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Biological and Mechanical Approaches to Sunscald Management in Bell Pepper Production

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BIOLOGICAL AND MECHANICAL APPROACHES TO SUNSCALD MANAGEMENT IN BELL PEPPER PRODUCTION

by

Samuel D. Day

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ABSTRACT

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Red bell peppers have not traditionally been grown in high air temperature and high light environments, because sunscald damage occurs when fruits are exposed to damaging levels of solar radiation. Increasing leaf area or supplying mechanical shade may decrease sunscald. Here we report the effect of biological and mechanical shade on the occurrence of sunscald in pepper production. Plants were grown under low tunnels after transplanting to optimize early plant growth in order to increase internal shading of fruit later in the year. In 2012, mechanical shade was installed on the west side of rows to produce shade in the afternoon. In 2013, mechanical shade was oriented vertically over the top of the crop to provide shade in the morning and evening and horizontally to provide shade throughout the day. Warmer soil and air temperatures under low tunnels increased the number of leaves and leaf mass per plant compared to plants in the no tunnel control. In high temperature and light conditions (air temperatures > 30°C; solar radiation > 900 $W \cdot m^{-2}$) increased internal shading did not reduce the amount of solar radiation reaching pepper fruit. Plants grown under low tunnels early in the season did not decrease sunscald or increase yield later in the season unless combined with mechanical shade. While vertical shade decreased sunscald occurrence and increased marketable yield compared to plants in the open control, it did so more effectively when combined with plants grown under low tunnels. Horizontal shade eliminated sunscald and produced the highest marketable yields and fruit quality. Reduced sunscald under horizontal shade was due to the average and maximum pepper fruit surface temperature (FST) being significantly lower compared to the open control. Mechanical shade should be installed to provide protection to all sides of the plant canopy when the sun is at 120° to 240° angles and before solar radiation levels exceed 752 $W{\cdot}m^{-2}$. Increased costs of mechanically shading a crop are offset by increased yield and quality due to sunscald elimination and reduced plant stress. Therefore mechanical shade is recommended for use in high stress conditions.

(150 pages)

PUBLIC ABSTRACT

Sunscald Management in Red Bell Pepper Production

Samuel Day

Producing red bell peppers in high temperature and light environments can be challenging because many new semi-indeterminate varieties produce small plant canopies that leave fruit exposed to damage (sunscald) caused by solar radiation. Pepper production in Utah coincides with high air temperatures and solar radiation levels during July, August, and September. Increasing plant canopy size is one way to protect fruit from solar radiation. Low tunnels optimize plant growth by increasing air and soil temperatures. Growing plants under low tunnels early in the season could increase fruit shading later in the season. Another way to protect fruit is by using mechanical shade. Hanging shade cloth over a crop has been shown to decrease air temperatures and solar radiation levels reaching fruit. While the common production practice is to horizontally orient shade cloth, vertically orienting shade cloth may also be effective by providing shade to the crop in the morning and evening.

These protection methods were evaluated in Layton, Utah for effectiveness of increasing yield by decreasing sunscald occurrence. While plants grown under low tunnels for two weeks after transplanting had larger canopies, they did not increase yield or decrease sunscald compared to plants not grown under low tunnels. Vertical shade increased yield and decreased sunscald most effectively when combined with plants grown under low tunnels. Vertical shade protected exposed fruit when the sun was at lower elevations while increased canopy shade protected fruit when the sun was at high solar elevations. Horizontal shade completely eliminated sunscald and produced the largest yields of high quality fruit. The additional costs associated with using supplemental shade were offset by increased yields and higher value of larger fruit.

Separate studies were carried out to determine how sunlight and wind influence the temperature of pepper fruit. Sunlight exceeding 550 $W \cdot m^{-2}$ increased pepper fruit surface temperature (FST) to damaging levels. Wind decreased pepper FST but moderate wind speeds (3.0 $m \cdot s^{-1}$) did not decrease it below damaging levels. To insure protection, growers should apply supplemental shade when solar radiation levels exceed 550 $W \cdot m^{-2}$. These results provide improved guidelines for growers interested in using supplemental shade to provide pepper fruit for local and national consumption. Additionally, pepper growers in high air temperature and light environments can increase productivity and profitability with the use of supplemental shade.

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Samuel D. Day

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Bell pepper history and taxonomy

Pepper or *Capsicum* species are members of the *Solanaceae* family that includes tomato and potato. Bosland and Votava (2000) stated that all *Capsicum* species, with the exception of *Capsicum anomalum* originated in the western hemisphere. Peppers are classified into different horticultural groups based on their size, shape, and color (Swiader and Ware, 2002). The most commercially important pepper cultivars belong to the genus and species *Capsicum annuum*.

Groups within *Capsicum annuum* can be separated into two categories which are; pungent (hot), and non-pungent (sweet) peppers. Bell peppers (*Capsicum annuum* L.) are the most common pepper in the non-pungent (sweet) category (USDA, 2001). *Capsicum annuum* was first domesticated and grown in Mexico and Central America, and the wild chiltepin (*Capsicum annuum* var. *aviculare*) is the most likely ancestor of *Capsicum annuum* (Bosland and Votava, 2000). Bell peppers are characterized by fruits that are large and blocky with fruit color that is green when immature and red when mature, although Simonne et al. (1997) observed fruits of newer varieties can be white, yellow, orange, red, purple, brown, or black at maturity.

Bell pepper dietary properties

Haytowitz and Matthews (1984) found that green bell peppers are an excellent source of ascorbic acid and a fair source of provitamin A carotenoids. Simonne et al. (1997) showed that a 100 g serving of fresh bell pepper will supply 100% of the recommended dietary allowance of ascorbic acid. They stated that although black, purple, and white bell peppers are good sources of ascorbic acid and provitamin A; green, red, and orange bell peppers have higher concentrations. Peppers are also rich in flavonoids (Lee et al., 1995) and other phytochemicals (Duke, 1992). Bosland and Votava (2000) noted that the antioxidant vitamins A, C, and E are present in high concentrations and that some peppers can contain six times as much Vitamin C as an orange. Bell peppers are not a significant source of fat, protein, or minerals (Simonne et al., 1997).

Bell pepper production

Most bell pepper varieties can be used in both the processing and fresh market so the bell pepper market is considered a dual use market (USDA, 2001). Bell peppers are produced and marketed year round with domestic shipments peaking in May and import shipments highest during winter months. While the majority of the green bell pepper crop is grown in open fields, colored peppers are extensively produced in greenhouses, high tunnels, and shade structures (Jovicich et al., 2005; López-Marín et al., 2013). Mexico, The Netherlands, Canada, Israel, and Spain all have large greenhouse areas dedicated to the production of colored bell peppers and are significant exporters of this commodity to the United States (U.S) (Jovicich et al., 2005).

Two thirds of all bell pepper imports enter the U.S. from December to April, when domestic production slows (USDA, 2001). China is the world's largest producer of *Capsicum* peppers (hot and sweet) followed by Mexico, Turkey, Spain, Nigeria, and the U.S. Peppers are grown on every continent except Antarctica, and the ability of pepper to be grown in a wide variety of climates has made it a common crop worldwide (Bosland and Votava, 2000).

Bell peppers account for a significant portion of the total pepper production in the U.S. at approximately 24,000 hectares (USDA, 2002). According to the 1997 Census of Agriculture (USDA, 2001) California produced 46% of the U.S. bell pepper crop followed by Florida (36%) and New Jersey (6%). California's shipping season goes from April to December with peak volume from May through July while Florida's shipments run from October through May with peak volume occurring in March and April. New Jersey's shipping season goes from July through early November with peak volume in August. Bell peppers are grown in 48 U.S states (production was too small to report in Alaska and Wyoming), and 4% of the farms that produced bell peppers accounted for 74% of the bell pepper area harvested.

Bell pepper demand

A strong locavore movement in the U.S. has increased consumer interest in buying locally grown produce, including pepper. According to the USDA (2012), the number of farmers' markets in the U.S. grew from 4,685 in 2008 to 7,864 in 2012 indicating consumer's preference for fresh, locally grown produce. It should also be noted that since 1970, per capita use of bell peppers has gradually increased, as its consumption in the U.S. has become more widespread.

The annual per capita consumption is 3.63 kg of bell peppers (2000), which is 80% higher than in 1990. Additionally, 24% of Americans consume at least one food containing bell peppers every day (USDA, 2001). This increase in consumption is due in part to an increased awareness of the dietary benefits of vegetables. Because of the growing consumer trend to eat healthy and buy locally, the demand for bell peppers should continue to increase. Additionally, since red bell peppers have more vitamin A and C, and a sweeter taste then green bells (Frank et al., 2001; Swiader and Ware, 2002; USDA, 2001) their demand will also continue to grow (Jovicich et al., 2005).

Bell pepper market and price trends

As the demand for bell peppers has increased, market prices have gone up as well. Between 1960 and 2000, seasonal average bell pepper shipping point prices gained an average of $1.48 per 100 kg per year (USDA, 2001). Additionally, the retail price for fresh market peppers rose 25% between 1994 and 1999. From 1998 to 2000, annual farm cash receipts for bell peppers averaged $535 million with an estimated retail value of over $1.7 billion (USDA, 2001).

Green bell peppers comprise the majority of the market (Frank et al., 2001), but strong markets also exist for orange, red, yellow, and even brown bell peppers. Market shares for green, red and yellow bell peppers are 80%, 10%, and 8% respectively. While most bell peppers are picked and sold at the mature green stage, growers can receive premium prices for red bell peppers (USDA, 2001). The higher price is due in part to higher field losses and lower total yields.

Bell peppers normally reach the mature green (horticultural maturity) stage 35 to 50 days after anthesis (DAA) (Bosland and Votava, 2000; Vidigal et al., 2011). Vidigal et al. (2011) found that bell pepper fruit diameter, weight and length increased until approximately 40 to 45 DAA, indicating the fruit had reached green maturity. The development of the mature fruit color (physiological maturity) takes an additional 20 to 30 days after horticultural maturity (Vidigal et al., 2011). Variations in the length of the coloring period may be due to the environmental conditions present throughout the maturation period (Jovicich et al., 2005). They explained that bell peppers can be exposed to adverse environmental conditions such as rainfall, extreme air temperatures, solar radiation, and insect pests and diseases during the growing period. Therefore allowing fruit to go through the coloring period increases their exposure to factors that can further reduce quality and yield in comparison with mature green bell pepper harvests.

Green and colored bell peppers produced in field, greenhouses, high tunnels, and shade structures have different production costs and receive different prices. Jovicich et al. (2005) found that greenhouse-grown colored bell peppers were worth three to five times as much as field grown bell peppers from 1993 to 2002. They reported that a large portion of the U.S demand for high quality colored bell peppers is currently supplied by imports, but the increase in the U.S. demand has been satisfied with both increased imports and domestic production.

Pepper botany and physiology

Pepper can be grown as an annual or perennial crop (Bosland and Votava, 2000). Bell pepper seed germinates between 16 and 35ºC, with optimum germination occurring at 29ºC. Swiader and Ware (2002) report that bell pepper is adapted to mean growing temperatures between 18 to 29ºC. Pepper is highly susceptible to frost, and plant growth slows when temperatures drop below 16ºC (Bosland and Votava, 2000). Peppers can be propagated in a variety of ways including; direct seeding in the field, by transplants grown in a greenhouse, or by bare root transplants that are field grown. Bell peppers may be planted on un-mulched or plastic-mulched beds, and while many growers use double rows, some prefer single rows for disease control (Swiader and Ware, 2002). Pepper plants require well drained soils (Bosland and Votava, 2000; Maughan et al., 2012; Swiader and Ware, 2002) and fertilizer applications should be based on soil tests (Bosland and Votava, 2000).

Pepper is a dicotyledonous plant (Swiader and Ware, 2002) and the first flower bud develops where the main stem branches at its apex (Bosland and Votava, 2000). Two or more shoots create this branch and that each of the shoots bears one or two leaves, terminates in a flower, and then divides into two second-order branches (Bosland and Votava, 2000). One of the lateral branches forming this branch is sometimes suppressed, especially in the third and higher branches, so that the branch system tends towards a sympodium (Shah and Patel, 1970).

Bosland and Votava (2000) stated that a normal *Capsicum* flower is pentamerous, hermaphroditic and hypogynous. Flowers are self-pollinated, and flowering is considered day-neutral, but can be accelerated under long days and warm temperatures (Swiader and Ware, 2002). Air temperature, especially at night is an important factor determining if flowers will form (Bosland and Votava, 2000). Temperatures above 32ºC often result in flower abortion in bell peppers (Swiader and Ware, 2002). Fruit set does not occur when mean temperatures are below 16ºC or above 32ºC, and flowers may abort and fall off the plant if night temperatures exceed 24ºC (Bosland and Votava, 2000). While day and night temperatures above 32°C and 24ºC, respectively, may cause flower drop, temperatures in excess of 30ºC can harm pollen formation possibly resulting in reduced pollination and fruit set even though flowers do not immediately abort (Bosland and Votava, 2000).

Approximately 130 days are needed to grow a transplanted pepper crop for multiple harvests (Hegde, 1987). While pepper growth includes plant establishment, fruit set, and fruit development, all phases of growth overlap throughout the season. Vidigal et al. (2011) classified the maturation of bell pepper fruit based on their outside color and concluded that fruits are green until they begin to color 45 to 50 DAA. They explained that fruit then turn red by 55 to 65 DAA, and reach an intense red 70 to 75 DAA. Baranski et al. (2005) found that during coloring, chloroplasts change into chromoplasts and some carotenoids decline while others are accumulated. Deli et al. (2001) specifically found that capsanthin and other species-specific keto-carotenoids like capsanthin-5, 6-epoxide and capsorubin and their derivatives are synthesized giving maturing pepper fruits their red color. The carotenoid content of a pepper fruit is controlled by the genotype of the plant and the environment where the plant is grown (Bosland and Votava, 2000). Bell peppers can be harvested at horticultural (green) and physiological (red) maturity. While green fruit may reach horticultural maturity, they are physiologically immature because if picked, they are incapable of normal ripening (coloring) (Bosland and Votava, 2000).

Common bell pepper diseases and disorders

Bacterial soft-rot (*Erwinia carotovora* pv. *carotovora*). Bacterial soft-rot can be very destructive and is characterized by water-soaking and rapid softening of fruit tissue (Stommel et al., 1996). Under humid conditions and optimum temperatures, entire fruit can be reduced to a watery mass within approximately six days (Fig 1.1). Affected fruit produce a foul odor and hot and humid conditions promote the growth of this bacterium. Control measures include removing and disposing of diseased fruits and spraying copper fungicides when hot and humid conditions or inoculum are present (Bosland and Votava, 2000). Additionally, because this bacterium can enter the fruit through cuts, bruises, sun scalded tissue, and insect feeding sites, any injury to fruits should be minimized or avoided.

Blossom end-rot. Blossom end-rot is caused by insufficient calcium availability during early fruit development (Swiader and Ware, 2002). Inadequate translocation of calcium to a developing fruit can be caused by drought, over watering, high nitrogen fertilization or root pruning due to mechanical cultivation (Bosland and Votava, 2000) or nematode feeding (Hochmuth and Hochmuth, 2012). Hochmuth and Hochmuth (2012) explained that excessive nitrogen fertilization can lead to rapid shoot growth and that if this occurs during fruit set and growth, calcium movement may be prioritized toward growing leaves instead of fruits. Even if sufficient calcium is present in the soil solution and shoot growth is not occurring, leaves can transpire heavily enough on hot sunny days to divert all of the water carrying calcium away from pepper fruit (Alexander and Clough, 1998). A lack of calcium in the soil can exacerbate this disorder (Bosland and Votava, 2000).

The symptoms of blossom end-rot (Fig 1.2) start as water soaked areas on the blossom end of the fruit that turn dry, light colored, and papery with time (Swiader and Ware, 2002). The affected tissue shrinks until it is flat or concave and fruit with this disorder usually ripen prematurely (Bosland and Votava, 2000). Alexander and Clough (1998) found that losses due to blossom end-rot can be up to 15%.

The control measures for blossom end-rot include maintaining adequate soil moisture (Madramootoo and Rigby, 1991) specifically during warm, sunny, and windy periods of the growing season and especially during fruit set (Hochmuth and Hochmuth, 2012), adding calcium to the soil, and shading the crop (Alexander and Clough, 1998). Foliar calcium sprays may be required in areas where calcium forms insoluble compounds in high pH soils (Gale et al., 2001). While high levels of radiation, low relative humidity, and high wind speeds increase leaf transpiration and water loss, shade material (cloth or screen) decreases the radiation and wind reaching the crop (Möller and Assouline, 2007). This reduces leaf transpiration and water loss resulting in a balanced calcium distribution between fruits and leaves.

Flower and bud drop. Heat stress, excessive or deficient nutrient levels, and insufficient water can cause peppers to abort flower buds, flowers, or immature fruits

(Bosland and Votava, 2000). Additionally, excessive shading can cause flower drop and reduce fruit set (Rylski and Spigelman, 1986a). Because flower and bud drop is a major problem in the U.S. (Bosland and Votava, 2000), growers in affected areas should: plant varieties that are more resistant to extreme temperatures, avoid over-fertilization of nitrogen, and maintain adequate soil water throughout production.

Sunscald

Terminology and damage. Sunscald refers to a group of disorders associated with damaging levels of solar radiation and radiant heating (Barber and Sharpe, 1971). The terms sunburn and solar injury can also be used to describe this disorder (Racsko and Schrader, 2012). Sunscald affects many horticultural crops including fruits (Racsko and Schrader, 2012) and vegetables (Barber and Sharpe, 1971; Rabinowitch et al., 1986). In Washington State where half of the U.S apple crop is grown, annual losses of 10% due to sunscald are not uncommon. In warmer climates such as Australia, South Africa, and Chile losses can be up to 40% in unprotected apple orchards (Racksco and Schrader, 2012).

Sunscald also causes important economic losses in pepper production (Barber and Sharpe, 1971). When sunscald affects developing peppers, blemishes are created which render the peppers unmarketable as fresh produce (Madramootoo and Rigby, 1991). Rylski and Spigelman (1986a) reported losses of 36% in field produced red bell peppers grown in Besor, Isreal while Barber and Sharpe (1971) reported losses of 12% in field grown mature green bell peppers in Sydney and Wellington, Australia.

Cause. Plants require light for life, but as the quantity of light in natural environments can vary over several orders of magnitude in a matter of seconds, plants often receive more sunlight than they can use for photosynthesis (Müller et al., 2001). While there are plant mechanisms to regulate the amount of energy absorbed, these processes are not fail-safe and sometimes toxic compounds are produced as a result of excess energy absorption (Taiz and Zeiger, 2010).

When light harvesting exceeds utilization, one pathway plants use to dissipate energy is by a light-harvesting pigment-protein complex exciting a chlorophyll molecule which transfers the energy to ground-state 0_2, generating singlet oxygen (Müller et al., 2001). Singlet oxygen is extremely damaging and reactive and can cause photo-oxidative (photodynamic) damage which in extreme cases leads to pigment bleaching and death. It reacts with and damages many cellular components and especially lipids (Taiz and Zeiger, 2010). Excess light energy can lead not only to the production of singlet oxygen but also to other toxic species such as superoxide and peroxide (Taiz and Zeiger, 2010).

Carotenoids can provide photo-protection from photo-oxidative damage by quenching the excited state of chlorophyll (Taiz and Zeiger, 2010). Damage does not occur because the excited state of carotenoids does not have enough energy to form singlet oxygen, so it decays back to its ground state while losing its energy as heat. Li et al. (2009) and Müller et al. (2001) found that there are other non-photochemical quenching processes that protect photo-system II from damage by converting a large fraction of the excitations in the antenna harvesting system into heat.

Barber and Sharpe (1971) conducted a study in Sydney and Wellington, Australia to determine the factors that influence the development of sunscald in bell pepper. They found that the transmission of solar radiation through intact pepper fruits was small and that energy not reflected by fruits was absorbed. Absorbed energy can be photo-chemically stored in the form of organic compounds, emitted as fluorescence or converted into heat. Because chemically stored energy and fluorescence are negligible (Gates et al., 1965), extra absorbed energy is converted into heat that can be dissipated by long-wave radiation, convective heat loss, latent heat loss (transpiration), or conducted through the fruit itself.

Makeredza et al. (2013) found that apples absorb radiation but are unable to use or dissipate excess radiation. Accumulating radiation causes a rise in fruit surface temperature (FST) which can lead to a localized burning of the fruit skin if the FST exceeds the threshold for damage. Fruit surface temperature is a function of heat exchange through radiation, evaporation, and convection between the fruit surface and the surrounding plant canopy microclimate (Makeredza et al., 2013). Thus the main cause of sunscald is absorbed solar radiation being converted to heat (FST) or diverted from photosynthesis into damaging photo-oxidative reactions.

Heat loss from fruit. Barber and Sharpe (1971) calculated the local heat transfer coefficient based on a sphere for the sunscald region of bell pepper and it varied from 0.084 to 0.126 $J \cdot cm^{-2}\ min^{-1}\ {}^{\circ}C^{-1}$. These values should only be considered an approximate range as the field conditions they were calculated in were more variable than in a laboratory. Heat loss from insolated bell peppers due to conduction and convection is minimal because large pepper fruits have a low surface to volume ratio compared to leaves. Additionally, large fruits have large boundary layers (Barber and Sharpe, 1971) especially at low wind speeds and high air temperatures (Drake et al., 1970), which could reduce heat transfer from insolated fruit to the ambient air.

Transpiration through bell peppers does occur but at very low levels (Barber and Sharpe, 1971) which can be explained by fruit having few stomata and a thick layer of wax on their epidermis (Banaras et al., 1994; Weryszko-Chmielewska and Michalojć, 2011), while the mean water loss rate and permeability to water vapor declines with increases in fruit size and ripeness (Díaz-Pérez et al., 2007). Barber and Sharpe (1971) measured the transpiration of whole fruits under natural conditions and reported the latent heat flux as a percentage of total incident energy with bell peppers at 3.5% and 1.5% if loss through the pedicel was ignored. While leaves increase energy (heat) loss by increasing transpiration at high temperatures (Drake et al., 1970), heat produced from photo-protection, non-photochemical quenching, or as a direct result of absorbed radiation cannot be dissipated through transpiration in pepper fruits.

Barber and Sharpe (1971) suggested that a portion of the heat from the insolated side of a pepper might be conducted through the fruit itself by a process similar to an industrial heat pipe. Eastman (1968) explains that a large quantity of energy is absorbed from a heated area to evaporate a liquid. As the liquid vaporizes, the thermal excitation of the molecules comprising the newly created vapor increases the pressure at the evaporative end of the pipe. This creates a pressure gradient that causes the vapor to move toward the unheated area where it turns back into a liquid and releases the thermal energy stored in its heat of vaporization. This situation could occur inside of a whole intact pepper fruit and Barber and Sharpe (1971) calculated the conductivity of a vapor saturated air filled space at 41°C and 50°C to be 0.142 $J \cdot cm^{-1} \cdot min^{-1} \cdot °C^{-1}$ and 0.234 $J \cdot cm^{-1}$ $min^{-1} \cdot °C^{-1}$, respectively. Because bell peppers cannot lose large amounts of heat through the aforementioned processes, excess absorbed solar radiation can accumulate to damaging levels.

Browning (bleaching). Browning is not the result of tissue death but is due to a loss of pigmentation in fruit that results in a yellow, bronze, or brown spot on the insolated side of apples (Racsko and Schrader, 2012). Similar damage occurs on bell peppers (Fig. 1.3). Wade et al. (1993) reported bronzing damage when green bananas were irradiated with ultra-violet (UV) light and Kossuth and Biggs (1978) noticed an increase in bronzed blueberry fruit under high UV-B levels. High levels of UV-B radiation in combination with a high FST is required for browning to occur in apples (Racsko and Schrader, 2012). The FST threshold for browning (46°C) is lower than for necrosis (52°C) in apples (Makeredza et al., 2013 and references therein) but specific thresholds for pepper have not been determined. Rabinowitch et al. (1986) showed that light in the visible spectrum was essential for browning (bleaching) to occur in pepper. Browning damage is commonly found on fruits growing at high altitudes (Barber and Sharpe, 1971), which is explained by an increase in UV levels with elevation (Teramura and Sullivan, 1991).

