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Cultural Techniques to Improve Yield and Cost Efficiency of Greenhouse Grown Tomatoes

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To the Graduate Council:

I am submitting herewith a thesis written by Susannah Kate Amundson entitled "Cultural Techniques to Improve Yield and Cost Efficiency of Greenhouse Grown Tomatoes." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

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Cultural Techniques to Improve Yield and Cost Efficiency of Greenhouse Grown Tomatoes

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Abstract

Tomatoes (*Solanum lycopersicum)* are the most commonly grown greenhouse vegetable crop, preferred for their high consumer demand and high value. To improve profitability, growers continuously seek new techniques to improve yield and cost efficiency of production. Four studies were conducted between Fall 2008 and Spring 2010 in greenhouses at the University of Tennessee Plateau Research and Education Center (35°56 N lat.) and the University of Tennessee (35^{o} 57’38” N lat.) to investigate the impact different plant spacings (12, 16, 20, 24, or 28 inches in-row), pruning systems (one leader versus two leaders), cluster thinning (three, four, five, or six fruit/cluster or not thinned at all), and pest control practices (chemical versus biological aided by banker plants) had on yield and fruit size of hydroponically grown ‘Trust’ tomatoes. A cost analysis was performed to compare one leader versus two leader pruning systems and pest control regimes by chemical versus biological methods. A plant spacing of 28 inches resulted in significantly more tomato fruit per plant than the 12 inch plant spacing. However, yield per area (lb/ft^2) decreased with wider plant spacings. Pruning two tomato plants to one leader increased total yield and was more economical in the fall; whereas, in the spring the double leader production system did not affect yield but was more economical. For fall production, thinning to three or four fruit/cluster resulted in more jumbo tomatoes than the control or treatments thinned to five or six fruit/cluster. Total marketable yield was greater when plants were not thinned or thinned to six fruit/cluster, but average fruit weight decreased. For spring

production, cluster thinning did not affect marketable yield, percentage of culls, or fruit weight. Chemical pest control and biological pest control had comparable effects on whitefly (*Trialeurodes vaporariorum)* pest populations without affecting yield. However, biocontrol methods were more expensive. Marigold banker plants were successful in Orius reproduction, but thrips (*Frankliniella occidentalis)* populations were not affected by the presence of banker plants. Data from these studies demonstrate the ability to improve production and profitability of greenhouse tomato systems through simple changes to cultural management techniques.

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INTRODUCTION

Tomatoes (*Solanum lycopersicum)* are the most commonly grown greenhouse vegetable crop. Consumer demand for tomatoes all year long has increased 30% in the past 30 years. Fresh market tomato consumption per capita in the U.S was 12.1 lbs in 1970 and 17.8 lbs in 2000 (Lucier et al.,2000). To meet the growing demand for tomatoes, greenhouse production has become a year-round endeavor. In 1998 the U.S. produced 117,466 tons of greenhouse tomatoes on 635 acres. Production had increased to 175,949 tons on 815 acres by 2003 (Cook and Calvin, 2005). While U.S. tomato production has increased to meet demand, imported tomatoes still exceed domestic production. In 2003, the U.S. imported 308,799 tons of tomatoes worth US$365.5 million and only produced 175,949 tons (Cook and Calvin, 2005). This gap offers an opportunity for growers to expand production.

The U.S. greenhouse market is a young industry that is less than 20 years old. In the early stages, greenhouse growers were concentrated in the northern states and focused on summer production. Competition with Canada and decreased yield in the fall just as tomato prices increased spurred growers to target winter production by expanding firms to warmer climates, mainly the southwest (Cook and Calvin, 2005). The mild winters in southern states, with high light intensity and low humidity, allow for off-season production and growers can receive a premium price for the out-of-season fruit. Greenhouse production has many advantages over field production. Hydroponic growing systems, which, together with carefully controlled environments, appropriate variety selection, and proper maintenance techniques, allows for year-round production. As a result, greenhouse growers produce approximately 15 times more yield per acre than field production with greater than 90% being marketable fruit compared to field production producing 40 - 60% marketable fruit (Selina, 2002).

The majority of greenhouses are categorized as 'large' with production area over one acre, with a single greenhouse being as large as 20 acres. These large greenhouses are mainly glass and consist of highly sophisticated mechanisms that allow for producers to grow all year long for an average yield of 12.3 lb/ft^2 (235 - 308 tons per acre). Whereas small growers (less than one acre), produce mostly in poly-ethylene covered houses with less sophisticated controls, many without heating and therefore follow the summer growing cycle and produce an average of 7.12 lb/ft^2 (Selina, 2002).

Hydroponic production is the culture of plants in a root substrate consisting exclusively of water and dissolved nutrients (Nelson, 2003). It is favored by almost all producers, regardless of size, although some small greenhouses still plant in soil. It is the most commonly used production system because it starts out relatively disease free and offers superior control of irrigation, fertilization, and pH. There are many types of hydroponic media, 75% of U.S acreage (mostly large commercial operations) uses rockwool (an extruded rock fiber mat), 13% uses coir (coco fiber), 10% uses perlite (siliceous volcanic rock) or peat (partially decomposed organic debris), and approximately 2% uses sawdust or pine bark (Selina, 2002). To determine the best media to use, considerations need to be made regarding initial costs and impact on yield. Pine bark is the least expensive media and perlite is the most expensive (Hanna, 2009). Perlite is an excellent growing medium for tomatoes (Szmidt et al., 1988). It is inert, sterile, lightweight, easy to handle, with a low cation exchange capacity (C.E.C), high water holding capacity, and provides good root aeration (Papadopoulos, 1991). Another benefit to using perlite is its potential to be reused in multiple growing seasons, thereby cutting costs (Hanna, 2010). In order to reuse perlite, it must be reconditioned to restore structure, desalinized to remove salt buildup, and disinfected to reduce pest contamination. Hanna (2005 and 2010) has investigated three methods for perlite reconditioning with hot water treatments that have proven to be effective, cost efficient, and had no negative impact on fruit yield. Pine bark is a great alternative to perlite, especially in areas like the southern U.S, where the product is prevalent and therefore inexpensive, $0.17/plant (Snyder, 1994). Snyder (1993 and 1994), found that yields from plants grown in pine bark were either superior or did not differ compared to other growing media, like perlite and rockwool. Pine bark, while initially cheaper, does not have the capacity to be reused as its structure is destroyed when it decomposes. This frequent replacement can be time consuming and labor intensive. Rockwool shares the same desirable characteristics as perlite, but is available in large slabs for tomato production. Rockwool, which is also expensive, is the most commonly used media, despite its need to be replaced frequently and costly disposal (Straver,1995). It can be reused once but then needs to be disposed of due to the breakdown of fibers

(Papadopoulos, 1991). Hanna (2009) concludes that the most productive media for greenhouse grown tomatoes is perlite. Tomatoes planted in perlite can produce higher yields and can be successfully recycled for many years which compensates for the high initial cost.

For successful greenhouse tomato production there are many cultural requirements to consider, and many of them have been extensively researched to offer the best recommendations for growers. These include plant density, variety selection, planting schedules, pest control, irrigation schedules, pruning and training.

Correct spacing is crucial to ensure adequate and uniform distribution of light. Previous greenhouse tomato studies have demonstrated that plant density can affect yield. Greenhouse tomato plant populations can vary between 8,000 to 11,000 plants per acre, depending on climate, lighting, and cultivar. Hanna (2009) recommends that each plant should have at least $4ft^2$ of greenhouse space with 18 inches between grow bags and 2 plants per bag with 3 ft between rows. Similarly, Snyder (2007) recommends that each tomato plant should receive $4.3\text{-}ft^2$ growing area, with approximately a 13.7 – 15.7-inch spacing between plants, and 4 ft between rows. With greenhouse grown cherry tomatoes (*Solanum lycopersicum* var. *cerasiforme)*, Charlo et al. (2007) found that increasing plant spacing resulted in greater yield per plant but lowered yield per area (lb/ft^2), while decreasing plant spacing resulted in greater yield per area but smaller and more non-marketable fruit. Similarly, Saglam and Yazgan (1995) reported that tomatoes grown in unheated greenhouses saw overall yield per area (lb/ft^2) increase with an increased density.

Cultivar selection is a critical management decision that can impact yield, fruit quality, and profitability. It can be tempting to use varieties developed for field production in the greenhouse because seeds are cheaper; however field cultivars are not adapted to low light greenhouse conditions and disease pressure and plants will not yield well (LSU Ag Center, 2009). Indeterminate varieties are used exclusively in tomato greenhouse production. In 2001, 61% of U.S production was in beefsteak tomatoes and 39% was in cluster or Tomatoes-On-Vine (TOV) production (Selina, 2002). 'Trust' tomatoes are the most popular and commonly used tomato in greenhouse production. However, Hanna (2009) found that when compared to 'Geronimo' and 'Quest', 'Trust' produced the lowest yield, smaller fruit, and the highest percentage of cull. Variety selection should be based on disease resistance, light intensity and fertility requirements, and market demands for size, color, shape, flavor, and productivity. U.S markets value tomatoes large in size, fruit over 6 ounces is preferred, 4-6 ounces is marketable, and less than 4 ounces is considered small and undesirable.

There are two planting schedules typically used in greenhouse production. Large growers usually conduct a single planting and harvest fruit for 20-35 weeks, and small growers usually perform double plantings and harvest fruit for 13-30 weeks. A single rotation tomato crop is seeded in July or early August and transplanted into greenhouse when seedlings are 3-6 weeks old. Large growers usually receive transplant tomato plugs from propagators and skip the seeding step. Tomatoes will usually flower and set their first cluster at 6-8 weeks after germination and continue to set clusters every 7-10 days. The first cluster is harvestable 6-9 weeks after flowering and clusters will continue to ripen every 6-12 days. Single crop harvest begins mid-October to early November and continues into June or July. Such long harvest periods are unusual for most agricultural crops because most have a separation between vegetative and harvest phases, but for tomatoes these phases are concurrent throughout most of the year. For a double crop rotation, the fall planting follows the same schedule as the single crop. It's terminated in late December to mid-January. The spring crop is seeded in late November to mid-December (30-35 days before transplanting). Harvest begins in late March to early April and continues through June. (Selina, 2002; Snyder 2007).

The most economically important greenhouse pests are the two-spotted spider mite (*Tetranychus urticae)*, western flower thrips (*Frankliniella occidentalis*), whiteflies (*Trialeurodes vapoporium*), and aphids (Aphidoidea). The two-spotted spidermite (TSSM) feeds on plant tissues and sap which destroys chlorophyll and results in reduced photosynthesis, growth, and yield. A total loss of tomato crop can result from TSSM damaging as low as 30% of leaf surface (Malais et al, 2003). Western flower thrips (WFT) prefer to populate flowers, which leads to damaged unmarketable fruit even at low pest densities. Another threat of thrips is their ability to vector viruses, the tomato spotted wilt virus being of most concern. Whitefly damage is mostly attributed to the excretion of honeydew that encourages sooty mold growth on leaves and fruit, reducing photosynthesis and transpiration and making fruit unmarketable. Aphids are notorious virus vectors and feed on plant sap which stunts plant growth, killing the plant if infestation occurs early on or affecting yield by reducing photosynthesis. Like whiteflies, aphids also produce honeydew which results in sooty mold on fruit, rendering it unmarketable. Chemical control measures are the most common pest control practice used in the U.S. However, pesticide use has been falling out of favor in recent years due to issues surrounding the use of chemical sprays. Integrated pest management (IPM) has become more attractive. IPM utilizes a variety of different control measures including use of screens, greenhouse microclimate management, beneficial insects, and pesticides as a last resort. The major concerns to chemical use are: resistance of pests due the continued use of the same pesticides (Opit, 2009; McMahon, 1992); discontinuations of reliable pesticides (McMahon, 1992); limited pesticide options for greenhouse use since the enclosed area increases risks to human health; environmental concerns, exposure of the applicator to the chemicals, and consumer trends desiring chemical free produce. Another problem is that many growers act preventatively by applying pesticides on a set schedule regardless of pest presence. This practice often leads to unnecessary pesticide applications that magnify the problems of resistance, human exposure, and environmental concerns, as well as increase the cost of production (chemicals and labor), thereby reducing profitability (Opit, 2009). There is ample evidence to show that biological control can be a successful alternative or additive to chemical control in the greenhouse vegetable industry worldwide. Whitefly control by *E. formosa* on tomatoes were shown to be successful with nymph parasitism between 47 and 97% by the end of the tomato growing season (Gu, 2008; Lopez, 2010; Tello, 2007; Vis, 2008). Biological control or integrated pest management using *Orius* spp. gives acceptable and comparable, if not better, control of thrips in comparison to chemical control (Santonicola, 1998; Vergara, 2009). Two releases of *Orius* spp. controlled thrips to acceptable levels with negligible damage to fruit (Choi, 2009). Spider mites are adequately controlled by *Phytoseiulus* spp. provided a high predator-prey ratio is maintained and control by *P. persimilis* is comparable to conventional chemical control *(*Choi, 2009; Ferrero, 2011; Mansour, 2010). Release of *Aphidius colemani* decreases aphid pest populations (Moon, 2011; Cota, 2009).

Irrigation, and in hydroponic production this means fertilization as well since the two are applied together, takes careful consideration as adequate water is imperative for proper plant and fruit development but over-watering can reduce fruit quality, as well as add to production costs. Finding the right balance between providing adequate water for tomatoes and conserving water to reduce costs and minimize nutrient and pesticide loaded effluent is essential. The best estimates for irrigation requirements accounts not just for quantity and frequency but for timing as well, since not all stages of plant development are as demanding. Nuruddin et al. (2003) found that the flowering stage was least sensitive to water stress compared to the fruit growth and fruit ripening stages. They also concluded that water stress imposed during flowering had fewer but larger fruit than fully irrigated plants and therefore did not affect overall yield. Greenhouse crop production requires daily monitoring of leachate to ensure sufficient water discharge in order to prevent water shortages or salt buildup (Saha et al., 2008). The recommended ratio (leachate : irrigation water) is 25% to 50% depending on climate and electro conductivity (EC) (Klaring, 2001). Ideally, the EC of the leachate will be close to the EC of the nutrient solution. If it rises above 3.0 mmhos, fertilizer is accumulating in the grow bag and there is risk of burning the roots (Snyder, 2007) and should be corrected by irrigating or flushing with plain water. Most large greenhouse growers have sophisticated computer controlled fertigation systems that monitor and adjust quantities as needed. Irrigation requirements also depend on the growing media. Saha et al (2008) established that the most accurate way to supply the correct amount of water to tomatoes grown in rockwool is to base irrigation on slab water content less than 70% or a 500-g weight loss. Typically greenhouse tomato watering cycles usually consist of ~4 oz of nutrient solution to each plant up to 7 times/hr depending on season, plant age, and solar radiation which ensures no water shortages to plants or excess salt buildup (Selina, 2002).

In soilless hydroponic culture, the growing media releases little to no nutrients therefore plant nutrition management can be more precise and influential (Hao, 2004). Current tomato production requires high levels of Nitrogen (N) for optimum growth (Wahle, 2003). Greenhouse leachate with high levels of nutrients and pesticides entering ground water has come under scrutiny recently (Nuruddin et al., 2003), and efforts to reduce nutrient pollution are being researched. To develop better practices, growers need to have a better understanding of macronutrient (N, P, K, Mg, Ca) utilization within tomatoes to be able to adjust fertilization as needed. Nitrogen is an essential plant nutrient that accumulates continuously throughout its life cycle. As seedlings, tomatoes store ~80% of the total plant N in the leaves, by harvest, only 24% of total N is still in the leaves and ~69% is in fruit (Wilcox, 1993). Nutrient extraction is greatest during vegetative growth and the greatest uptake rate occurs at 59-74 days after transplant (DAT). Nutrient efficiency improves 24% to 54% at 74 DAT compared to 40 DAT (Pineda). Factors other than plant age can affect plants nutritional needs as well and must be accounted for in fertilization regimes. Climatic conditions like solar irradiance, humidity, and temperature will affect optimal levels of Ca and Mg (Papadopolous et al., 2002). The pH of the nutrient solution should be monitored frequently and if outside the optimum range of 5.5 and 6.5 adjustments need to be made. The nutrient solution pH determines the availability of nutrients for plant uptake and therefore must be monitored and controlled. Corrective measures for high pH consist of adding sulfuric acid, nitric acid, or phosphoric acid. However, these acids are expensive and Papadopolous et al (1998) found that using the less expensive hydrochloric acid controlled pH and had no effect on growth, fruit quality, or yield. A benefit of greenhouse hydroponic production is the capacity to cater to the exact nutritional needs at any given time because it lacks the complexities of soil that can hinder plant uptake.

After the first flowers have opened, the tomato begins to develop numerous lateral shoots (Logendra, 2004). Pruning these shoots is mandatory for greenhouse production to minimize shading and avoid competition with developing fruits for nutrients. The most common type of pruning system is to prune plants to a single stem by removing all lateral shoots. However, there is research that shows that yield per area increases when using the alternative method of pruning to two stems, which is accomplished by leaving the axillary shoot below the first flower cluster and removing all others. