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The Effect of High Tunnels and Row Covers on Tomato Plant Growth and Production in Louisiana

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THE EFFECT OF HIGH TUNNELS AND ROW COVERS ON TOMATO PLANT GROWTH AND PRODUCTION IN LOUISIANA

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ABSTRACT

Field studies were conducted to evaluate the effect of high tunnels (HT) and spunbonded polyester row covers (RC) on tomato plant growth and yield during the spring growing season. High tunnels significantly increased minimum, mean and maximum air and soil temperatures and high tunnels used in combination with row covers had the highest minimum, mean, and maximum air and soil temperatures. The minimum air and soil temperature for the 3 coldest days each season were highest in the combination high tunnel and row cover treatment and growing degree days were highest with this treatment. Plants in high tunnels grew faster as indicated by higher growth rates compared to plants in the no tunnel treatments. At the end of harvest, leaf area of plants in high tunnels was higher compared to those without. Plants in the combination HT+RC treatment had higher fresh and dry weights compared to RC treatment at the last harvest and harvest index was the lowest in the combination treatment at both harvests. The high tunnel treatment had a higher early marketable yield compared to the plastic mulch (control). Total marketable yield was highest in the HT treatment and lowest in the HT+RC treatment. The combination treatment of high tunnel and row covers increased fruits in the small size category and decreased the number of large size fruit. The HT treatment showed economic benefit when sufficient early and late yield were obtained.

CHAPTER 1

INTRODUCTION

Modifying the natural environment is a common technique to enhance plant growth and increase yield. The primary goal of environmental modification is optimum control of microclimates such as atmosphere, water, temperature, light, and soil nutrient status for the crop grown. Recent developments in environmental modification by the plastic industry has enabled sophisticated control of these environmental factors using plasticulture techniques such as plastic mulch film, trickle irrigation, row covers, high tunnels, and greenhouses. High tunnels are simple greenhouse structures without automated controls or a heating or cooling system. High tunnels in the U.S. are primarily used from the early spring to fall season in Northern states for the purpose of increasing the average daily temperature and sheltering crops from wind, rain, snow, hail, and protecting against insects and diseases (Jett, 2004; Wells and Loy, 1993). In contrast, they are extensively used in Europe, Asia, and the Middle East for early vegetable production (Wells and Sciabarrasi, 1992).

High tunnels modify the environment to enhance crop growth, yield, and quality although it's not as precise as a conventional greenhouse (Lamont and Orzolek, 2003). Recently, researchers have investigated the feasibility of integrated production system using high tunnels (Waterer, 2003; Wells and Sciabarrasi, 1992). These researchers reported increased earliness and yield of tomatoes. High tunnels primarily contribute increased temperature and result in yield increases. In addition, higher soil temperature allows earlier planting and active root growth. Earliness with high tunnels is generally two weeks earlier in planting and two weeks earlier fruit maturity (Wells and Sciabarrasi, 1992). Increased air temperature accelerates shoot growth and provides suitable condition for fruit development and ripening. Row covers are also used in high tunnels to ensure higher temperatures required to grow warm-season vegetable under low temperature conditions. With a number of studies, the effect of a high tunnel system on temperatures and physiological response of tomatoes under cold climate has been established. However, the effect under a moderate climate such as Louisiana is still unknown.

High tunnel production is more costly than field culture because of the higher initial investment and increased labor cost for manual operation of the tunnel. Research is also necessary to determine if the added costs of high tunnels and row covers increase are economically beneficial.

The objectives of this study were 1) to evaluate the effect of high tunnels and row covers on air and soil temperature and growth and yield of tomato. Another objective was 2) to evaluate if the use of high tunnels and row covers results in higher economic return which justifies the increased production costs compared to traditional field culture.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The goal of environmental modification is to optimize the plant microclimate and increase productivity of a crop closer to its genetic potential (Boyer, 1982). Efficient control of desirable environmental factors such as temperature, light, water availability and carbon dioxide concentration within the crop zone is essential for the optimal growth and development, and a modern greenhouse is the ultimate in environmental modification today. In contrast to the precise microclimate control in greenhouse, the major environmental effect provided by high tunnels is higher temperatures that are achieved passively (Takakura, 1993). Temperature, however, is a leading microclimate factor which determines the rate of physiological reaction in plants and promotes plant growth when temperature is at the optimum for the crop. High tunnels improve plant growth and increase yield by increasing air temperature. Air temperature in high tunnels is controlled by stored solar radiation energy and natural ventilation. Soil temperature is modified by plastic mulch and trickle irrigation. Floating row cover also contributes to increased air temperature.

2.2. Environmental Effects of Plasticulture Components

Most growers who use high tunnels use several plasticulture techniques which affect the microclimate. Black plastic mulch and trickle irrigation are generally employed as fundamental components while floating row covers are used depending on crop and temperature condition. For example, row covers are used in high tunnels to grow hardy winter vegetables such as spinach, scallions and turnips in Nebraska (Byczynski, 2003).

I. Black Plastic Mulch

Mulching with plastic film is one of the greatest innovations in crop production in the last 100 years (Massey, 1972). The use of plastic mulch has greatly increased since its first application in commercial use, and the proportion of films for mulch as a percentage of sales of agricultural films in North America was the highest in 1998 (Laverde, 2002). Plastic mulch provides several benefits such as increased soil temperature, conservation of soil moisture, texture and fertility, and control of weeds, pests and diseases (Hanada, 1991). It’s also used in soil sterilization and fumigation to avoid the escape of methyl bromide or chemicals to the atmosphere (Laverde, 2002). The modern chemical industry produces plastic films of various colors and qualities such as black, white, silver, red, blue, yellow, coextruded and infrared thermal mulch, and each mulch with different color or quality provides specific environmental modification (Naegely, 2002; Pusztai, 1972). Black plastic is currently the most popular mulch among growers worldwide due to its high overall potential to modify microclimates and due to cost.

A. Soil Temperature Increase

Black plastic mulch significantly warms up soil underneath. Black mulch absorbs most of the incoming solar energy and reflects approximately 10% (Diaz-Perez and Batal, 2002). Soil temperature at 10 cm below the mulch can be up to 4°C higher than that in bare soil (Diaz-Perez and Batal, 2002; Renquist et al., 1982). Optimum soil temperature by heating soil with black plastic mulch accelerates plant development because transport of photosynthates, growth regulators, water and nutrients which are required for plant growth are highly influenced by root temperature (Martinez, 1994). Wilcox and Pfeiffer (1990) observed that root and shoot growth of beans, corn, cucumber, eggplant, pepper and watermelon increased as soil temperature increased from 16.7 to 21.1°C. Black polyethylene mulch significantly increased plant spread and dry weight of tomato compared to control treatment (Bhella, 1988). Accelerated growth resulted in early fruit production as well as rapid shoot growth. Teasdale and Abdul-Baki (1995) observed greater early tomato yield in black mulch treatment compared to those from hairy vetch mulch and bare soil and attributed it to optimum soil temperature conditions in the early growing season. In addition, Rykbost et al. (1975) observed earlier yield of lima beans, tomatoes, broccoli, peppers, and strawberries due to soil warming.

B. Soil Moisture Conservation

Evaporation of soil water is reduced 10-50% by mulching, and plastic mulch is generally more efficient in water conservation compared to organic materials (Rivera and Goyal, 1986; Splittstoesser, 1990). In a study using maize and cowpea, Maurya and Lal (1981) observed higher soil moisture in plots mulched with plastic compared to that with straw in the dry season. Higher soil water conservation not only reduces required frequency of irrigation but also provides more uniform soil moisture. Reduced evapotranspiration due to mulching, however, was a minor factor for tomatoes whose water demand under trickle irrigation was tied closely to plant vigor and yield (Bogle et al., 1989).

C. Supplemental Carbon Dioxide

Black plastic mulch may promote photosynthetic activity of crops by supplying supplemental carbon dioxide in field conditions. Carbon dioxide generated by respiration of roots and biological degradation in soil is accumulated under mulch due to its impermeability to CO_2 and elevates the concentration within planting the hole (Hopen and Oebker, 1975). Soltani et al. (1995) observed nearly twice as much CO_2 concentration inside the transplanting holes as that in ambient in a study with watermelon. However, this high concentration seems to be transitory and dissipated rapidly by air movement (Hopen and Oebker, 1975; Soltani et al., 1995).The benefit of elevated CO_2 may be, therefore, limited to a specific condition such as early stages of seedling growth on a calm day (Oebker and Hopen 1974; Soltani et al., 1995).

D. Improved Nutrient Environment

Mulching can improve the nutrient condition in the soil. Increased soil moisture and temperature near the surface of plastic-covered soil favor higher soil microbiological populations (Black and Greb, 1962). It was observed more than twice as much NO_3-N accumulation in plastic-covered soil as that in bare fallow soil for 12 weeks. Li et al. (2004) reported that microbial biomass C, which was an indicator of the fertility status of a soil, was promoted by mulching during the 2 year experiment using spring wheat.

E. Prevention of Soil Compaction

Plastic mulch prevents soil compaction due to heavy rain. External compression of soil increases the bulk density restricting root growth and decreases pore space volume reducing permeability and the diffusivity of gases, which may result in anaerobic conditions (Hussain et al., 1999). Decreased yield and shorter cucumber fruit resulted from unfavorable soil property conditions (Smittle and Williamson, 1977).

F. Weed Control

Unlike clear plastic mulch, black mulch sufficiently suppressed emergence of weeds without soil fumigant (Gorske, 1979). Germination of weeds is significantly restricted because seeds in soil cannot receive adequate light to germinate due to high light absorption of black mulch. In an experiment with Japanese quince, Kviklys et al. (2004) observed weeds were limited to planting holes in black mulch treatment and easily removed by hand during the experiment. In Finland, black plastic mulch was used in herbicide-free production of herbs. Mulch increased yield by 20-40% and decreased the need for manual weed control by 65-80% (Galambosi and Szebeni-Galambosi, 1992). Weed control with black plastic is comparable to some organic mulches recognized as useful for weed management. Black plastic mulch suppressed annual grass and broadleaf weeds in an experiment using tomatoes as well as shredded and chopped newspaper with the thickness of 17.8 cm and 7.6cm, respectively (Monks et al., 1997). Less application of chemicals enables growers to reduce cost for weed control. This also may protect growers in structures where applying volatile herbicide may be hazardous (Wells, 1991).

II. Trickle Irrigation

Trickle irrigation is the application of water and nutrients delivered directly to the root zone at a low controlled rate from an emission device (Wolfram, 2003). Trickle irrigation is often efficient as high as 75 to 95%, in contrast with 20 to 80% of those of conventional seepage systems (Clark et al., 1991). Generally, it's employed in conjunction with plastic mulch and raised beds.

A. Optimum Water Environment

Trickle irrigation maintains moisture at an optimum level in the soil around the root zone (Grove and Wells, 1985). Dripped water from irrigation tube provides abundant and uniform water distribution with adequate aeration. Due to the flexibility in timing application in relation to crop demand regardless of the growth stage, a steady optimum moisture condition can be maintained (Bhella and Wilcox, 1985). Marketable tomato yield increased 22% on average by trickle irrigation compared to furrow-irrigated treatments with considerable water saving (Bogle et al., 1989). Uniform water application also reduced physiological fruit problems such as cracking and blossom end rot of tomatoes (Jett, 2004).

Improved soil moisture levels can be achieved with the aid of plastic mulch and raised beds. This results from decreased evaporation by mulch and rapid removal of excess soil water from raised beds. Hochmuth and Howell (1983) observed the highest total marketable root yield of sweet potato in the combination treatment of trickle irrigation, black mulch and raised beds. Total yield of fresh-market field tomatoes was doubled by using trickle irrigation with black mulch and raised beds compared to the unmulched treatment (Abdul-Baki et al., 1992).

Maintaining sufficient soil moisture also contributes to moderate extremes of soil temperature. Soil beds covered with black polyethylene mulch irrigated by trickle irrigation had lower maximum and higher minimum daily temperature than those without irrigation (Renquist et al., 1982). This is because increased soil moisture content greatly increased both the soil thermal conductivity and heat capacity (Al-Kayssi et al., 1990).

Soil moisture levels need to be carefully monitored when trickle irrigation is used with plastic mulch because irrigation water is not supplemented by rainfall. Obreza et al. (1996) found that a water deficit under mulch increased plant disease and blossom end rot severity and resulted in decreased plant height and yield of tomato.

B. Fertigation

Trickle irrigation or fertigation, is also used for nutrient application because water provides the medium in which nutrients are carried (Treshow, 1970). This allows growers to deliver a more precise amount of nutrients to the root zone with flexible response for crop needs that varies according to the stage of development and climate condition resulting in accelerated plant growth and increased yield (Grove and Wells, 1985; Papadopoulos, 1992). Bhella and Wilcox (1985) concluded that nitrogen applied with fertigation resulted in higher yield of muskmelon than a comparable amount of preplant N fertilization. Goyal et al. (1985) observed higher yield of tomato, peppers and eggplant by nitrogen application through fertigation compared to a sidedress treatment or non-fertilized treatment. Yields increased in proportion to the fertigation rate.

C. Chemigation

Chemicals such as pesticides, herbicides, nematicides and algaecides can also be injected through trickle irrigation systems (Grove and Wells, 1985). Leib et al. (2000)

reported that application of imidacloprid by chemigation under black plastic mulch increased muskmelon yield ten-fold compared to no chemigation and bare ground treatment. Chalfant et al. (1993) reported chemigation reduced crop damage caused by mechanical incorporation of insecticide as well as lower application cost in the study with sweet potato.

III. Row Covers

Spunbonded floating row covers are synthetic fabrics that have been used in vegetable production to enhance crop quality and accelerate plant growth. The materials used include spunbonded polyester, polyethylene and polypropylene plastic. Row covers are light-weight and provide good permeability to air and water required to promote plant development. They are ultraviolet-light stabilized to prevent premature degradation under agricultural environments allowing 80% light transmission (Wells and Loy, 1993). The primary effects of row covers are as follows.

A. Temperature Increase

Spunbonded row covers increase air and soil temperatures during the daylight hours (Himelrick et al., 2001). Row covers have the properties of high light transmittance, while trapping energy within covers and elevating inside temperatures. This warmer environment raises plant and soil temperature under covers and accelerates plant development (Hanada, 1991; Hochmuth et al., 1986). Rapid vegetative growth, flowering, and ripening of fruit resulted from the increased temperature provided by row covers have been observed in peppers and strawberry (Gent, 1989a; Gent, 1989b). Accelerated growth and increased yield of radish, cabbage, and corn with increased temperature have been reported (Nelson and Young, 1987). Jett (2004) reported that temperatures were two to three times higher when row cover is used in high tunnels compared to their use in the field. However, it's suggested row covers should be used in climates with a long frost free season and with relatively cool late spring and summer temperatures to maximize this benefit and avoid its adverse effect such as flower abortion and delay of ripening (Gent, 1990).

B. Wind Break

Floating row covers often alleviate wind damage and conserve an ideal microclimate condition. Prolonged exposure of plants to strong wind should be avoided because wind can injure, break, and destroy above-ground portions of plants and cause disturbance of the microclimate in the crop zone (Rubatzky and Yamaguchi, 1997). Wind velocity decreased to as little as a half under covers supported by a hoop or frame, compared to the control in study with pak-choi (Hanada, 1991). Decreased air movement can also protect plants from desiccation (Himelrick et al., 2001).

Row covers may sometimes be deleterious for plants because of wind abrasion. Gent (1989a) observed highly branched pepper plants under row covers and attributed this to abrasive action of the floating row cover on the stem apex.

C. Bird and Pest Control

Row covers function as physical barriers for insects and diseases by application over the crops directly or supported on hoops or a frame. Orozco et al. (1995) observed that floating row covers completely excluded some typical insects for cantaloupe and delayed appearance of virus-diseased plants. Polyester row covers have been found to reduce insect damage markedly on cabbage production (Nelson and Young, 1987). The use of row covers where there is likelihood of overwintering insects and weeds emerging from the soil under the cover should be avoided, however, because the environment provided by cover is also favorable for pests (Wells and Loy, 1993).

IV. High Tunnels

A high tunnel is a portable walk-in, greenhouse-like structure without a permanent electrically powered heating or ventilation system, covered with one layer of plastic, and sited on field soil (Wells and Loy, 1993). High tunnels function similarly to greenhouse elevating temperature and protecting the crop from low temperature, heavy rain, wind, and insects and resulting in enhanced plant growth (Lamont and Orzolek, 2003; Wells, 1991). High tunnels are extensively used throughout Europe, the Mid-East, and Asia with the alterative name of hoophouse or unheated greenhouse (Wells, 1991). In some countries such as Spain, Portugal, Chile, Italy and Greece, high tunnels accounted for more than 80% of cropping systems used for Solanaceae vegetable production (Monteiro and Portas, 1986).

Although utilization of high tunnels in North America is relatively limited, studies to investigate the feasibility of high tunnels have been conducted in some regions (Waterer, 2003). Researchers in New Hampshire and Pennsylvania developed production systems using high tunnels modified for local production and have shown vegetable and flower production to be successful (Lamont et al., 2003; Wells and Loy, 1993). In Canada, increased yield and earlier harvest of tomato and muskmelon were observed in comparison with conventional low tunnels (Waterer, 2003). In Florida, high tunnels enabled researchers to grow a class of high quality vegetable crops which were not suitable for the local climate condition as well as to achieve successful production of tomato, cucumber and muskmelon (Cantliffe et al., 2001). These advantages are mainly attributed to increased temperature and crop protection provided by high tunnels.

A. Temperature Increase

The primary environmental effect of high tunnels is increased air temperature. Incoming solar radiation heats air confined in high tunnels raising the air temperature. Without ventilation, the temperature may be extremely high even in the cool season. Air temperatures in high tunnels can reach about 38°C when ambient temperature is about 15.5°C (Jett, 2004). It is possible to generate temperatures as high as 54.5°C at a 1 inch depth in the beds in tunnels by keeping side walls closed in summer, and this makes soil solarization more efficient (Byczynski, 2003). In order to control temperatures, high tunnels are ventilated manually depending on factors such as season, weather condition, and the specific crop. This increased temperature not only accelerates plant development and fruit ripening but also enables growers to transplant seedlings earlier. Wells and Sciabarrasi (1992) observed a month earlier harvest of determinate tomatoes in high tunnels compared to those in field culture and attributed the earliness to a half month earlier planting and fruit maturity.

B. Crop Protection

High tunnels provide crop protection from disease, wind, and possibly insects as well as protection from frost damage by increased temperature (Wells, 1991). Because rain water that wets foliage and increases relative humidity is eliminated under the tunnels, occurrence and spread of disease is significantly decreased. Lamont et al. (2003) reported that the only disease found to be a problem in their high tunnel project was powdery mildew of cucurbits. Protection from the wind provides reduced evapotranspiration that enhances early maturity and improves growth, increases production, and results in a better-quality product (Cavins et al., 2000; Wittwer and Castilla, 1995).

2.3. Physiological Responses of Tomatoes to Environmental Factors

Tomatoes are often used in research of environmental modification because they are a warm season crop and they respond to changes in the microclimate. The physiological responses of tomato to environment have been studied previously.

I. Solar Radiation

Solar radiation is a major requirement for dry matter production and has great influence on growth of tomatoes both in the vegetative and reproductive stage. McAvoy and Janes (1990) studied the influence of light intensity and development stage of tomato seedlings on plant growth and found that flowering and final truss position at anthesis were influenced by the light environment in early and late stage, respectively. The irradiation plants receive in the young stages significantly affects their growth in subsequent stages. It was reported that days to first ripe fruit of tomatoes were negatively correlated with the amount of light the plant received during the seedling stage (McAvoy. et al., 1989). Net photosynthetic activity of tomatoes was highest in the canopy during early anthesis and then steadily declined while whole plant photosynthetic activity peaked during rapid fruit development (McAvoy and Janes, 1989).

II. Temperature

A. Air Temperature

Plant growth is more influenced by daily air temperature than root zone temperature because of its greater influence on distribution of photosynthetic assimilates (Shishido and Hori, 1979). Leaf number of tomatoes per plant linearly increased with increasing daily air temperature is a typical example (Papadopoulos and Hao, 2001). Some researchers separate the effect of night air temperature from that in daytime because it appears to have a more dominant effect (Went, 1944). According to Gosselin and Trudel (1983a), plant height and growth is determined by a combination of root temperature and night air temperature. Stem diameter, an index of vegetativeness of plants, progressively decreased with increased night air temperature (Papadopoulos and Hao, 2001).

The reproductive stage is the most temperature-sensitive stage of tomato plants and excessive temperatures may cause deleterious effects on flower and fruit development. In low air temperatures, both vegetative and reproductive growth of tomato are very limited, and an extended period of plant growth at 12°C or less can result in chilling injury (Rubatzky and Yamaguchi, 1997). Papadpoulos and Tiessen (1983) reported low air temperature (13/8°C) drastically reduced yield of spring tomato compared with a high air temperature (19/14°C). Ercan and Vural (1994) observed decreased number of pollen and viability at 5°C and 10°C depending on cultivar and concluded that pollen degeneration was the main factor of reduced fruit set and weight in low temperatures. Change in pollen quality and quantity also occurs under excessively high temperature conditions. Abdul-Baki and Stommel (1995) observed significantly poor fruit set of heat-sensitive tomatoes caused by higher air temperature (35/23°C, day/night) than the optimum range (27/23°C). Sato et al. (2004) reported that high air temperatures (32/28°C) increased the proportion of undeveloped and aborted flowers and parthenocarpic fruit.

Air temperature affects fruit quality as well. Fruit maturity is hastened by elevated fruit temperature (Adams et al., 2001) increasing pH values and decreasing titratable acidity (Koskitalo and Ormrod, 1972). On the other hand, supraoptimal temperature for maturing (25.9°C) may produce significantly softer and unevenly ripened fruit (Mulholland et al., 2003). Picton and Grierson (1988) explained that the negative effects of high temperature on fruit ripening were due to inhibition of expression of ripening-related genes. Papadopoulos and Hao (2001) found that increased daily average air temperature resulted in higher early tomato yield and concluded that night temperature should be elevated to increase early yield without producing smaller fruits and lowering late yields.

B. Soil Temperature

Growth and fruit development of tomatoes is also accelerated by raised root zone temperature. Root zone temperature correlated to growth parameters such as shoot, yield, fruit fresh weight, and fruit number fitting a quadratic curve with the estimated optimum temperature for total growth of tomato of 26°C (Diaz-Perez and Batal, 2002).

Enhancement of nutrient uptake of roots is thought to be a beneficial effect of raising root zone temperature. In warm soil, the root system of tomatoes was longer, thinner, and more highly branched (Gosselin and Trudel, 1983a). In addition, low to moderately high root temperature (12°C to 24C°) increased contents of major nutrients in leaves such as P, K, Mg, Ca, Fe, and Mn (Gosselin and Trudel, 1983b). Excessively high root zone temperature (36°C), however, decreased phosphorous uptake and resulted in decreased shoot growth (Klock et al., 1997).

III. Relative Humidity

High relative humidity also has been reported to be beneficial to tomato plants. According to Choi et al. (1997), vegetative growth of tomatoes was accelerated by high night humidity at 90-95%. Whipps and Budge (2000) observed progressively less occurrence of tomato powdery mildew with increasing relative humidity in the range of 80 to 95% under constant temperature (19°C).

There are, however, negative effects of high humidity on tomato production. Blossom End Rot (BER) is caused by a deficiency of Ca resulting from reduced transpiration due to high humidity (Banuelos et al., 1985). With higher levels of solar radiation, the reduced transpiration may raise the temperature of plant tissue to a lethal level because of lack of transpirational cooling (Lipton, 1970). Fruit cracking is also attributed to high humidity (Maroto et al., 1995). In contrast, extreme low humidity in the nighttime may accelerate respiration and delay plant growth.

IV. Carbon Dioxide Concentration

Carbon dioxide is required for photosynthesis, and the concentration in ambient atmosphere influences plant growth and development. In high CO_2 levels, tomatoes had a lower transpiration rate and higher photosynthetic rate than plants in a normal atmosphere (Behboudian and Lai, 1994). Accelerated assimilate production in leaves hastened total vegetative growth (Reinert et al., 1997). Studies investigating assimilate production with light have also been reported. Fierro, et al. (1994) showed that tomato and pepper plants increased accumulation in shoot and root dry matter and also early yield when high concentrations of CO_2 is applied in combination with enhanced supplementary lighting.

V. Wind

The role of wind is important, since the development of microclimates depends on reducing fast transfer processes, such as turbulent mixing, that would decrease steep temperature and moisture gradients (Wilken, 1972). Increased soil and air temperatures by windbreaks can extend the growing season in sheltered areas, resulting in increased crop development, earlier crop maturity, and market advantage (Hodges and Brandle, 1996).

2.4. Physiological Responses of Other Solanaceae Vegatables to Environmental Factors

Tomatoes are the leading crop for high tunnel production, although a variety of crops including small fruit and cut flowers can also be grown successfully in high tunnels (Lamont et al., 2003; Wells, 1991). In particular, vegetables in the Solanaceae family are suitable for high tunnel production because of their biological similarity to tomatoes.

I. Eggplant (*Solanum melongena L.*)

The thermal requirement of eggplant is similar to that of tomatoes, however, it is more sensitive to cold conditions. Romano and Leonardi (1994) reported that both vegetative and reproductive growth of eggplant were significantly reduced or delayed as air temperature decreased from 13°C to 9°C. This appears to be supported by the finding of Tesi and Tognoni (1986) that air temperature lower than 10°C stopped vegetative growth of eggplant. Sensitivity to low temperature is more evident in the reproductive stage for eggplant, and pollen germination progressively decreased to very low percentage 16% even at 15°C (Tesi and Tognoni, 1986). Wilcox and Pfeiffer (1990) concluded that critical root temperatures for active root and shoot growth of eggplant was 14.5°C and between 16.7 and 18.9°C, respectively.

Eggplant is more tolerant to drought than tomatoes (Rubatzky and Yamaguchi, 1997). Recent research suggested that proline synthesis in eggplant leaves acted as part of survival mechanism from water stress (Sarker et al., 2005). Adequate water supply, however, is required for maximum yield. Tedeschi and Zerbi (1985) reported increased total and marketable yield correlated with increased irrigation water levels. Chiaranda and Zerbi (1986) also observed a linear relationship between fruit yield and evapotranspiration ranging from 400 to 800 mm. Excessive soil moisture, however, is to be avoided because eggplant is sensitive to waterlogging (Rubatzky and Yamaguchi, 1997).

According to Bakker (1990), the rate of plant development of eggplant was unaffected by humidity while the best balance of yield and fruit quality was achieved with vapor pressure deficit between 0.5 and 0.7kPa.

II. Peppers (*Capsicum annuum L.*)

Peppers are more tolerant to high temperatures than tomatoes (Rubatzky and Yamaguchi, 1997). Generally, plant growth of peppers is improved when night temperatures do not exceed 20°C (Rubatzky and Yamaguchi, 1997). Abou-Hadid et al. (1994) showed that pepper yield increased almost in proportion to increased nighttime air minimum temperature with a maximum of 15.2°C. The number of leaves, total and marketable yield, fruit weight and fruit size were increased by higher temperature resulting from black polyethylene mulch (Siwek et al., 1994).

Pepper flowers are not fertilized at temperatures below 16°C or above 32°C (Rubatzky and Yamaguchi, 1997). Karni and Aloni (2002) found high temperature reduced the activity of enzymes in pollen, which resulted in decreased germination rate, and anther. On the other hand, Shaked et al. (2004) observed less number of pollen grains with reduced germinability in plants grown at low night temperature of 10±2°C compared to those grown at a normal temperature of 20±2°C. They suggested that this defect was attributed to decreased concentration of soluble sugars in the mature pollen grains due to low temperature. Low temperature produced parthenocarpic and malformed fruits and affected fruit shape, pericarp cracking and pigmentation. In addition, the severity of cracking increased under conditions of low night temperature and large diurnal temperature changes (Rylski et al., 1994).

Although peppers are generally drought resistant, even intermittent periods of moisture and/or nutritional stress can dramatically reduce plant growth and limit fruit size and yield (Rubatzky and Yamaguchi, 1997). Kirnak et al. (2003) observed significant reduction in bell pepper plant growth, water use efficiency, fruit yield and quality, leaf relative water content, and macro-nutrition in plants applied water stress. They also observed improvement in fruit yield, fruit size, plant dry matter, relative water content, and chlorophyll concentrations in leaves of stressed plants by the use of black plastic mulch.

III. Potatoes (*Solanum tuberosum L.*)

One of the important environmental factors for potato is temperature (Rubatzky and Yamaguchi, 1997). Stem elongation of potato proceeds almost linearly as temperature increases below 30°C while no tuber initiation occurred with minimum temperature below 25°C (Manrique, 1990). Bennett et al. (1991) found that diurnal temperature fluctuation (22°C /14°C, light/dark) resulted in higher plant height, plant and tuber dry weight and harvest index of potato compared to a constant temperature regime (18°C) depending on cultivar. They attributed this to photosynthetic responses to different temperature regimes. Potato is a drought sensitive, and water shortage during the tuber bulking period decreases yield to a larger extent than drought during other growth stages (Van Loon, 1981).

2.5. Economics

High tunnels provide a practical means of entry into intensive crop production for new growers or others with limited capital assets because of the low capital investment and high returns (Wells and Loy, 1993). It can also be an incentive for those growers that high tunnels are not qualified as taxable structures (Wells and Loy, 1993).

High tunnels are relatively inexpensive and the construction cost of a 14 × 96 feet high tunnel was approximately $1600 including the clear plastic cover, black plastic mulch, and trickle irrigation system (Wells, 1991). The cost of Penn State system is between $1800 and $4500 depending on the size, however, it's still much lower compared to that of a greenhouse in the same size, which may reach $20,000 to $25,000 (Gordon, 2002). Labor costs may increase compared to field production, however, because of frequent operation of sidewalls for ventilation and temperature control. A high tunnel study conducted in Pennsylvania indicated that the second highest variable cost in tomato production was for ventilation and monitoring labor (Orzolek et al., 2004). However, this may not be crucial because it's less than labor cost for harvest. The average cost for spunbonded row covers alone is $800/acre, and the installation cost varies depending on application method (Wells and Loy, 1993). According to Orzolek et al. (2004), the production cost using high tunnels for tomatoes was $0.16 per kg of fruit.

Earlier yields from high tunnels compared to those from field production provide an extra marketing opportunity at premium prices for small to medium-scale producers (Wells and Sciabarrasi, 1992). Orzolek et al. (2004) estimated that retail and/or wholesale prices received for tomatoes produced in high tunnels should be 25 to 50% greater than field produced tomatoes. Wells and Loy (1993) reported the net return of tomatoes grown in high tunnels was $0.71/lb based on the production of 2000lb in a 14 × 96 feet high tunnel and at a retail selling price of $1.60/lb. According to Orzolek et al. (2004), the breakeven price of tomatoes was $0.36/lb. These high rates of return enable growers to retrieve their initial investment in a relatively short term. Waterer (2003) concluded that it would take 2 to 5 years for the enhanced gross returns obtained with the high tunnels to cover their capital costs based on wholesale commodity prices.

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CHAPTER 3

THE EFFECT OF HIGH TUNNELS AND ROW COVERS ON TOMATO PLANT GROWTH AND PRODUCTION IN LOUISIANA

3.1. Introduction

Protected cultivation with greenhouse structures has been adopted by farmers as a practical method for vegetable production. These structures modify the environment which often accelerates plant growth, improves fruit quality, and extends the growing season. Growers are often able to increase the commercial value of their product and expand their profit through the use of greenhouse structures. Another aspect is that environmental modification may require considerable investment as well as greater risk depending on the particular system. Greenhouse structures require a large initial investment and automated equipment to maintain an ideal production environment.

In Northern states, high tunnels, which are similar to greenhouse structures, have been used to provide environmental modification at lower cost. Previous research with tomato (*Lycopersicon esculentum L.*) production in high tunnels in New Hampshire resulted in an earlier yield compared to standard field culture (Wells and Sciabarrasi, 1992). However, very little research has been conducted in the Gulf South to evaluate high tunnels for vegetable production. Tomato is the second leading vegetable crop in Louisiana (Boudreaux and Hinson, 2004), and evaluating the effect of high tunnels on tomato production and its economic feasibility may provide local growers an alternative production method. Row covers were also evaluated in combination with high tunnels as the use of row covers is a standard industry practice for microclimate modification and insect management.

The objective of this research was to determine the effect of high tunnels and row covers on tomato plant growth, yield and economics for spring seasons in Louisiana.

3.2. Material and Methods

Field experiments were conducted in the spring production seasons of 2004 and 2005 at the LSU AgCenter Burden Center, Baton Rouge, Louisiana. Tomato 'Sunstart' (Rupp Seeds Inc., Wauseon, Ohio) seeds were sown into 128 cell styrofoam trays on January 9, 2004 and January 5, 2005, and grown in a greenhouse and fertilized (20-10-20) as needed. After hardening off, tomato transplants were transplanted into single rows on raised beds at a 45cm in-row spacing on March 13, 2004 and March 4, 2005. Three high tunnels (Ledgewoods Farms, Moultonboro, New Hampshire), based on the Penn State high tunnel design (5.2m wide × 11m long × 2.7m high in the center), were used with a single layer 6ml transparent polyethylene cover. High tunnel treatments were the main plots with row covers as the subplot randomly assigned in the high tunnel or on black plastic mulch. Treatments (Table 3.1.) were assigned to subplots and a subplot consisted of four raised beds 15cm high × 60cm wide on 2.4m centers. After applying preplant fertilizer (72kg/ha, 8-24-24, N-P_2O_5-K_2O), black plastic mulch and trickle irrigation tape were installed 10cm off center at a 7cm depth using a plastic mulch layer machine. Plots were irrigated daily based on the Vegetable Production Guide for Florida (Maynard and Hochmuth, 2001) as modified by the Louisiana Cooperative Extension Service. During the growing season, 1.8kg/ha of N was applied with $CaNO_3$ through the fertigation system every week until harvest. Side shoots lower than the first flower were pruned once. Commercial pest management practices were followed. In general, sidewalls were opened in the morning and closed in the evening to ensure inside temperatures were kept within the optimum range for tomato (daytime: 25~30°C, nighttime: 15~20°C). Spunbonded polyester row covers (AG-06, Ken-Bar Inc., Reading, Massachusetts) were installed at transplanting. Two pieces of 1.2m wide row cover were attached at the soil line on both sides of the raised bed with landscape fabric staples. They were joined above the plants to form a tent-like structure by attaching with clothes pins to horizontal wires attached stakes. Row covers were removed at 7 weeks when the air temperatures in the row covers became excessive and/or abrasion of the plants caused damage. Soil and air temperatures for each subplot were measured 10 cm below and 15 cm above the plastic mulch surface respectively, and minimum, maximum and mean were determined. Temperatures were measured using copper constantan thermocouples and recorded with a data logger (Campbell Scientific, Logan,

Table 3.1. Treatments evaluated in the study. Black plastic mulch and trickle irrigation was applied to all treatments.

Treatment	High tunnel	Row cover
HT	High tunnel	none
RC	none	Row cover
HT+RC	High tunnel	Row cover
Control	none	none

Utah). Thermocouples were located between plants on one of the subplot rows on the opposite side of the trickle irrigation tape position. All air and soil temperatures were pooled for the period from transplanting to removal of row covers. Diurnal air and soil temperatures pooled over the period in each year were calculated with mean air and soil temperatures. In addition, diurnal maximum and minimum temperatures on a hot and cold day in each year were investigated. The yield results from 2004 suggested that insufficient pollination caused by restricted airflow in the high tunnels with row covers treatment resulted in reduced yields. To ensure adequate pollination in 2005, a leaf blower was used for minutes three times a week in the row covers treatment in high tunnels.

Plots were harvested beginning May 12, 2004 and May 9, 2005. Tomatoes at the pink stage were harvested three times a week for six weeks from sixteen plants per subplot both years. After removing fruits damaged by bird, insect, and disease, tomatoes were graded according to USDA standards for small, medium, large, and extra large fruit categories (USDA, 1997). Marketable yield was considered fruit graded into medium, large and extra large, and the harvest in the first two weeks was regarded as early yield. At the first and last harvest, two plants were harvested from each subplot and leaf area and stem and leaf fresh weight were quantified. Plant samples were dried in a forced air oven at 60°C and dry weights were measured. Cumulative yield from each of these plants was separately recorded for determining harvest index. Growing degree day (GDD) for the period from transplanting to removal of row cover was calculated from maximum and minimum air temperatures with the thresholds of 10°C. In addition, the three coldest days were identified from the same period each year, and the average minimum air and soil temperatures were determined. Plant height was measured for eight plants out of sixteen harvested plants once a week in the period, and the growth rate expressed as slope of simple linear regression for days and height was determined for each plant. All data were subjected to analysis of variance using SAS/STAT v. 9 (SAS institute, 2002) followed by mean separation by Tukey's HSD at the 0.05 significance level. All data were pooled over years as interactions were not significant.

Due to difference in yield and market price of tomatoes between 2004 and 2005, the economic analysis for the different treatments was conducted separately by year following a partial budgeting procedure (CIMMYT, 1988). Budgets were tailored for a main plot. The total varying costs, which were the sum of all the costs that vary for a particular treatment, were first estimated (Table 3.2., 3.3.). The estimation was developed by the Mississippi State Budget Generator, a d-Base program developed by Mississippi State University, using projected costs for Louisiana vegetable crops (Hinson and Boudreaux, 2005). Average yields were then calculated for each treatment pooled over repetitions of the experiment and the statistical difference between treatments was investigated. After detecting differences, the gross benefits for each treatment were calculated. Representative prices for early and late fresh market tomatoes were used for calculation of the gross benefits (early yield: \$3.00/lb, late yield: \$2.00/lb). Net benefit was calculated by subtracting the total varying costs from the gross benefits for each treatment. The tomato price required to cover production costs (breakeven price) was also calculated.

