand harvest	Hours	68	$10.00	$680.00
Post-harvest				
House clean out	Hours	4.5	$10.00	$45.00
Total Labor				**$1,545.00**
Total Operating Expenses (supplies and labor)				**$2,110.73**
Fixed Expenses (Depreciation)				
High Tunnel Annual				$248.17
Irrigation System Annual				$58.82
Total Fixed Expenses				**$306.98**
Total Expenses				**$2,417.71**
Net Income				**$1,944.27**

Table 4.2. Annual depreciation for high tunnel structure and irrigation system.

	Units	Useful Life (yrs)	Quantity	Unit Cost	Total
High Tunnel					
High Tunnel	Each	6	1	$497.00	$497.00
High Tunnel Construction Labor	Hours	6	25	$10.00	$250.00
6 mil Greenhouse Film	24'x100' sheet	3	2	$221.00	$442.00
Shade Cloth	20' x 100' piece	6	1	$300.00	$300.00
High Tunnel Total					$1,489.00
Annual Depreciation Cost of High Tunnel					**$248.17**
Irrigation system					
3/4" Poly Pipe	Ft	6	14	$0.42	$5.88
1" Valve	Each	6	1	$5.15	$5.15
Misc. Fittings	Each	6	10	$1.00	$10.00
Drip Hose Adapter	Each	6	6	$0.56	$3.36
Injector*	Each	6	1	$265.00	$265.00
Filter*	Each	6	1	$12.50	$12.50
Pressure Regulator*	Each	6	1	$11.00	$11.00
Installation*	Hours	6	4	$10.00	$40.00
Irrigation System Total					$352.89
Annual Depreciation Cost of Irrigation System					**$58.82**

*can be used for multiple high tunnels

Table 4.3. Partial budget comparing high tunnel strawberry production with high tunnel + low tunnel production for 'Seascape'.*

Revenues	
High Tunnel Only	
Early Out-of Season Strawberries	$ 1,336.21
In-Season Strawberries	$ 1,705.86
High Tunnel Only Total	$ 3,042.07
High Tunnel + Low Tunnel	
Early Out-of Season Strawberries	$ 1,799.87
In-Season Strawberries	$ 2,536.61
High Tunnel + Low Tunnel Total	$ 4,336.49
Costs	
Added Costs of Low Tunnel	
Annual Supplies	
Bailing Twine	$ 8.55
Labor	
Installation and Removal (7.75 hrs)	$ 77.50
Annual Depreciation of Low Tunnel*	$ 64.25
Total	$ 150.30
Resulting Change in Net Income	
Difference in Revenue	$ 1,294.41
Difference in Costs	$ (150.30)
Total Change	**$ 1,144.11**

*Annual depreciation costs detailed in Table 4.7

Table 4.4. Partial budget comparing high tunnel strawberry production with high tunnel + low tunnel production for 'Chandler'.

Revenues				
	High Tunnel Only			
		Early Out-of Season Strawberries		$2,238.70
		In-Season Strawberries		$2,122.61
	High Tunnel Only Total			$4,361.31
	High Tunnel + Low Tunnel			
		Early Out-of Season Strawberries		$ 2,151.81
		In-Season Strawberries		$ 1,821.96
	High Tunnel + Low Tunnel Total			$ 3,973.77
Costs				
	Added Costs of Low Tunnel			
		Annual Supplies		
			Bailing Twine	$ 8.55
		Labor		
			Installation and Removal (7.75 hrs)	$ 77.50
		Annual Depreciation of Low Tunnel*		$ 64.25
	Total			$ 150.30
Resulting Change in Net Income				
	Difference in Revenue			$ (387.54)
	Difference in Costs			$ (150.30)
Total Change				**$ (537.84)**

*Annual depreciation costs detailed in Table 4.7

Table 4.5. Comparison of the effect of supplemental root zone heating at 7 and 15 °C on ‘Chandler’ June-bearing Strawberry.

Partial budget comparing **'Chandler'** high tunnel+low tunnel strawberry production with and without the use of **7 °C** supplemental heating.	
Revenues	
Unheated High Tunnel	
Early Out-of Season Strawberries	$2,238.70
In-Season Strawberries	$2,122.61
Unheated Total	$ 4,361.31
Heated High Tunnel + Low Tunnel	
Early Out-of Season Strawberries	$ 3,154.34
In-Season Strawberries	$ 2,568.38
Heating Total	$ 5,722.72
Costs	
Added Costs of Low Tunnel	$ 150.30
Added Costs of Heating	
Supplies (Annual cost)	
Electricity	$ 23.20
Labor	
Installation and Removal (3.5 hrs)	$ 35.00
Annual Depreciation of Heating Tape*	$ 93.46
Total Additional Costs	$ 301.96
Resulting Change in Net Income	
Difference in Revenue	$ 1,361.40
Difference in Costs	$ (301.96)
Total Change	**$ 1,059.45**

Partial budget comparing **'Chandler'** high tunnel+low tunnel strawberry production with and without the use of **15 °C** supplemental heating.	
Revenues	
Unheated High Tunnel	
Early Out-of Season Strawberries	$2,238.70
In-Season Strawberries	$2,122.61
Unheated Total	$ 4,361.31
Heated High Tunnel + Low Tunnel	
Early Out-of Season Strawberries	$ 3,599.74
In-Season Strawberries	$ 2,360.28
Heating Total	$ 5,960.02
Costs	
Added Costs of Low Tunnel	$ 150.30
Added Costs of Heating	
Supplies (Annual cost)	
Electricity	$ 127.36
Labor	
Installation and Removal (3.5 hrs)	$ 35.00
Annual Depreciation of Heating Tape*	$ 93.46
Total Additional Costs	$ 406.12
Resulting Change in Net Income	
Difference in Revenue	$ 1,598.71
Difference in Costs	$ (406.12)
Total Change	**$ 1,192.59**

*Annual depreciation costs detailed in Table 4.7.

Table 4.6. Comparison of the effect of supplemental root zone heating at 7 and 15 °C on ‘Seascape’ day-neutral strawberry.

Partial budget comparing **'Seascape'** high tunnel+low tunnel strawberry production with and without the use of **7 °C** supplemental heating.

Revenues	
Unheated High Tunnel	
Early Out-of Season Strawberries	$ 1,336.21
In-Season Strawberries	$ 1,705.86
Unheated Total	$ 3,042.07
Heated High Tunnel + Low Tunnel	
Early Out-of Season Strawberries	$ 1,365.42
In-Season Strawberries	$ 2,191.61
Heating Total	$ 3,557.03
Costs	
Added Costs of Low Tunnel	$ 150.30
Added Costs of Heating	
Supplies (Annual cost)	
Electricity	$ 23.20
Labor	
Installation and Removal (3.5 hrs)	$ 35.00
Annual Depreciation of Heating Tape*	$ 93.46
Total Additional Costs	$ 301.96
Resulting Change in Net Income	
Difference in Revenue	$ 514.95
Difference in Costs	$ (301.96)
Total Change	**$ 213.00**

*Annual depreciation costs detailed in Table 4.7.

Partial budget comparing **'Seascape'** high tunnel+low tunnel strawberry production with and without the use of **15 °C** supplemental heating.

Revenues	
Unheated High Tunnel	
Early Out-of Season Strawberries	$ 1,336.21
In-Season Strawberries	$ 1,705.86
Unheated Total	$ 3,042.07
Heated High Tunnel + Low Tunnel	
Early Out-of Season Strawberries	$ 1,788.92
In-Season Strawberries	$ 2,097.42
Heating Total	$ 3,886.34
Costs	
Added Costs of Low Tunnel	$ 150.30
Added Costs of Heating	
Supplies (Annual cost)	
Electricity	$ 127.36
Labor	
Installation and Removal (3.5 hrs)	$ 35.00
Annual Depreciation of Heating Tape*	$ 93.46
Total Additional Costs	$ 406.12
Resulting Change in Net Income	
Difference in Revenue	$ 844.26
Difference in Costs	$ (406.12)
Total Change	**$ 438.14**

Table 4.7. Annual depreciation for low tunnel and supplemental heating material.

	Units	Useful Life (yrs)	Quantity	Unit Cost	Total
Low Tunnel					
2 mil Plastic for Low Tunnels	8' x 300' Sheet	2	3	$ 81.00	$ 243.00
Low Tunnel Supports (1/2" conduit)	Each	6	30	$ 1.65	$ 49.50
1/2"X24" rebar	Each	6	60	$ 1.55	$ 93.00
Low Tunnel Total					$ 385.50
Annual Depreciation Cost of Low Tunnel					**$ 64.25**
Additional Heating					
Heat Cables					
Cables (250' HD. Gro-Quick)	Each	3	3	$ 154.27	$ 462.81
Thermostat	Each	6	1	$ 89.95	$ 89.95
Extension Cord (20')	Each	6	1	$ 7.98	$ 7.98
Additional Heating Total					$ 560.74
Annual Depreciation Cost of Heat Cables					**$ 93.46**

CHAPTER 5

DEFENDING THE CASTLE: INTEGRATED PEST MANAGEMENT IN HIGH TUNNEL STRAWBERRIES (USU EXTENSION FACTSHEET)[1]

In recent years, the use of high tunnels for extending the growing season has become fairly widespread. High tunnels operate and look like greenhouses, but are passively heated and cooled which helps keep operating costs low. They are temporary structures typically constructed with galvanized steel, PVC pipe, or wood framing and covered with greenhouse grade plastic. Even without additional heating, high tunnels can be 15-30˚F warmer than the outside air temperature during the day. This temperature increase extends the growing season earlier into the spring and later in the fall. Extending the season can significantly increase the amount of produce grown, increasing profits. In areas where season extension is not as critical, high tunnels are often used for rain exclusion and wind protection. Insect and disease pest management differs in high tunnels as compared to field production. Following is an outline of integrated pest management for high tunnel strawberries; however, the concepts presented hold true for many high tunnel fruit and vegetable crops.

Integrated Pest Management (IPM) is a comprehensive approach to pest control that uses a combination of methods to keep pests at tolerable levels while maintaining a quality environment. An effective IPM program requires four steps. *First*, know your pest, disease, or plant health problems. Knowing which pests to monitor for and how to identify them (either by the insect itself, frass, damage, or symptoms) is critical for

---

[1] Coauthored by T. Ernst, Dr. B. L. Black and Dr. D. Drost

proper IPM implementation. Correctly identifying diseases can be challenging. Monitor for pathogens by looking for characteristic signs and symptoms. If needed, samples can be sent to pathology labs for identification. *Second*, decide upon the level of crop damage that is unacceptable for your situation. Although it may be tempting to leap for the sprayer at the first sign of damage, it is important to determine if the number of pests present warrant a control action. *Third*, consider all available management practices. A successful pest management system integrates chemical, biological, cultural, and mechanical control methods. *Finally*, time insect and disease control actions to correspond with points during the pest or disease life cycle when they are most susceptible to controls.

IPM in high tunnels. While high tunnel IPM practices differ significantly from field pest control there are similarities between greenhouse and high tunnel IPM. Many IPM practices used in greenhouse production can be implemented within a high tunnel. Both can utilize biological control methods effectively in their enclosed environments. Pesticides listed for greenhouse use are also safe for a high tunnel, however the enclosed environment may prolong pesticide residual activity and potential exposure for workers. Therefore, soft pesticides, such as insecticidal soaps or horticultural oils, may be more appropriate.

Despite similarities of high tunnels to greenhouses, there are several important differences. Greenhouse production uses sterile potting media while high tunnel plants are often grown in existing soils, which contain potential insects and diseases. Soil solarization is an effective and inexpensive way to combat pests in field soils. Soil solarization uses solar energy to heat the soil which controls insect populations and soilborne diseases. High tunnels are well suited to solarization. Methods of ventilation are another major difference between greenhouses and high tunnels. Unlike greenhouses, high tunnel temperature is controlled manually. Tunnel doors and walls are opened to the outside for ventilation, creating access for pests. To mitigate this problem, varying sizes of mesh covers can be used in conjunction with the polyethylene tunnel to exclude pests ranging in size from flea beetles to grasshoppers.

Timing of pesticide and biological control applications will be different for a high tunnel than a greenhouse. Temperature and humidity influences the effectiveness of pesticides and biological control agents, such as predators, parasitoids, nematodes, and fungi. Because weather conditions significantly affect the environment inside a high tunnel, they should be monitored to determine the proper time to introduce a biological control agent, or to apply a pesticide. Cool temperatures and low light levels in winter production are a great deterrent for many pest problems. However, increased spring and fall temperatures may result in extended pest life cycles and higher population densities.

One interesting component of high tunnel IPM is the effect of UV-blocking properties of the polyethylene cover on insect behavior within the tunnel. The greenhouse-grade plastic that is typically used in high tunnel construction blocks most, if not all, UV radiation and also has an effect on the dispersal of light. Insect eyes detect light in the UV spectrum and use this mechanism to locate food sources (Briscoe and Chittka, 2001). UV-blocking plastic film has been shown to decrease populations of aphids, thrips, whiteflies, leafhoppers, and beetles compared to tunnels without UV-blocking plastic covers.

Strawberry production timeline. June-bearing strawberry cultivars have been successful in a high tunnel system in Cache Valley, Utah (Fig. 5.1). For optimal yields in a high-elevation, cool climate, strawberries are planted as plug plants on approximately September 1st (Rowley et al. 2010). In colder climates, strawberry plugs need to be planted from late July to August. In climates warmer than Cache Valley, plant from mid-September to October. Because of the additional heat in a high tunnel, strawberries usually come into production in mid-April, approximately four weeks sooner than field strawberry production. Harvest continues until temperatures are too hot for strawberry production, usually in mid-July. This high tunnel strawberry production system requires pest management through three seasons: fall, winter, and spring.

Common insects in high tunnel production. The season extending properties of high tunnels also extend the pest season. Insects can be present later into the fall than in the field. Cold temperatures are a good deterrent for most insects, simplifying winter management. However, some insects can be present all year. In the spring, temperatures within the high tunnel warm up much sooner than outside production. Spring insect pests may appear several weeks earlier than they would normally appear in field production. See table 5.1 for a summary of common insect pests in high tunnel production.

Common diseases in high tunnel production. Most modern cultivars have some level of disease resistance. Using resistant cultivars reduces the need for expensive chemical disease control. Cold winter temperatures slow the growth and spread of disease, making disease incidence rare in winter production, but as temperatures rise in the spring, diseases become more common. Because of the humid, cooler conditions that are present within high tunnels in late fall and early spring, fungal diseases can become a problem. Table 5.2 provides a summary of common diseases in high tunnel strawberry production.

Rodent. Rodents have the potential of being a severe pest during the winter season. High tunnels provide rodents with a warm winter home with an abundant food supply. Once established, rodents can become difficult to eliminate, and have the capacity to eat large amounts of plant material. Control methods vary in effectiveness and require a combination of traps, baits, and poisons to control the population. Keep high tunnels a minimum of 50 feet from compost or garbage piles to minimize rodent occurrence.

Conclusion. Whether the high tunnel is being used to grow strawberries, vegetables, or cut flowers, implementing a combination of IPM practices within a high tunnel can be very effective in controlling undesired pests. Since the semi-closed environment of a high tunnel can create an ideal environment for the growth and development of pests, vigilant monitoring is needed to detect increasing pest populations in time to take appropriate action to prevent unacceptable crop damage. As the use of high tunnels becomes more common in modern production systems, more research is needed to test the effectiveness of new IPM practices within a high tunnel system.

Literature Cited

Briscoe A.D., L. Chittka. (2001). The evolution of colour vision in insects. Ann. Rev. Entomol. 46: 471–510.

Koike, S. G. Browne and T. Gordon. 2008.Strawberry powdery mildew. UC Pest Management Guidelines: Strawberry. UC ANR Publication 3468.

Rowley, D., D. Feuz, D. T. Drost, and B. L. Black. (2010). Early-season extension using June-bearing ‘Chandler’ strawberry in high-elevation high tunnels. HortScience 45(10): 1464-1469.

Zalom, F., M. Bolda, and P. Phillips. 2010. Strawberry aphids. UC Pest Management Guidelines: Strawberry. UC ANR Publication 3468.

Table 5.1. Common insects in high tunnel strawberry production.

Insect Pests	Identification/Life cycle	Action Threshold	Control Options
Aphid (Fig. 5.2a)	Soft bodied, piercing-sucking mouthparts, various colors. Many species are parthenogenic during the growing season (can reproduce without fertilization); short life cycles of several weeks lead to many generations per year.	30 aphids per plant or 30% of plants infested	Use pest-free transplants and keep high tunnel weed free. Bio control: lady beetle, lacewings, predatory midge (*Ahpidoletes ahpidimyza* L.) Home use Insecticides: Insecticidal soap, horticultural oil, malathion, neem oil. Commercial use insecticides: Imidacloprid, Thiamethoxam
Slugs (Fig. 5.2b)	Soft, slime-covered bodies, usually tan. Hermaphroditic (both female and male reproductive organs present), lay eggs up to 6 times a year.	Monitor by trapping (shelter traps or pits) Action Threshold: 3-5 slugs per trap.	Remove debris in high tunnel, lower humidity levels, and hand removal. Insecticides: iron phosphate or metaldehyde bait.
Mites (Fig. 5.2c)	Extremely small (0.5 mm long), live on the underside of leaves, various colors. Hot, dry conditions favor mites. Sexually mature in several weeks and lay hundreds of eggs in a lifetime.	Collect 60 leaves throughout the tunnel at random and examine underside for mite presence. If 15 or more leaves have mites present, control measures should be taken.	Reduce dust on leaves. Predatory mites can be effective if released before mite densities are high. High pressure water wash. Home use insecticides: horticultural oil, insecticidal soap, sulfur. Commercial use insecticides: Miticides can be used if labeled for strawberries and greenhouse use, but they kill beneficial mites as well as pests.
Root Weevil (Fig. 5.2d)	Larvae are C-shaped, without legs, a dark head, and feed on roots. Adults are 3 to 9 mm long, dark colored, and feed on foliage (characteristic scallops on leaf edges). Parthenogenic females lay eggs in soil 2-4 weeks after emergence.	More than two weevil larvae per plant cause economic damage.	Scout for night-feeding adults and damage with a flash light. Crop rotation, remove weeds. Home use insecticides: carbaryl, malathion, pyrethrin. Commercial use insecticides: azadirachtin, thiamethoxam. Soil fumigation can be used in extreme cases, but should be considered a last resort.

Table 5.2. Common diseases in high tunnel strawberry production.

Diseases	Identification	Control
Powdery Mildew (Fig. 5.3a)	First sign is an upward curling of leaves. White or gray somewhat powdery coating on leaf of strawberry follows.	Lower humidity levels, keep leaf surface dry. Some resistant cultivars available. Home use fungicides: Sulfur, fixed copper, myclobutanil. Commercial use fungicides: Triflumizole, Pyraclostrobin
Botrytis Blight (Grey Mold) (Fig. 5.3b)	Silver or gray spores on dead tissue. Infected fruit soft with gray spores, usually in spots. Pre- and post-harvest disease.	Keep humidity levels low, encourage air circulation. Some resistant cultivars available. Home use fungicides: captan, fixed copper. Commercial use fungicide: Pyraclostrobin.
Leather Rot	Bleached or light pink area. Lesion tissue is tough and bitter.	Pre-plant soil solarization, minimize water on leaf surface, good air circulation. Keep berries from contacting soil.

Figure. 5.1. Strawberry high tunnel production on raised beds.

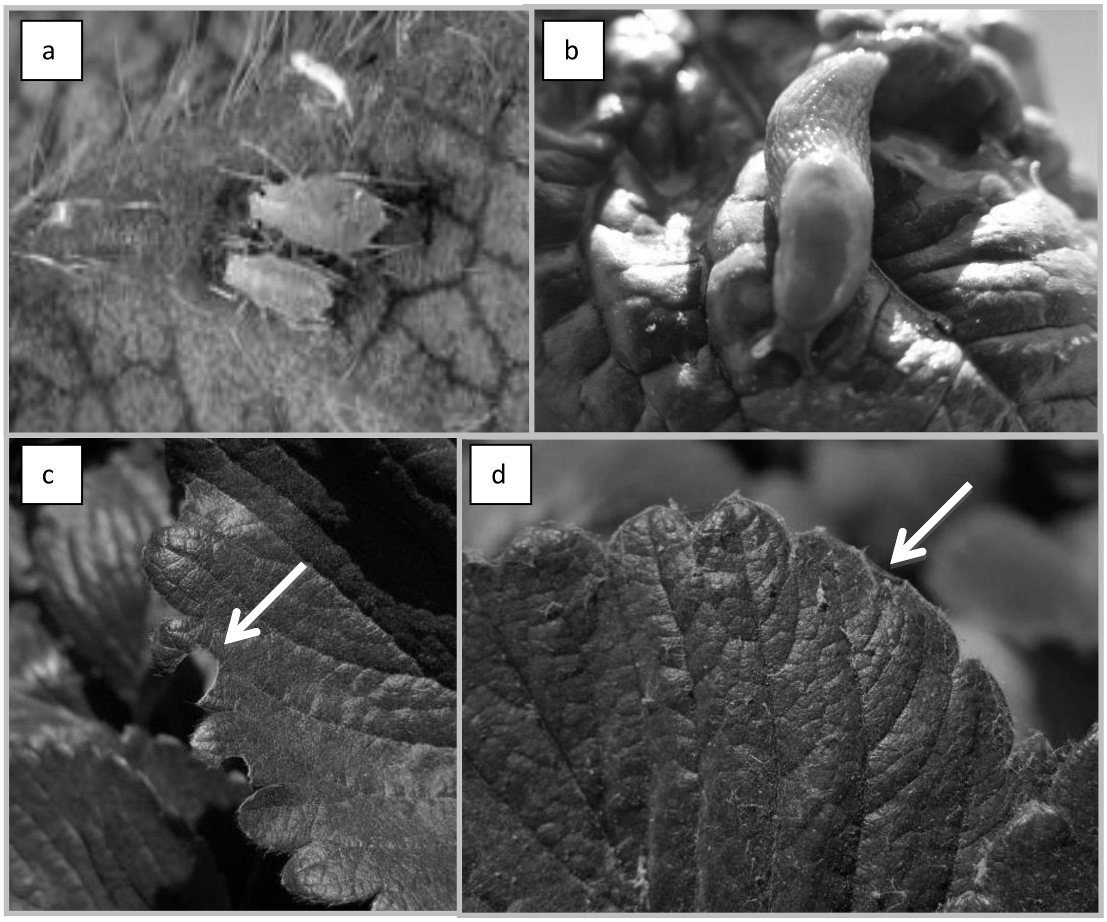

Figure 5.2. Aphids on the bottom of a strawberry leaf (a) (Zalom et al., 2013). Slug on spinach leaf (b). Strawberry root weevil damage, characteristic notch along leaf margin (c). Mite webbing on leaf. Plants are often stunted by mite feeding (d).

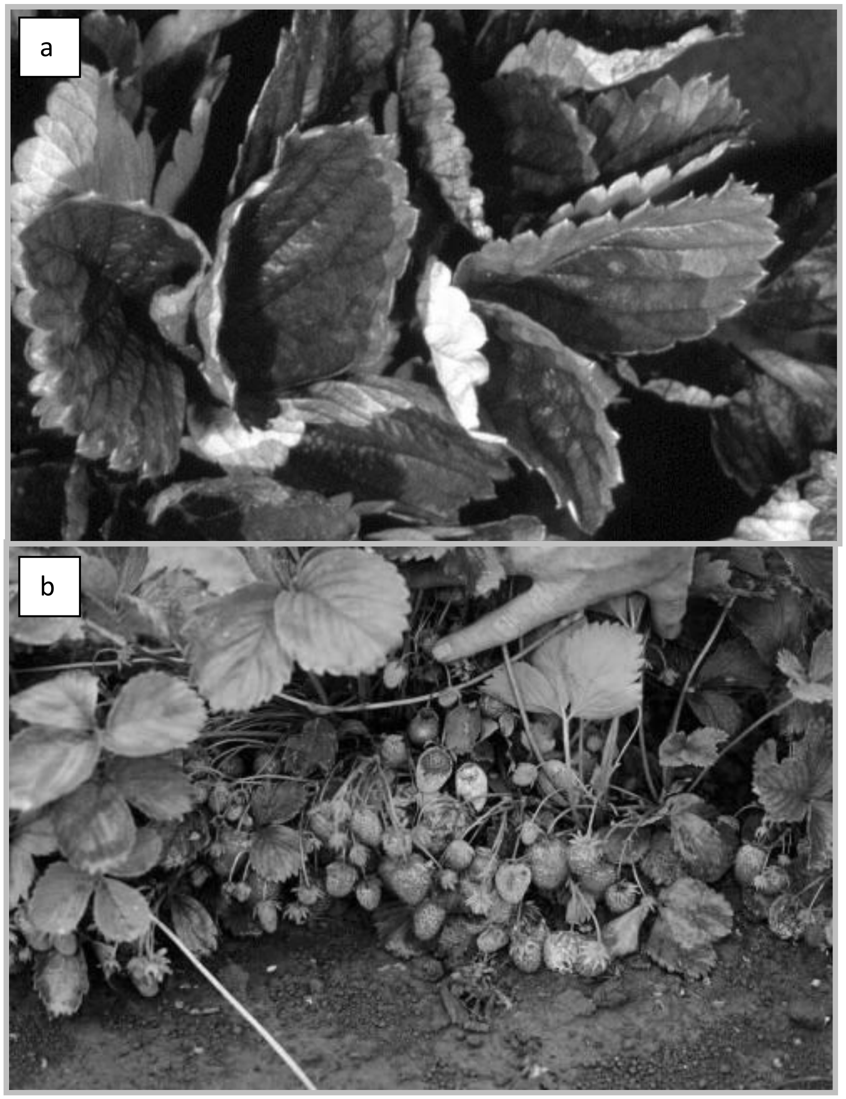

Figure 5.3. Upward curling of strawberry leaves infected with powdery mildew (a) (Koike et al., 2013). Botrytis blight (grey mold) on strawberry (b).

CHAPTER 6

CRITICAL TEMPERATURE FOR SUB-LETHAL COLD INJURY OF STRAWBERRY LEAVES

Abstract. Freezing temperatures are a major limitation to strawberry production in temperate regions, and protected-cultivation strategies have been devised to minimize this limitation. In order to optimize management under protected cultivation, it is necessary to understand the damage thresholds for strawberry plant tissues. The effects of freezing temperatures (-3, -5, and -7 ˚C) on leaf CO_2 assimilation were evaluated on 'Chandler', 'Seascape' and 'Jewel' strawberry (*Fragaria* × *ananassa*). Growth chambers were used to expose intact leaves to freezing temperatures under carefully defined conditions. Net assimilation was then measured on the cold-exposed leaves, after the plants had been returned to 10 ˚C. Exposure to -3 ˚C did not significantly reduce CO_2 assimilation when compared to a control maintained at 10 ˚C day/5 ˚C night. Leaves exposed to -5 ˚C for one night had a net CO_2 assimilation rate that was 49% of the control. When leaves were first exposed to a conditioning night of -3 ˚C and then exposed to -5 ˚C the net assimilation rate was 62% of the untreated control. Repeated exposure to -5 or -7 ˚C night temperatures resulted in a further decrease in net assimilation after each successive exposure. Leaves exposed to -7 ˚C had a net assimilation rate of 6% of the control. Leaves exposed to -5 ˚C or -7 ˚C did not show significant recovery over a 28 day period. There was no significant difference among cultivars in the sensitivity of leaves to cold temperatures. These results indicate that protected cultivation systems should be managed to maintain strawberry leaf temperatures above -5 ˚C in order to preserve full

photosynthetic activity of existing leaves which would allow for extend crop growth later into the year.

Introduction

Strawberries are produced under a wide variety of conditions, from mild maritime to severe temperate continental climates. They are remarkably adaptable, in part due to diverse genetics, but also due to the high adaptability of the plant itself (Darrow, 1966). Despite this adaptability, temperature is a major limiting factor in production, with ideal temperatures for leaf growth being 20 to 26 ˚C (Darrow, 1966). Plant growth responds predictably to temperature. For strawberry, baseline temperature for growth is just above freezing (Galletta and Himmelrick, 1990), with growth rates increasing with temperature to an optimum of approximately 20 to 26 ˚C, depending on cultivar and acclimation. Growth slows dramatically above the optimum temperature range with higher temperatures eventually resulting in tissue necrosis (Carlen et al., 2009; Hancock, 1999).

Strawberry plants acclimate to cold conditions and can survive sub-freezing temperatures by tolerating ice formation in crown tissues. This is accomplished by water moving from within the cell to outside the cell to form extracellular ice (Hancock, 1999; Koehler et al., 2012; Warmund, 1993). Significant work has been done to assess cold temperature damage on crowns and inflorescences. Crowns have been found to be severely injured at -9 ˚C when unprotected (Galletta and Himmelrick, 1990; Nestby and Bjorgum, 1999; Warmund, 1993) and killed at about -12 ˚C when acclimated, with some variation by cultivar (Darrow, 1966). Once inflorescences begin to expand in the spring, floral organs are susceptible to damage at -1 ˚C (Hummel and Moore, 1997; Maas, 1998).

Although somewhat limited, work has also been done to assess cold temperature damage on leaves. Even in relatively cold temperate regions, leaves may remain green throughout the winter months. However, it is not known whether these leaves maintain photosynthetic activity and contribute to continued plant growth once environmental conditions improve. Most research on cold temperature damage in leaves has been conducted on detached leaves or excised leaf disks. Detached leaves sustain significant damage, as assessed by solute leakage, when exposed to temperatures between -5 and -12 ˚C (O'Neill et al., 1981; Owens et al., 2002).Working with detached leaves does not allow for determining to what extent tissues recover from these damaging temperatures. We are unaware of published reports investigating photosynthetic response of attached leaves to freezing temperatures.

The bulk of commercial strawberry production in North America occurs in mild maritime climates where temperatures rarely drop to levels that would damage leaves. However, small-scale production continues throughout North America to target the increasing demand for locally grown food. In regions with cold fall temperatures and frequent spring frost events, growing strawberries under protected cultivation such as high tunnels, low tunnels, or floating row covers is becoming more common (Fernandez, 2001; Himmelrick et al., 2001; Rowley et al., 2010). Since protected cultivation involves actively managing temperature, understanding the critical temperature thresholds for plant injury is essential to developing optimized management strategies. Knowing the temperature at which the leaves lose photosynthetic capacity will provide guidelines in employing and managing these protected cultivation strategies. In this study we investigated the effect of cold temperature exposure on subsequent leaf injury, as determined by photosynthetic activity.

Materials and Methods

Plant production. The cultivar ‘Chandler’ was used for the first set of experiments. Plug plants were grown as described by Rowley (2010). Briefly, cold-stored dormant plants were obtained from a commercial nursery (NorCal Nursery Inc, Red Bluff, CA) and planted into soilless media in PVC gutters. Plants were kept in a greenhouse maintained at 22 °C day/15.5 °C night, with a day length of 14 h maintained with supplemental light from metal-halide lamps. The soilless media used was a mixture of 1:1:1 peat moss, vermiculite, and perlite. Dormant plants were allowed to establish and produce runners for approximately 10 weeks. Water soluble fertilizer (20N-4.4P-16.6K) was supplied to the mother plants 3 to 4 times per week through the irrigation at a rate of 100 $mg\cdot L^{-1}$ N.

Runner tips were removed from the mother plant when root initials were visible, when the first trifoliate leaf was fully expanded, and when a second leaf was present but not expanded. Tips were immediately planted into plug trays (cell volume of 63 cm^3). Trays of runner tips were kept under intermittent mist for 2 weeks, then removed from the mist and maintained under greenhouse conditions for an additional 2 to 3 weeks. When plants had three fully open trifoliate leaves they were transplanted to 2.0 dm^3 containers containing soilless media described above. Plants were maintained in the greenhouse until they had developed 5 fully-expanded trifoliate leaves (typically 7 to 8 weeks after runner tip removal), and then used for the specific experiments. Runner tips were harvested and planted once per week to provide a constant supply of plants at approximately the same age and developmental stage for all studies.

In a second study, cold-stored dormant plants of ‘Chandler’, ‘Seascape’ and ‘Jewel’ were obtained from a commercial nursery (Lassen Canyon Nursery, Redding, CA) and planted into 2.0 dm^3 containers of the soilless media described previously. Plants were grown under greenhouse conditions until 5 fully-expanded trifoliate leaves were present (typically 4 weeks) and then used for the specific experiments. Inflorescences were removed upon emergence.

Freezing tests. Prior to the beginning of freeze tests, plants were acclimated for 7 days in a walk-in growth chamber (EGC Plant Growth Chamber; Chagrin, OH) at 10 °C day/5 °C night temperatures, with a light period of 9 hours, at a light intensity of 200 to 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Once acclimated, individual plants were selected for uniformity and transferred to an environmental test chamber (Tenney Environmental Test Chamber, Winona, MN) for exposure to one of the freezing regimes. The environmental test chamber’s performance was verified using thermocouples connected to a CR 1000 data logger (Campbell Scientific, Logan, UT). The freezing cycle was programmed to simulate a cold night in a high tunnel during the winter, where temperatures regularly fall below 0 °C (Chapter 3). Briefly, as lights turned off in the growth chamber, a selected plant was placed in the environmental test chamber with the pot placed in an insulated box to prevent freezing of the roots and crown. Air temperature was then held at 5 °C for 4.5 hours, and then slowly decreased to the target temperature over 3.5 hours. Once the target freezing temperature was reached, it was held for 4 hours, and then the temperature increased to 5 °C over a 3-hour period. The plant was then returned to the growth chamber, where leaf injury was determined based on net CO_2 assimilation rate (*A*), using a portable infrared gas analyzer (LI-6400, Li-Cor; Lincoln, NE) equipped with a LED supplemental light head that supplied 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ light. Injury assessment was carried out on the youngest fully-expanded leaf and data was recorded continuously for 4 hours. The controls were untreated plants of the same developmental stage, kept in the growth chamber at a constant 10 °C day/ 5 °C night temperature regime.

Temperature step-down. For the first experiment, plants of ‘Chandler’ were exposed to successively lower temperatures (-3, -5, -7, -9, and -11 °C) in the environmental test chamber on 5 consecutive nights. Each morning the plant was moved back to the growth chamber and leaf gas exchange was monitored for 4 hours to determine *A*. This trial was replicated 4 times. In a second trial ‘Chandler’, ‘Seascape’ and ‘Jewel’ cultivars were evaluated under the same temperature regimes.

Repeated freeze. Acclimated plants were subjected to the same target temperature, (-3, -5, or -7 °C) for three consecutive nights, and *A* monitored between freeze cycles for 4 hours immediately upon removal from the test chamber. The -5 and -7 °C trials were replicated 5 times on five uniform plants; the -3 °C trial was replicated twice.

‘*Conditioned’ repeat freeze.* Acclimated ‘Chandler’ plants were subjected to a conditioning night of -3 °C, followed by three consecutive nights of -5 °C using the methods described above. Gas exchange was monitored for 4 hour periods in the morning between each freezing cycle. This trial was replicated 3 times. In a second trial, ‘Chandler’ and ‘Seascape’ plants were conditioned for one night of -3 C, followed by six consecutive nights of -5 °C.

Recovery. Each 13 hour night for five consecutive nights, two acclimated plants were exposed to either -5 or -7 °C as described above, and then returned to the growth chamber. After the fifth night, leaf *A* was measured every 30 seconds for 15 minutes on the youngest fully expanded leaf and the second oldest leaf (leaf plastochron index of 5; Erickson and Michelini, 1957) on each of these plants, representing 0 to 4 days of recovery after cold temperature exposure. Plants were maintained in the growth chamber for another 5 days, and *A* again measured to determine the degree of recovery after 5 to 9 days. Measurements were repeated after 5 more days to determine recovery after 10 to 14 days. Measured leaves were tagged to insure repeated measurement on the same leaf.

To further evaluate the recovery of leaves exposed to freezing temperatures, a second trial was carried out on ‘Chandler’, ‘Seascape’ and ‘Jewel’ plants. Two plants of each cultivar were exposed to -5 °C for a single night. *A* was measured as described the following morning and again every 4 days for 4 weeks, providing an additional two weeks of observed recovery beyond that of the first trial.

Field-grown comparison. Fall-planted ‘Chandler’ and ‘Seascape’ plants from the Greenville Research Farm in North Logan, UT were dug with over-wintering leaves still intact and transplanted into 2.0 dm^3 pots on 1 March, 2013, just as they were breaking winter dormancy. Plants were from three different treatment plots from another experiment (Chapter 3): unprotected outdoor field, high tunnel protection, and high tunnel plus low tunnel protection. Two replicate plants were removed from each treatment. Plants were placed in the 10 °C day/ 5 °C night growth chamber with 11 hour day/ 13 hour night, and *A* was only measured on over-wintering leaves approximately 3 hours after being brought into the growth chamber.

Statistical analysis. Experimental data were subjected to analysis of variance (ANOVA) by standard procedures using the PROC REGWQ in SAS (version 9.3, SAS Institute, Cary, NC). The step-down trial was analyzed using a non-linear regression to determine the LT_{50} (temperature resulting in 50% loss of activity). A sigmoid 3 parameter curve was fit to the data (f = a/(1+exp(-(x-x))/b) where a = max value, b = slope at x0 and x0 = LT_{50}, using Sigma Plot (Version 10.0, Systat Software, San Jose, CA).The recovery trial was analyzed as a repeated measures design using orthogonal contrast statements in PROC GLM. The cultivar comparison experiments were analyzed as a cultivar by temperature factorial. Means separation was by Tukey-Kramer at the 0.05 level of significance.

Results

Temperature step-down. Leaves of the same plant were exposed to incrementally lower temperatures for 5 consecutive nights, with *A* measured the day after each exposure. Leaf *A* for plants exposed to -3 °C did not differ significantly from that of the untreated control (Fig. 6.1). After one night of exposure to -5 °C, *A* was numerically lower than the untreated control, but differences were not statistically significant until after exposure to -7 °C, when *A* rate was 39% lower than the control ($P < 0.0001$). Leaves exposed to -9 °C and -11 °C had *A* rates that were not significantly different from zero. These results indicate that much of the damage to photosynthetic activity occurred at -5 to -7 °C, and subsequent experiments targeted this temperature range.

In a second cold temperature step-down trial, three cultivars were compared to see if plant response to freezing temperatures varied among cultivars. There was no significant difference in *A* among the three cultivars Chandler, Seascape, and Jewel (*P* = 0.11) and the plant response was very similarly to that of the previous study, with plants exposed to -3 °C for 4 hours having no significant difference from control plants. As cultivars were exposed to colder temperatures there was a reduction in *A* with each successively colder temperature. A nonlinear regression using combined data for all three cultivars predicted an overall LT_{50} of -5.3 °C (Fig. 6.2). Table 6.3 shows predicted LT_{50} for the three cultivars ranging from -5.07 to -5.80 °C.

Repeat freeze. Leaves of the strawberry cultivar 'Chandler' exposed to 3 consecutive cycles of -3 °C had the same leaf *A* as untreated controls. Plant leaves exposed to 3 consecutive nights of -5 °C had *A* rates significantly lower than the control. Additionally, there was a 50% reduction in *A* with each additional exposure to -5 °C (Fig. 6.3). Plants exposed to -7 °C had *A* rates that were not significantly different from zero after a single night exposure.

'*Conditioned' repeat freeze.* Interestingly, 'Chandler' plants exposed to three consecutive nights of -5 °C showed lower leaf *A* after a single night of exposure than plants first exposed to -3 °C then exposed to -5 °C during the next dark period. Expressed as a percent of the untreated control, *A* was 49% after a single night exposure to -5 °C (Fig. 6.3), compared to 89% of control after -5 °C in the step down study (Fig. 6.2). Similarly, *A* was more affected by one night of -7 °C (6% of control) than when first exposed to -3 °C, then -5 °C before being subjected to -7 °C (62% of control). These results suggest that previous exposure to sub-zero temperatures improves tolerance to subsequent cold temperatures.

To test this hypothesis, plants were exposed to a single night of -3°C followed by three nights of -5 °C and compared to plants that received three nights of -5 °C without the -3 °C preconditioning (Table 6.1). Preconditioning resulted in significantly less injury (42% reduction in *A* vs 10% of control by day three) than the non-conditioned plants. However, *A* capacity continued to linearly decline with each successive night of cold exposure in both the conditioned and non-conditioned plants. For non-conditioned plants, *A* rate after day 3 was significantly different from *A* rate after day 1 ($P < 0.001$). Although the *A* rates also trended downward for the conditioned plants, differences between the first and third exposure were not statistically significant at $P < 0.05$.

In the second trial of the 'conditioned' repeat freeze experiment, we looked at the cultivars 'Chandler' and 'Seascape'. Additionally, the number of days exposed to freezing temperature was expanded from three to seven. As with the cultivar comparison for the step-down experiment, the cultivars responded similarly to the initial 'Chandler'-only trial. Each additional exposure to -5 °C resulted in a reduction in *A* the following day. Both cultivars had dead leaves after 5 nights of -5 °C. There was no significant difference between cultivars ($P = 0.26$).

Recovery over time. Based on the damage observed from exposure to -5 and -7 °C, an experiment was designed to assess the ability of leaves to recover from a single exposure to -5 °C. Again, leaves exposed to -5 °C sustained less damage to *A* capacity than those exposed to -7 °C. Interestingly, there was no significant recovery in net photosynthesis over time for either treatment (Fig. 6.4). Leaves exposed to -5 °C had a slightly upward trend in *A* over 14 day, but this trend was not statistically significant. Leaves exposed to -7 °C showed a slight downward trend in *A* over 14 days. This lack of perceptible recovery was evident in both young and old leaves for both temperature treatments (*P* = 0.41 and 0.15, respectively).

For the second recovery trial, leaf recovery was monitored for 28 days and three cultivars (‘Chandler’, ‘Seascape’ and ‘Jewel’) were monitored. Even with additional recovery time, there was no statistical improvement in leaf *A* rate in any of the cultivars in either young or old leaves over a 28 day period (Fig. 6.5).

Field-grown comparison plants. Fall-planted ‘Chandler’ and ‘Seascape’ plants grown under unprotected field conditions had significantly lower *A* than plants grown with the protection of a high tunnel or high tunnel plus low tunnel (*P* = 0.0003, Table 6.2). The additional protection provided by a low tunnel in a high tunnel did not improve photosynthetic rate (*P* = 0.086), although high tunnel plus low tunnel plants had slightly higher *A*, which corresponds to warmer temperatures observed in this treatment (Chapter 3). There was no statistically significant difference between cultivars (*P* = 0.55). When compared to plants grown under greenhouse conditions and kept in growth chambers, unprotected field grown, high tunnel, and high tunnel + low tunnel field-grown plants had photosynthetic rates that were 12, 34 and 41% of growth chamber plants held at 10 °C day/ 5 °C night, respectively (Table 6.2).

Discussion

Strawberries have been successfully produced in the Intermountain West using high tunnels and low tunnels (Chapter 2; Rowley et al., 2010). In these high tunnel systems, strawberries are planted in the fall and harvested the following spring. Fall growth is important for high spring yields, as plants need to have time to establish and initiate crown division and flower buds formation. Early fall and late spring frosts are common throughout the Intermountain West. Providing strawberry producers with minimum temperature thresholds will help growers make better decisions regarding temperature management within the tunnels, and decide when supplemental heating might be justified (Chapter 3).

Work with detached leaves by O'Neill et al. (1981) and Owens et al. (2002) found that significant damage (measured by solute leakage) occurred when excised leaf disks were exposed to temperatures between -5 and -12 °C. With intact leaves attached to the plant, we found a significant drop in *A* rate after a single night exposure to -5 °C, with a nearly complete loss of *A* capacity after multiple exposures to -5 °C, or a single night of exposure to -9 °C.

The effect of a single conditioning night at -3 °C on *A* after subsequent exposure to colder temperatures was particularly interesting. It is generally accepted that strawberry plants acclimate to cold temperatures (Darrow, 1966). However, acclimation is primarily thought to take longer than a single night of exposure. Based on results from the step-down and repeat freeze experiments, we found some acclimation occurs after only one night of exposure to freezing temperature.

The lack of recovery in photosynthetic rate over time suggests that leaves, once exposed to damaging temperatures, are not capable of returning to previous *A* rates. This indicates that the plant recovers from severe freezing damage by growing new leaves, rather than repairing damage done to existing leaves. Therefore, to gain the most benefit from protected cultivation, temperature at plant level should remain at -3 °C or above. However, the existing leaves that were damaged, while not fully photosynthetically active, can still contribute to growth at a lower rate, at least until exposure to -9 °C when loss of activity is complete. The use of high tunnels increases air temperature above ambient outside air temperature, especially during the day, but additional heating may be warranted at night. Analysis of the field-grown comparison plants further indicates benefits of using protected cultivation since *A* rates of overwintered leaves under the high tunnel were significantly higher than those grown without protection.

Growth chamber studies may dramatically underestimate the potential damage that may occur in the field, as none of the leaves in the growth chambers were simultaneously exposed to extreme cold and sunlight, as would be the case at sunrise when the air temperatures are often the coldest. Theoretically, freezing temperatures in conjunction with bright sunlight would be more damaging than gradually warming the frozen leaves in darkness prior to light exposure. This is due to an increased susceptibility to light stress at low temperatures. As this is a condition strawberries repeatedly face in the Intermountain West, further investigation of the effect of freezing temperatures coupled with light exposure on leaf *A* would serve to provide a more complete view of leaf damage in the field.

Conclusion

Leaves exposed to -3 °C for 4 hours did not experience a significant reduction in net CO_2 assimilation. The LT_{50} (temperature at which 50% of leaf activity is lost) for all cultivars tested was approximately -5 °C (Table 6.3). When leaves were exposed to -5 and -7 °C without any conditioning to freezing temperatures, more severe damage was observed, as indicated by a significant reduction in photosynthesis. Leaves exposed to a single night of -5 °C did not recover their photosynthetic activity to pre-exposure levels even after 28 days at 10 °C day/5 °C night. There was no significant difference in recovery between old (plastochron index 5) and young (newest fully expanded) leaves. We recommend maintaining protected cultivation systems at -3 °C or above to minimize damage to strawberry leaves.

Literature Cited

Carlen, C., A.M. Potel, and A. Ancay. 2009. Photosynthetic response of strawberry leaves to changing temperatures. Acta Hort. 838: 73-76.

Darrow, G.M. 1966. Climate and the strawberry, p. 355-365. In: The Strawberry. Holt, Rinehart and Winston, New York, NY.

Erickson, R.O. and F.J. Michelini. 1957. The plastochron index. Amer. J. of Botany 44: 297-305.

Fernandez, G.E. 2001. Fall-applied rowcovers enhance yield in plasticulture strawberries. HortTechnology 11(3): 440-444.

Galletta, G.J. and D.G. Himmelrick. 1990. Strawberry Management, p. 83-156. In: Small fruit crop management. Prentice Hall, Englewood Cliffs, NJ.

Hancock, J.F. 1999. Structural and development physiology, p. 90-110. In: Strawberries. CABI Publishing, New York, NY.

Himmelrick, D.G., F.M. Woods, B.S. Wilkins, and J.A. Pitts. 2001. Use of floating row covers in annual hill plasticulture strawberries. Small Fruits Rev. 1(4): 63-71.

Hummel, R.L. and P.P. Moore. 1997. Freeze resistance of Pacific Northwest strawberry flowers. J. Amer. Soc. Hort. Sci. 122(2): 197-182.

Koehler, G., R. C. Wilson, J. V. Goodpaster, A. Sonsteby, X. Lai, F.A. Witzmann, J. You, J. Rohloff, S.K. Randall, and M. Alsheikh. 2012. Proteomic study of low-temperature responses in strawberry cultivars (*Fragaria* × *ananassa*) that differ in cold tolerance. Plant Physiol. 159: 1787-1805.

Maas, J.L. 1998. Compendium of strawberry diseases. 2nd edition. American. Phytopathiological Society. APS Press, St. Paul, MN.

Nestby, R. and R. Bjorgum. 1999. Freeze injury to strawberry plants as evaluated by crown tissue browning, regrowth and yield parameters. Scientia Hort. 81(3):321-329.

O'Neill, S.D., D.A. Priestley and B.F. Chabot. 1981. Temperature and aging effects on leaf membranes of a cold hardy perennial, *Fragaria virginiana.* Plant Physiol. 68: 1409-1415.

Owens, C.L., M.F. Thomashow, J.F. Hancock and A.F. Iezzoni. 2002. *CBF1* orthologs in sour cherry and strawberry and the heterologous expression of *CBF1* in strawberry. J. Amer. Soc. Hort. Sci. 127(4): 489-494.

Rowley, D. R. 2010. Season extension of strawberry and raspberry production using high tunnels. MS Thesis. Utah State University. Logan, Utah.

Rowley, D., B.L. Black, and D. Drost. 2010. Early-season extension using June-bearing 'Chandler' strawberry in high-elevation high tunnels. HortScience 45(10): 1464-1469.

Warmund, M.R. 1993. Ice distribution in 'Earliglow' strawberry crowns and tissue recovery following extracellular freezing. J. Amer. Soc. Hort. Sci. 118(5): 644-648.

Table 6.1. The effect of three successive nights of -5 °C on net CO_2 assimilation rate (*A*) with or without a conditioning night of -3 °C. Values are percent of control plants kept at 10 °C day/ 5 °C night.

Preconditioning	Day		
	1	2	3
	(% of control)		
None	49a	27a	10a
-3 °C	62b	46b	42b

Values within a column followed by the same letter are

Not significant at $P \leq 0.05$.

Table 6.2. Comparison of *A* among field-grown, high tunnel (HT) and low tunnel plants (LT), and greenhouse-grown plants kept at 10 °C day/ 5 °C night.

Cultivar	Treatment			
	Greenhouse	Field	HT	HT + LT
Chandler	9.23	0.59b	3.08a	3.97a
Seascape	8.76	1.64b	3.07a	3.39a

Analysis of Variance	*P*
Treatment	<0.001
Cultivar	0.548

Numbers within row followed by the same letter are not significantly different. Greenhouse plant values listed as a reference and are not included in statistical analysis.

Table 6.3. Threshold temperatures for damage of leaf *A* activity of three cultivars. Values are temperature at which 50% of leaf activity is lost (LT_{50}). Analyzed using a non-linear regression fit to a sigmoid 3 parameter curve.

Cultivar	LT_{50}	St. Err	R-Square
Chandler	-5.80	0.328	0.827
Seascape	-5.45	0.353	0.783
Jewel	-5.70	0.175	0.943

See Figure. 6.2 for corresponding extinction curve.

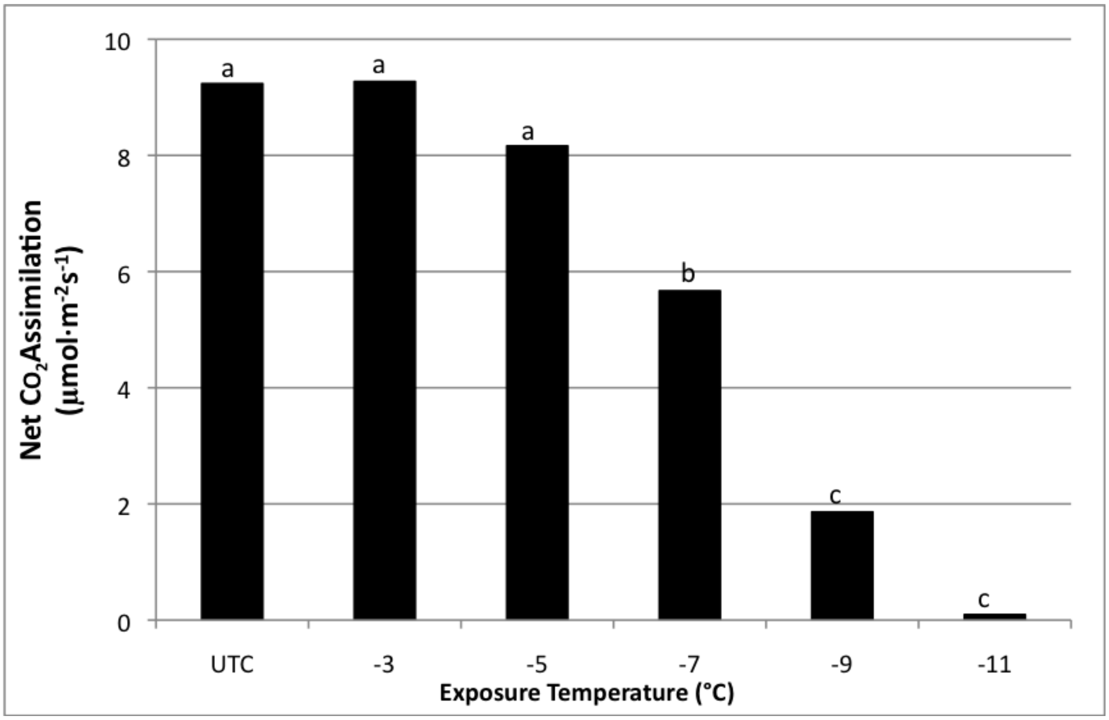

Figure 6.1. The effect of progressively colder temperatures on net CO_2 assimilation rate (µmol·m^{-2}·s^{-1}) for 'Chandler' strawberry leaves. The untreated control (UTC) was kept in a growth chamber at 10 °C day/ 5 °C night temperatures. Plants were exposed to progressively colder temperatures each night and returned to the 10 °C chamber during the day, where net CO_2 assimilation rate was determined after plants had come to steady state. Values are the mean of 4 replicate plants.

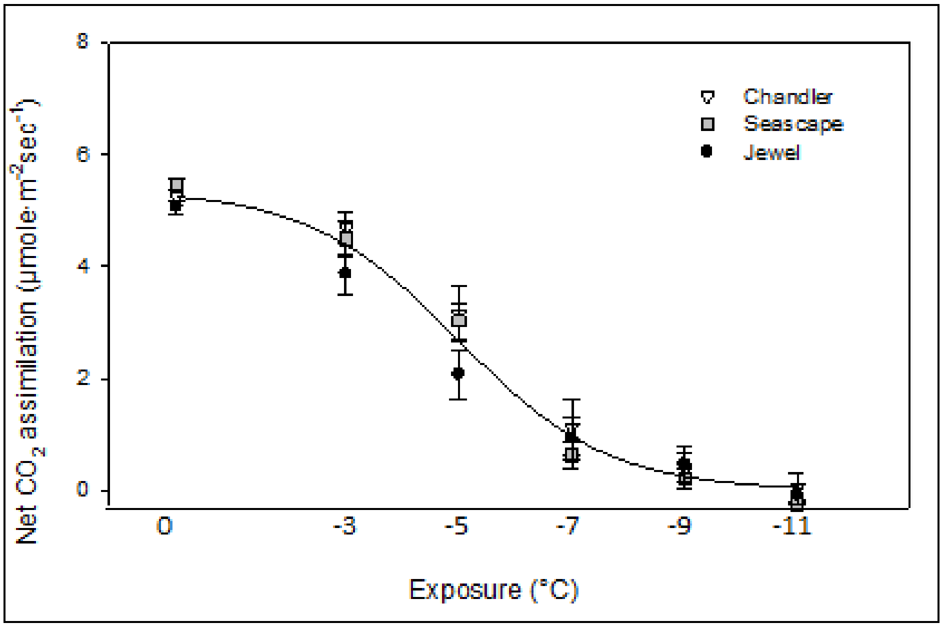

Figure 6.2. Extinction curve showing the effect of progressively colder temperatures on net CO_2 assimilation. Symbols represent mean ± standard error for individual cultivars, based on 4 replicate plants. The extinction curve was calculated using data from all three cultivars and predicts an LT_{50} of -5.3 °C.

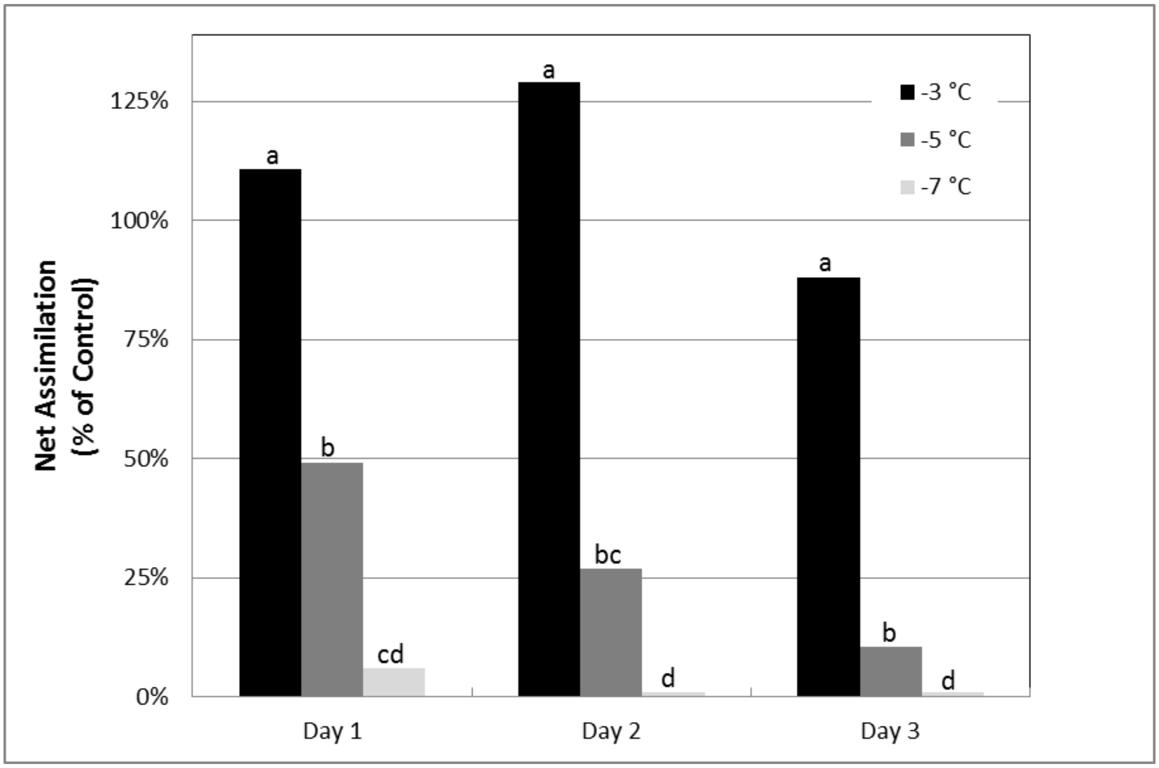

Figure 6.3. The effect of repeated cold temperature exposure on net CO_2 assimilation rate (µmol·m^{-2}·s^{-1}) as a percent of the untreated control plant. Net CO_2 assimilation rate was determined when plants had come to steady state after approximately 3 h under lights at 10 °C. Bars with same the letter are not significantly different at $P \leq 0.05$.

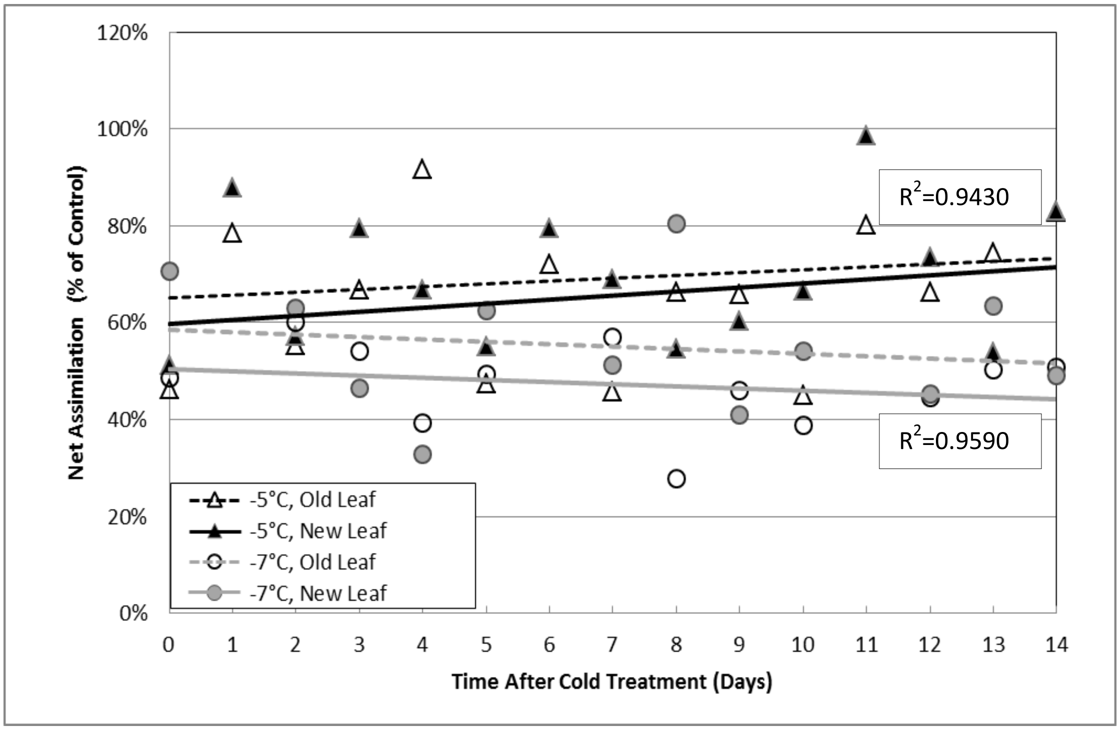

Figure 6.4. Net assimilation rate of the newest fully expanded leaf or the second oldest leaf over 14 days after being subjected to one night of either -5 or -7 °C. None of the regression lines have slopes significantly greater than zero, indicating no significant recovery of *A*.

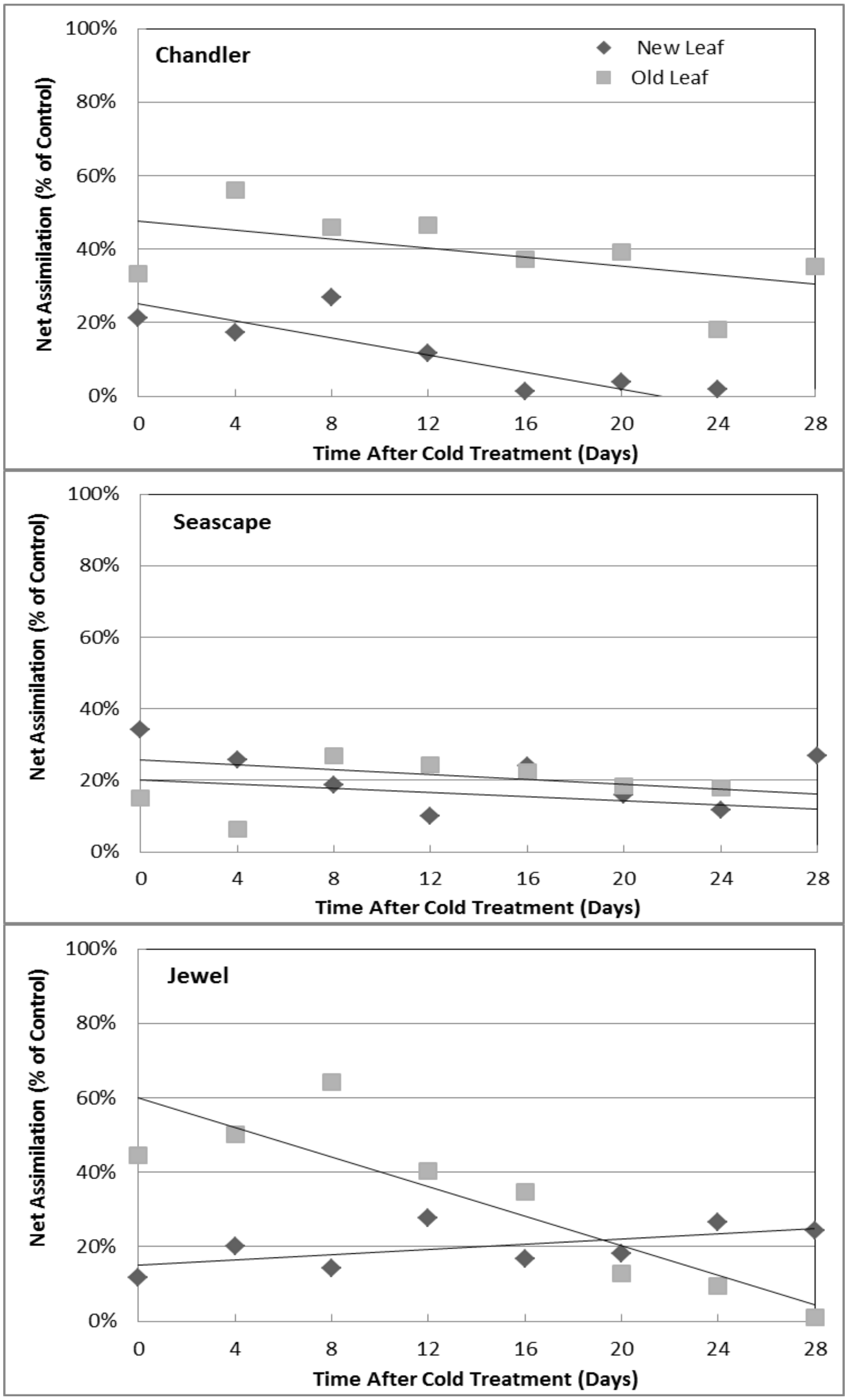

Figure 6.5. Effect of one night of -5 °C exposure on net assimilation over 28 days. Net assimilation rate expressed as % of untreated control. None of the cultivars had statistically significant upward trends in leaf *A* rate in either young or old leaves.

CHAPTER 7

SUMMARY AND CONCLUSION

A high tunnel management system for the Intermountain West was previously developed by Rowley (2010). The purpose of this study was to advance and refine that work. Candidate advancements and refinements included: investigating the use of additional levels of environmental modification such as low tunnels and supplemental heating; investigating a wider range of plant types and cultivars; and determining cold temperature thresholds.

Additional environmental modification. Temperature increase under a low tunnel has been seen both during the day and at night when low tunnels are used in conjunction with high tunnels (Ernst, 2012; Wien et al., 2008). Hypothesizing that this temperature increase could further increase strawberry yield above the higher yield already achieved under high tunnel protection, a treatment of low tunnels within a high tunnel was included. High tunnels used in conjunction with low tunnels provide frost protection, increasing yields and extend the season earlier into the spring (Chapter 3). With price premiums afforded by early produce in direct markets, as well as increased total yield, the additional cost of high tunnels is warranted. High tunnels used in conjunction with low tunnels were beneficial and economically viable (Chapter 4) for ‘Seascape’ but not ‘Chandler’ in 2012. However, in spring conditions with more extreme cold temperatures, low tunnels may still be justified.

Although complete heating of a high tunnel would be cost prohibitive, targeted supplemental heating has been successful in high tunnel production of leafy greens and tomatoes (Ernst, 2012; Hunter, 2010). To evaluate the effect of supplemental heating on strawberry growth and yield, targeted root zone heating was applied within a high tunnel plus low tunnel at two set point temperatures, 7 and 15 °C. Supplemental heating increased early and total yield, although not significantly for all plant types and cultivars tested (Chapter 3). Additional heating also moved production time sooner than high tunnel production alone by 4 to 7 weeks depending on plant type, cultivar and level of heating. The additional cost of heating can be justified based on increased yields of high-value early fruit (Chapter 4). Of the two temperatures evaluated (7 and 15 °C) there was no significant difference on total or early yield between the two, although the 15 °C heat treatments did have slightly higher total yield for both cultivars and advanced the harvest by an average of 3.8 weeks, as determined by first harvest date.

Finally, to investigate a lower input protection method, a low tunnel only management system was evaluated for frost protection and season extension and compared to a high tunnel system. Low tunnels did not provide adequate protection to increase yield compared to unprotected field plants (Chapter 3), which may have been due to the difficulty of constructing a low tunnel that retained canopy temperatures in the presence of wind.

Plant type and cultivar. In addition to evaluating and comparing these protection methods, planting date for two plant types was optimized. Comparisons among cultivars and performance of nursery plant type were also evaluated. The optimal planting date for June-bearing, dormant plants in a fall-planted high tunnel system is approximately 29

July (Chapter 2). This is one month sooner than the optimum planting date previously determined for plug plant types (Rowley, 2010). ‘Chandler’ had highest early and total yields of three June-bearing cultivars compared in a preliminary study. ‘Festival’ and ‘Allstar’ also appeared to have similar optimum planting dates as Chandler, both for dormant and plug plants.

In 2012, the June-bearing cultivar ‘Chandler’ had higher early yield than ‘Seascape’ in the high tunnel treatments (Chapter 3), although differences in total yield were not significant. The higher early yield is important to note as early yield commands a price premium compared to fruit produced later in the season (Chapter 4). Considering this increase in return for early fruit, planting a June-bearing cultivar may increase net income even without having significantly higher total yield.

Plug plants performed best of the three plant types tested (plug, dormant and fresh dug) with high yield, high plant survival and vigor, and low runner production (Chapters 2 and 3). Although dormant plants had similar yield per plant as plug plant types, dormant plants had lower survival rate resulting in a much lower yield per m^2. In 2011, dormant plants had a higher survival rate than in 2012. Dormant plants could only be justified if survival could be dramatically improved, and runners could be efficiently prevented or removed.

Pest management practices for high tunnel strawberry differ from field production. As life cycles for many pests are temperature dependent, and high tunnels increase temperatures, many pests will begin to appear within the high tunnel well before they would be expected in field production. Vigilant monitoring is important for successfully implementing an integrated pest management program. As the high tunnel is an enclosed space, it is also important that labels for pesticides are carefully read and followed with regards to greenhouse considerations.

Cold temperature thresholds. Even with the afore-mentioned protection methods, strawberry plants are exposed to freezing temperature during the winter and early spring in the Intermountain West. To further understand the effect on net CO_2 assimilation of leaves exposed to freezing temperatures, greenhouse grown strawberry plants were exposed to freezing temperatures ranging from -3 to -11 °C (Chapter 6). The LT_{50} (temperature at which 50% of carbon assimilation activity is lost) of strawberry leaves was -5.3 °C. Once exposed to -5 °C, leaves are not able to recover, even after 28 days. With these findings, it is recommended that protective systems be managed to maintain air temperature above -3 °C to minimize reduction in the photosynthetic capability of the leaves.

Literature Cited

Hunter, B.L. 2010. Enhancing out-of-season production of tomatoes and lettuce using high tunnels. M.S. Thesis. Utah State University, Logan Utah.

Ernst, T. 2012. Optimizing winter spinach production in high tunnels. M.S. Thesis. Utah State University, Logan Utah.

Rowley, D.R. 2010. Season extension of strawberry and raspberry production using high tunnels. M.S. Thesis. Utah State University, Logan Utah.

Wien, H.C., J.E. Reid, C. Rasmussen, and M.D. Orzolek. 2008. Use of low tunnels to improve plant growth in high tunnels. July 9, 2012 <http://www.hort.cornell.edu/hightunnel/about/research/general/USEOFLOWTUNNELSarticle2008.pdf >

APPENDIX

To Whom It May Concern:

I hereby give permission to Tiffany Maughan to reprint the following material in her thesis in its entirety.

Maughan, T., T. Ernst, B. Black and D. Drost. 2012. Defending the Castle: Integrated Pest Management in High Tunnel Strawberries. Utah State University Extension. Logan, Utah. <http://extension.usu.edu/files/publications/publication/Horticulture_HighTunnels_2012-04pr.pdf>

Fee: None

Signed

Taunya Ernst