Browning is the most common type of sunscald damage on apples (Makeredza et al., 2013). This could be explained by browning having a lower FST threshold in high light environments than necrosis. They found that as favorable environmental conditions raised the FST of apples to the threshold for necrosis, the percentage of fruit with browning damage decreased. These findings suggest a progression in the severity of sunscald (from browning to necrosis) with increases in FST. Rabinowitch et al. (1986) also found that sudden exposure of green peppers to sunlight can result in photodynamic (photo-oxidative) damage causing bleaching that can progress to the death (necrosis) of exposed cells. Browning (discoloration) in tomatoes is due to lycopene biosynthesis and the accumulation of beta-carotene stopping in tissues affected by sunscald (Baranski et al., 2005).

Necrosis. Necrosis is where skin, peel, or fruit tissue dies on the insolated side of the fruit. Tissue death is caused by a supra-optimal FST that leads to thermal cell death in apples (Racsko and Schrader, 2012). While Rabinowitch et al. (1986) differentiated between sunscald necrosis (cell death caused by photodynamic processes that require light and an elevated FST) and heat (thermal) damage (cell death only caused by an elevated FST), both have similar visual characteristics and are often combined. Necrosis is the most readily visible type of sunscald in apples (Racsko and Schrader, 2012), and is characterized by a dark brown or black necrotic spot on the insolated side of the fruit. Similarly, necrosis is visible on peppers and has many of the same characteristics (Fig 1.4).

Necrosis developed on previously shaded attached green bell peppers when their FST reached 49ºC for at least 15 min in full sunlight (Barber and Sharpe, 1971). A lower FST threshold (38 to 40°C) was required for sunscald to occur on detached pepper fruit in full sunlight (Rabinowitch et al., 1986) but these researchers did not specify what type of sunscald the threshold was for. Additionally a longer duration (not specified, as fruit were left in full sunlight for an entire day) was required for sunscald to occur at the lower threshold. Because 18 hours at a FST of 45.1°C was equivalent to 28 hours at a FST of 40.8°C in causing sunscald in tomato (Rabinowitch et al., 1974), there must be a relationship between the FST threshold and the time at that threshold required for sunscald to occur. While necrosis can occur on pepper in a matter of minutes at a high FST (Barber and Sharpe, 1971), these studies (Rabinowitch et al., 1974, 1986) suggest that a longer period at a more moderate FST will also cause sunscald. It can be assumed that as peppers FST increases the associated time required for sunscald to develop decreases.

Necrosis occurs at a higher FST on apples that have regularly been exposed (conditioned) to sunlight than fruit that are acclimated to a shady environment then become exposed to direct sunlight (Racsko and Schrader, 2012). Shaded pepper fruit are also easily damaged when they absorb visible energy (Barber and Sharpe, 1971). Because shaded fruit are damaged at a lower FST, many researchers differentiate between necrosis on conditioned and unconditioned fruit by calling the resulting damage necrosis (conditioned) and photo-oxidative (unconditioned) sunscald (Barber and Sharpe, 1971; Glenn and Yuri, 2013; Racsko and Schrader, 2012). Fruits can become exposed when plants are damaged during harvest, when leaf loss occurs due to an extreme weather event, as lower branches on the main shoot bend under fruit weight causing the plant canopy to open (Rylski and Spigelman, 1986a), when plants lodge, or when water stress causes leaf folding (Makeredza et al., 2013).

Environmental conditions. Makeredza et al. (2013) reported a high incidence of sunscald (necrosis and browning) on apple fruit during conditions of high temperatures (>30°C), vapor pressure deficits, and sunny conditions (>21 MJ m^{-2} day^{-1}). Likewise Rylski and Spigelman (1986a) reported a higher incidence of sunscald on bell peppers when daytime air temperatures and irradiance levels were greater than 30°C and 25 MJ m^{-2} day^{-1}, respectively. High light levels cause a reduction in ascorbic acid content, a well-known antioxidant and scavenger of free radicals, and high temperatures usually inhibit enzymes, decouple oxidative phosphorylation and release damaging free radicals (Prohens et al., 2004 and references therein).

Prohens et al. (2004) found that insolated *Solanum muricatum* fruit were 12.5°C warmer than ambient air temperatures while Gindaba and Wand (2005) reported temperature differences of 10°C to 12ºC between the FST of insolated apples and the ambient air temperature. While certain environmental conditions favor sunscald, solar absorptivity, interception of solar energy, temperature tolerance, specific photostability, tolerance to ultra-violet radiation, and the degree of adaption or sensitization to the environment all contribute to bell peppers susceptibility to sunscald (Barber and Sharpe, 1971).

Fruit size and color. Rabinowitch et al. (1983) conducted a study to determine if bell pepper maturity and variety changed fruits' tolerance to sunscald. They found that peppers were most prone to sunscald at the mature green stage, while immature green peppers were less susceptible, and red peppers were resistant. Apple maturity has also been shown to influence cultivars response to UV, photosynthetically active radiation (PAR), and ultimately FST (Glenn and Yuri, 2013). Bell peppers with darker pericarp color have been shown to be more prone to sunscald than bell peppers with a light green color (Rabinowitch et al., 1983). Barber and Sharpe (1971) also noted variations in pepper fruit susceptibility to sunscald with maturity and color. They attributed the differences to the total energy absorption of fruit and ultimately their FST which changed as reflectivity to sunlight increased with lighter colored fruit.

Rabinowitch et al. (1983) saw a similar response when they compared dark green bell peppers with light green to yellow bell peppers but stated that while pericarp temperatures between two similarly colored bell peppers (light green and light green to yellow) were similar, they differed in their percentages of sun-scalded fruit. They also found that bell peppers at different stages of maturity showed significant differences in their susceptibility to sunscald but only had slight differences in pericarp temperature. Differences in sunscald occurrence, observed when pericarp temperatures were similar were attributed to the acquired tolerance of certain varieties due to the position of their fruit in the plant canopy. They concluded that bell peppers that are partially exposed to sunlight were more tolerant to sunscald. Shaded tomato fruit have also been shown to be more susceptible to sunscald then partially exposed fruit when they are suddenly exposed to strong sunlight (Kedar et al., 1975). These findings suggest that exposed fruit have heat-conditioned tissues and that photosynthesis in these conditioned areas remains functional upon subsequent exposures to elevated FST, while non-hardened tissue loses its photosynthetic capacity resulting in sunscald caused by photo-oxidative damage.

Hardening or conditioning could be due to small heat shock proteins that accumulate to high levels in plants in response to heat stress. Waters et al. (1996) found that purified recombinant plant small heat shock proteins facilitate reactivation of chemically denatured enzymes and prevent heat-induced aggregation or reverse inactivation of protein substrates. They concluded that small heat shock proteins bind partially denatured proteins preventing irreversible protein inactivation and aggregation and that their activity contributes to the development of thermo-tolerance.

Bell peppers have been shown to have the highest susceptibility to sunscald during chlorophyll degradation as fruit start to color (Rabinowitch et al., 1983). During ripening, the green pigment becomes more sensitive to the disturbance caused by high temperatures so there is increased diversion of energy from normal photosynthetic pathways, leading to damaging photo-oxidative reactions. While Rabinowitch et al. (1983) believe that red bell peppers are resistant to sunscald, Barber and Sharpe (1971) observed water soaked blisters and the epidermis of red fruit separating from the underlying pericarp, giving the fruit a cooked appearance. While this type of damage differs from necrosis or browning, it does result in reduced fruit quality and should be considered sunscald.

Other factors affecting sunscald severity. While air temperature and sunlight are the direct factors causing sunscald in apples, many indirect factors including relative humidity, air movement, acclimation, cultivar susceptibility, individual fruit characteristics, geographic location, orchard characteristics, and cultural management practices can influence the severity of sunscald damage (Racsko and Schrader, 2012). All of these factors have the potential to influence sunscald severity in pepper and should be managed to reduce the severity of any sunscald that does occur. In order to manage the occurrence of sunscald, different biological or mechanical approaches are needed.

Sunscald management by biological approaches

Biotechnology. Wang et al. (2006) conducted a study to determine if by gene transfer, transformed tomato that over expresses escytosolic ascorbate peroxidase (cAPX), could increase tolerance to heat, UV-B light, and thereby reduce sunscald. These researchers explained that ascorbic peroxidase and superoxide dismutase are two enzymes that scavenge damaging reactive oxygen species such as hydrogen peroxide, superoxide and hydroxyl radicals that can denature enzymes and damage important cellular components. They found that the activity of ascorbic peroxidase was several times higher in the leaves of the cAPX transgenic plants, than in the leaves of the control plants. They concluded that the over expression of cAPX enzymes in tomato resulted in the enhanced resistance of leaf and fruit tissues to heat and UV-B light through enhanced protection of membrane lipid peroxidation during heat stress and by detoxifying large amount of reactive oxygen species during UV-B stress. Genetically engineering pepper is difficult due to the lack of a transformation system and specifically the lack of a good way to regenerate pepper plants via tissue culture (Bosland and Votava, 2000).

Additional research should be devoted to this area so the potential effects of biotechnology as tool to reduce sunscald in pepper can be determined.

Grafting. López-Marín et al. (2013) grafted sweet pepper cultivar Hermino onto three commercial rootstocks. Plants grafted onto 'Atlante' had 35 to 40% larger leaf area than the other graft combinations or the un-grafted controls. They found that the increase in leaf area increased fruit shading and resulted in a reduction in sun-scalded fruit in comparison to control plants. Some rootstocks increased the concentration of vitamin C and total antioxidant capacity under non-shaded conditions which might indicate a higher adaptive capacity to heat stress and result in a photo-system II complex more resistant to photo-inhibition under high radiation conditions. The development of new rootstocks based on these findings may improve crop performance in the face of environmental stress and make grafted pepper plants an efficient alternative to mechanical shading to reduce thermal stress (López-Marín et al., 2013). Grafting could prove to be an effective tool in managing sunscald in Utah because it decreased sunscald in southeast Spain when air temperatures exceeded 38°C (the FST threshold required for sunscald to occur in detached peppers, Rabinowitch et al., 1986) for 20 days between fruit set and harvest (López-Marín et al., 2013).

Fertilizer management: nitrogen and calcium. Pepper fruit yield has been shown to peak between 120 kg $N \cdot ha^{-1}$ to 180 kg $N \cdot ha^{-1}$ (Hartz et al., 1993; Hegde, 1987; Wiedenfeld, 1986). While nitrogen can have a positive effect on plant growth and fruit yield, an overabundance may result in flower abortion and spindly, brittle plants (Swiader and Ware, 2002). Excess nitrogen can over stimulate growth resulting in large plants with few early fruits and pepper maturity may be delayed during periods of high rainfall and humidity, increasing the risk of plant and fruit rots (Bosland and Votava, 2000). They stated that flower abortion and reduced fruit set due to excess nitrogen can cause a split in fruit set. When fruit set on initial branches, cease setting on subsequent branches, and then set again on later branches a split set occurs. This results in reduced yields and fruit possibly setting higher on the plant, making the plants more prone to wind damage and lodging. Makeredza et al. (2013) found that as a result of apples receiving more sunlight on the western sides of trees, they were more prone to sunscald than their shaded counterparts. Thus, bell pepper fruit that set and grow closer to the edge of the plant canopy should be more likely to sunscald because of their increased exposure to sunlight.

Nitrogen applications should be managed to maximize plant growth because increases in leaf area should improve fruit shading which has been shown to decrease the occurrence of sunscald (López-Marín et al., 2013; Madramootoo and Rigby, 1991). Increasing plant growth using nitrogen may be limited to the pre-flowering period because branching and leaf growth slows in commercially available semi-indeterminate bell pepper varieties as fruit set occurs (Bosland and Votava, 2000). Growth slows because peppers set fruit at most of the flowers on their lower nodes (second and third order branches) and these fruits become large sinks restricting further vegetative development and fourth order and greater branching (Rylski and Spigelman,1986b).

Nitrogen should not be applied in excess because high soluble salt concentrations in the soil solution can lead to a diffusion gradient that favors the movement of water from the root to the soil solution making it difficult for pepper plants to uptake water

(Hochmuth and Hochmuth, 2012). Water stress could result in an increase of sunscald by decreasing plant growth and fruit shading (Madramootoo and Rigby, 1991) or increasing leaf folding which can expose previously shaded fruit that are extremely susceptible (Makeredza et al., 2013). Alexander and Clough (1998) reported that sunscald was reduced by the application of calcium through a drip line but concluded that more research needs to be conducted to determine whether calcium nutrition and sunscald are related.

Irrigation management. Hegde (1987) stated that irrigation has a significant influence on increasing dry-matter accumulation, leaf area index, and pepper yield. He found that 40% to 60% available soil moisture increased these parameters while 20% and 80% available soil moisture had an inverse effect. Makeredza et al. (2013) found that decreased irrigation resulted in an increase in sunscald necrosis and browning incidence on apples. Additionally, they reported that increases in sunscald occurrence and severity resulted from a rise in the FST of apples as stem water potential decreased in response to a reduction in irrigation levels. Similarly, Madramootoo and Rigby (1991) found that when trickle irrigation emitter spacing decreased from 1.63 to 0.45 m, pepper plant height and canopy diameter increased. They reported that leaf mass increased from 58.8 g $plant^{-1}$ at the 1.62 m emitter spacing to 65.4 g $plant^{-1}$ at the 0.45 m emitter spacing. They showed that plants receiving more water were leafier and protected developing fruit from the sun's damaging rays leading to an inverse relationship between leaf mass and the percentage of unmarketable fruit that had sunscald damage.

It is worth noting however, that while narrower emitter spacing reduced the percentage of culls with sunscald damage (Madramootoo and Rigby, 1991) it did not eliminate sunscald occurrence, as 6.4% and 10.3% of the culls in years 1987 and 1988 were affected by sunscald. In addition to the benefits previously mentioned, adequate soil moisture may also decrease the plant canopy temperature as evaporative cooling increases, which could lead to an increase in convectional heat exchange from hot fruit surfaces to cooler ambient canopy air (Makeredza et al., 2013). This could result in a cooler pepper FST and a lower incidence of sunscald occurrence.

Low tunnels. Low tunnels are effective at altering microclimates under field conditions and are less expensive than greenhouses (Bosland and Votava, 2000). Low tunnels (Fig 1.5) consist of small wire hoops that support polyethylene or polypropylene sheets (Gerber et al., 1988). Tunnels can be installed over single or multiple rows of plants to enhance growth and yield (Bosland and Votava, 2000). The polyethylene sheets often have slits or perforations to increase ventilation. Polyethylene sheets are usually 1.1 mil thick and 1.8 m wide. Polypropylene sheets can vary in weight from 17 to 68 $g{\cdot}m^{-2}$ and are available in widths ranging from 1.8 to 15.2 m wide (Robert Marvel Plastic Mulch, LLC, Annville, PA). While most polyethylene sheets are clear, they are also available with a white coating.

Polypropylene sheets are spun-bonded and quite porous allowing for ventilation with the outside air. Gerber et al. (1988) conducted a study that looked at the effects of clear polyethylene with slits, white polyethylene with slits and spun-bonded polypropylene. They reported that air temperatures under the clear polyethylene were highest, followed by the spun bonded polypropylene, while white polyethylene had the lowest air temperature. Their tunnels had a base width of 61 cm and a height of 38 cm. The width and height of low tunnels ultimately depends on the size of the pepper bed, length of wire and width of the sheet used, and how long they would remain in the field.

Barber and Sharpe (1971) found that the frequency of sunscald in green bell pepper fruits was inversely proportional to the leaf to fruit ratio. These findings suggest that if the number of leaves or the leaf area per plant increased with the fruit number staying constant, sunscald occurrence would decrease. Gerber et al. (1988) observed increased vegetative growth under low tunnels and reported that bell pepper plant height, fresh weight, and number of branches per plant increased. Gaye et al. (1992) also noted increased vegetative growth of pepper plants under low tunnels while Jollife and Gaye (1995) found that low tunnels increased the leaf area index of bell pepper plants. These increases in vegetative growth, specifically increases in the leaf area indicate that low tunnels may be a possible approach to increase fruit shading and reduce the occurrence of sunscald.

Varietal selection for tolerance. Differences in susceptibility to sunscald between bell pepper varieties can be large (Barber and Sharpe, 1971). Small podded pepper varieties with erect fruits are less susceptible to sunscald then large podded varieties such as bell peppers (Bosland and Votava, 2000). Barber and Sharpe's (1971) research indicates that genetics play a role in sunscald occurrence as white or ivory colored bell peppers had 60% total reflectivity to solar radiation compared to only 25 to 35% total reflectivity of dark green fruited types. The decreased reflectivity to solar radiation of the dark green bell peppers resulted in 10 to12ºC higher FST, which resulted in up to a 10% increase in sunscald. Rabinowitch et al. (1983) also reported that bell peppers color affected sunscald incidence. Similarly, the temperature of detached tomato fruits are affected by their color with darker green fruits reaching higher pericarp temperatures when exposed to the sun than lighter colored fruit (Retig et al., 1974).

Wang et al. (2006) found that the production of ascorbic peroxidase and superoxide dismutase which aid in sunscald tolerance, varied in tomato varieties which might also help to explain differences in varietal sunscald tolerance in bell pepper. López-Marín et al. (2013) findings also suggest that bell pepper has varietal differences in sunscald tolerance due to factors other than reflectivity. Apple varieties have also been shown to vary in their susceptibility to sunscald (Gindaba and Wand, 2005). While the easiest solution to preventing sunscald in bell pepper production could be breeding for varieties with increased solar reflectivity, Barber and Sharpe (1971) advise against this approach because the lighter colored varieties they tested were inferior in taste and texture when compared with dark green varieties.

Sunscald management by mechanical approaches

Shade cloth effect. Supra-optimal levels of solar radiation can be the most important factor contributing to sunscald (Racsko and Schrader, 2012). If excessive levels of solar radiation can be reduced, the incidence of sunscald should decrease. Hanging shade cloth, screen, nets or another material is a proven way to mechanically reduce the radiative load reaching a crop (Möller and Assouline, 2007). López-Marín et al. (2013) found that under Aluminet® 40% shade screen, the average maximum temperature and radiation were 3°C and 167 µmol $m^{-2}s^{-1}$ lower respectively than in their un-shaded control. Díaz-Pérez (2013) stated that shading nets are one way to reduce heat stress of vegetable crops.

Sunscald was reduced in red bell peppers when 18% and 30% shade screens were installed over the crop after fruits on flowering nodes 1 and 2 reached horticultural maturity (Rylski and Spigelman, 1986b). Additionally, López-Marín et al. (2013) reported that 40% shade reduced the incidence of sunscald on 'Hermino' peppers by 3x compared to the un-shaded controls. Alexander and Clough (1998) shaded a bell pepper crop with spun-bonded polypropylene row covers and reported that sunscald was substantially (33%) reduced.

If a climate consists of sunny days with minimal cloud cover, the available light may exceed that required for maximum crop yield (Roberts and Anderson, 1994). When this occurs, shading could lower plant and fruit temperatures without reducing the amount of photosynthesis or crop yield. 20% black shade net has been shown to decrease the temperature of apple fruit by 5.4°C to 9.7ºC in comparison to un-shaded fruit on days with maximum air temperatures between 34°C and 37ºC (Gindaba and Wand, 2005). They concluded that in high radiation climates, shading reduces irradiance as well as fruit temperature and is more effective at reducing sunscald in apples than evaporative cooling which only reduces fruit temperature.

While shading in climates with high levels of solar radiation may not decrease crop productivity, it can alter pepper plant structure. Rylski and Spigelman (1986a) noted that plant height, number of flower nodes and leaf size increase as light intensity decreased with shading. López-Marín et al. (2013) showed that shading increased plant height, leaf area, leaf fresh biomass and leaf water content, and decreased leaf dry weight when compared with the un-shaded control. Díaz (2013) also noted increased plant leaf area with shading. While many studies report reduced occurrence of sunscald with shading, other notable benefits include a reduction in the crop water requirement leading to reduced irrigation (Möller and Assouline, 2007) and a reduction in the net amount of long wave radiation moving from the ground to sky at night, causing a decrease in damage during radiative frost events (Teitel et al., 1996).

Shade cloth or shade screen is available in a wide variety of shade percentages (10 to100%) and colors (white and black are most common). Shade screen is made by stitching strips that are cut from polyethylene sheets together to form a woven screen (Teitel et al., 1996). Aluminized shade screen is made by coating the polyethylene with a thin layer of aluminum which is then cut and stitched to form a woven screen. Shade cloth is made in a similar manner but Teitel et al. (1996) stated that polypropylene is used in the place of polyethylene. Möller and Assouline (2007) found the cost of a screen house structure including 30% black shading screen is 21,978 U.S. dollars hectare^{-1} while the cost of a steel shade cloth structure (25 year lifespan) including 40% black shade cloth (7-10 year lifespan) and sidewalls is 87,685 U.S dollars hectare $^{-1}$ (Gidco Ag. Design. personal communication, 2013).

Shade cloth position. Orienting shade cloth (or screen) horizontally (Möller and Assouline, 2007; Rylski and Spigelman, 1986a) above the crop has become the common practice in production systems. Because Barber and Sharpe (1971) found that shading of bell peppers by the leaves of a pepper plant is greatest at high solar elevations, vertically orienting shade cloth may also prove beneficial. It would allow plants to receive full sunlight and maximize photosynthesis when they can effectively shade fruit, while providing protection to exposed fruit during the early morning and late afternoon when this self-shading is less effective. If fruit exposure is greatest on the sides of plants that receive morning and afternoon sunlight, supplemental shade should be placed in such a position as to decrease solar radiation during these times.

Reducing sunscald will benefit Utah growers

While U.S. market prices and per capita use of bell peppers has risen (USDA, 2001), Utah's bell pepper acreage has not. Utah bell pepper acreage was so small in 2007 that the USDA did not include it in its database (USDA, 2007). Why are Utah growers not increasing their bell pepper acreage to match the increase in demand? One reason may be that, in Utah, bell peppers are exposed to supra-optimal levels of solar radiation and UV light throughout the growing season. As a result, sunscald damage occurs on a large portion of the harvested bell pepper crop in Utah (10% to 50%).

Because bell peppers affected by sunscald are unmarketable (Madramootoo and Rigby, 1991), the value of Utah's bell pepper crop is severely reduced. Since field grown green and red bell peppers in Utah are subjected to stressful growing conditions for two to three months before harvest, management strategies need to be found to decrease damaging levels of radiation without reducing production levels. If supra-optimal radiation levels can be reduced, a much smaller proportion of fruit will be lost to sunscald and the economic viability of Utah vegetable farms will benefit through increased marketable yields, quality, and ultimately profit.

If a cost-effective biological or mechanical approach to reducing sunscald is developed, Utah growers may increase production and revenue from sunscald sensitive crops including pepper. Because there is a growing demand for green and red bell peppers in the U.S. (Jovicich et al., 2005) and their value is increasing (USDA, 2001), growing these commodities will allow Utah bell pepper growers to more efficiently supply local markets during the growing season and enter new out of state markets, when national production slows during the warm summer months.

In conclusion, this study will be conducted to identify biological and mechanical approaches to reduce the amount of solar radiation reaching bell pepper fruit. This reduction will reduce the total energy absorbed by pepper fruit resulting in lower FST. While extensive research has been conducted to determine how to successfully manage sunscald in apple production (Racsko and Schrader, 2012), this study will look to add to the limited information regarding sunscald management in bell pepper production.

The hypotheses and sub hypotheses of this study are listed below.

Biological Hypotheses

1. Higher air and soil temperatures under low tunnels will increase early plant growth (specifically leaf area).

2. Increasing biological (canopy) shading of pepper fruit will increase crop value.

A. Improved growth will result in increased biological shading of fruits later in the year.

Mechanical Hypotheses

3. Shade cloth will reduce solar radiation and temperature of peppers.

A. Peppers with a lower FST are less prone to sunscald.

B. Shade cloth orientation will alter peppers fruit heat load.

C. Altering peppers fruit heat load will decrease the duration that FST is above the threshold for sunscald.

D. Shading will increase yield by decreasing sunscald occurrence.

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Fig. 1.1. Advanced stage of bacterial soft-rot: The bacterium has spread throughout the fruit turning its tissue into a soft, watery mass, rendering the fruit unmarketable.

Fig. 1.2. Blossom end-rot: insufficient calcium during fruit development led to the development of light colored and papery tissue along the bottom of fruit, rendering it unmarketable.

Fig. 1.3. Sunscald browning: pigment bleaching has occurred on the insolated side of fruit, rendering it unmarketable.

Fig. 1.4. Sunscald necrosis: photo-oxidative (photodynamic) damage has killed the tissue on the insolated side of this pepper. The affected tissue is thin and dry, rendering the fruit unmarketable.