Table 3.2. Estimated production costs for common items per a main plot[z] for tomatoes using high tunnels and row covers (Louisiana State University AgCenter).[y]

Item	Unit	Price($)	Quantity	Amount($)
Direct Expenses				
Fertilizer				
8-24-24	lb	0.10	8.40	0.84
20-10-20	lb	0.96	5.00	4.80
$CaNO_3$	lb	0.35	225.00	78.75
(A)				
Insecticides				
(B)				
Fungicides				
(C)				
Transplants				
'SunStart' plants	each	0.40	80.00	32.00
Irrigation system				
Drip t-tape	roll	111.00	0.03	3.33
Lay flat hose	roll	90.00	0.01	0.90
Other				
(D)				
Twine	roll	25.00	0.028	0.70
Back plastic	roll	76.80	0.040	3.07
Labor				
(E)				
(F)				
Field operation labor[x]	hour	7.50	7.90	59.25
Harvest labor	hour	7.50	36.00	270.00
Other labor[w]	hour	7.50	1.14	8.55
Interest on operating capital				
(G)				
Repair and Maintenance	each	27.75	1.00	27.75
(H)				
Costs for tunnels and covers				
(I)				

[z]Main plot = 612ft^2 (17'×36'), 4 row plots on 4 foot centers
[y]Modified from tomato budgets. Hinson, R. and J. Boudreaux, 2005.
[x]Includes labor for spray, rebar installation, pruning and tying
[w]Includes labor for mulch and irrigation installation and transplant growing

Table 3.3. Direct expenses and costs that vary depending on treatment for spring planted tomato

Item	Treatment[z]	Unit	Price($)	Quantity	Amount
Direct Expenses					
Fertilizer					
Epsom salt (A)	ALL, 2005	lb	0.90	0.4200	0.38
Insecticides (B)					
Agrimek	ALL, 2004	pt	100.00	0.0070	0.70
Ambush	ALL, 2004	pt	14.00	0.0030	0.04
Asana	ALL, 2005	gal	76.25	0.0010	0.08
Fungicides (C)					
Benlate	ALL, 2004	lb	16.00	0.0070	0.11
Bravo	ALL, 2005	pt	6.35	0.0250	0.16
Quadris	ALL, 2005	pt	33.60	0.0050	0.17
Other (D)					
Clothespin	HT+RC, RC	bag	3.00	3.00	9.00
Landscape staple	HT+RC, RC	box	8.30	0.064	0.53
Labor					
Blowing (E)	HT+RC, 2005	hour	7.50	1.3000	9.75
Operation labor (F)					
High tunnels	HT+RC,HT	hour	7.50	28.8000	216.0
Row covers	HT+RC,RC	hour	7.50	1.0000	7.50
Interest on operating (G)	ALL	each			
Repair and maintenance (H)	HT+RC, HT	each	27.75	1.00	27.75
Costs (I)					
High tunnels	HT+RC, HT	each	667.76	1.00	667.7
Row covers	HT+RC, RC	acre	302.06	0.014	4.23

[z]ALL=all treatments, HT=high tunnels, RC=row covers, number=year

3.3. Results and Discussion

I. Temperature

A. Air Temperature

High tunnels and row covers significantly affected air temperature (Table 3.4.). Highest minimum, mean and maximum air temperatures were observed in the combination treatment (HT+RC) while minimum and mean temperatures in high tunnel treatments (HT+RC, HT) were higher than those in no tunnel treatments (RC, control). All temperatures in high tunnel treatments were higher than those in the control. There was an interaction between high tunnels and row covers observed for minimum air temperature.

B. Soil Temperature

High tunnels affected minimum, mean and maximum soil temperatures while row covers affected minimum and mean temperatures only. The HT+RC treatment had the highest minimum, mean and maximum soil temperatures and all temperatures in the high tunnel treatments were higher than those in the no tunnel treatment. An interaction between high tunnels and row covers was observed for minimum soil temperature.

C. Lowest Temperatures

During a cold event, the lowest air and soil temperatures experienced in the high tunnel treatments were higher than those in the no tunnel treatments. The HT+RC treatment had the highest air and soil temperatures indicating a distinct warming advantage with the combination of row cover and high tunnel. The combination HT+RC treatment increased the minimum temperature compared to the control by 4.8°C and 5.2°C for the air and soil,

Table 3.4. Minimum, mean, and maximum air and soil temperatures, temperatures on coolest days and growing degree days from transplanting to removal of row covers as influenced by row cover (RC) or high tunnel (HT) treatment[z]

Treatments	Air			Soil			Lowest temperature[y]		Growing degree days[x]
	Min	Mean	Max	Min	Mean	Max	Air	Soil	
	°C								
HT	12.6 b	20.7 b	34.3 b	19.6 b	23.2 b	27.3 a	5.8 b	15.8 b	621 b
RC	11.2 c	19.8 c	33.8 b	17.8 c	21.6 c	25.8 b	3.4 c	12.9 c	576 b
HT + RC	14.1 a	22.7 a	38.6 a	20.4 a	23.8 a	27.6 a	7.5 a	16.5 a	761 a
Control	10.6 c	18.4 d	28.7 c	16.6 d	20.7 d	25.5 b	2.7 c	11.3 c	441 c
Significance[w]									
HT	***	***	***	***	***	**	***	***	***
RC	***	***	***	***	***	NS	***	***	***
HT×RC	**	NS	NS	*	NS	NS	**	*	NS

[z]Data pooled over years (2004, 2005), mean separation by Tukey's HSD test ($P \leq 0.05$)
[y]Minimum temperature on 3 coolest days in each year (April 1, 14, and 15 and March 4, 10, and 18 in 2004 and 2005, respectively)
[x]Growing degree days from transplanting to removal of row covers with threshold at 10°C (7 weeks)
[w]NS, *, ** and *** means nonsignificant, significant at $P \leq 0.05$, 0.01 and 0.001, respectively

respectively. Interactions between high tunnels and row covers were significant for air and soil temperatures.

D. Growing Degree Days

High tunnels and row covers increased growing degree days compared to the control with no interaction (Table 3.4.). The temperatures with the HT+RC treatment for the period from transplanting to removal of row covers were about 73% higher than the control. GDD in the HT treatment was 41% higher than that in the control. Waterer (2003), however, reported a 91% higher GDD in the high tunnel treatment compared to that in the control. The smaller difference in GDD in our study may be due to the lower temperature setting point for ventilation (about 5°C lower) and the warmer climate in Louisiana compared to Canada.

Diurnal temperatures from transplanting to removal of row covers indicate that the difference in daytime air temperature between HT and RC treatments is relatively small compared to that between each of these treatments and other treatments (Figure 3.1. A,B). Soil temperatures in high tunnel treatments were higher than those in no tunnel treatments throughout the day (Figure 3.1. C,D). Soil temperature started increasing about 2 hours later than air temperature, and the temperature peak was delayed about 4 hours compared to air temperature. Under conditions such as intense solar radiation and no wind, maximum air temperature in the HT+RC treatment around noon exceeded 40°C even though the sides of high tunnels were opened for ventilation (Figure 3.2. A,B). The difference in air temperature of 4 to 5°C between the HT+RC and HT treatment suggests a larger contribution of row covers in high tunnels in increasing air temperature on a hot day. During a cold event, the temperature difference between the HT+RC and HT treatments was less, suggesting that high tunnels were more dominant in maintaining high temperature on a cold day (Figure 3.3. A,B). Similar differences were observed in soil temperatures as well, and the minimum soil temperature in HT+RC treatment was about 5°C higher than that in control treatment all day both years (Figure 3.3. C,D).

The results of minimum, mean, and maximum air and soil temperatures and lowest temperatures indicate that both high tunnels and row covers significantly increased air and soil temperatures under the moderate climate in Louisiana. Temperatures increased most when high tunnels and row covers were used in combination. The significant interactions observed in minimum and lowest air and soil temperatures suggest that the combination treatment was particularly effective in increasing temperatures during low temperature periods. Researchers in New Hampshire have reported harvest of determinate tomatoes to be one month earlier compared to those in field culture (Wells and Sciabarrasi, 1992). Increased earliness was due to earlier planting by 2 weeks and enhanced fruit maturity. Because the climate in the spring is milder in Louisiana than in New Hampshire, growers may be able to transplant much earlier in high tunnels and be successful. Investigation of diurnal temperatures indicated that high tunnel treatments maintained higher air and soil temperature than the no tunnel treatments throughout most of the day. In addition, it was found that row covers in high tunnels increased air temperature particularly in a hot day and the air temperature in HT+RC treatment reached more than 40°C.

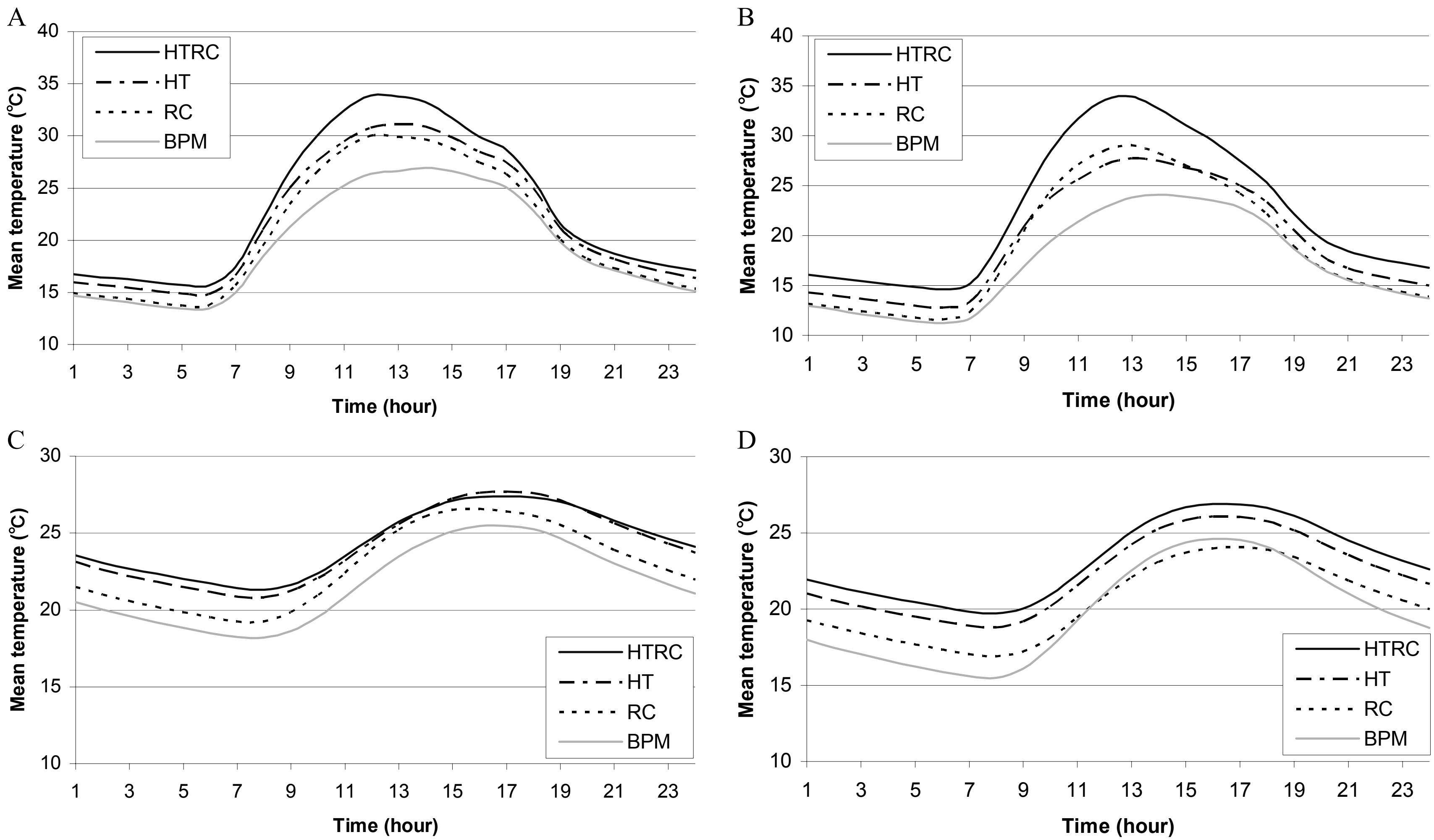

Figure 3.1. Diurnal temperatures from transplanting to removal of row covers pooled over time for high tunnels (HT), row covers (RC), combined high tunnels and row covers (HTRC) and the black mulch control (BPM) treatment for spring production in Louisiana (A: air temperature in 2004, B: air temperature in 2005, C: soil temperature in 2004, D: soil temperature in 2005).

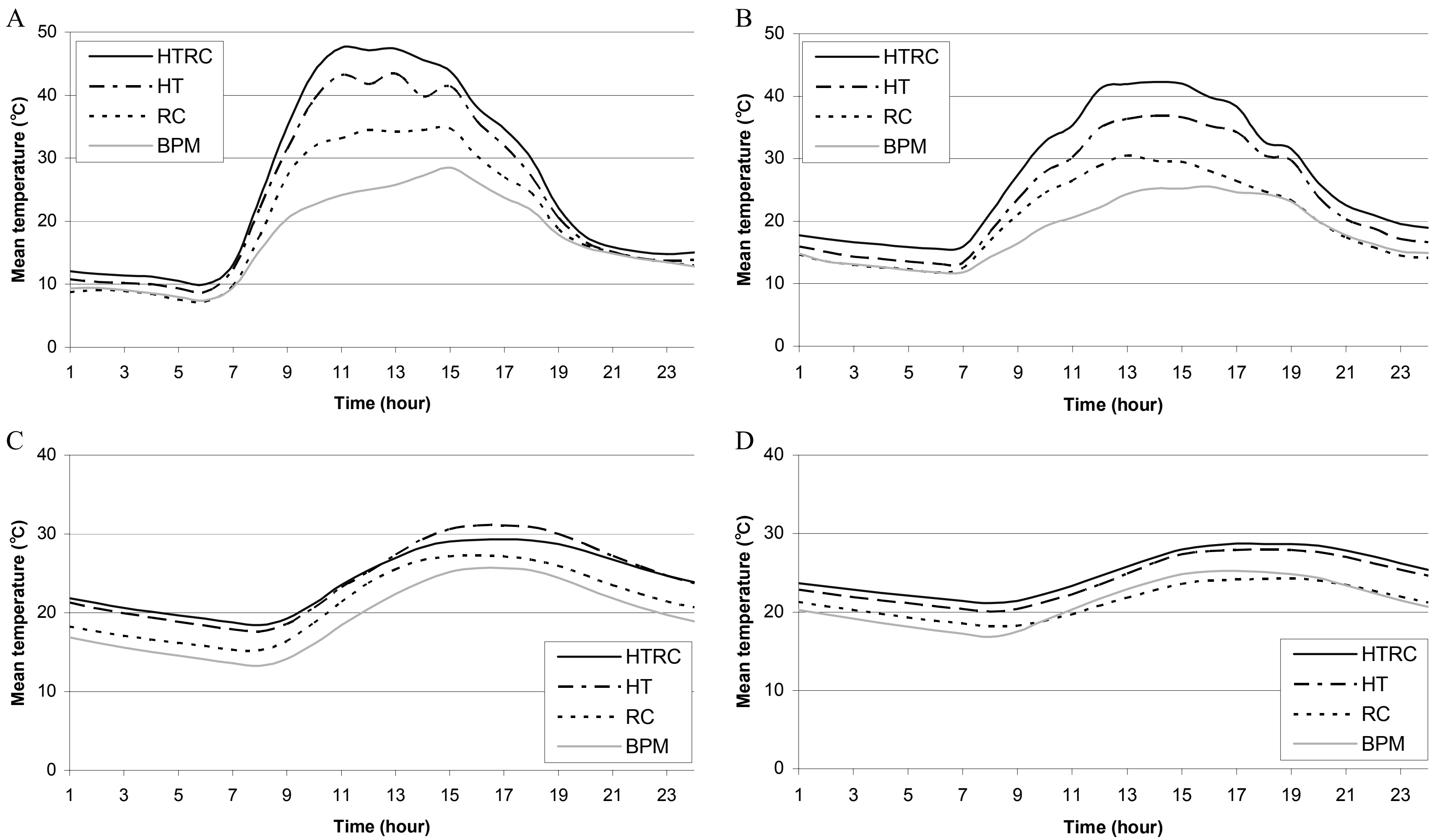

Figure 3.2. Diurnal maximum temperatures for high tunnels (HT), row covers (RC), combined high tunnels and row covers (HTRC) and the black mulch control (BPM) treatment on March 23 and April 14 in 2004 and 2005, respectively (A: air temperature on March 23, B: air temperature on April 14, C: soil temperature on March 23, D: soil temperature on April 14).

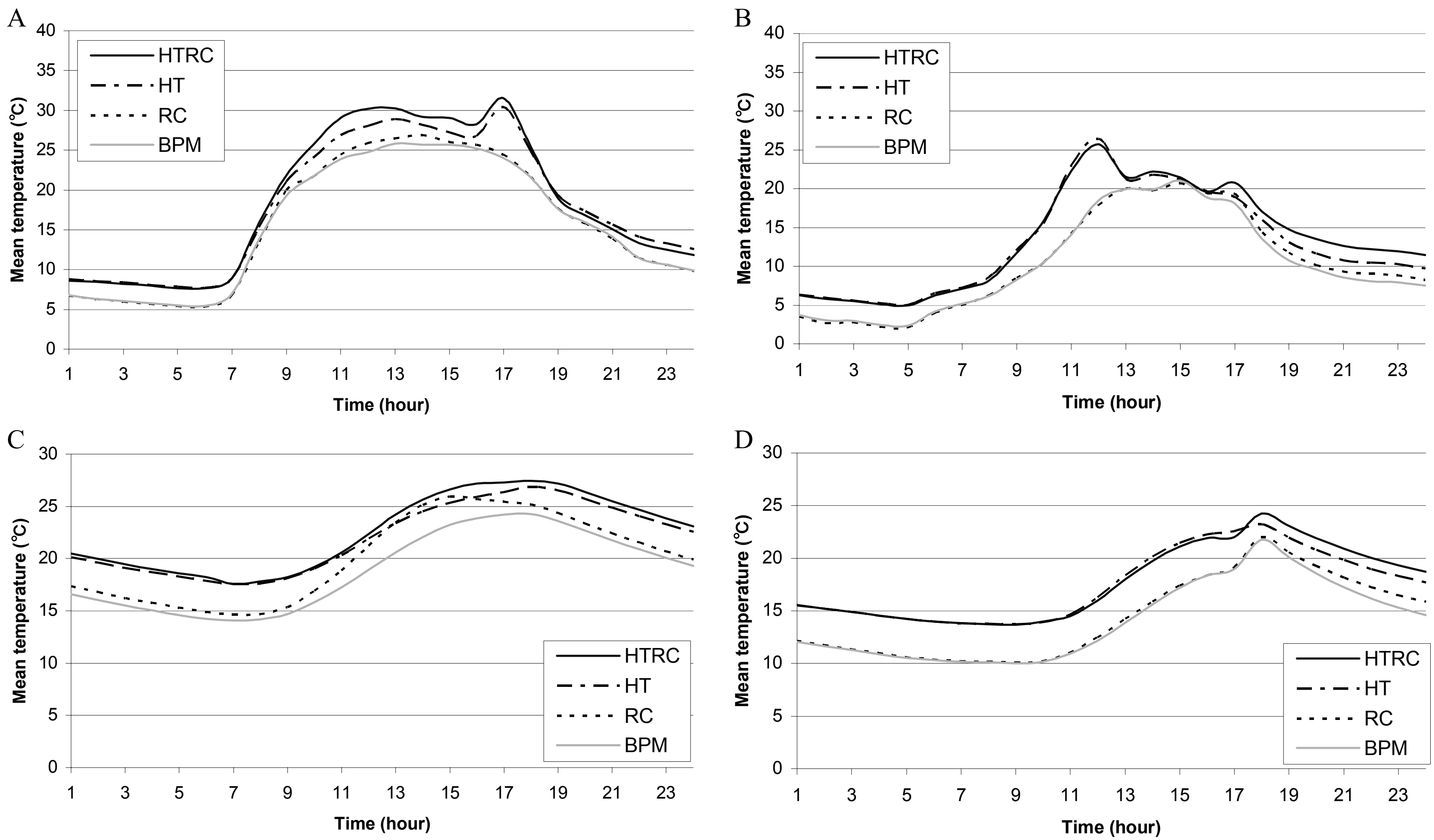

Figure 3.3. Diurnal minimum temperatures for high tunnels (HT), row covers (RC), combined high tunnels and row covers (HTRC) and the black mulch control (BPM) treatment on April 15 and March 4 in 2004 and 2005, respectively (A: air temperature on April 15, B: air temperature on March 4, C: soil temperature on April 15, D: soil temperature on March 4).

II. Plant Growth Parameter

A. Plant Height

There was a significant difference in growth rate of plants between the high tunnel and no tunnel treatments (Table 3.5.). The plant growth rate in high tunnel treatments was 33% higher compared to that in the no tunnel treatments. The difference in plant growth between high tunnel and no tunnel treatments was more obvious in the second year than the first year (Figure 3.4.). According to Gosselin and Trudel (1983a), plant height and growth is determined primarily by a combination of root temperature and night air temperature. Our results are similar, in that higher temperatures experienced in high tunnels apparently resulted in higher plant growth rates. The growth rate in the HT+RC treatment was not

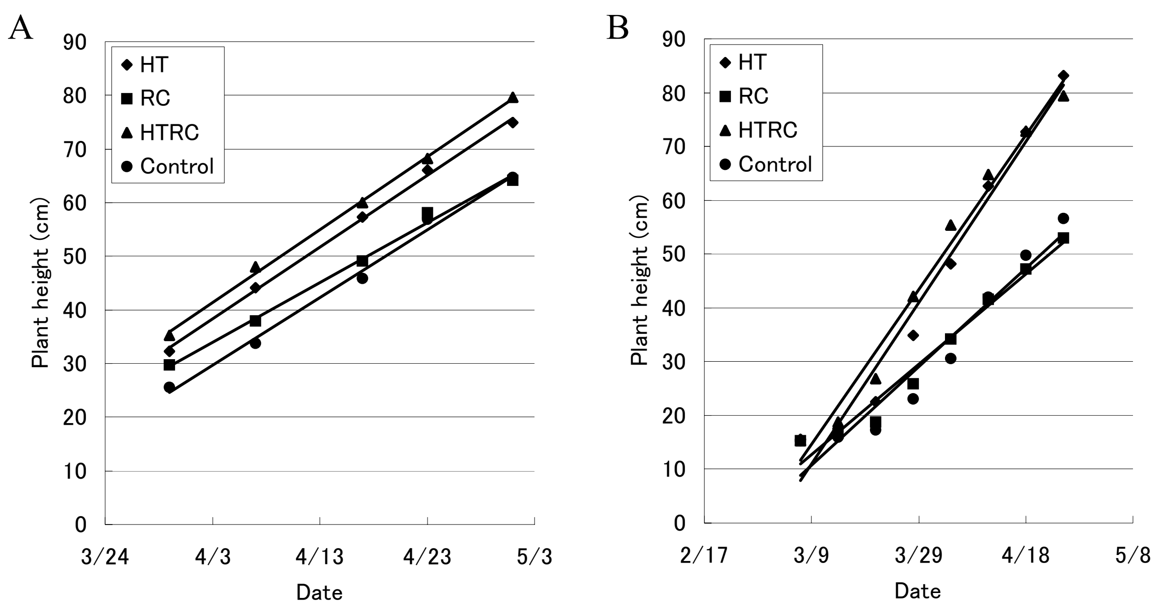

Figure 3.4. Tomato plant growth from transplanting to removal of row covers averaged by treatments in each year (A:2004, B:2005). High tunnels (HT), row covers (RC), combined high tunnels and row covers (HTRC) and the black mulch control treatment. Plant growth rate was expressed by slope of simple linear regression for plant height in each treatment.

Table 3.5. Plant growth parameters as affected by row cover (RC) and high tunnel (HT) treatment for spring planted tomato[z]

Treatments	Growth rate[y]	Leaf area		LAR[x]		Fresh weight[w]		Dry weight[w]		Harvest Index[v]	
		First	Last	First	Last	First	Last	First	Last	First	Last
	cm·d^{-1}	cm^2		cm^2·g^{-1}		g		g		g·g^{-1}	
HT	1.4 a	5120	7595 a	61.6 ab	47.3 a	815 a	1191 ab	83	157 ab	0.7 a	0.8 ab
RC	1.0 b	3706	3810 b	68.9 ab	36.5 b	504 b	685 c	54	102 b	0.7 a	0.8 a
HT + RC	1.4 a	4207	7753 a	56.0 b	43.0 ab	713 ab	1353 a	78	173 a	0.5 b	0.7 b
Control	1.1 b	5168	4522 b	72.4 a	39.4 ab	691 ab	781 bc	72	112 ab	0.6 ab	0.8 a
Significance[u]											
HT	**	NS	**	*	*	NS	**	NS	*	NS	**
RC	NS	**	NS	NS	NS	*	NS	NS	NS	NS	NS
HT×RC	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*

[z]Data pooled over years (2004, 2005) and taken at the first and last harvest, mean separation by Tukey's HSD test ($P \leq 0.05$)
[y]Average of slopes of simple linear regression for days and height of individual plant from transplanting to removal of row covers (7 weeks)
[x]Lear Area Ratio = leaf area / plant dry weight
[w]Weight = stem weight + leaf weight
[v]Harvest Index = fruit weight / (fruit weight + plant weight) on a fresh weight basis
[u]NS, * and ** means nonsignificant, significant at $P \leq 0.05$ and 0.01, respectively

significantly higher than the HT treatment, however, even with the high temperatures. This may have been due to restricted growth due to space limitation under row covers and abrasion resulting from the covers. Another aspect is that the maximum temperatures in the combination HT+RC treatment may have been excessive (averaging 38.6°C) and resulted in hindered growth.

B. Leaf Area

Plants in high tunnel treatments had greater leaf area than no tunnel treatments at the last harvest while there was no difference between treatments at the first harvest. Plants grown in high tunnels had 84% higher leaf area compared to those grown in no tunnel treatments at the last harvest. This suggests that development and expansion of new leaves on plants in high tunnels continued even after flower and fruit development was initiated. Distribution of photosynthetic assimilates is strongly influenced by daily air temperature, and vigorous vegetative growth might result from high temperatures in high tunnel treatments (Shishido and Hori, 1979).

C. Leaf Area Ratio

The leaf area ratio (LAR) showed inconsistent trends at the two harvests. The highest LAR was observed in the control and the lowest was in the HT+RC treatment at the first harvest while highest and lowest LAR at the last harvest were observed in the HT and RC treatment, respectively. High tunnels had a lower LAR at the first harvest and higher LAR at the last harvest. The specific leaf area (leaf area / leaf weight) was not significant for either harvest (data not shown).

D. Fresh and Dry Weight

At the last harvest, plant fresh weight in high tunnel treatments was 74% greater than that in the no tunnel treatments. Increased plant growth and leaf area, a result of warmer temperatures in the high tunnels, could be responsible for higher plant weight at harvest. High tunnel treatments showed 54% greater dry weight than no tunnel treatments at the last harvest. Adams et al. (2001) reported that tomato plants grown at 26°C distributed dry matter to stems and leaves at a higher level compared to those grown at lower temperatures. It was assumed that increased temperature in high tunnels altered dry matter distribution and constructed larger more leafy plants by the last harvest.

E. Harvest Index

There was significant difference in harvest index between the HT and RC treatments and the HT+RC treatment at the first harvest. The HT+RC treatment also had the lowest harvest index at the last harvest. The lower harvest index for the HT+RC treatment resulted from the lower yield (Table 3.6.) and higher shoot and leaf weight. Significant interaction both at the first and last harvest indicated the HT+RC treatment resulted in a decreased harvest index.

III. Yield

The HT treatment resulted in significantly higher early marketable yield compared to the control (Table 3.6.). For total marketable yield, the lowest yield was observed in the HT+RC treatment while the highest was in the HT treatment. The yield results of this study, 6.9 pounds per plant pooled over years, were slightly lower than results reported for a

Table 3.6. Early and total marketable yield, culls, and marketable fruit number by grade as affected by row cover (RC) or high tunnel (HT) treatment for spring planted tomato[z]

	Marketable yield[y]		Culls[x]		Number of fruits in each grade for marketable yield		
Treatments	Early	Total	Small	Damaged	M	L	EL
	lb·plant^{-1}				%		
HT	1.7 a	6.9 a	0.2 b	0.7 b	27.0 b	46.3	27.0 a
RC	1.1 ab	5.3 ab	0.1 b	0.8 b	23.2 b	45.8	31.0 a
HT + RC	1.2 ab	4.8 b	0.5 a	0.8 ab	41.8 a	43.3	14.5 b
Control	0.7 b	6.2 ab	0.1 b	1.2 a	17.0 b	48.2	34.8 a
Significance[w]							
HT	NS	NS	***	NS	**	NS	*
RC	NS	**	**	NS	**	NS	**
HT×RC	**	NS	*	*	NS	NS	NS

[z]Data pooled over years (2004, 2005), 80 plants in a high tunnel, means separation by Tukey's HSD test ($P \leq 0.05$)
[y]Early and total yield equal the first two and six weeks cumulative yield, respectively
[x]Cull fruits consist of small or damaged by bird, insect, and disease
[w]NS, *, ** and *** means nonsignificant, significant at $P \leq 0.05$, 0.01 and 0.001 respectively

tomato cultivar trial in high tunnels in Pennsylvania (8.5 to 10.7 pounds per plant) and a trial in Canada (8.0 to 16.7). This is the normal yield for field production of this particular cultivar in Louisiana (James Boudreaux, personal communication). The results suggest that cultivar selection for high tunnel production for a particular climate may be an important factor. Annual variation in weather and the resulting environmental factors inside high tunnels such as relative humidity, light intensity, and diurnal temperature variation may also be important to consider. The lower marketable yield in HT+RC treatment was probably due to flower abortion caused by the extreme high air temperatures observed with this treatment. In the daytime, air temperature in the HT+RC treatment sometimes became excessively high even when tunnels were ventilated and the average maximum temperature reached 38.6°C (Table 3.4.). Researchers have reported that decreased pollen viability and subsequent flower abortion occurs at temperatures lower than the temperatures in our study. Pressman et al. (2002) observed decreased number and viability of pollen grains of tomato exposed to high temperature (32/26°C, day/night) and attributed it to the decrease in starch concentration in the grains due to the high temperature. In a study conducted by Sato et al. (2004), most tomato cultivars had very few or no seeded fruit set at high temperature regime (32/28°C). This suggests different sensitivity to high temperature depends on the cultivar.

The higher number of small-size fruits with the HT+RC treatment could have resulted in reduced marketable yield. Adams et al. (2001) observed continuous production of smaller fruits throughout the experiment from tomato plants grown at 26°C and attributed it to more distribution of dry matter to stems and leaves and less to fruits compared to plants grown at lower temperatures. Our results of higher leaf area and plant fresh weight with the HT+RC treatment (Table 3.5.) are in agreement with their results, especially at the last harvest. Papadopoulos and Hao (2001) attributed smaller fruits to the effect of high air temperature on shortening of growing period more than increasing fruit growth rate. Gent (1990) observed smaller tomato fruits in high tunnels than those produced outside and attributed it to the greater diurnal temperature variation in high tunnels. Fluctuation of diurnal temperature in HT+RC treatment was 35% greater than that in control in our study, and this large fluctuation may have contributed to production of small fruit.

In relation to marketable yield, the HT+RC treatment produced more medium size fruits and less extra large size fruits compared to the other treatments. Use of high tunnels and row covers increased the percentage of medium size fruit and decreased extra large size fruit. There was no difference in the large size fruit percentage between treatments.

There were significant differences in fruit number by grade between treatments (Table 3.7.). The interaction between high tunnels and row covers in the number of small and extra large size fruit was significant, indicating that the combination treatment increased the number of small fruit while decreasing large sized fruit. The most medium size fruit was harvested in the HT+RC treatment while there were no differences due to treatment in large sized fruit. In addition, the no tunnel treatments (RC, control) had higher average fruit weight than that in HT+RC treatment.

Table 3.7. Number of marketable fruits by grade and average fruit weight as affected by row cover (RC) or high tunnel (HT) treatment for spring planted tomato[z]

Treatments	S[y]	M	L	EL	Average fruit weight[x]
	Number of fruits				kg
HT	23.3 b	51.7 ab	96.5	60.5 a	0.22 ab
RC	12.3 b	37.0 b	70.7	50.0 ab	0.23 a
HT + RC	51.8 a	69.0 a	71.3	28.3 b	0.17 b
Control	8.2 b	27.2 b	81.5	62.8 a	0.25 a
Significance[w]					
HT	***	**	NS	NS	NS
RC	***	NS	*	***	*
HT×RC	**	NS	NS	*	NS

[z]Data for a main plot (80 plants) pooled over years (2004, 2005), means separation by Tukey's HSD test ($P \leq 0.05$)
[y]S = small, M = medium, L = large, EL = extra large size fruit
[x]Average fruit weight = total fruit weight / total fruit number
[w]NS, *, ** and *** means nonsignificant, significant at $P \leq 0.05$, 0.01 and 0.001, respectively

The use of a leaf blower in 2005 to enhance pollination didn't result in significant yield difference due to year (data not shown).The reduced marketable yield in HT+RC treatment, therefore, could be attributed to increased flower abortion due to high temperatures as well as more small size fruits and less extra large fruit.

IV. Economics

Due to difference in total marketable yield between 2004 and 2005, an economic evaluation was conducted separately by year. In 2004, net benefits in high tunnel treatments were negative because of low marketable yield (Table 3.8.). In 2005, the HT treatment made a profit although it was still lower than the no tunnel treatments. In this year, gross benefit obtained from the HT treatment was 27% higher than that from the control. Early fruit yield in the HT treatment accounted for 18% of the total yield while that in the control this was only 2% (data not shown). The higher early yield in the HT contributed to increased net benefits while achieving a higher tomato price ($3 per pound). Late yield in the HT treatment was 69% higher than that in HT+RC treatment while the difference in early yield was just 10% (data not shown). The breakeven price for the high tunnel treatments in 2004 were considerably high (> $4 per pound), however, they were lower the second year ($1.8 and 3.1 per pound for HT and HT+ RC treatment, respectively), and resulted in making a profit with the higher yields achieved in 2005.

In this study, varying cost (Table 3.8.) per unit area of high tunnel treatment was 27% higher than that reported in Oklahoma (Byczynski, 2003). This higher cost was mainly attributed to higher direct expenses. Because direct expenses are higher with increased

Table 3.8. Varying costs, gross and net benefits, additional varying costs and benefits and breakeven price per a main plot[z] for tomatoes in 2004 and 2005 (Louisiana State University AgCenter).

Treatment	Cost for high tunnels and row covers[y]	Total direct expenses	Varying costs[x]	Gross benefits[w]	Net benefits[v]	Breakeven price[u]
	$					$/lb
	2004					
HT	667.76	744.91	1412.67	825.7	-586.97	4.1
RC	4.23	503.38	507.61	908.6	400.99	1.3
HT+RC	671.99	762.97	1434.96	613.4	-821.56	5.3
Control	0.00	485.32	485.32	800.5	315.18	1.4
	2005					
HT	667.76	744.86	1412.62	1647.3	234.68	1.8
RC	4.23	503.33	507.56	907.6	400.04	1.2
HT+RC	671.99	773.30	1445.29	1104.3	-340.99	3.1
Control	0.00	485.27	485.27	1292.7	807.43	0.8

[z]Main plot = 612ft^2 (17'×36'), 80 plants
[y]Depreciation of high tunnels : 5years, row covers: 3years
[x]Varying costs equals cost for high tunnels and row covers plus total direct expenses.
[w]Gross benefits equals total yield multiplied by unit tomato prices ($3.00/lb and $2.00/lb for early and late yield, respectively).
[v]Net benefits equals gross benefit minus varying costs.
[u]Breakeven price equals varying costs divided by total yield.

production, it's necessary to maximize yield per plant in order to ensure profit. In Pennsylvania, researchers reported a low breakeven price of $0.36 in a study with the same type of high tunnels (Orzolek et al., 2004). Because the varying costs in our study were lower than the Pennsylvania study and the number of plants was the same, it's evident that it is necessary to maintain sufficient marketable yield to lower the breakeven price. Further research is required to examine cultural practices including cultivars in order to maximize yield in high tunnel systems. The tomato cultivar used in this study 'Sunstart' is an early season cultivar that is known for producing large size fruit. Selection of an appropriate cultivar for high tunnel production that is high yielding with large fruit will be critical to maximize the potential during this production season. Another aspect is the timing of production in the spring and achieving an early crop for market. High tunnels provide an opportunity for growers to begin production earlier than field grown tomatoes enabling them to increase profit while obtaining a higher tomato price. A harvest of 2000 pounds of marketable fruit make a profit of more than $1300 when the tomato price is $1.50/lb while 3500 pounds are needed to obtain profit of only $94.77 when the price is $0.50/lb (Byczynski, 2003). In this study, gross benefits per unit area in the HT treatment were $\$0.24/m^2$, which was more than 6 times as high as that observed in a study conducted by Waterer (2003). This was attributed to the relatively high unit tomato prices assumed for sales to retail outlets such as farmers' markets. Research is necessary to determine how early production is feasible with high tunnels in the spring in order to capture high prices at local markets when tomato growers using standard black plastic and row covers have not entered the marketplace.

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CHAPTER 4

CONCLUSIONS

High tunnels and row covers significantly increased air and soil temperatures during the course of this study. The highest temperatures were achieved when high tunnels and row covers were used in combination. This combination treatment was particularly effective in increasing temperatures under a nighttime cool event. In addition, plant growth was significantly accelerated in high tunnel treatments. This is probably due to the higher air and soil temperatures experienced with the high tunnels. The high tunnel treatment resulted in the highest early and total marketable yield. In contrast, the combination of high tunnels and row covers resulted in the lowest total marketable yield which was probably due to increased flower abortion and a higher number of small size fruits.

The combination high tunnel and row cover treatment was not economically beneficial both years because of low marketable yield resulting from this treatment. The use of high tunnels alone the first year was also not beneficial. This treatment made a profit the second year, however, due to higher marketable yields. These results indicate that high tunnels could achieve sufficient marketable yield to justify increased investment in this cultural practice under favorable growing conditions. The variability in yield that was observed between years may be limited or reduced by selecting appropriate varieties for the local climate and specifically chosen for conditions in a high tunnel such as high humidity and wide diurnal temperature fluctuations and high temperatures. Research investigating optimal timing of transplanting in this region should also be conducted to ensure profits in high tunnel production of tomato. The crop may be transplanted earlier than the date planted in this study (early March) due to the warmer temperatures experienced in high tunnels as well as the mild spring climate generally experienced in Louisiana. In general, the temperature data in this study indicates the potential of high tunnels to increase temperatures and result in plant growth and yield responses. Conducting additional research with spring planted tomato in high tunnels may result in more growers to realize the potential for using high tunnels in Louisiana.

VITA

Koji Takeuchi was born on February 18, 1977, in Tokyo, Japan. He graduated from the Gifu University, Japan, where he received the title of Bachelor of Science in soil physics in March, 1999, and the title of Master of Science in soil physics in March, 2001. In August, 2003, he enrolled in the Graduate School at Louisiana State University under the direction of Dr. Carl E. Motsenbocker to pursue the degree of Master of Science in horticulture, which will be awarded at the May 2006 commencement.