Fig. 1.5. Pepper transplants growing under a perforated 0.03 mm thick 1.83 m wide clear plastic low tunnel that was supported by 0.5 cm x 193 cm wire hoops placed every 1.2 m. The low tunnel was 41 cm wide and 41 cm tall.

CHAPTER 2

BIOLOGICAL AND MECHANICAL APPROACHES TO SUNSCALD MANAGEMENT IN BELL PEPPER PRODUCTION

Abstract. The effect of biological and mechanical shading of bell pepper planted on north to south oriented rows under high air temperatures (>30°C) and solar radiation levels (>900 $W \cdot m^{-2}$) was investigated during the summer months in Northern Utah (41°N, 1309 m elevation). Plants were grown under low tunnels after transplanting to promote leaf growth before fruit set to increase canopy shading later in the season. Shade cloth was vertically and horizontally oriented above the crop to determine the effect of partial and complete mechanical shading. The number of leaves, leaf and stem mass, mass per leaf, leaf area, fruit surface temperature (FST), solar and UV radiation, air temperature, soil temperature, wind speed, affected fruit orientation and location in the canopy, sunscald incidence, sunscald severity, and fruit yield and quality were recorded. Sunscald was categorized as browning or necrosis. Low tunnels significantly increased air temperatures during the day and soil temperatures during the day and night, resulting in plants with more leaves and leaf mass. Shade decreased the number of leaves per plant but increased leaf size. Increased canopy shading induced by low tunnels did not decrease sunscald occurrence later in the season unless combined with mechanical shade. While vertical shade reduced sunscald occurrence it did so more effectively when combined with plants grown under low tunnels. The additive benefit of vertical shade protecting fruit when the

sun was at lower elevations while the larger canopy protected fruit when the sun was at high solar elevations resulted in a large reduction in sunscald and increase in marketable yield. Sunscald was completely eliminated under horizontal shade which resulted in the highest yields and quality obtained in these studies. Sunlight from lower sun angles (<120° and >270°) did not cause sunscald but protection was extremely important between 150 to 210° sun angles. Fruit toward the top of the canopy are more prone to sunscald because of their increased exposure to solar radiation. Air temperatures above 31.4°C and radiation levels exceeding 752 $W \cdot m^{-2}$ produce a FST above the threshold for sunscald (40°C). These studies show that shade is essential if sunscald is to be eliminated in peppers grown in high temperature and light environments.

Introduction

Like many horticultural crops, bell pepper (*Capsicum annuum* L.) fruit are susceptible to sunscald browning (pigment loss or bleaching) and necrosis (cell death) in high light and temperature environments (Barber and Sharpe, 1971; Rylski and Spigelman, 1986a). Sunscald refers to blemishes that are associated with damaging levels of solar radiation and radiant heating (Barber and Sharpe, 1971) which render affected fruit commercially un-marketable (Madramootoo and Rigby, 1991). Sunscald frequently occurs on pepper when air temperatures and radiation levels exceed 30º C and 25 MJ m^{-2} per day (Rylski and Spigelman, 1986a).While many countries mitigate this problem by shading (Jovicich et al., 2005; López-Marín et al., 2013), the majority of the U.S. crop is un-shaded and exposed to environmental conditions that can cause sunscald.

Supra-optimal levels of solar radiation contribute to sunscald (Racsko and Schrader, 2012). Since the transmission of solar radiation through peppers is small, the majority of energy not reflected is absorbed (Barber and Sharpe, 1971). Large fruit have large boundary layers, which reduce heat transfer from insolated fruit to the ambient air. Heat transfer further declines as boundary layers expand at low wind speeds and high air temperatures (Drake et al., 1970). Pepper fruit have few stomata, a thick layer of wax on their epidermis (Banaras et al., 1994; Weryszko-Chmielewska and Michalojć, 2011), and their mean water loss and permeability to water vapor decreases with increases in fruit size and ripeness (Díaz-Pérez et al., 2007), thus heat loss via transpiration is minimal. Excess absorbed solar radiation causes heat energy accumulation that raises pepper fruit surface temperature (FST). Cell death may occur if energy is diverted from photosynthesis into damaging photo-oxidative (photodynamic) reactions when energy absorption exceeds utilization by photosynthesis and dissipation by heat transfer (Rabinowitch et al., 1986).

Supplemental shade can reduce or eliminate sunscald (Alexander and Clough, 1998; López-Marín et al., 2013; Rylski and Spigelman, 1986a) by decreasing solar radiation levels. Shade does not decrease yield if light levels exceed photosynthesis requirements (Roberts and Anderson, 1994). Shade can adversely affect plant growth (Díaz-Pérez, 2013), fruit set, and ultimately yield (Rylski and Spigelman, 1986a) if light levels are reduced below what photosynthesis requires. Díaz-Pérez (2013) showed that during the production of bell pepper in Tifton, GA 30% and 47% shade cloth are best for increasing leaf area while maintaining high levels of photosynthesis. Because light levels change with time and location, the optimum percentage of shade for sunscald protection and maximizing yield will change.

While horizontally orienting shade cloth (Möller and Assouline, 2007; Rylski and Spigelman, 1986a; Teitel et al., 1996) decreases sunscald, vertically orienting shade cloth could have the same effect. Because the shading of bell peppers by the leaves of plants is greatest at high solar elevations and less effective at lower solar elevations (Barber and Sharpe, 1971), vertical shade could reduce sunlight in the morning and evening while allowing plants to receive full sunlight during midday hours when the plants leaves can shade fruit. In addition to decreasing sunscald, vertically orienting shade with preexisting trellis posts used in certain crops (grapes) may prove easier than building a new structure.

Low tunnels could decrease sunscald by increasing biological (canopy) shading. Because the frequency of sunscald is inversely proportional to the leaf to fruit ratio (Barber and Sharpe, 1971), increasing foliage cover should decrease sunscald. Low tunnels have been shown to increase pepper plant growth and leaf area (Gaye et al., 1992; Gerber et al., 1988; Jolliffe and Gaye, 1995).

While green bells are commercially desirable because of their high nutritive value (Duke, 1992; Haytowitz and Matthews, 1984; Lee et al., 1995), red bells have a higher concentration of Provitamin A (Simonne et al., 1997) and a sweeter taste. Because markets exist for colored bells (Frank et al., 2001) and growers receive premium prices for them (USDA, 2001), this study focused on sunscald prevention in red bell pepper production. After reaching green (horticultural) maturity, bell peppers take an additional 20 to 30 days to color and reach (physiological) maturity (Vidigal et al., 2011). During the coloring period, losses due to sunscald can increase if extreme air temperatures and high solar radiation levels persist (Jovicich et al., 2005).

The objectives for this study were: (1) to determine if higher air and soil temperatures under low tunnels increase early plant growth (specifically leaf area); (2) to determine if increased biological (canopy) shading of peppers increases crop value; (3) to determine if shade cloth will reduce solar radiation and temperature of peppers. We hypothesized that improving early plant growth will result in increased biological (canopy) shading of peppers later in the year, that peppers with a lower FST are less prone to sunscald, that shade cloth position will alter peppers fruit heat load, that altering peppers fruit heat load will decrease the duration that pepper FST is above the threshold for sunscald, and that shading will increase pepper marketable yield by decreasing sunscald.

Materials and methods

Location and experimental layout. Studies were conducted on Day Farms in Layton, Utah (41° N, 112° W, 1310 m elevation, 165 frost free days). The soil was a Kidman fine sandy loam (Coarse-loamy, mixed, superactive, mesic Calcic Haploxerolls) with a pH of 7.5. This study was conducted in 2012 and 2013. In 2012 the experimental design was a randomized complete block with four replications, two low tunnel (no tunnel or tunnel) and two shade (open or partial shade) treatments for two cultivars ‘Aristotle’ and ‘Paladin’ (Siegers Seed Co., Holland MI). In 2013, the experiment was a split block design with four replications and two low tunnel (no tunnel or tunnel) and three shade (open, vertical, and horizontal) treatments for one cultivar ‘Aristotle’.

Site preparation. In 2012 and 2013, Trust® herbicide (0.6 $kg \cdot ha^{-1}$) was applied 3 and 2 weeks, before planting, respectively. The ground was worked with a spring toothed harrow after both the herbicide and pre-plant fertilizer applications in both years.

In 2012, the soil was fertilized with 56 $kg \cdot ha^{-1}$ of nitrogen (N), 56 $kg \cdot ha^{-1}$ of phosphorous (P), and 56 $kg \cdot ha^{-1}$ of potassium (K) using a combination of 46-0-0, 11-52-0, and 0-0-60 granular fertilizer, six weeks before planting. An additional 56 $kg\ N \cdot ha^{-1}$ was side-dressed using 46-0-0 at 4 and 6 weeks after transplanting.

In 2013, the soil was fertilized with N, P, and K at 51 $kg \cdot ha^{-1}$, 59 $kg \cdot ha^{-1}$, and 91 $kg \cdot ha^{-1}$, respectively, using a combination of 16-16-16, 11-52-0, and 0-0-60 granular fertilizer, two weeks before planting. An additional 56 $kg\ N \cdot ha^{-1}$ was side-dressed three weeks after transplanting using 46-0-0. Five weeks after transplanting, 50 kg N and 34 kg $K \cdot ha^{-1}$ were side-dressed using a combination of 46-0-0 and 0-0-60. All fertilizer applications were made using a broadcast spreader.

Plant material. The cultivars ‘Aristotle’ and ‘Paladin’ were planted in 2012 but only ‘Aristotle’ was grown in 2013 because the quality of coloring ‘Paladin’ fruit deteriorated in high temperature conditions. This resulted in reduced yields in comparison to ‘Aristotle’ in 2012. In 2012 and 2013, peppers were seeded on 10 Mar. and 19 Mar., respectively. Pepper transplants were produced in a greenhouse using peat based medium and standard 1020 (28 cm W x 54.3 cm L x 6.2 cm D) trays. Approximately 22 days after seeding a puncher (Fig. 2.1a) was used to make 91 holes in the soil medium of new flats

(Fig. 2.1b) where seedlings were planted after being removed from the seed flat (Fig. 2.1 c). After the appearance of the first true leaf, plants were fertilized weekly with a 2% 20-20-20 soluble fertilizer solution. Irrigation took place as needed but only as the soil medium dried.

Plants were removed from the greenhouse for hardening approximately 2 weeks before transplanting. In 2012 and 2013, transplanting occurred on 14 May and 21 to 22 May, respectively. At planting, plants were watered with approximately 0.2 L of a 0.2% 20-20-20 soluble fertilizer solution. Rows were spaced 0.66 m apart with plants spaced 0.41 m apart in row. Rows were oriented north to south in both years and split into 6 m long plots in 2012 and 9 m long plots in 2013. Two guard rows were planted to both sides of test rows in both years.

Irrigation. In 2012, peppers were furrow irrigated weekly starting on June 17. In 2013, one line of drip tape with emitters every 10 cm (7.45 $L \cdot hr^{-1} \cdot m^{1}$) was installed 5 cm away from the plants on the soil surface. Irrigation of all plants using the drip tape occurred on 23 May (approximately 3 $L \cdot plant^{-1}$) and on 2 June (approximately 1.5 $L \cdot plant^{-1}$) to insure plant hydration under the low tunnels. After tunnel removal all plants were watered via the drip tape on 14 June (approximately 1 $L \cdot plant^{-1}$). Plants were then furrow irrigated weekly starting on 20 June. The duration of furrow irrigation in both years was determined by the soil moisture status at the time of watering. Irrigation through the drip line in 2013 ceased after furrow irrigation started, unless mid-week watering was required when the water turn was unavailable.

Low tunnels. In 2012 and 2013, tunnels were installed on 15 May and 23 May and removed on 14 June and 7 June, respectively. The tunnels consisted of a 1.83 m wide 1.1 mil clear perforated plastic sheet (Robert Marvel Plastic Mulch, LLC, Annville, PA) supported by 193 cm wire hoops. The hoops were placed every 1.2 m and arches were 41 cm wide and tall. In 2012, one side of the plastic sheet was buried with soil while the other side was anchored with bags filled with soil. When air temperatures exceeded 24º C, low tunnels were ventilated by moving the bags and lifting one side of the plastic. The plastic remained in place during periods of cool weather (when maximum daytime air temperature stayed below 24°C).

In 2013, both sides of the plastic sheet were buried with soil and vents (30 cm x 30 cm) were cut into the tunnels to facilitate ventilation. Clear packing tape was used to close vents during periods of cool weather (per 2012). In 2013, three type T thermocouples (epoxied in 2.54 cm long 0.64 cm thick copper pipe) were inserted approximately 5 cm into the soil and three shielded type T thermocouples (21 cm above the ground) were placed at approximately 3 m intervals both inside and outside the tunnel. Due to the size of the study and distance of replications from each other, temperature data collection was limited to one replication but sensors were periodically moved. Thermocouples were connected to a CR 1000 data logger (Campbell Scientific, Logan, UT).

Shade cloth. Shade cloth is available in a variety of shade percentages and colors. Black knitted shade cloth (30%; FarmTek, Dyersville, IA) was used in both years, because it has been shown to significantly reduce the radiative load reaching a pepper crop (Möller and Assouline, 2007), promote good pepper plant development (Díaz-Pérez, 2013), and produce high yields of quality fruit (Rylski and Spigelman, 1986a). In 2012, a 0.6 m wide section of shade cloth was fastened to the same wire hoops used to support the low tunnels. Shade cloth was placed on the west side of each row (Fig. 2.3) to shade peppers from the afternoon sun. In 2013, a 6.1 m wide by 15 m long (exceeded plot width and length to insure complete shading) section of shade cloth was oriented horizontally, 1.5 m above the crop (Fig. 2.4), to shade the plants throughout the day. Additionally, 0.6 m wide by 15 m long sections of shade cloth were oriented vertically (Fig. 2.4), 0.6 m above six adjacent rows (exceeded plot width and length to insure data rows were adequately shaded). This allowed adjacent rows to shade each other when the sun was at low solar elevations (morning/evening) while allowing full sunlight to reach the crop when the sun was at high solar elevations. Horizontal and vertical shade was supported by 2.4 m t-post and twine frames. In both years, shade clips (FarmTek, Dyresville, IA) were used to connect shade cloth to the low tunnel hoops or the t-post and twine frames. In 2013, six adjacent rows were shaded in each treatment and data were collected from the middle two rows (assigned to tunnel and no tunnel). Shade cloth was installed mid-July in both years.

Micro-climate. In 2013, a SP-110 pyranometer and SU-100 UV sensor (Apogee Insturments, Logan, UT) were positioned 45 cm above the ground in each of the shade treatments in one replication. A type E thermocouple (epoxied in 2.54 cm long 0.64 cm thick copper pipe) inserted approximately 5 cm into the soil and a shielded type E thermocouple (21 cm above the ground under a white melamine ashtray) were installed in the same treatments. A 03191-5a wind sentry anemometer (R. M. Young, Traverse City, MI) was located approximately 1 m high and a hmp-50 temperature and humidity sensor (Vaisala, Vantaa, Finland) inside of a 6 plate gill shield (0.5 m high) was set 1 m to the side of an open control. All sensors were connected to a CR 1000 data logger and an AM 16/32 relay multiplexer (Campbell Scientific, Logan, UT).

Fruit surface temperature. In 2013, three ST-200 fine-wire thermistors (Apogee Instruments, Logan, UT) were used to monitor bell pepper fruit surface temperature (FST) in the treatments of one replication. Fine-wire thermistors were inserted into a hole made by a soldered fine gauge wire that was pushed 1 mm to 2 mm into the fruit pericarp and then pushed parallel under the epidermis for 1 cm (Fig. 2.5). Packing tape was used to fasten the fine-wire to the fruit so the thermistor would not move.

Three fruit (one on: the east side, the top, and west side) on one plant in each shade treatment were selected for temperature measurement. A thermistor was inserted into the side of a pepper fruit that would receive the most direct sunlight. After 3 days of continuous measurement, the thermistors were inserted into a new hole on the same fruit and any leaves shading the fruit were removed from the plant. After an additional three days of continuous measurement, the thermistors were moved to three fruit on a new plant and a new replication of FST measurement (3 days leaves on, 3 days leaves off) began. This was repeated until three replications were completed.

Low tunnel temperature measurements. In 2013, air and soil temperatures were recorded from 24 May to 6 June. Data were collected every 10 seconds and the average, maximum, and minimum were calculated and recorded every hour and day.

Early plant growth measurements. On 2 July 2013, six plants were randomly selected from the no tunnel and tunnel plots in each replication to evaluate the effect of tunnels on plant growth. Plants were cut at ground level, leaves removed, counted, and fresh weight recorded. Stems were weighed and the number of buds, open flowers, and immature fruit were recorded. The leaf area was measured using a LI-3100 area meter (Li-Cor, Lincoln, NE) for no tunnel and tunnel plots in two replications. Stems and leaves were then dried for 48 hours at 55°C and weighed.

Late plant growth measurements. On 21 Aug. 2013, four consecutive plants from the middle of each low tunnel and shade combination were cut at ground level to evaluate the effect of tunnel and shade on plant growth. Leaves were removed from the plant, counted and weighed. Stems were weighed and leaf area was measured for all replications using a LI-3100 area meter. Stem and leaf dry weights were not taken for late plant growth analysis.

Micro-environment measurements. Solar radiation, air and soil temperature, wind, and humidity data were recorded from 19 July to 18 Oct. in 2013. Data were collected every second and averages, maximums, minimums, and totals were calculated and recorded every 5 min, 30 min, hour and day.

Fruit surface temperature measurements. Data were collected every second and the average and maximum FST were calculated and recorded every 5 min, 30 min, and 60 min from 20 July to 15 Aug. in 2013. The first replication (3 days leaves on, 3 days leaves off) was taken from 25 July to 27 July and 28 July to 30 July, respectively. The second replicate was monitored from 2 Aug. to 4 Aug. and 6 Aug. to 8 Aug., while the third rep was measured from 9 Aug. to 11 Aug. and 12 Aug. to 14 Aug., respectively.

Sunscald occurrence measurements. On 21 Aug. 2013, fruits from four consecutive plants (in the non-measurement areas of the rows) in each low tunnel and shade combination were used to determine the effect of plant quadrant (north, east, south, or west) and canopy height (top or bottom half) on sunscald occurrence. Affected fruit were classified according to the severity (1 = tissue softening or premature ripening, 2 = browning, 3 = small necrotic spot less than 2 cm^2, 4 = medium necrotic spot 2 cm^2 to 4 cm^2, and 5 = large necrotic spot greater than 4 cm^2) of sunscald, based on plant quadrant and canopy location. While Rabinowitch et al. (1986) separated heat injury (tissue turned brown or yellow and was sunken and dry, or bloated) from sunscald necrosis (bleached area became sunken and dry, or bloated and changed from white to tan), we grouped heat injury with sunscald necrosis because of their similar visual characteristics. A visual estimate of sunscald damage location based on the sun angle (90 to 270º split into 30º intervals) and plant location was determined.

Fruit yield and quality measurements. In 2012, peppers with greater than 50% red color were harvested weekly from four consecutive plants in the middle of each low tunnel and shade combination starting on 29 Aug. and ending on 12 Sept. (three harvests). A season ending harvest occurred on 14 Oct. which included both red and green fruit. Fruit were graded into fancy, first, second, and cull classes (USDA, 2005). Each class was counted and fresh weight recorded.

In 2013, a single harvest of green fruit from four consecutive plants in each low tunnel and shade combination took place on 21 Aug. to determine green fruit yield prior to coloring. After the coloring period, peppers with greater than 75% red color were harvested twice weekly from 26 Aug. until 27 Sept. (10 harvests) from four consecutive plants (different plants than green harvest) in each low tunnel and shade combination. A final harvest occurred on 3 Oct. and included only green fruit. Fruit were graded at each harvest as discussed for 2012. Furthermore in 2013, all cull fruit were graded according to the type of disorder (size, sunscald, misshapen), and severity of sunscald (1 = tissue softening or premature ripening, 2 = browning, 3 = small necrotic spot less than 2 cm^2, 4 = medium necrotic spot 2 cm^2 to 4 cm^2, and 5 = large necrotic spot greater than 4 cm^2) they had.

Statistical design

In 2012, the experiment was a randomized block design with low tunnel (no tunnel or tunnel) and shade (open or partial shade) as the factors. The low tunnel and shade combinations were randomly assigned to plots in each of the four replications. The analysis for the two cultivars took place separately because ‘Aristotle’ matures before ‘Paladin’ and cultivar comparisons were not of interest.

In 2013, the experiment was a split-block design with tunnel (no tunnel or tunnel) and shade (open, vertical, or horizontal) as strip plot factors. Two blocks of six adjacent north to south oriented rows were planted approximately 9 m apart. Each block was then divided in half resulting in four replications. The no tunnel or tunnel treatments were randomly assigned to one of the middle rows in each replication. After the tunnels were removed the rows in each replication were divided into three sections and open, vertical, or horizontal shade was randomly assigned to sections in each replication.

Data analysis

In 2012, all fruit yield data were analyzed using the PROC GLM procedure of the SAS statistical analysis software (version 9.3, SAS Institute, Cary NC) with a significance threshold of $P \leq 0.05$. The model $Y_{ijk} = M + R_i + L_j + S_k + (LS)_{jk} + E_{ijk}$ was used to evaluate the data. M represents the overall mean while R is the replications, L the low tunnel treatment, S the shade treatment, and E the random error term. R and E are random terms in the model, while L and S are fixed factors and LS is a fixed interaction. The number of levels for R, L, and S are four, two, and two, respectively. Single fixed factors were not evaluated for significance unless the LS interaction was non-significant ($P < 0.05$). Contrasts were used to evaluate the effects of levels from individual factors if the LS interaction was non-significant ($P < 0.05$).

In 2013, the early plant growth data and low tunnel temperature data were analyzed using the PROC GLM procedure of the SAS statistical analysis software with a significance threshold of $P \leq 0.05$. Because the 2013 experiment represented a completely randomized block design with one fixed factor (low tunnel) before shade cloth installation, the model $Y_{ij} = M + R_i + L_j + E_{ij}$ was used to evaluate pre-shade data. M represents the overall mean, while R is the replications, L the low tunnel treatment, and E the error term. R and E are random factors in the model while L is a fixed factor. The number of levels for R and L are four and two, respectively.

All of the micro-environment and FST data were also analyzed using the PROC GLM procedure of the SAS statistical analysis software with a significance threshold of $P \leq 0.05$. The model $Y_{ij} = M + R_i + S_j + E_{ij}$ was used to evaluate this data. M represents the overall mean, while R is the replications, S the shade treatment, and E the error term. R and E are random factors in the model while S is a fixed factor. The number of levels for R and S are four and three, respectively. Because there was only one fixed factor (shade) the micro-environment and FST experiment represented a completely randomized block design.

The 2013 late plant growth, fruit yield, and sunscald occurrence data were analyzed using the PROC MIXED procedure of the SAS statistical analysis software with a significance threshold of $P \leq 0.05$. The model $Y_{ijk} = M + R_i + L_j + (RL)_{ij} + S_k + (RS)_{ik} + (LS)_{jk} + (RLS)_{ijk}$ was used to evaluate the data. M represents the overall mean while R is the replications, L the low tunnel treatment, S the shade treatment, and RLS the random error term. R is a random factor in the model while RL, RS, and RLS are random interactions. L and S are fixed factors in the model while LS is a fixed interaction. The number of levels for R, T, and S are 4, 2, and 3, respectively. Single fixed factors were not evaluated for significance unless the LS interaction was non-significant ($P < 0.05$). Contrasts were used to evaluate the effects of levels from individual factors if the LS interaction was non-significant ($P < 0.05$).

Results

2013 Low tunnel temperature data. Low tunnels installed over pepper plants did not significantly increase the average air temperature during the night (Table 2.1). Tunnel air temperature was 8.1°C warmer during the day (8 am to 8 pm) compared to the no tunnel control. Tunnel soil temperature at 5 cm was 3.5°C and 1.2°C warmer during the day and night (8 pm to 8 am) respectively, compared to the no tunnel control. In comparison to no tunnel, tunnels significantly increased the maximum air and soil temperatures by 13°C and 4.5°C, respectively, during the day and by 6.1°C and 2.1°C, respectively, at night. Tunnels did not have a significant effect on the minimum air temperature during the day. The minimum air temperature at night was significantly lower under tunnels than the no tunnel control but the difference was minimal (0.2°C). The minimum tunnel soil temperature during the day and night was 2.5°C and 1.2°C higher, respectively, than the no tunnel control.

2013 early plant growth. Pepper transplants grown under tunnels in 2013 had significantly more leaves, dry leaf mass (Table 2.2), fresh leaf and stem mass and fresh and dry mass per leaf (data not shown). Tunnels did not significantly increase dry stem mass compared to the no tunnel control. Tunnels increased leaf area by 546 cm^{-2} per plant but these differences were non-significant because measurements came from only two replications and the no tunnel control was highly variable in leaf area. Tunnels did not have a significant effect on the number of flower buds, open flowers, or fruit at the time of early plant growth analysis (data not shown).

Late plant growth. Plants grown under tunnels for approximately two weeks in the spring of 2013 still had more leaves, fresh leaf and stem mass, and more leaf area compared to plants in the no tunnel control (Table 2.3) when measured approximately 13 weeks after transplanting. Vertical and horizontal shade significantly decreased fresh stem mass by 17 and 26 $g{\cdot}plant^{-1}$, respectively, compared to the open control. Shade grown plants (vertical or horizontal) had significantly fewer leaves than plants in the open control. While average leaf area increased with shading the number of leaves decreased. As a result, plants under horizontal shade had significantly larger leaves compared to plants in the open control (Table 2.3).

Micro-environment. Daytime (9 am to 7 pm) air temperature, VPD, and amount of incoming solar radiation was monitored from 20 July to 18 Oct. in 2013. The average maximum daytime air temperature from July 20 to Aug. 31 was 33°C (Fig. 2.6). The average maximum amount of incoming solar radiation from July 20 to Aug. 31was 882 $W{\cdot}m^{-2}$. Vertical and horizontal shade reduced average daytime air and soil temperatures throughout the fruit production period of July to Oct. (Table 2.4). From 25 July to 14 Aug. vertical shade significantly reduced air and soil temperatures compared to the open control while horizontal shade significantly decreased air and soil temperatures compared to vertical shade and the open control (Table 2.5).

Fruit surface temperature with canopy. From 9 am to 7 pm vertical and horizontal shade significantly reduced the time each pepper's FST exceeded 40°C by 205 $min{\cdot}day^{-1}$ and 297 $min{\cdot}day^{-1}$ respectively, and the time each pepper's FST exceeded 50°C by 33 $min{\cdot}day^{-1}$ and 39 $min{\cdot}day^{-1}$, respectively, compared to the open control (Table 2.5).

Pepper FST was 3.3°C lower under vertical shade and 5.7°C lower under horizontal shade compared to the open control.

Pepper FST was not different between peppers on the east side of the plant canopy (32.1°C) and peppers in the top of the canopy (32.3°C). Peppers on the west side of the canopy (30.3°C) did have a significantly lower daytime FST than peppers in the top of the canopy. There was no difference in the time peppers on the east side of the canopy exceeded a 40°C FST (130 $min \cdot day^{-1}$) then peppers in the top of the canopy (247 $min \cdot day^{-1}$). Peppers on the west side of the canopy exceeded a 40°C FST for a significantly shorter time (84 $min \cdot day^{-1}$) than peppers in the top of the canopy. Peppers in the east side of the canopy exceeded a 50°C FST for the longest period of time (22 $min \cdot day^{-1}$), followed by peppers in the top of the canopy (21 $min \cdot day^{-1}$), then peppers on the west side of the canopy (7 $min \cdot day^{-1}$). These differences were non-significant because of high variability in the data (standard deviation east side ± 25 $min \cdot day^{-1}$, top ± 36 $min \cdot day^{-1}$, and west side ± 2 $min \cdot day^{-1}$).

Fruit surface temperature without canopy. To determine the influence of leaf cover on pepper FST, leaves were removed from plants. Peppers under vertical and horizontal shade spent 310 $min \cdot day^{-1}$ and 715 $min \cdot day^{-1}$ less time above a 40°C FST compared to the open control (Table 2.6). Peppers under vertical shade had a FST above 50°C for a similar amount of time as peppers in the open control (mean = 232 $min \cdot day^{-1}$) while peppers grown under horizontal shade did not exceed a FST of 50°C. Pepper FST under vertical and horizontal shade from 9 am to 7 pm was 4.3°C and 6.9°C lower than the open control.

The average FST of peppers on the east side of the canopy (34.2°C) was not significantly different compared to peppers in the top of the canopy (36.3°C). Peppers on the west side of the canopy had a significantly ($P < 0.05$) lower average FST (32.7°C) than peppers in the top of the canopy (data not shown). Peppers on the east side of the canopy exceeded a 40°C FST for a significantly ($P < 0.05$) shorter amount of time (332 $min \cdot day^{-1}$) than peppers in the top of the canopy (492 $min \cdot day^{-1}$). There was no statistical difference between the amount of time peppers in the top of the canopy and peppers on the west side of the canopy (302 $min \cdot day^{-1}$) experienced a FST exceeding 40°C because of high variability in the data (standard deviation west side ± 230 $min \cdot day^{-1}$).

Peppers on the east side of the canopy exceeded a 50°C FST for the shortest period of time (50 $min \cdot day^{-1}$, data not shown). Peppers in the top of the canopy exceeded a 50°C FST for the longest time (122 $min \cdot day^{-1}$) followed by peppers on the west side of the canopy (94 $min \cdot day^{-1}$). These differences were non-significant because of high variability in the data (standard deviations east side ± 39 $min \cdot day^{-1}$, top ±138 $min \cdot day^{-1}$, and west side ±80 $min \cdot day^{-1}$).

Sunscald occurrence. The incidence of sunscald relative to fruit orientation on the plant (north, east, west, or south) and location (top or bottom) in the canopy was quantified in 2013. The solar azimuth angle when damage occurred was also estimated. Fruits exposed to sunlight when the sun was at 90 to 120° and 240 to 270° angles did not exhibit sunscald injury (browning or necrosis). Sunlight from 120 to 150° and 210 to 240° angles was responsible for 3% and 7% of the total sunscald that occurred. Sunlight from

150° to 180° sun angles was responsible for 37% of all sunscald while sunlight from 180 to 210° sun angles was responsible for 53% of all sunscald.

Light at low sun angles (120 to 150° and 210 to 240°) caused a small portion (4% and 9% respectively) of sunscald in the open control, but was not responsible for any sunscald under vertical and horizontal shade (Table 2.6). Light from 150° to 180° sun angles caused approximately equal damage in the open control and under vertical shade (37% and 39%, respectively). Most of the sunscald that occurred was caused by sunlight from 180 to 210° sun angles (50% in open control and 62% under vertical shade). Horizontal shade eliminated sunscald while vertical shade was equally effective at significantly reducing sunscald from the open control when the sun was at low angles (120 to 150° and 210 to 240° angles). While not as effective as horizontal shade, vertical shade significantly reduced sunscald compared to the open control when the sun was at 150 to 180° and 180 to 210° angles.

Sunscald incidence changed with fruit orientation (north, east, west, or south) in the canopy. When the shade treatments were combined the majority of fruit with sunscald damage were located in the south (37%), west (29%), and east (26%) quadrants of plants. A much smaller portion was located in the north quadrant (8%). The average number of fruit with sunscald per plant was lower under vertical shade (approximately $1 \cdot plant^{-1}$) compared to the open control (approximately 4·plant), while no fruit had sunscald under horizontal shade (Table 2.7). A large portion of the total number of sun-scalded fruit under vertical shade (43%) and in the open control (38%) came from the south quadrant. A smaller portion came from the east and west quadrant under vertical shade (21% and

30%, respectively) and in the open control (31% and 21%, respectively). The north quadrant had the smallest portion under vertical shade and in the open control (6% and 10%, respectively). Vertical shade only significantly reduced sunscald in the north, south, and west plant quadrants.

Fruit position in the canopy influenced injury as a higher portion of sun-scalded fruit came from the top half of the plant canopy (data not shown). In the open control 89% of sun-scalded fruit came from the top half of the canopy compared to vertical shade (73%). Horizontal shade eliminated sunscald occurrence throughout the entire plant canopy.

The average severity of sunscald damage was quantified on a scale of 1 to 5 with 1 being softened tissue, 2 browning, 3 small necrotic spot (< $2cm^2$ affected area), 4 medium necrotic spot (2 cm^{-2} to $4cm^2$ affected area), and 5 large necrotic spot (>$4cm^2$ area). Average sunscald severity was approximately equal in the open control and under vertical shade at 2.8 and 2.7, respectively (data not shown).

2012 yield and quality. The use of tunnels early in the growing season increased fancy red fruit yield of 'Aristotle' by 5 $Mg{\cdot}ha^{-1}$ and 'Paladin' by 1.7 $Mg{\cdot}ha^{-1}$ compared to the no tunnel controls. Tunnels had little effect on the yield of first or second red fruit for either cultivar. While tunnels increased total marketable (fancy, first, and second class) red fruit yield of 'Aristotle' by 4.7 $Mg{\cdot}ha^{-1}$ compared to no tunnel it did not have a significant effect on any of the yield parameters measured for either cultivar (Fig. 2.8).

Fancy red fruit yield was 3.4 $Mg{\cdot}ha^{-1}$ and 3.7 $Mg{\cdot}ha^{-1}$ higher for 'Aristotle' and 'Paladin' under partial shade compared to the open control. Partial shade had little effect on first and second class red fruit yield but did decrease the yield of ‘Paladin’ culls by 9 $Mg{\cdot}ha^{-1}$ compared to the open control. Partial shade significantly increased the yield of ‘Paladin’ high quality (fancy and first class, data not shown), total marketable, and percent marketable red fruit in comparison to the open control (Table 2.7). The yield for marketable green fruit from the last harvest for ‘Aristotle’ and ‘Paladin’ was 8.9 $Mg{\cdot}ha^{-1}$ and 4.2 $Mg{\cdot}ha^{-1}$ respectively, in the open control and 10.4 $Mg{\cdot}ha^{-1}$ and 3.9 $Mg{\cdot}ha^{-1}$ respectively, under partial shade.

2013 yield and quality. The tunnel and vertical shade interaction was not significant for the yield of fancy green fruit, high quality green fruit, total marketable green fruit (Fig. 2.8), or percent marketable green fruit for the early green fruit harvest (Aug. 21, before red harvest). This was due to the tunnel and vertical shade combination not having as large of an effect on yield parameters compared to later red harvests when yields under horizontal shade were reduced by bacterial soft-rot.

During the later red harvests, the yield of fancy, high quality, total marketable, and percent marketable red fruit increased dramatically when tunnel and vertical shade were combined compared to the no tunnel and vertical shade combination. This resulted in a significant interaction between tunnel and vertical shade for these yield parameters. Reduced yields under horizontal shade were due to bacterial soft-rot. During the second week of Sept. a wet cool period coupled with an irrigation event led to wet soil conditions for an extended period of time (approximately 5 days) under horizontal shade. Because radiation and wind levels reaching the crop were reduced, the soil took longer to dry out under horizontal shade than under vertical shade or in the open control. Plants were carrying a heavy fruit load and fruits in contact with the soil surface were damaged. Bacterial soft-rot caused many fruit in this treatment to turn to a soft watery mass in a matter of days (Stommel et al., 1996).

Shade increased fancy red fruit yield by 17.0 $Mg \cdot ha^{-1}$, first class red fruit yield by 3.8 $Mg \cdot ha^{-1}$, and second class red fruit yield by 3.5 $Mg \cdot ha^{-1}$, compared to the open control. Shade increased total marketable red fruit yield by 25 $Mg \cdot ha^{-1}$ and percent marketable red fruit by 44%. Marketable green fruit yield during the final harvest in the open control and under vertical and horizontal shade was 12.9 $Mg \cdot ha^{-1}$, 16.2 $Mg \cdot ha^{-1}$, and 13.7 $Mg \cdot ha^{-1}$, respectively, which were not statistically different from each other.

The no tunnel and horizontal shade treatments in combination produced the highest yield of fancy red fruit, followed by the tunnel and vertical shade combination (Fig. 2.10). The tunnel and vertical shade combination and the no tunnel horizontal shade combination had the highest marketable red fruit yield followed by the tunnel and horizontal shade combination (Fig. 2.11). Percent marketable red fruit yield was highest with the no tunnel and horizontal shade combination followed by the tunnel and horizontal shade combination (Fig. 2.12). The no tunnel and no shade, tunnel and no shade, and no tunnel and vertical shade combinations had reduced fancy, marketable, and percent marketable red fruit yield compared to the other combinations.

Cull (un-marketable) fruit were misshapen, small, rotten, or had a defect such as sunscald. Tunnels did not have a significant effect on cull fruit yield but shade significantly decreased cull yield by 25.1 $Mg \cdot ha^{-1}$ compared to the open control. Vertical shade significantly reduced cull yield by 16.4 $Mg \cdot ha^{-1}$compared to the open control while horizontal shade significantly reduced cull yield by 17.3 $Mg \cdot ha^{-1}$ compared to vertical shade and by 33.7 $Mg \cdot ha^{-1}$ compared to the open control (Fig. 2.13).

Fifty-two of fruit in the open control had sunscald while 23% of fruit under vertical shade had sunscald. No fruit under horizontal shade had sunscald (Table 2.9). Twelve percent of all fruit in the tunnel and vertical shade combination had sunscald compared to 33% of all fruit in the no tunnel and vertical shade combination. Fifty-nine percent of cull fruit had sunscald damage in the tunnel and vertical shade combination compared to 85% in the no tunnel and vertical shade combination. When vertical shade was used the additional reduction in the percentage of all fruit and culls with sunscald resulted in a significant tunnel and vertical shade interaction for these parameters.

Discussion

In 2013, tunnels had little effect on the average night air temperature because the many perforations and ventilation holes allowed thorough mixing with outside air. While lower minimum air temperatures at night under tunnels were noted (5.4°C under the tunnel and 5.6°C outside of the tunnel), differences are minimal and can be explained by cold ambient air filtering into the tunnel through perforations and then a warmer air mass replacing cooler outside air near the tunnel. If there is little wind to mix the warmer ambient air with the cold air inside the tunnel, the cold air could get trapped until mixing occurs.

In 2013, tunnels increased average air temperatures closer to the ideal (20°C to 25°C,) for bell pepper (Bosland and Votava, 2000) when conditions were cool but caused the average and maximum air temperature to exceed the ideal when conditions were warm and sunny. From May 23 to June 3, tunnels increased the average daytime air temperature above the ideal for bell pepper (31.6°C). Additionally, tunnels raised the average maximum daytime temperature 18°C above the ideal for pepper. Extreme air temperatures and increased leaf boundary layers under tunnels resulted in minor leaf-scald and plant stress. Clear slitted polyethylene tunnels have also been shown to have air temperatures that exceed 40°C (Gerber et al., 1988).

In both years, the majority of days during the period that tunnels were installed were warm and sunny. Because the average ambient daytime air temperature (23.5°C) was as high as the normal maximum daytime temperature (22°C to 24°C) from 23 May to 7 June, tunnels would likely increase plant growth at a greater rate in average conditions. It should be noted that the average, maximum, and minimum air and soil temperatures would increase under perforated low tunnels on sunny days beyond what we saw if ventilation was not provided.

Increased soil and air temperatures under tunnels (Table 2.1) did increase certain growth parameters (Table 2.2). Tunnels have been shown to increase plant growth (Gaye et al., 1992; Gerber et al., 1988) and Jolliffe and Gaye (1995) found that they increased bell pepper leaf area. Our findings support these claims as plants grown under tunnels had more leaves, leaf mass, and fresh stem mass compared to the no tunnel control. Tunnels also increased leaf area though due to low sample number and high variability the results were not significant. Future fruit shading should increase as a result of bigger plant canopies. While tunnels promoted vegetative growth, they did not increase earliness or fruit development at the time early plant growth data were recorded.

Late plant growth analysis (Table 2.3) indicated that tunnels continued to have a positive effect on plant size, leaf number, and leaf area. These findings indicate that tunnels are important to plant growth and positively influence canopy shading later in the year. Tunnels may further increase canopy shading if ambient air temperatures are below what we saw in this study. Increased biological (canopy) shading can be accomplished with the use of tunnels.

Shade increased leaf area but decreased stem mass and number of leaves per plant (Table 2.3). Shade increased leaf area by increasing leaf size. Previous studies have also shown that shading alters pepper plant structure (Rylski and Spigelman, 1986a) and increases leaf area (Díaz-Pérez, 2013; López-Marín et al., 2013).

Air temperatures above 32.6°C and solar radiation level in excess of 824 $W \cdot m^{-2}$ produced a pepper FST from 40 to 45°C in plants when the plant canopy should naturally shade peppers. In our study fruits fully exposed to incoming solar radiation after leaf removal had a 40 to 45°C FST when air temperatures were above 31.4°C and radiation levels exceeded 752 $W \cdot m^{-2}$. These findings suggest that the plant canopy reduces the amount of radiation reaching pepper fruit. Therefore lowering FST can reduce the incidence of sunscald. Others have shown that the occurrence of sunscald decreases as canopy shading increases (Barber and Sharpe, 1971; López-Marín et al., 2013). Since partial canopy shading decreases pepper FST, plants with greater leaf area may withstand higher air temperatures and solar radiation levels. Our data suggests that increased canopy shading due to improved environmental conditions under tunnels provided some protection to developing fruit later in the season.

Tunnels did not significantly increase yield or decrease sunscald in either year. While plants grown under tunnels had increased canopy shading, air temperatures and light levels regularly exceeded those required to raise pepper FST above 40°C. In 2012 and 2013, environmental conditions were favorable for sunscald development for much of July and Aug. Air temperatures and light levels often exceeded 30°C and 21 $MJ \cdot m^{-2} \cdot day^{-1}$ during these months, which are the environmental conditions reported to contribute to sunscald (Makeredza et al., 2013; Rylski and Spigelman, 1986a). The vapor pressure deficit regularly exceeded 4.5 kPa in 2013, suggesting that plants may have been unable to meet transpirational demands. This likely led to leaf folding (wilting) (Makeredza et al., 2013) that exposed previously shaded fruit to damaging levels of solar radiation which explains the high frequency of sunscald (approximately 52%) in the open control. Our data confirms that in high temperature (>30°C) and light (>900 $W \cdot m^{-2}$) environments, plant canopies do not adequately protect peppers from damaging levels of solar radiation.

Tunnels did not significantly increase yield or decrease sunscald occurrence unless combined with vertical shade. If increases in leaf number and leaf area are to provide biological shade, other growth stimulating management techniques need to be identified. Other biological methods to increase leaf area may be to select cultivars with large canopies, graft plants onto vigorous rootstocks that can increase canopy shading

(López-Marín et al., 2013), increase leaf area through improved fertilizer or irrigation management (Hegde, 1987), or alter where peppers are located on the plant.

Since fruit set at occurs at most flowers, early fruit set results in the development of carbon sinks that restrict further vegetative development (Rylski and Spigelman, 1986b). Therefore increasing plant growth with nitrogen or other management practices may be limited to the pre-flowering period. Biological tools that may decrease sunscald include selecting for cultivars that have a lighter fruit color that reflects more solar radiation (Barber and Sharpe, 1971) or that have fruit that are more resistant to sunscald (Gindaba and Wand, 2005; López-Marín et al., 2013; Wang et al., 2006).

The benefits of biological shade can be reduced or entirely lost due to leaf folding, wind damage, lodging, when the canopy opens as branches bend under fruit weight (Rylski and Spigelman, 1986a), or when branches break during harvest. Shade cloth is the only way to permanently decrease the amount of radiation reaching the crop (López-Marín et al., 2013). Möller and Assouline (2007) showed that 30% black shading screen significantly reduced solar radiation and wind speed inside of a screen-house. Díaz-Pérez (2013) found that PAR, air temperature, and soil temperature decreased with shade. Our findings support these claims as solar and UV radiation were significantly reduced under vertical shade when the sun was at lower solar elevations (early and late in day) and under horizontal shade for the entire day. Vertical and horizontal shade were shown to reduce the average daytime air temperature in July and Aug. by 1.5°C and 3.4°C, respectively, compared to the open control. Additionally, vertical and horizontal shade decreased soil temperatures in July and August by 3.0°C and 4.5°C, respectively, compared to the open control. Reductions in air and soil temperatures decrease plant stress which may increase plant performance.

Gindaba and Wand (2005) reported that a reduction in solar radiation under 20% black shade net resulted in a 5.4°C to 9.7°C lower apple FST compared to un-shaded fruit when air temperatures were between 34°C and 37°C. Our findings support these findings as daytime pepper FST on intact plants (with leaves) was 3.3°C lower under vertical shade and 5.7°C lower under horizontal shade compared to the open control. Additionally, daytime pepper FST was 4.3°C lower under vertical shade and 6.9°C lower under horizontal shade compared to the open control when leaves were removed from plants.

There must be a relationship between the FST threshold and duration of time at the threshold temperature for sunscald to occur. Rabinowitch et al. (1974) reported that 18 hours at a FST of 45.1°C was equivalent to 28 hours at a FST of 40.8°C in causing sunscald in tomato. While necrosis can occur on pepper in 15 min at a FST of 49°C (Barber and Sharpe, 1971), Rabinowitch et al. (1974) suggest that a longer exposure at a more moderate FST will also cause sunscald. It can be assumed that as peppers FST increases the associated time required for sunscald to develop decreases.

The average FST of peppers under vertical shade exceeded 40°C for 126 $min \cdot day^{-1}$ ± 69 $min \cdot day^{-1}$ when canopies were intact. In contrast, the FST of peppers under horizontal shade exceeded 40°C for 68 $min \cdot day^{-1}$ ± 35 $min \cdot day^{-1}$ when leaves were removed from plants. Since sunscald developed under vertical shade when canopies were intact but did not develop under horizontal shade when leaves were removed, we conclude that pepper FST must exceed 40°C for somewhere between 68 min·day^{-1} to 126 min·day^{-1} for sunscald to develop.

Average pepper FST was 3.7°C higher in the open control, 2.7°C higher under vertical shade and 2.5°C higher under horizontal shade when leaves were removed from plants compared to when plant canopies were left intact. Providing supplemental shade for pepper cultivars that have poor canopy development is critical because pepper FST increases with decreases in canopy shade and sunscald develops more quickly as FST rises. As canopy shade decreases, increased supplemental shade should be provided to decrease pepper FST below the temperature threshold for sunscald.

Vertical shade only reduced the length of time that pepper FST exceeded 40°C and 50°C when leaves were left on plants while horizontal shade reduced the duration of time pepper FST exceeded 40°C and 50°C when leaves were both on and off plants. These findings suggest that canopy shade protects fruit from damaging levels of solar radiation when vertical shade is incapable of doing so (at high solar elevations). Barber and Sharpe (1971) suggested that canopy shading is most effective when the sun is at higher solar elevations. Our results prove the importance of complete canopy or supplemental shading when the sun is at high solar elevations and environmental conditions are favorable for sunscald development. While vertical shade increased yield and decreased sunscald occurrence, the combination of tunnel and vertical shade increased yield and decreased sunscald occurrence even more. This was due to better canopy development increasing pepper shading during the part of the day when vertical shade was ineffective.

The time pepper FST exceeded 40°C and 50°C under vertical shade was not statistically different from the open control when leaves were removed from plants. However 52% of all fruit had sunscald in the open control, while only 33% of fruits under vertical shade had sunscald when tunnels were not used. These findings demonstrate that vertical shade decreases sunscald by shading those fruits exposed when the sun is at lower solar elevations. Tunnels used in combination with vertical shade had only 12% of fruit with sunscald. Thus there is an additive effect of increased canopy shade reducing the amount of radiation reaching peppers when the sun is at high solar elevations and vertical shade reducing radiation levels when the sun is at lower solar elevations. Because some sunscald developed under vertical shade, 'Aristotle' is not able to provide sufficient canopy shading in high temperature and light environments particularly when the sun is at higher solar elevations.

Supplemental or canopy shading is important on all sides of the pepper plant since pepper FST exceeded 40°C on the east, top, and west orientations in the open control. Additionally, we did not see sunscald when sun angles were less than 120° or greater than 240°. Therefore, supplemental shade is not needed early and late in the day. Retractable shade systems could allow photosynthesis to be maximized when light levels are low (< 120° and > 240°) during the early morning and late evening while providing protection when high light conditions favor sunscald development between 120 to 240°.

Complete canopy or supplemental shade is extremely important during the mid-morning to early evening hours. Sun angles between 150 to 210° were responsible for 87% of sunscald in the open control and 100% of sunscald under vertical shade. López-

Marín et al. (2013) reported that 40% shade reduced the incidence of sunscald on 'Hermino' peppers by 3x compared to un-shaded controls while Rylski and Spigelman (1986a) found that under high solar radiation levels (> 25 MJ m^{-2} day^{-1}), sunscald damage was decreased from 36% of fruits affected (full sunlight) to 3% to 4% under 26% and 47% shade screens, respectively. We found that only horizontally oriented 30% shade cloth eliminated sunscald occurrence when air temperatures and light levels exceeded 30°C and 900 $W \cdot m^{-2}$, respectively.

Supplemental shade increased fancy red fruit yield in both years of this study compared to the open control. In 2012, 'Paladin' cull fruit yield was decreased under partial shade compared to the open control while partial shade significantly increased 'Paladin' total marketable and percent marketable red fruit yield compared to the open control. Increases in fancy red fruit yield and percent marketable red fruit were greatest under horizontal shade in 2013. While providing supplemental shade may cost an additional $14,573 per hectare a year, the resulting $30,875 per hectare a year change in net income indicates that it will increase the profitability of red bell pepper production (see Chapter 4). Total marketable fruit yield from the early green harvest (Aug. 21) was highest under horizontal shade, therefore we conclude that total marketable red fruit yield would have been highest under horizontal shade if bacterial soft-rot had been controlled. If cool wet conditions persist under horizontal shade, control measures should be taken to prevent fruit rots. Control measures include removing and disposing of diseased fruits and spraying copper fungicides when hot and humid conditions or inoculum is present (Bosland and Votava, 2000).

Conclusion

Higher air and soil temperatures under tunnels increased ‘Aristotle’ leaf area but this increase was not sufficient to reduce the amount of solar radiation reaching pepper fruit for the air temperatures and light levels seen in this study (air temperatures > 35°C; solar radiation > 900 $W \cdot m^{-2}$). While biological shade does decrease solar radiation reaching pepper fruits its effects may have been reduced by leaf folding or canopy opening brought on by wind, excessive fruit load or harvest damage. Only the additive benefits of tunnels and vertical shade increased yield or decreased sunscald significantly.

Increasing biological shade to reduce sunscald may be limited to the pre-flowering period because many new semi-indeterminate pepper cultivars have an early concentrated fruit set that restricts further canopy development (Rylski and Spigelman, 1986b). Additionally, because canopy shade can be compromised by management practices or weather events, supplemental shade should be provided when environmental conditions favor sunscald to insure fruit protection. Shade cloth is essential when growing bell pepper cultivars that have poor canopy development in high temperature and light environments if high yield, improved fruit quality, and lower fruit damage are expected.

Horizontally oriented shade cloth effectively decreased solar radiation and the FST of peppers which eliminated sunscald. While pepper FST reached the threshold for sunscald under horizontal shade, the duration of exposure to damaging temperatures was so short that no sunscald developed. If leaf area can be increased, a lower shade percentage may sufficiently provide protection. Pepper FST was significantly cooler under vertical and horizontal shade compared to the open control while sunscald occurrence was highest in the open control, reduced under vertical shade, and eliminated under horizontal shade.

Changing shade cloth orientation changed pepper fruit heat load dramatically. Altering pepper fruit heat load with vertically oriented shade cloth decreased the duration that pepper FST was above the threshold for sunscald when leaves were left on plants but horizontal shade was more effective. The reduction in time that pepper FST exceeded 40°C and 50°C resulted in sunscald being reduced under vertical shade and entirely eliminated under horizontal shade. Fruit toward the top of the canopy are more prone to sunscald because of their increased exposure to solar radiation coming from 150° to 210° sun angles. Shade cloth should be installed to provide protection to all sides of the plant canopy when the sun is at 120 to 240° angles.

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Table 2.1. Influence of low tunnel on average, maximum, and minimum air and soil temperatures for the day (8:00 AM to 8:00 PM) and night (8:00 PM to 8:00 AM) periods from 23 May to 3 June 2013.

	Air Temperature °C		Soil Temperature[1] °C	
Treatment	Day	Night	Day	Night
		Average		
No Tunnel	23.5a	10.6a	22.6a	15.6a
Tunnel	31.6b	10.6a	26.1b	16.8b
		Maximum		
No Tunnel	30.0a	17.8a	26.7a	21.6a
Tunnel	43.0b	23.9b	31.2b	23.7b
		Minimum		
No Tunnel	14.7a	5.6a	14.0a	12.1a
Tunnel	14.7a	5.4b	16.5b	13.3b

[1] Soil temperature taken at a 5 cm depth.
Numbers followed by the same letter are not significantly different at $P \leq 0.05$.

Table 2.2. Influence of low tunnel on number of leaves, leaf and stem dry mass, leaf area, leaf area ratio (LAR), and percent leaf mass (PLM) of 'Aristotle' plants on 2 July 2013.

Treatment	Leaves ($n \cdot plant^{-1}$)	Leaf mass ($g \cdot plant^{-1}$)	Stem mass ($g \cdot plant^{-1}$)
No tunnel	58a	6a	5a
Tunnel	79b	12b	7a
	Leaf area ($cm^2 \cdot plant^{-1}$)	LAR*	PLM**
No tunnel	795a	166a	57a
Tunnel	1341a	105a	64a

*LAR = leaf area divided by leaf mass.
**PLM = leaf mass divided by total mass.
Numbers in the same column and section followed by the same letter are not significantly different at $P \leq 0.05$.

Table 2.3. Influence of low tunnel and shade on number of leaves, fresh leaf and stem mass, and leaf area of ‘Aristotle’ plants on 21 August 2013.

Treatment	Leaves ($n^*\cdot$plant)	Leaf mass ($g\cdot plant^{-1}$)	Stem mass ($g\cdot plant^{-1}$)	Leaf area ($cm^2\cdot plant^{-1}$)	Area per leaf ($cm^2\cdot leaf^{-1}$)
No tunnel	164a	181a	102a	4394a	27a
Tunnel	190b	222a	130b	5361a	28a
No shade	191a	205a	130a	4769a	25a
Ver. shade	170b	198a	113b	4857a	29ab
Hor. shade	169b	202a	104b	5008a	30b

*Number of leaves per plant.
Tunnel*Shade interaction was non-significant ($P < 0.05$) for all parameters.
Numbers in the same column and section followed by the same letter are not significantly different at $P \leq 0.05$.

Table 2.4. Influence of shade on average daytime (9:00 AM to 7:00 PM) air and soil temperatures during July, August, September and October in 2013.

	July		August		September		October	
Treatment	Air	Soil	Air	Soil	Air	Soil	Air	Soil
No Shade	30.5	27.9	28.4	23.6	21.3	17.6	13.1	10.1
Ver. Shade	29.3	24.2	26.7	21.4	20.0	16.7	12.1	9.3
Hor. Shade	27.1	22.6	25.1	20.0	18.9	15.8	11.8	9.6

Temperatures reported in °C.
Data recorded from July 20 to October 18, 2013.

Table 2.5. Influence of shade treatment on air and soil temperature and time each ‘Aristotle’ fruit exceeded a 40°C and 50°C fruit surface temperature (FST) from 9:00 AM to 7:00 PM in 2013.

Treatment	Temperature		Minutes FST >		Average
	Air	Soil	40°C	50°C	FST °C
With canopy					
No Shade	32.5a	29.7a	331a	39a	34.5a
Ver. Shade	31.2b	25.0b	126b	6a	31.2b
Hor. Shade	28.7c	23.7c	34b	0a	28.8b
Without canopy					
No Shade	32.1a	27.5a	783a	217a	38.2a
Ver. Shade	30.0b	23.9b	473b	247a	33.9b
Hor. Shade	27.9c	22.7c	68b	0a	31.3b

Temperatures reported in °C
With canopy data taken from three replicates
Rep 1 (July 25 to 27), Rep 2 (August 6 to 8), and Rep 3 (August 9 to 11)
Without canopy data taken from three replicates
Rep 1 (July 28 to 30), Rep 2 (August 2 to 4), and Rep 3 (August 12 to 14)
Numbers in the same column followed by the same letter are not significantly different at $P \leq 0.05$.

Table 2.6. Sunlight from various angles responsible for sunscald damage of ‘Aristotle’ pepper fruit as affected by vertical and horizontal shade in 2013.

	Sun Angle					
	1	2	3	4	5	6
Treatment	(Affected fruit per plant)					
No Shade	0.0	0.2a	1.7a	2.3a	0.4a	0.0
Ver. Shade	0.0	0.0b	0.5b	0.8b	0.0b	0.0
Hor. Shade	0.0	0.0b	0.0c	0.0c	0.0b	0.0

Sunlight from
1 = 90° to 120° angles
2 = 120° to 150° angles
3 = 150° to 180° angles
4 = 180° to 210° angles
5 = 210° to 240° angles
6 = 240° to 270° angles
Numbers in the same column followed by the same letter are not significantly different at $P \leq 0.05$

Table 2.7. Influence of shade treatment on the canopy distribution of sun-scalded 'Aristotle' pepper fruit in 2013.

Treatment	North	East	South	West	Number of sun-scalded fruit·plant^{-1}
	Direction (Sun-scalded fruit·plant^{-1})				
No Shade	0.3a	1.1a	1.4a	0.8a	3.6a
Ver. Shade	0.1b	0.2b	0.4b	0.3b	1.0b
Hor. Shade	0.0b	0.0b	0.0c	0.0b	0.0c

Numbers in the same column followed by the same letter are not Significantly different at $P \leq 0.05$.

Table 2.8. Red fruit yield of ‘Aristotle’ and ‘Paladin’ pepper as influenced by partial shade in 2012.

	TMY* ($Mg \cdot ha^{-1}$)	PMY** (%)	TMY* ($Mg \cdot ha^{-1}$)	PMY** (%)
Treatment	Aristotle		Paladin	
Open	22a	34a	2a	4a
Shade	26a	40a	7b	13b

*Total marketable red fruit yield

**Percent marketable red fruit yield

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

Table.2.9. Influence of tunnel and shade on the percentage of all fruit and cull fruit affected by sunscald, and the percentage of sun scalded fruit with type 1,2,3,4, and 5 damage for the first 10 red harvests (26 Aug. until 27 Sept) in 2013.

Treatment	**Percentage with sunscald**		**Percentage of sun scalded fruit with sunscald type**				
	All fruit	Culls	1	2	3	4	5
No tunnel No shade	49	85a	25	19	27	17	12
Tunnel No shade	55	89a	33	19	26	11	11
No tunnel Ver. shade	33	85a	34	13	38	13	2
Tunnel Ver. shade	12*	59b	16	6	59	13	6
No tunnel Hor. shade	0	0c	0	0	0	0	0
Tunnel Hor. shade	0	0c	0	0	0	0	0

*Tunnel and vertical shade interaction is significant.
1= side of fruit has been softened
2= sunscald browning
3=small necrotic spot damage area (< 2 cm^2)
4=medium necrotic spot damage area (2 cm^2 to 4cm^2)
5=large necrotic spot damage area (> 4 cm^2)
All numbers expressed as a percentage
Numbers in the same column followed by the same letter are not significantly different at $P \leq 0.05$.

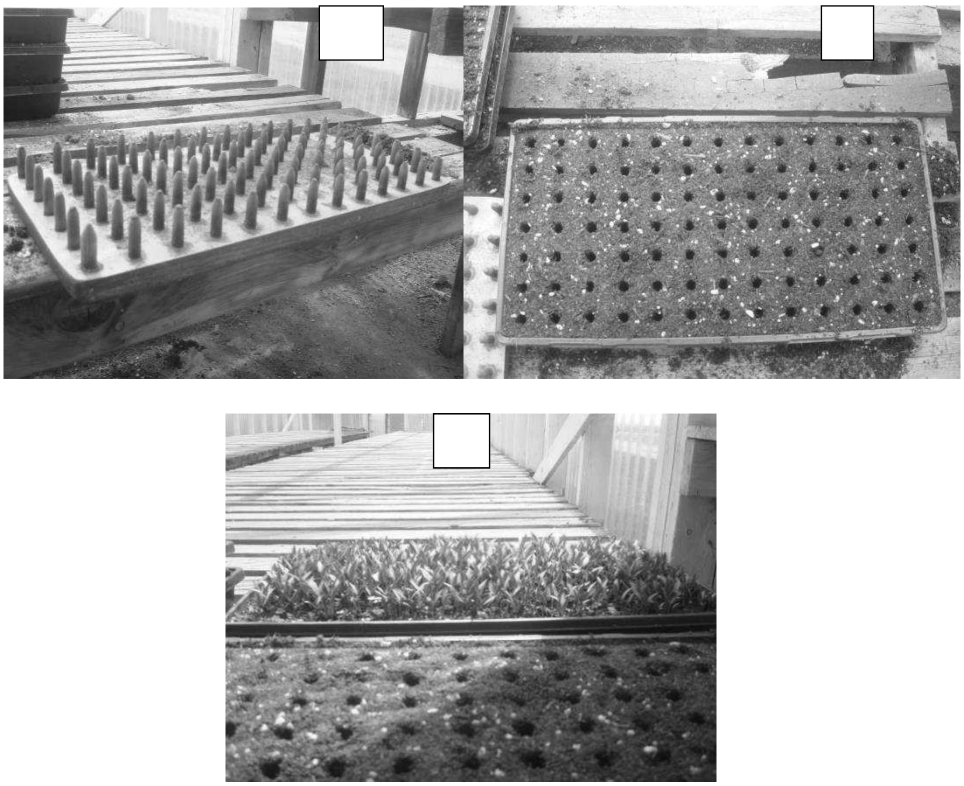

Figure. 2.1. Puncher used to make holes (a), 91 holes in a standard 1020 tray (b), plants from the seed flat ready to be placed in a punched 1020 tray (c).

Figure. 2.2. Air and soil temperature sensors location outside and under the low tunnel in 2013.

Figure. 2.3. 30% shade oriented on the west side of the rows and supported by wire hoops in 2012.

Figure. 2.4. Horizontal and vertical shade treatments in 2013. Data collected from center 2 rows.

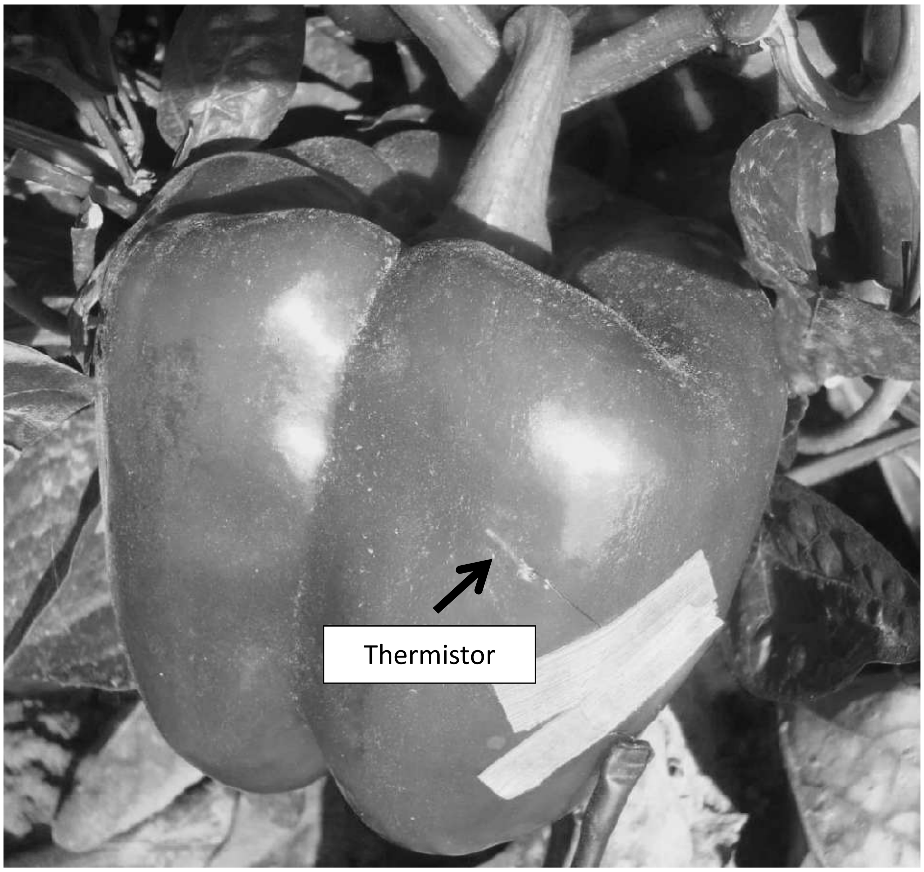

Figure. 2.5. A fine-wire thermistor was inserted into a hole made by a soldered fine gauge wire. Thermistors were positioned under the epidermis of pepper fruit and held to the fruit by clear packing tape.

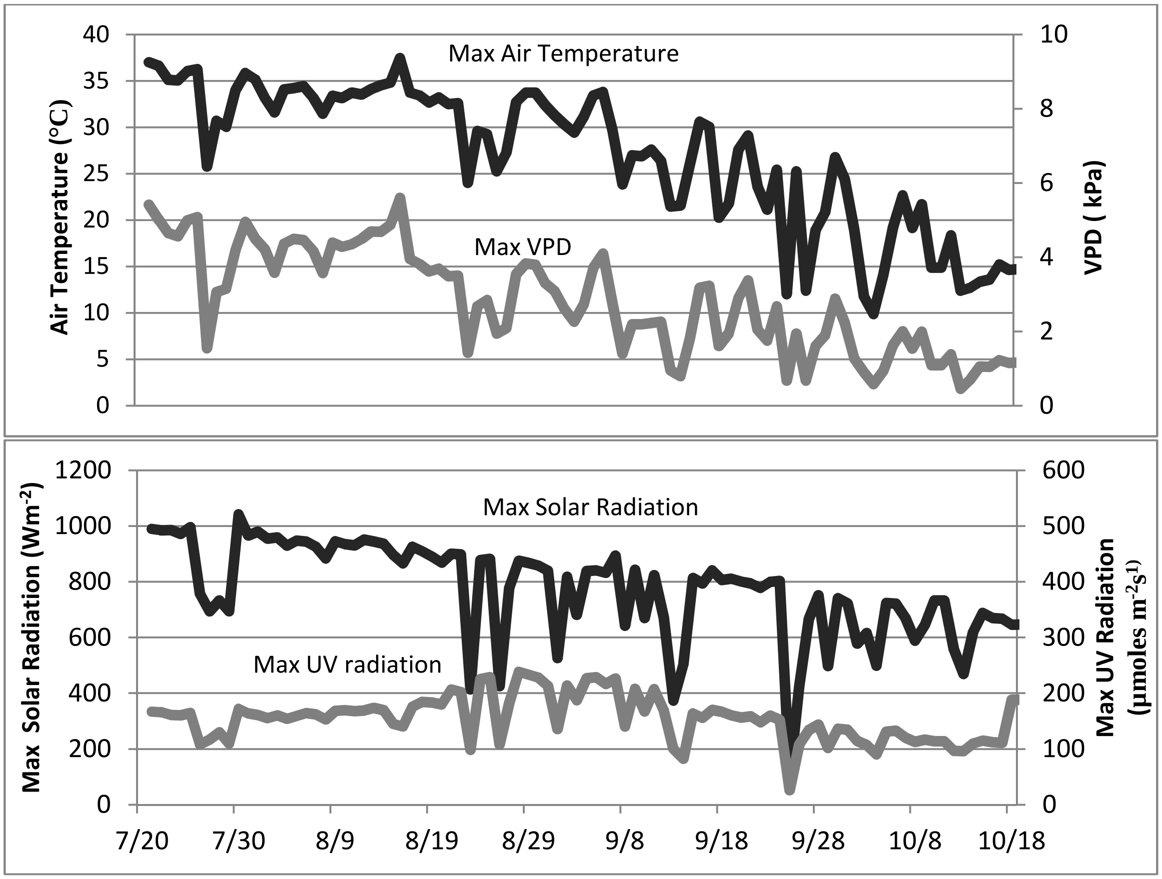

Figure. 2.6. Maximum air temperature, vapor pressure deficit (VPD), and solar and UV radiation from 9:00 AM to 7:00 PM from July 20 to October 18 in 2013. Data were collected in the open control.

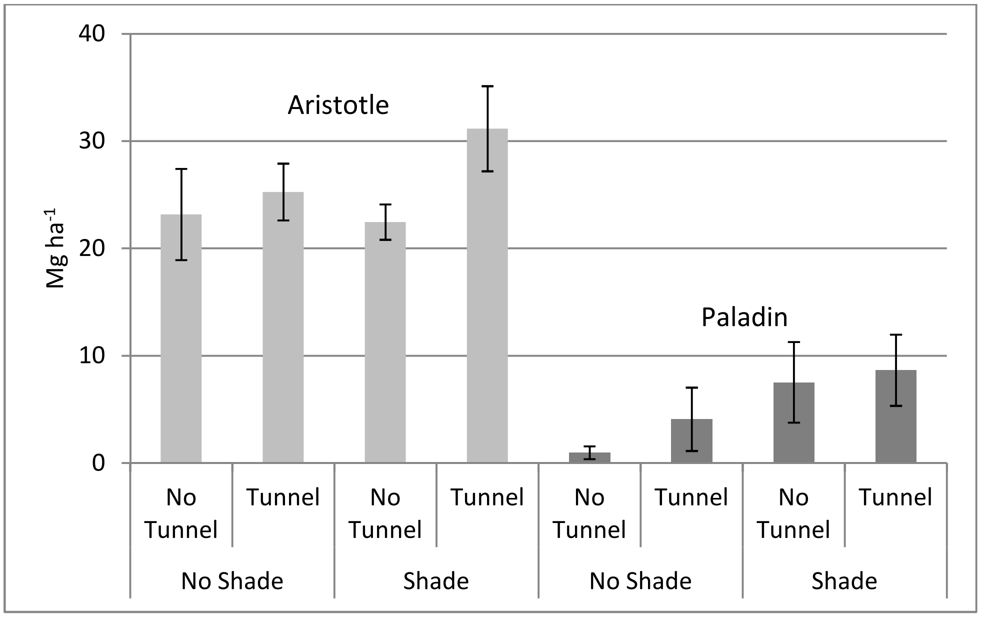

Figure.2.7. Influence of tunnel and shade on marketable red fruit yield of ‘Aristotle’ and ‘Paladin’ peppers for the first three harvests in 2012. Error bars represent standard error of the mean (n=4).

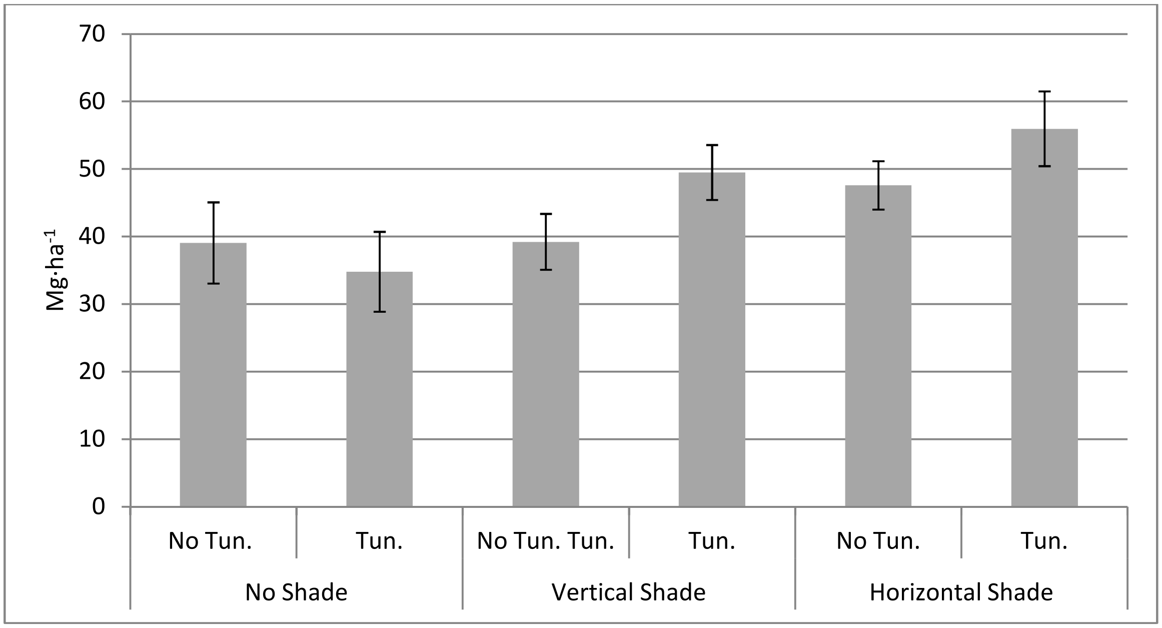

Figure.2.8. Effect of tunnel and shading on total marketable green fruit yield of ‘Aristotle’ pepper from the early (Aug. 21) green fruit harvest in 2013. Error bars represent standard error of the mean (n=4).

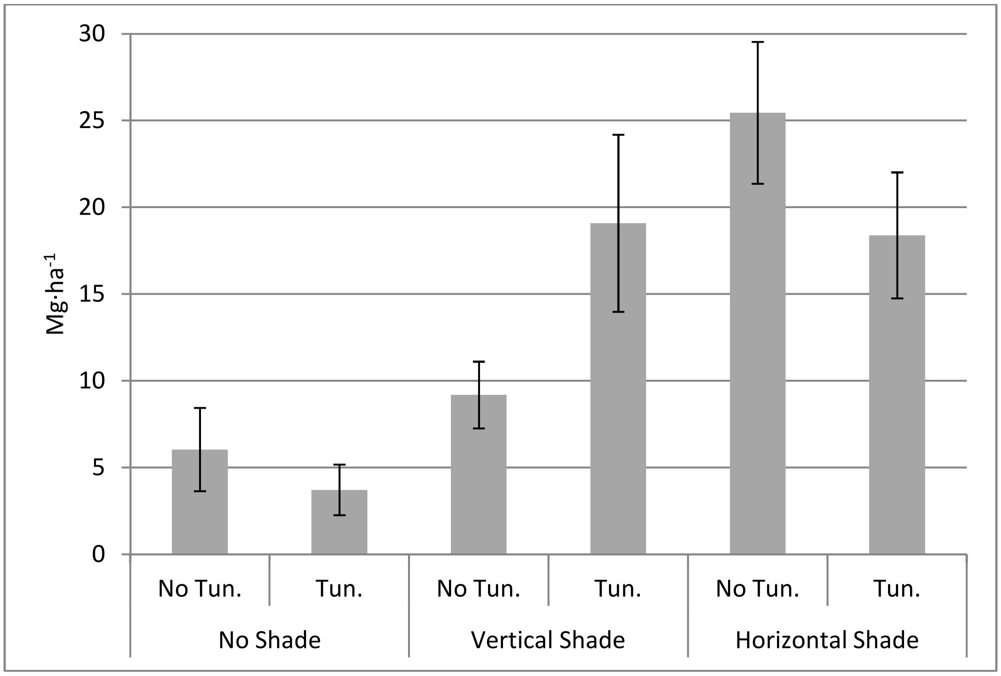

Figure.2.9. Influence of tunnel and shade on fancy red fruit yield of 'Aristotle' peppers in 2013. Error bars represent standard error of the mean (n=4).

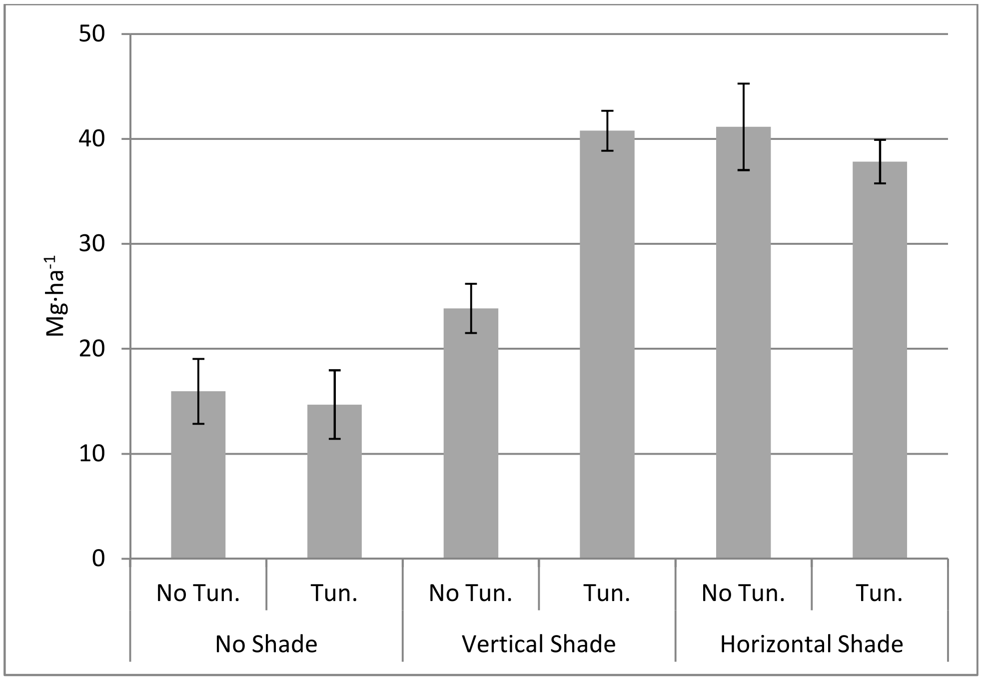

Figure.2.10. Influence of tunnel and shade on total marketable red fruit yield of ‘Aristotle’ peppers in 2013. Error bars represent standard error of the mean (n=4).

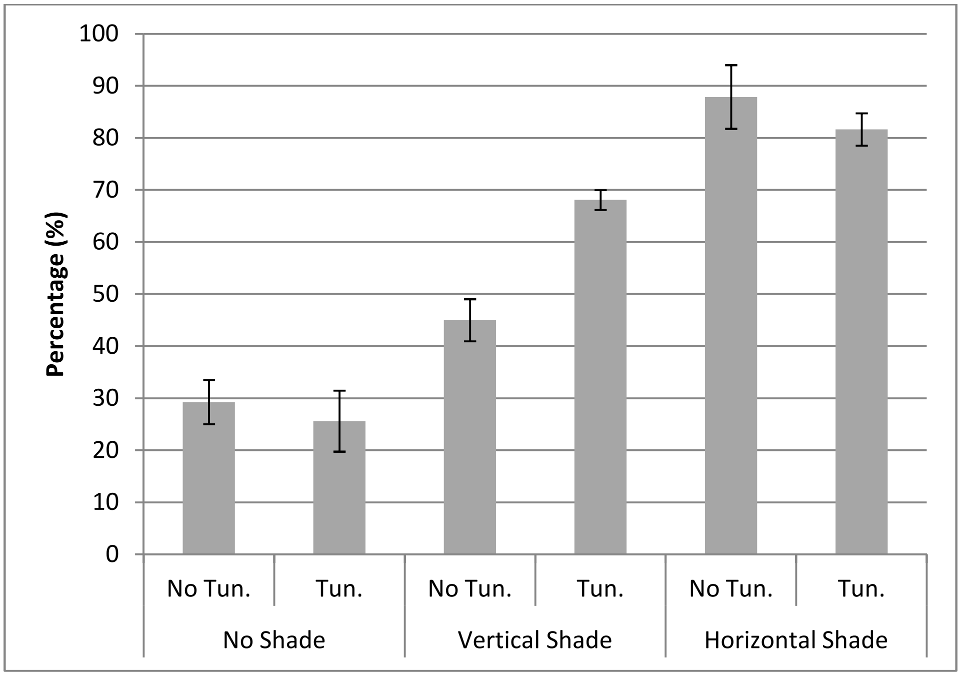

Figure.2.11. Influence of tunnel and shade on percent marketable red fruit of ‘Aristotle’ peppers in 2013. Error bars represent standard error of the mean (n=4).

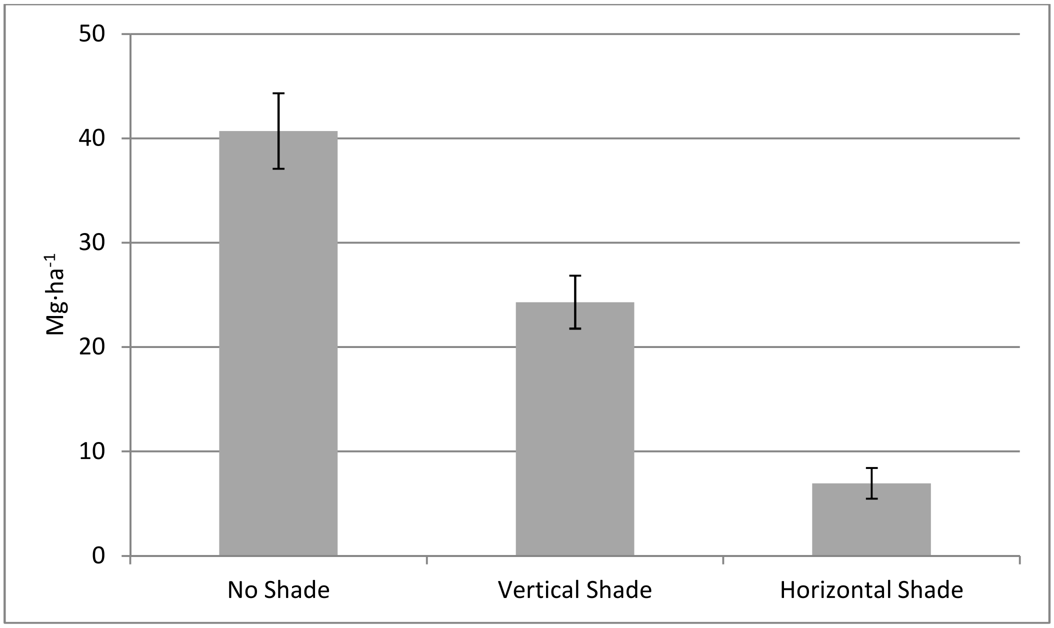

Figure.2.12. Influence of shade on cull (un-marketable fruit) biomass of ‘Aristotle’ peppers in 2013. Error bars represent standard error of the mean (n=4).

CHAPTER 3

ENERGY BALANCE ANALYSIS OF PEPPER FRUIT SURFACE TEMPERATURE

Abstract. Detached and attached pepper (*Capsicum annuum* L.) fruits were exposed to varying light levels and wind speeds in a controlled laboratory environment and under local field conditions during the summer of 2013 to determine the influence of solar radiation and wind speed on pepper fruit surface temperature (FST). Air temperature, incoming shortwave radiation, wind speed, and FST were continuously measured. Attached pepper fruits in the lab exposed to radiation levels of 30 $W \cdot m^{-2}$, 60 $W \cdot m^{-2}$, and 250 $W \cdot m^{-2}$ had FST 1°C, 4°C and 5°C lower respectively compared to detached fruit. As wind speed increased to 1.5 $m \cdot s^{-1}$ pepper FST decreased by 8°C while a wind speed of 3 $m \cdot s^{-1}$ reduced pepper FST by 14°C when the air temperature was 21°C and incoming radiation was 250 $W \cdot m^{-2}$. The average maximum air temperature, solar radiation, wind speed, and vapor pressure deficit for the field trial was 35°C, 946 $W \cdot m^{-2}$, 1.6 $m \cdot s^{-1}$, and 5 kPa. Wind decreased pepper FST less effectively in the field as wind speeds were quite variable. Under high radiative levels, a wind speed of 3.0 $m \cdot s^{-1}$ did not decrease FST below the threshold for sunscald (40°C). Supplemental shade should be provided whenever solar radiation levels exceed 550 $W \cdot m^{-2}$ to insure protection from sunscald if leaf cover is inadequate.

Maximum FST increased at a greater rate than air temperature from 9:00 AM to approximately 10:30 AM resulting in an increasing delta T value (FST- air temperature).

From 10:30 AM to 5:00 PM maximum FST and air temperature increased at similar rates resulting in a delta T that was more constant. After 5:00 PM, maximum FST decreased at a much faster rate than air temperature resulting in a decreasing delta T.

Introduction

Light energy absorbed by fruit can be photo-chemically stored, emitted as fluorescence, or converted into heat (Barber and Sharpe, 1971). The absorbed heat can be dissipated by long-wave radiation, conductive and convective heat loss, latent heat loss (transpiration), or conducted through the fruit itself. Transpiration is minimal in peppers because fruit have few stomata and a thick layer of wax on their epidermis (Banaras et al., 1994; Weryszko-Chmielewska and Michalojć, 2011). Additionally, large bell peppers can have large boundary layers (Barber and Sharpe, 1971) at low wind speeds and high air temperatures (Drake et al., 1970) reducing convective heat transfer from insolated peppers to the ambient air. Photo-chemically stored energy and fluorescence have been shown to be negligible in pepper fruit (Gates et al., 1965), so we assume that energy utilization through photosynthesis is minimal. Barber and Sharpe (1971) suggest that some energy is conducted through the fruit itself, but found that heat loss through this pathway was minor.

Poor heat transfer through transpiration, conduction and convection leads to insolated pepper FST increasing more than the ambient air temperature. While long-wave emission increases as fruit surface temperature (FST) increases, localized fruit tissue injury (thermal cell death) resulting in sunscald necrosis (Makeredza et al., 2013) may occur if energy absorption exceeds total emission and utilization (transpiration, conduction and convection, long-wave emission and photosynthesis). Excess absorbed energy from excited chlorophyll molecules can also be moved to ground state 0_2, creating singlet oxygen which can cause photodynamic damage (pigment bleaching and cell death) resulting in sunscald browning and necrosis (Müller et al., 2001). Sunscald (necrosis and browning) affects the marketing quality of many kinds of fruits and vegetables (Barber and Sharpe, 1971) resulting in significant losses in crop production (Makeredza et al., 2013; Retig et al., 1974) including pepper (Rylski and Spigelman, 1986a).

Since insolated peppers are inefficient dissipaters or utilizers of light energy, control measures such as mechanical shading are currently used to reduce the amount of solar radiation peppers absorb (López-Marín et al., 2013; Rylski and Spigelman, 1986a). Mechanical shade significantly reduces the amount of radiation reaching the crop (Díaz-Pérez, 2013; Möller and Assouline, 2007) resulting in reduced fruit energy absorption, FST (see Chapter 2), and sunscald occurrence (López-Marín et al., 2013; Rylski and Spigelman 1986a, 1986b). Barber and Sharpe (1971) suggested that mature red peppers sunscald less then mature green peppers because they have increased reflectivity to solar radiation. Increased reflectivity would decrease energy absorption, pepper FST, and sunscald occurrence as well.

Excess shading leads to decreased photosynthesis and yield (Díaz-Pérez, 2013; Rylski and Spigelman, 1986a). Therefore, knowing how much solar radiation is required to raise FST and how changes in wind speed lowers FST is important to determine how much mechanical shade is necessary and when it should be applied. The objectives of this study were: (1) to determine the effect of incoming radiation on pepper FST; (2) to determine the effect of wind on pepper FST; (3) and to determine if fruit age differences alter reflectivity to solar radiation. While complex equations have been created to model the FST of apples (Saudreau et al., 2011), we would like to add to the limited knowledge of how solar radiation and wind speed affect pepper FST.

Materials and Methods

Detached fruit. Mature-green, detached peppers of similar size and shape were purchased from a local grocery store and used in laboratory studies in Logan Utah. Fruits were fastened to a large cardboard box using zip ties. A CMP-3 black-body pyranometer (Kipp and Zonen, Delft, The Netherlands) was attached next to the pepper. Both fruit and pyranometer were placed at equal heights. A hmp-50 air temperature and humidity sensor (Vaisala, Vantaa, Finland) was used to monitor environmental conditions 0.3 m away from the fruit.

Two ST-200 fine-wire thermistors (Apogee Instruments, Logan, UT) were used to monitor fruit surface temperature (FST). The fine-wire thermistors were inserted into small holes made by a soldered fine gauge wire. The holes were made by inserting the wire 1 mm to 2 mm into the fruit pericarp and then under the epidermis for 1 cm. The thermistors were inserted approximately 1.5 cm above and below the estimated center of the lobe (Fig. 3.1) being analyzed. Packing tape was used to fasten the thermistors to the fruit. Thermistors were located equal distances from the light source and at equal heights with the pyranometer. All sensors were connected to a CR 1000 data logger (Campbell Scientific, Logan, UT).

A 500 W halogen light was used to illuminate the fruits. Three radiation levels: 30 $W \cdot m^{-2}$, 65 $W \cdot m^{-2}$, and 250 W m^{-2} (named RL30, RL65, and RL250, respectively) were achieved by moving the light source closer to the fruit (0.9 m, 0.6 m, and 0.3 m from the fruit). Data were collected every second, and one minute averages of FST, incoming radiation, and laboratory air temperature were recorded.

Fruit surface temperature (FST) measurements began with the light located 0.9 m away from the fruit (RL30) and FST was monitored until the temperature increase was less than 0.1°C min^{-1} for 10 min. At that time, the light was repositioned to 0.6 m from the fruit (RL65) and FST was monitored again until the increase in FST was less than 0.1°C min^{-1} for 10 min. The process was repeated with the light positioned 0.3 m from the fruit (RL250). Two additional fruits were measured in similar fashion for a total of six temperature measurements (2 thermistors x 3 fruit) for each radiation level.

A handheld LI-189 Quantum/Radiometer/Photometer (Li-Cor, Lincoln, NE) was held directly in front of the thermistors and pyranometer between each radiation level change, to insure the radiation levels were similar. If radiation levels differed by more than 5 micromoles m^{-2} s^{-1} from the desired level (RL30, RL65, or RL250) the light angle was adjusted until radiation levels were similar. A handheld MI-210 infrared radiometer (Apogee Instruments, Logan, UT) was used to periodically verify FST readings.

Attached fruit in a controlled environment. The pepper cultivar ‘Socrates’ (Seedway, Hall, NY) was planted into 4 L pots filled with a peat based medium. Plants were grown to maturity in a heated greenhouse. When fruits reached the mature green stage, three plants were selected and used to evaluate the FST of attached fruits. One plant was placed next to the pyranometer (attached to an adjustable lab stand, Fig. 3.2). An hmp-50 air temperature and humidity sensor and a 03191-5a wind sentry anemometer (R. M. Young, Traverse City, MI) 0.3 m away from the fruit were used to monitor environmental conditions (Fig. 3.3). Fruit surface temperature was measured as per detached fruit. Plants were well watered prior to the studies and watered again at each radiation level change to insure plants were well hydrated throughout the experiment.

Influence of wind speed on attached pepper FST in a controlled environment. After pepper FST stabilized at RL250, a fan was turned on to create a wind speed of approximately 1.5 $m \cdot s^{-1}$. When the FST decrease was less than 0.25°C$\cdot min^{-1}$ for 10 min the fan speed was increased to create a wind speed of approximately 3 $m \cdot s^{-1}$ until the FST decrease was less than 0.25°C$\cdot min^{-1}$ for 10 min.

Attached fruit in a field environment. Data collected from field grown ‘Aristotle’ plants from the summer months of 2013 (see Chapter 2) was further evaluated to determine the influence of solar radiation and wind speed on pepper FST under field conditions. A SP-110 pyranometer, a hmp-50 temperature and humidity sensor, and a 03191-5 wind sentry anemometer were positioned 0.5 m, 0.5 m and 1.0 m respectively, above the ground in the open (un-shaded) control. Fine-wire thermistors inserted 1 mm to 2 mm into the fruit pericarp and then pushed under the epidermis for 1 cm were secured to the insolated side of three fruit on one plant. Fruits that had an east, west, or top position on the plant were selected and all the leaves were removed from the plant to insure the fruit were minimally shaded. Fruit surface temperature was monitored continuously from July 28-30, Aug. 6-8 and Aug. 12-14 and new plants were used during each period.

Sensors were connected to a CR 1000 data logger and an AM 16/32 relay multiplexer (Campbell Scientific, Logan, UT). Data were collected every second and the average FST, air temperature, solar radiation level, and wind speed were recorded every five min, 30 min, hour and day. Only the data from 9 am to 7 pm on three sunny days with similar environmental conditions (Aug. 6, Aug, 13, and Aug. 14) were used in the analysis.

Pepper reflectance. Reflectance measurements were taken with a PS-200 spectroradiometer (Apogee Instruments, Logan, UT) and fruit reflectance from 400 nm to 850 nm was determined. Measurements were taken on the top half of one lobe of each fruit. Four immature green, four mature green, and four mature red fruit (>90% colored) of the variety ('Socrates'), grown in the greenhouse for the controlled environment experiment were used to assess changes in reflectance based on fruit age.

Results

Detached fruit. Radiation levels RL30, RL65, and RL250 averaged 30 $W \cdot m^{-2}$, 66 $W \cdot m^{-2}$, and 251 $W \cdot m^{-2}$ respectively, while the average maximum FST measured at those radiation levels was 26°C (±0.8°C), 36°C (±1.3°C), and 62°C (±2.6°C), respectively (Fig. 3.4). A maximum FST was calculated by taking the average FST once the temperature increase was less than 0.10°$C \cdot min^{-1}$ for RL30 and RL65, and once the temperature increase was less than 0.25°C·min^{-1} for RL250. Infrared FST readings were within 2.5°C of thermistor FST measurements. The ambient air temperature in the laboratory was 21°C (± 1.0°C), however air temperature next to the fruits was not measured directly as the light source was moved closer to the fruit.

Attached fruit in a controlled environment. Radiation levels RL30, RL65, and RL250 averaged 32 W·m^{-2}, 65 W·m^{-2}, and 249 W·m^{-2} respectively, and at these levels the average maximum FST was 25°C (±0.6°C), 32°C (±1.3°C), and 57°C (±3.1°C) respectively (Fig. 3.4). The maximum FST was calculated by taking the average FST once the temperature increase was less than 0.10°C·min^{-1} for RL30 and RL65, and once the temperature increase was less than 0.25°C·min^{-1} for RL250.

Average radiation when the wind speed was 1.5 and 3.0 m·s^{-1} was 246 W·m^{-2}. The average minimum FST for 1.5 and 3.0 m·s^{-1} was 49°C (±3.4°C) and 43°C (±3.0°C) respectively, compared to 57°C (±3.1°C) when there was no wind (Fig. 3.5).

Attached fruit in a field environment. The average maximum air temperature, incoming solar radiation level, wind speed, and VPD for Aug. 6, 13, and 14 were 35°C (±0.7°C), 946 W·m^{-2} (±4 W·m^{-2}), 1.6 m·s^{-1} (±0.1 m·s^{-1}) and 5 kPa (0.1± kPa), respectively. Average mean air temperature, incoming solar radiation level, wind speed, and VPD during the measurement period (9 am to 7 pm) used for analysis were 32°C (±3.0°C), 679 W·m^{-2} (±231 W·m^{-2}), 1.1 m·s^{-1} (±0.4 m·s^{-1}), and 4 kPa (±0.9 kPa), respectively. A delta T value was calculated by taking the difference between the highest FST and the air temperature. Average maximum FST and delta T (FST - air temperature) were 54°C (±1.6°C) and 20°C (±0.5°C), respectively. Average mean FST and delta T from 9 am to 7 pm was 48°C (±5.9°C) and 16°C (±4.1°C) respectively. As solar radiation increased, delta T increased (Fig. 3.6a). Increases in solar radiation increased delta T less as wind speed increased (Fig. 3.6b-d). Moderate wind speeds (0.5 $m \cdot s^{-1}$ to 1.5$\cdot m^{-1}$) decreased delta T while low wind speeds (< 0.5 $m \cdot s^{-1}$) increased delta T (data not shown). Wind did not decrease FST as much as in the controlled environment experiment (Fig. 3.7).

Fig. 3.7 shows that maximum FST increased more than the air temperature from 9:00 am to approximately 10:30 am resulting in an increasing delta T. From 10:30 am to 5:00 pm maximum FST and air temperature increased similarly resulting in a delta T that was more stable. After 5:30 pm, maximum FST decreased at a much faster rate than air temperature resulting in a decreasing delta T.

Reflectance analysis. The difference in reflectance of immature green and mature green and red pepper fruits is illustrated in Figure 3.8. Mature red fruit have a significantly higher reflectance between 570 nm and 730 nm compared to immature or mature green fruit. Between 600 nm and 700 nm, mature red fruit reflectance was approximately 50% while immature and mature green reflectance was less than 5%. There was little difference in reflectivity between immature and mature green fruit until approximately 525 nm. Mature green fruit had slightly higher reflectivity from 525 nm to 725 nm compared to immature green fruit. At 725 nm to 850 nm immature green fruit had approximately 5% greater reflectance than mature green fruit.

Discussion

Differences in FST measurements between the two fine-wire thermistors (±1.6°C) are likely due to the different positions of each thermistor on the fruit. Since the fruit surface was not flat, slight changes in fruit shape may alter energy absorption and FST. Rabinowitch et al. (1983) reported that attached fruit had significantly lower temperatures compared to detached fruit. In our laboratory studies, the average maximum FST of attached peppers were 1°C, 4°C, and 5°C lower than detached fruit, when fruit were exposed to RL30, RL65, and RL250 respectively. These temperature differences are likely due to the accumulated effect of fruit transpiration and heat conduction through the fruit. Rabinowitch et al. (1983) suggest that pepper fruit may transfer some heat via water circulation within the plant as well. Since changes in fruit color have been shown to influence FST (Rabinowitch et al., 1983), reflectance differences between the purchased fruit (unknown variety) and 'Socrates' the cultivar grown in the greenhouse, may have also influenced pepper FST (Barber and Sharpe, 1971). Sunscald developed on all detached and attached fruit as fruits approached maximum FST at RL250 but the extent of damage was more severe on detached fruit. Rabinowitch et al. (1986) stated that as pepper FST increases the extent of sunscald damage increases as well.

As wind speed increased from 1.5 $m \cdot s^{-1}$ to 3.0 $m \cdot s^{-1}$, FST decreased by 8°C and 14°C, respectively. While wind speed had a large effect on insolated pepper FST at 3.0 $m \cdot s^{-1}$, it did not reduce FST below 40°C, the threshold for sunscald (Rabinowitch et al., 1986) even when the air temperature was 21°C. We estimated that a wind speed in excess of 3.5 m·s^{-1} are required to decrease pepper FST below 40°C under the conditions tested. Higher wind speeds may be required when air temperatures during the summer pepper production season exceed those experienced in the laboratory studies.

At wind speeds of 1.5 m·s^{-1}, FST was 8°C lower, compared to the no wind control. However, doubling the wind speed (3 m·s^{-1}) only reduced FST an additional 6°C. While higher wind speeds were not measured, these results suggest that additional FST cooling decreases as wind speed increases. This is likely due to the decrease in delta T as wind speed increases.

Based on this data, we can assume that higher wind speeds are necessary to lower FST as the FST to air temperature difference (gradient driving conductive and convective heat loss) decreases. Therefore, when delta T is smaller (at low radiation levels), a higher wind speed is required to lower FST compared to when delta T is larger (at high radiation levels). Since the light source used produces a different light spectrum than the sun, we did not estimate the amount of solar radiation needed to increase pepper FST over 40°C from controlled laboratory experiments.

The average air temperature in the 2013 field study was 32°C (9 am to 7 pm), which was 11°C higher than in the laboratory study. While wind decreased maximum FST in the field, it was less effective than in the laboratory. This is due in part to higher air temperatures in the field resulting in a lower delta T compared to the laboratory study. At RL250 and a wind speed of 1.5 m·s^{-1} the delta T was 28°C in the laboratory. In comparison, the maximum delta T in the field study was 21°C. Additionally, plants grown in close proximity to each other in the field would also alter wind speed in the canopy by shielding fruit on the side of the canopy opposite to the prevailing wind direction. Therefore, wind speeds recorded above the canopy are a poor indicator of wind speed at the fruit surface. Plants in the field also experience inconsistent (gusty conditions) wind speeds that may be less effective at decreasing FST compared to a constant wind speed. A sustained 3.0 $m \cdot s^{-1}$ wind speed has been shown to significantly lower 'Red Globe' grape FST after 6 min of exposure (Kuai et al., 2009).

As a result of higher air temperatures in the field decreasing delta T, and because wind is less consistent in the field, wind had a reduced cooling effect in the field compared to the laboratory. Additionally, because the average field wind speed was only 1 $m \cdot s^{-1}$, we assume it has minimal effect on pepper FST. Kuai et al. (2009) reported that wind speeds of 1.5 $m \cdot s^{-1}$ were needed to significantly lower the fruit surface temperature of 'Red Globe' grapes. Thus, increasing or decreasing solar radiation levels striking the fruit is the main contributor to FST.

Delta T increased as solar radiation increased until radiation levels reached approximately 600 $W \cdot m^{-2}$ in the morning. Delta T was fairly constant at approximately 19°C when solar radiation exceeded 600 $W \cdot m^{-2}$. As solar radiation dropped below 600 $W \cdot m^{-2}$ in the evening, delta T decreased. FST responds to solar radiation differently in the morning (9 to 11am) and evening (5 to 7 pm). FST and delta T increase more rapidly in the morning in response to solar radiation than the air temperature. In the evening, FST and delta T decrease at a faster rate in response to solar radiation than the air temperature. The stabilization of delta T around 19°C during midday hours is due to the FST and air temperature increasing or decreasing at approximately equal rates. This is caused by the air temperature taking longer than FST to heat up in the morning and taking longer to cool down then FST in the evening.

Solar radiation has a decreased influence on the FST of red fruit due to their increased reflectivity. Rabinowitch et al. (1983) reported that red fruit were resistant to sunscald. Reflectance data suggests that this scald resistance is due to increased solar radiation reflectivity between approximately 575 nm and 725 nm compared to green fruit. Immature and mature green fruit have a similar reflectance of solar radiation between 400 nm to 850 nm.

Conclusion

While a constant wind speed significantly decreased heated pepper FST when the air temperature was 21°C, more work needs to be conducted in field environments to determine how wind direction and consistency, fruit location, row management and other factors influence FST of peppers. While changes in wind speed can decrease FST, its ability to do so decreases as air temperature and solar radiation increase or delta T decreases. Solar radiation had a bigger effect on FST when wind speeds in the field experiment were low.

Photosynthesis and yield may increase when using mechanical shade if: mechanical shade is removed from retractable shade systems when pepper FST is below the threshold for sunscald, and the correct mechanical shade percentage is used allowing plants to maximize photosynthesis while lowering pepper FST below the threshold for sunscald. Since wind did not effectively decrease pepper FST at field levels, mechanical shade should provide fruit protection when solar radiation levels exceed damaging levels regardless of wind speed.

Based on a 40°C FST causing sunscald (Rabinowitch et al., 1986) we estimated that mechanical shade should be provided to exposed pepper fruit when solar radiation exceeds 550 $W \cdot m^{-2}$ if the air temperature is below 25°C. When air temperatures are between 25°C and 30°C, mechanical shade should be provided when solar radiation exceeds 350 $W \cdot m^{-2}$. To reduce sunscald when the air temperatures are 35°C and above mechanical shade should remain in place. Values are estimates, and do not take into account the added effect of canopy shading. Pepper FST can reach damaging levels at moderate air temperatures and solar radiation levels.

Since mature red peppers have significantly higher reflectivity of solar radiation between 400 nm to 850 nm compared to green peppers their resistance to sunscald is likely due to decreased energy absorption. Barber and Sharpe (1971) also reported that differences in the FST of lighter colored fruit was due to their increased reflectivity to sunlight which decreased total energy absorption and ultimately FST. As a result of lighter colored fruit being more sunscald resistant than darker colored fruit, plant breeders should increase efforts to produce varieties with good eating quality and increased reflectivity of solar radiation.

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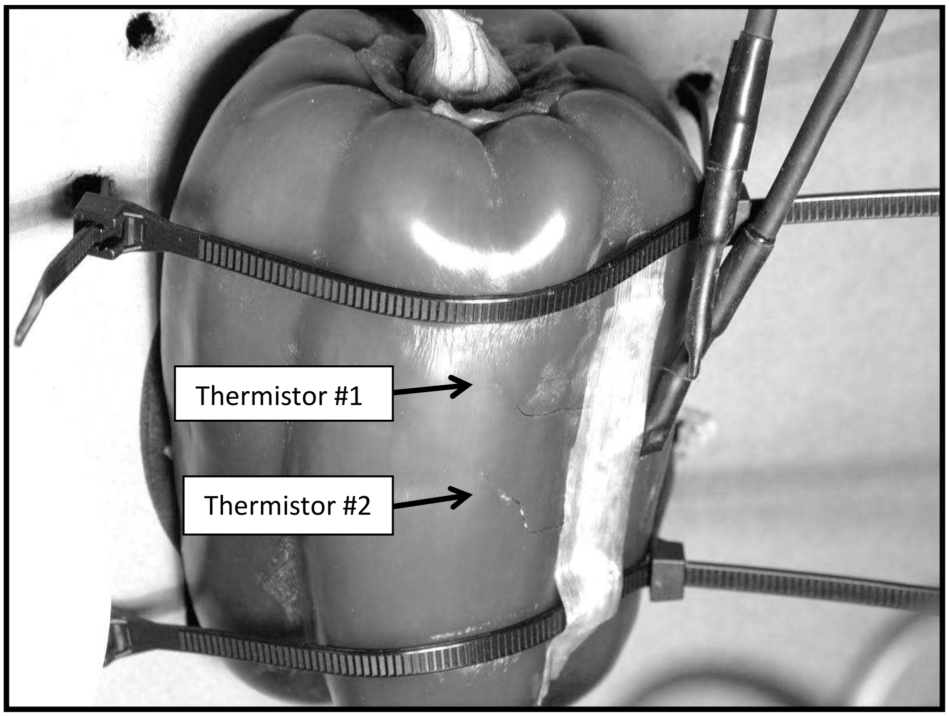

Figure 3.1. Fine-wire thermistors inserted 1.5 cm above and 1.5 cm below the center of the lobe on a detached bell pepper.

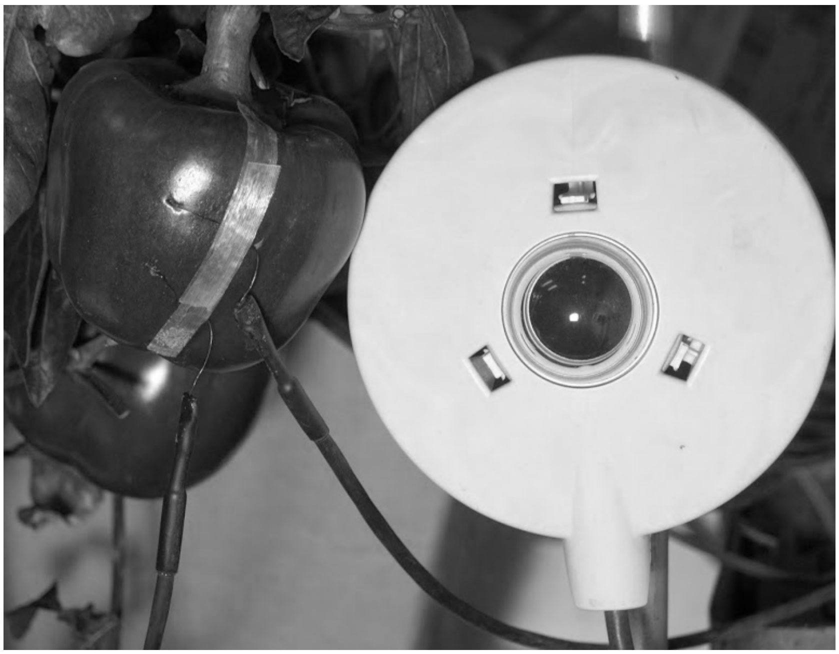

Figure 3.2. Thermistors and pyranometer located at approximately equally heights and distances from the light source.

Figure 3.3. Light source, shielded thermocouple, cup anemometer, and pyranometer used during attached pepper fruit surface temperature measurement in a controlled environment.

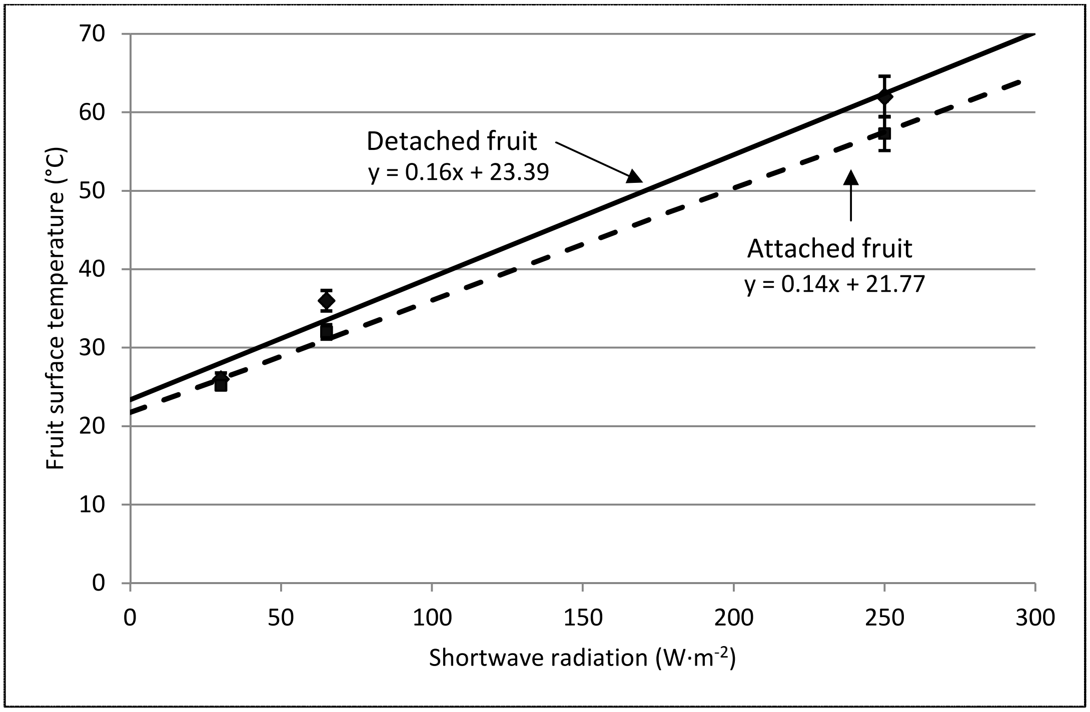

Figure 3.4. Detached and attached pepper fruit surface temperature as affected by incoming shortwave radiation in a controlled environment. The error bars represent the standard deviation from the mean.

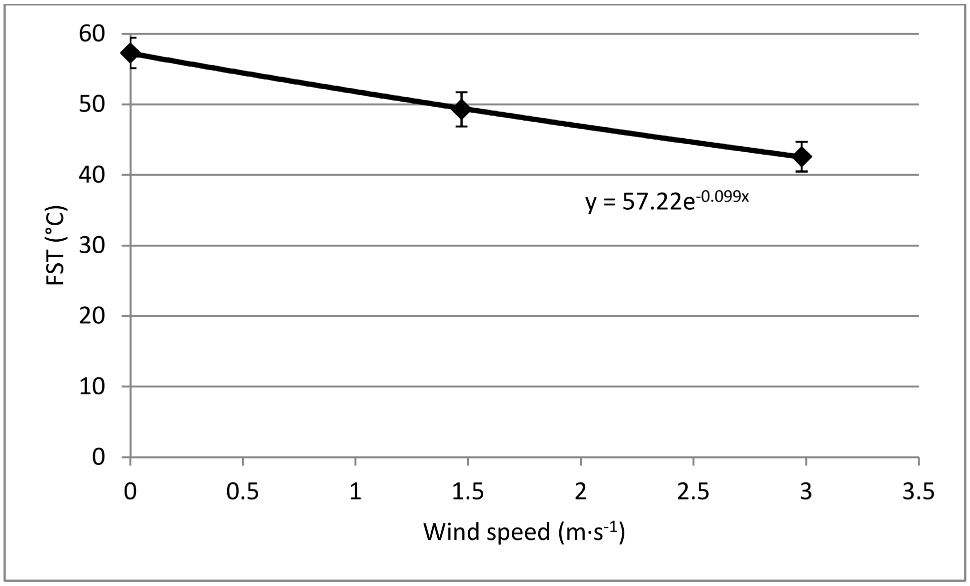

Figure 3.5. Attached pepper fruit surface temperature (shortwave radiation at 246 $W \cdot m^{-2}$) as influenced by wind speed in a controlled environment. Error bars represent the standard deviation from the mean.

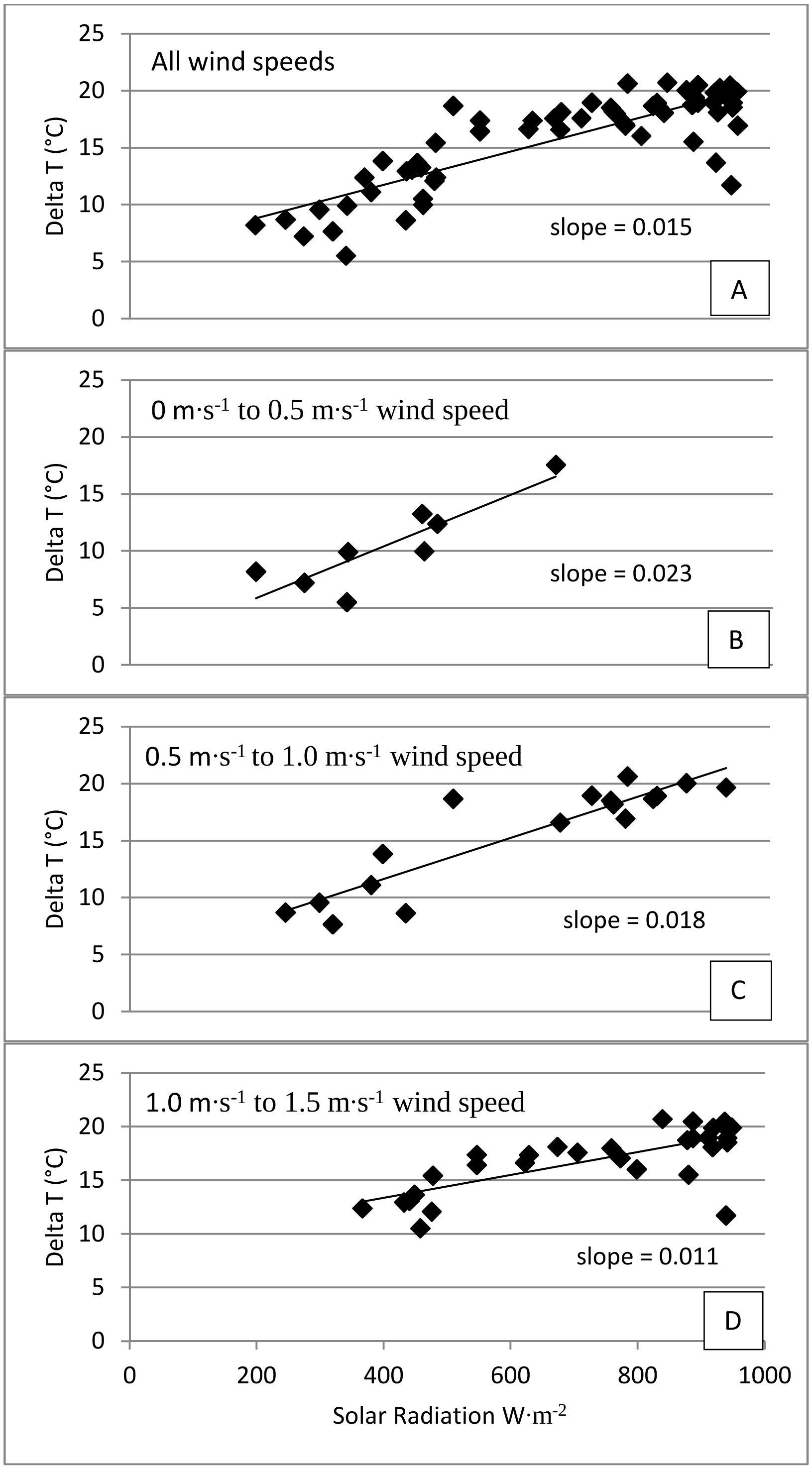

Figure 3.6. Attached in field pepper delta T (fruit surface temperature – air temperature) decreases as wind speed increases.

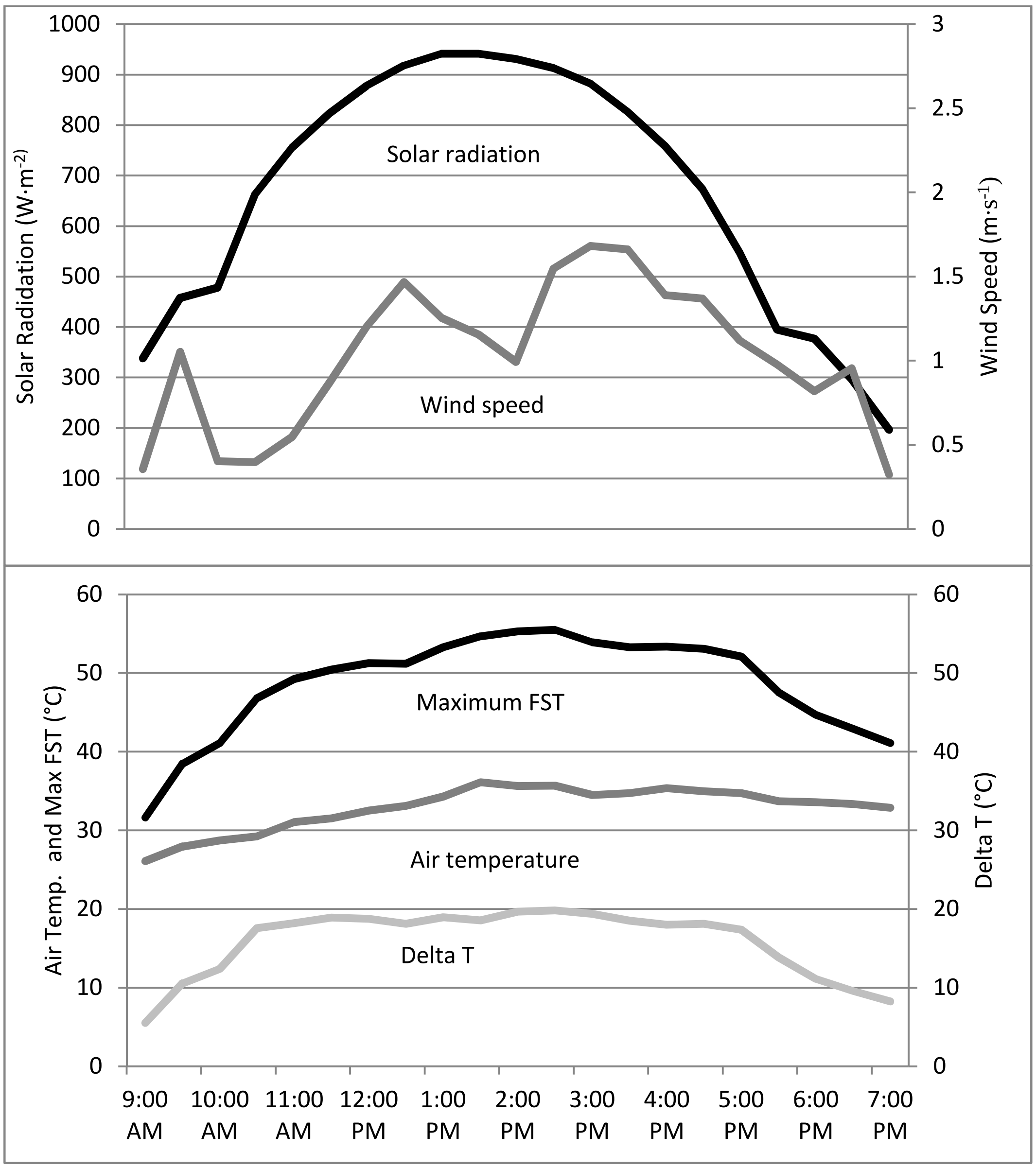

Figure 3.7. In field air temperature, attached pepper delta T (fruit surface temperature – air temperature) and maximum fruit surface temperature (FST) as affected by solar radiation and wind speed (measured 1 m above the ground) on August 14, 2013.

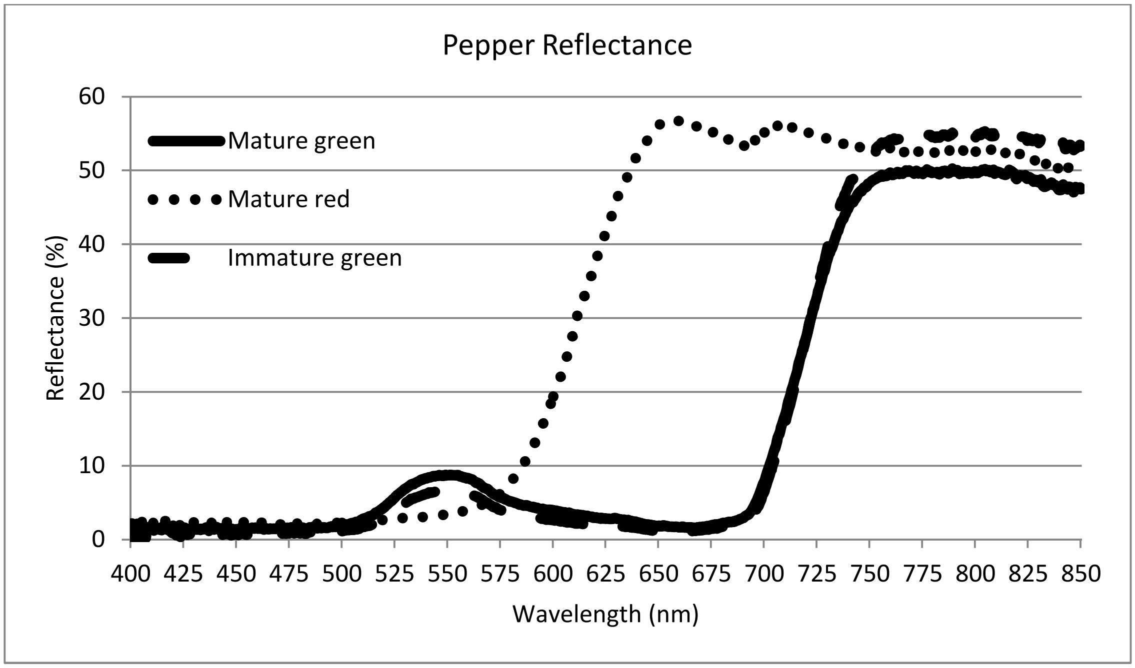

Figure 3.8. Percent reflectance of greenhouse grown ‘Socrates’ immature and mature green bell peppers and mature red bell peppers from 400 to 850 nm. Reflectance values are averages from measurements taken on four fruit with a spectroradiometer.

CHAPTER 4

ECONOMIC EVALUATION OF SUPPLEMENTAL SHADE SYSTEMS ON RED BELL PEPPER PRODUCTION

Abstract. Increased costs of mechanically shading a crop are offset by increased yield and quality due to sunscald elimination and reduced plant stress. Therefore mechanical shade can increase the profitability of red bell pepper production in high temperature and light environments and is recommended for use in high stress conditions.

Introduction

The number of farmers markets in the U.S. increased from 4,685 in 2008 to 7,864 in 2012 (USDA, 2012) while the annual per capita consumption of bell peppers in 2000 (3.63 kg) was 80% higher than in 1990 (USDA, 2001). Additionally, 24% of Americans now consume at least one food containing bell peppers every day (USDA, 2001).These statistics indicate there is an increased consumer demand for local products, including pepper.

Increases in demand are due in part to an increased awareness of the dietary benefits of vegetables. Bell peppers are a good source of ascorbic acid (Haytowitz and Matthews, 1984), flavonoids (Lee, Howard, and Villalon, 1995), and phytochemicals (Duke, 1992). Because of the growing consumer trend to eat healthy and buy locally, the national demand for bell peppers should continue to increase. Additionally, because red bell peppers have more vitamin A and C, and a sweeter taste then green bells (Frank et al., 2001; Swiader and Ware, 2002; USDA, 2001) their demand will also continue to grow (Jovicich et al., 2005).

As the demand for bell peppers increased, market prices have gone up as well. Between 1960 and 2000, seasonal average bell pepper shipping point prices gained an average of $1.48 per 100 kg per year (USDA, 2001). Furthermore, the retail price for fresh market peppers rose 25% between 1994 and 1999. Green bell peppers comprise the majority of the market (80%) while colored bell peppers (red 10%, yellow 8%, brown etc. 2%) comprise the rest (Frank et al., 2001).

While growers can receive premium prices for red bell peppers (USDA, 2001), Utah has not historically been a major producer of red bell peppers. This is due in part to a large portion of the crop being lost to sunscald. Sunscald refers to a group of disorders associated with damaging levels of solar radiation and radiant heating (Barber and Sharpe, 1971). Sunscald affects developing peppers by creating blemishes which render fruits unmarketable (Madramootoo and Rigby, 1991). Rylski and Spigelman (1986a) reported sunscald losses of 36% in field produced red bell peppers grown in Besor, Isreal while in Utah fruit losses due to sunscald in field grown red bells were approximately 50% (see Chapter 2). Both studies showed significant reductions in sunscald occurrence by using supplemental shade. Shade cloth or screen has proven to mechanically reduce the amount of solar radiation reaching a crop (Möller and Assouline, 2007). Thus producers of many crops worldwide now use supplemental shade to reduce plant stress and fruit disorders caused by excessive air temperatures and solar radiation levels (Gindaba and Wand, 2005; López-Marín et al., 2013; Makeredza et al., 2013).

While Rylski and Spigelman (1986b) showed that 18% and 30% shade screens reduced sunscald in red bell pepper production, they did not conduct an economic analysis to determine if increases in crop value outweigh the added costs of supplemental shade. This chapter includes an enterprise budget calculated for one acre of red bell pepper production in Utah. In order to illustrate how sunscald elimination impacts marketable yield and profit, depreciation tables and a partial budget were included to show additional revenues and costs associated with supplemental shade.

All profit estimates were made using the pepper cultivar ‘Aristotle’ (Siegers Seed Co., Holland MI) for which we have significant productivity data. Plants were grown in a heated greenhouse for six weeks and hardened outside for two weeks before being transplanted in Layton, UT. Transplanting occurred in the spring (May) and supplemental shade was installed in July. Red bell peppers were harvested semiweekly from August 26 to September 27. A final harvest of green bell peppers occurred on October 3 which ended the production season. A discussion of costs involved in red bell pepper production (Table 4.1) and an assessment of the additional costs associated with supplemental shade (Tables 4.2, 4.3, and 4.4) are included. Prices shown in budgets were estimated based on current market prices from local retailer and online distributors and from bell pepper enterprise budgets from state extension websites in Florida (Hewitt, 2003), South Carolina (Clemson University, 2009), Georgia (Fonsah and Ferrer, 2011), and California (Takele, 2001).

Enterprise budget

Revenues were divided into four fruit classes: fancy red fruit, first class red fruit, second class red fruit (USDA, 2005), and green fruit from the final harvest. Average yield data for red bell pepper production was collected in Layton, UT during the 2013 production year. The price for fancy, first, and second class red fruit were calculated using national data from a terminal vegetable price website (University of Florida, 2014). A three-year (2011, 2012, and 2013) average September red bell pepper price for each size class and an average October green bell pepper price (all size classes combined) were calculated.

Growing supplies (fertilizer, herbicide, etc.) were estimated based on costs incurred during production and adjusted with an average from other enterprise budgets when needed. Plants were grown on site but their production could also be contracted through a local nursery. Our seedling cost is high due to the price of ‘Aristotle’ seed ($0.07 per seed). All granular fertilizer prices were obtained from Bear River Valley Co-op (personal communication, 2013). Other supply amounts and prices were determined from online quotes or by taking an average from other enterprise budgets. Supplies ordered online will have additional shipping costs.

Labor was valued at $12.00 per hour, but is subject to change among farms, locations or other aspects unique to local or custom operations. Quantity of hours required to accomplish each task was estimated and adjusted with an average from published enterprise budgets (Clemson University, 2009; Fonsah and Ferrer, 2011; Hewitt, 2003; Takele, 2001). The ground was plowed the previous fall and tilled with a spring toothed harrow in the spring. After pre-plant herbicide and fertilizer was applied, the ground was tilled again with a spring toothed harrow then transplanted. Two additional fertilizer applications were made at three and five weeks after transplanting. All fertilizer applications were made with a broadcast spreader. The field was disked twice after harvest.

The number of hours required for hauling, grading, and packing peppers were calculated on a per carton basis. It was assumed that one person could grade and pack approximately nine cartons per hour and haul approximately 23 cartons per hour. Harvest costs did not change as marketable yield increased because both un-marketable and marketable fruit must be removed from plants at harvest. Costs for tractor and machinery repairs were calculated based on Painter’s (2011) machinery cost tables. Cost estimates were calculated based on the number of hours the tractor or implement was used, multiplied by the cost of repairs per hour of use for the tractor and each implement. Calculations were based on a 85 horse power tractor, three bottom moldboard plow, 12’ spring toothed harrow, 30’ (150 gallon) sprayer, small broadcast fertilizer spreader, four row cultivator, two row trans-planter, and a 9’ offset disk. Since a four row cultivator and two row trans-planter were not included in the machinery cost tables (Painter, 2011) we estimated the cost of repairs for these implements.

Painter’s (2011) machinery cost tables were also used to calculate the cost of owning the machinery needed to grow one acre of red bell peppers. This was done by dividing the purchase price of each piece of machinery minus the salvage value (10% of purchase price) by the lifetime (15 years) of the machinery. Because the machinery would also be used on additional acreage throughout the year, calculated values were then divided by 100 acres. The total machinery cost of ownership was calculated and included in Table 4.1. A $500 land and water rental and crop insurance purchase cost for Layton, UT was estimated and a $360 management cost to reimburse the farm manager for oversight was included.

Supplemental shade costs and benefits

Costs for supplies needed to build an approximately 160’ wide 270’ long (approximately one acre) shade structure are detailed in Table 4.2. Costs for purchasing the shade cloth needed to cover the top and sides of the structure are detailed in Table 4.3. Asset depreciation of the structure and shade cloth were calculated using straight line depreciation that assumed no salvage value at the end of the 7 year investment period. The total structure and shade cloth price was divided by the number of years they are assumed to be useful (7 years) resulting in the annual depreciation costs. Shade cloth useful life is 7 to 10 years (Gidco Ag. Design and Consulting, personal communication, 2013).

Based on 2013 production data (see Chapter 2) sunscald was eliminated under shade cloth. Therefore fancy red yield increased by 542 cartons per acre while first and second class red fruit yield increased by 106 and 120 cartons per acre respectively, and green fruit yield increased by 71cartons per acre compared to un-shaded production (Table 4.4). These changes in productivity resulted in an additional $18,407 per acre of revenue compared to un-shaded bell pepper (red and green) production. An additional

232 hours were needed to haul, grade, and pack extra fruit (839 more cartons) and to install and remove the structure and shade cloth every year. A $100 annual maintenance cost for both the structure and shade cloth was included in case seasonal repairs are needed.

Supplemental shade costs $5,889 per acre per year resulting in a $12,518 change in net income, indicating that the reduction in sunscald outweighs the costs of supplemental shading. Therefore supplemental shade increases the profitability of Utah red bell pepper production. It should be noted that while this system is profitable it may not be feasible for every grower as a $13,403 per acre initial investment is needed.

Table 4.5 shows that red bell pepper production is more profitable at lower yields with supplemental shade than without. As prices and yields increase, net income increases more rapidly with supplemental shade in comparison to un-shaded production. Increased production efficiency under shade could also reduce land costs and allow more room for other crops to be grown. Supplemental shade has also been shown to reduce the crop water requirement leading to reduced irrigation (Möller and Assouline, 2007). In conclusion supplemental shade increases the profitability of red bell pepper production in Utah by eliminating sunscald.

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Table 4.1. Red Bell Pepper Enterprise Budget for 1 acre

Revenues	Units	Quantity	Price	Total
Red bell peppers				
Fancy class	Carton[1]	156	$23.50	$3,666.00
First class	Carton	235	$21.25	$4,993.75
Second class	Carton	98	$19.75	$1,935.50
Green bell peppers	Carton	159	$14.75	$2,345.25
Total Revenue				**$12,940.50**
Variable Costs				
Supplies				
Fuel	Gallon	12	$3.50	$42.00
Seedlings	Each	15,100	$0.14	$2,114.00
Fertilizer				
0-0-60	Pound	223	$0.27	$60.21
11-52-00	Pound	232	$0.29	$67.28
46-0-0	Pound	248	$0.27	$66.96
20-20-20 soluble	25 lb. Bag	1	$15.00	$15.00
Herbicides (Trust®)	Pint	1.5	$6.30	$9.45
Carton or Box	Carton	648	$1.18	$764.64
Total Supplies				**$3,139.54**
Labor				
Tillage pre-plant	Hours	3	$12.00	$36.00
Herbicide application	Hours	1	$12.00	$12.00
Transplanting	Hours	25	$12.00	$300.00
Fertilizer applications	Hours	3	$12.00	$36.00
Cultivating	Hours	2	$12.00	$24.00
Weeding	Hours	10	$12.00	$120.00
Irrigation	Hours	10	$12.00	$120.00
Harvesting	Hours	225	$12.00	$2,700.00
Hauling	Hours	28	$12.00	$336.00
Grading and packing	Hours	74	$12.00	$888.00
Marketing	Hours	50	$12.00	$600.00
Tillage post-harvest	Hours	1	$12.00	$12.00
Total Labor				**$5,184.00**
Other				
Tractor and machinery			$64.23	$64.23
Interest on operating capital			$483.53	$483.53
Total Other				**$547.76**
Total Variable Costs				**$8,871.30**
Fixed Costs				
Tractor and machinery			$50.04	$50.04
Land, water, and crop insurance			$500.00	$500.00
General overhead and management	Hours	30	$12.00	$360.00
Total Fixed Costs				**$910.04**
Total Costs				**$9,781.34**
Net Income				**$3,159.16**

[1]28 lb. carton

[2]Obtained from weekly terminal vegetable market national prices (University of Florida, 2014)

Table 4.2. Annual depreciation of a shade structure (seven year useable lifespan).

	Units	Quantity	Unit Cost	Total
Shade Structure				
4’’ x 4’’ x 12’ pressure treated lumber[1]	Each	88	$20.97	$1,845.36
Earth auger anchors[2]	Each	50	$4.90	$245.00
Stainless steel aircraft Cable 1/16’’[3]	Foot	4000	$0.26	$1,040.00
Polyester chord 1/8’’[3]	Foot	1000	$0.03	$30.00
Eyebolt 8’’ x 3/8’’[3]	Each	212	$1.16	$245.92
Cable cutters [4]	Each	1	$32.95	$32.95
Wire tensioning tool[4]	Each	1	$99.00	$99.00
Anchor connectors[4]	Each	56	$4.60	$257.60
Wire tensioners[4]	Each	264	$1.37	$361.68
Earth auger 6’’[5]	Each	1	$688.97	$688.97
Ladder[6]	Each	1	$81.00	$81.00
Total Structure Cost				$4,927.48
Annual Depreciation of Shade Structure				$703.93

Additional shipping charges will apply
[1] http://www.homedepot.com
[2]http://www.greenhousemegastore.com
[3] http://www.farmtek.com/farm/supplies/home
[4] http://www.gripple.com/us/products/catalogue/agricultural/
[5] http://www.ruralking.com
[6] http://www.sears.com

Table 4.3. Annual Depreciation of shade cloth (seven year useable lifespan).

	Units	Quantity	Unit Cost	Total
Shade Cloth				
32’ wide x 270’ long shade cloth*	Each	5	$1,351.69	$6,758.45
9’ wide x 270’ long shade cloth*	Each	2	$532.33	$1,064.66
9’ wide x 160’ long shade cloth*	Each	2	$326.08	$652.16
Total shade cloth cost				$8,475.27
Annual depreciation of shade cloth				$1,210.75

Additional shipping charges will apply

* 30% black knitted shade cloth with taped edges with brass grommets on 2’ centers from http://www.greenhousemegastore.com

Table 4.4. Partial Budget for supplemental shade on 1 acre of ‘Aristotle’ red bell peppers.

		Units	Quantity	Price	Total
Additional revenues with supplemental shade					
Field Produced Red Bell Peppers + Supplemental Shade					
	Red bell peppers				
	Fancy	Carton	542	$23.50	$12,737.00
	First Class	Carton	106	$21.25	$2,252.50
	Second Class	Carton	120	$19.75	$2,370.00
	Green bell peppers	Carton	71	$14.75	$1,047.25
Total additional revenue with supplemental shade					**$18,406.75**
Additional costs with supplemental shade					
Supplies					
	Cartons	Each	839	$1.18	$990.02
Labor					
	Hauling	Hours	36	$12.00	$432.00
	Grading and Packing	Hours	96	$12.00	$1,152.00
	Installation and Removal (structure and shade cloth)	Hours	100	$12.00	$1,200.00
Added Costs of Shade Structure					
	Annual Depreciation of Shade Structure*				$703.93
	Annual Maintenance of Shade Structure				$100.00
Added Costs of Shade Cloth					
	Annual Depreciation of Shade Cloth**				$1,210.75
	Annual Maintenance of Shade Cloth				$100.00
Total additional costs with supplemental shade					**$5,888.70**
Resulting Change in Net Income					**$12,518.05**

*Annual shade structure depreciation costs detailed in Table 3.2

**Annual shade cloth depreciation costs detailed in Table 3.3

Table 4.5. Yield and price sensitivity analysis for 1 acre of un-shaded and shaded red bell pepper production at three prices and yield levels. Prices were calculated from weekly national terminal vegetable transactions. Yields were based off of research plots in 2013.

Treatment	$5.00/Carton Lower	Mean Price[1]	$5.00/Carton Higher
No Supplemental Shade			
400 Cartons[2]	($3,032.60)	($1,032.6)	$967.40
650 Cartons[A]	($60.68)	$3,189.32	$6,439.32
900 Cartons	$2,918.49	$7,418.49	$11,918.49
W/Supplemental Shade			
1250 Cartons	$5,161.35	$11,411.35	$17,661.35
1500 Cartons[B]	$8,411.02	$15,911.02	$23,411.02
1750 Cartons	$11,660.57	$20,410.57	$29,160.57

Results are change in net income per acre.
The same percentage of yield for each size class and fruit color was used for all price and yield combinations of un-shaded and shaded production
1 = Mean price ($23.50 per carton fancy, $21.25 per carton first class, $19.75 per carton second class, and $14.75 per carton for green fruit) calculated from weekly national terminal vegetable market prices (University of Florida, 2014).
2 = one 28 lb. carton.
A = Un-shaded mean yield (Day, 2013; Chapter 2).
B = Shaded mean yield (Day, 2013; Chapter 2).

CHAPTER 5

SUMMARY AND CONCLUSION

Introduction

The purpose of this study was to advance and refine work that has been done on the effects of biological and mechanical shading. Candidate advancements and refinements included: investigating the use of low tunnels in bell pepper production to increase biological shading; investigating the orientation of mechanical shade and its influence on sunscald; determining how solar radiation and wind speed influence pepper fruit surface temperature (FST); and investigating the profitability of mechanical shade .

Biological shade

The frequency of sunscald is inversely proportional to the leaf to fruit ratio (Barber and Sharpe, 1971), so increases in canopy shading should decrease sunscald occurrence. Low tunnels increased air and soil temperatures during the day which resulted in greater plant growth under low tunnels early in the season compared to plants in the no tunnel control. Increased biological shading can be accomplished with the use of low tunnels. However the benefits of biological shade can be reduced or entirely lost due to leaf folding, wind damage, lodging, or when the canopy opens as branches bend under fruit weight (Rylski and Spigelman, 1986), or branches break during harvest. Low tunnels did not significantly decrease sunscald or increase marketable yield unless combined with mechanical shade. We concluded that in high temperature (>30°C) and light (900 W·m^{-2}) environments, biological shade does not adequately shade fruit from damaging levels of solar radiation. Improved water and nutrient management along with varietal selections may further improve plant growth, thus improving biological shade.

Mechanical shade

While biological shade can be reduced or lost, mechanical shade (shade cloth) is the only way to permanently decrease the amount of radiation reaching the crop. Solar and UV radiation were significantly reduced under vertical shade when the sun was at lower solar elevations (early and late in day) and under horizontal shade for the entire day. Vertical shade significantly reduced air and soil temperatures compared to the open control while horizontal shade significantly decreased air and soil temperatures compared to both the vertical shade and the open control. Vertical and horizontal shade were shown to reduce the average daytime air temperature in July and Aug. by 1.5°C and 3.4°C respectively, compared to the open control. Additionally, vertical and horizontal shade decreased soil temperatures in July and August by 3.0°C and 4.5°C, respectively, compared to the open control. Reductions in air and soil temperatures decreased plant and fruit stress which increased plant performance and yield.

Pepper FST on intact plants (with leaves) was 3.3°C cooler under vertical shade and 5.7°C cooler under horizontal shade compared to the open control. Additionally pepper FST was 4.3°C cooler under vertical shade and 6.9°C cooler under horizontal shade compared to the open control when leaves were removed from plants. While necrosis can occur on pepper in 15 min at a FST of 49°C (Barber and Sharpe, 1971), Rabinowitch et al. (1974) suggest that a longer exposure at a more moderate FST will also cause sunscald. Our study shows that pepper FST must exceed 40°C for somewhere between 68 $min \cdot day^{-1}$ to 126 $min \cdot day^{-1}$ for sunscald to develop.

Mechanical shade protection is important on all sides of the canopy since pepper FST regularly exceeded 40°C in the east, top, and west canopy orientations in the open control. Sunscald primarily occurred when sunlight was between sun angles of 150° to 210°. Thus, fruit in the top of the canopy are more prone to sunscald because they are exposed to solar radiation at those sun angles. Shade cloth should be installed to provide protection to all sides of the plant canopy but particularly to protect fruits when the sun is directly overhead.

More than 50% of fruit in the open control had sunscald compared to 23% of fruit grown under vertical shade. No fruit under horizontal shade had sunscald. This resulted in a significant increase in the yield of marketable red fruit. Vertical and horizontal shade increased percent marketable red fruit yield by 28% and 58%, respectively, and reduced cull fruit yield by 16.4 $Mg \cdot ha^{-1}$ and 33.7 $Mg \cdot ha^{-1}$, respectively, compared to the open control.

Influence of solar radiation and wind speed on FST

A constant wind speed of 3.0 $m \cdot s^{-1}$ significantly decreased insolated pepper FST when the air temperature was 21°C. More work needs to evaluate how wind direction and consistency, fruit location, row management and other production factors influence pepper FST. While changes in wind speed can decrease FST, its ability to do so decreases as air temperature and solar radiation increase (delta T (FST – air temperature) decreases). Since wind cannot be controlled in the field, alternative approaches to reducing FST are necessary. Solar radiation had a bigger effect on FST when wind speeds in the field experiment were low.

Based on a 40°C FST causing sunscald (Rabinowitch et al, 1986), we estimated that mechanical shade should be provided to pepper when solar radiation exceeds 550 $W \cdot m^{-2}$ if the temperature is below 25°C. When air temperatures are between 25°C and 30°C, mechanical shade should be provided when solar radiation exceeds 350 $W \cdot m^{-2}$. To reduce sunscald when air temperatures are above 35°C, mechanical shade should remain in place. Additional work is needed using various levels of shade and shading plants for different durations each day to verify these conclusions.

Profitability of mechanical shade

By eliminating sunscald, horizontal shade increased the yield of fancy, first class, and second class red fruit by 542, 106, and 102 cartons, respectively, while green fruit yield increased by 71 cartons compared to the open control. This resulted in $18,407 per acre of additional revenue. Materials and installation costs were $3,315 dollars per acre per year and additional production and labor costs were $2,574 per acre per year. This resulted in a positive change in net income of $12,518 per acre. In conclusion, while there are added costs, mechanical shade is a profitable alternative when producing red bell peppers in high temperature and light environments.

Conclusion

As leaf area increases, the amount (percent shade) of supplemental shade required to protect fruit decreases. Small increases in plant growth (leaf area) due to warmer air and soil temperatures during early plant development are not sufficient to protect fruit from damaging levels of solar radiation. Larger increases in plant growth (leaf area) may be accomplished using other practices (varietal selection, grafting etc.) but only decrease sunscald if environmental conditions are not favorable to leaf wilting and the plant canopy is not damaged. Supplemental shade permanently decreases the amount of solar radiation reaching the crop and the air and soil temperature surrounding the crop. This results in increased heat transfer away insolated fruit.

Bell pepper yield may increase if supplemental shade is only applied when damaging levels of solar radiation occur. Future research should investigate possible yield increases with reduced (< 30%) supplemental shade. While yield may increase by only providing supplemental shade when solar radiation levels are high enough to damage fruit the feasibility and economic impact of this practice should be determined. The balance between increasing yield by increasing light levels reaching the crop (decreasing supplemental shade) and decreasing sunscald by decreasing light levels reaching the crop (increasing supplemental shade), should be examined to determine the economic optimum (marketable yield) for growers.

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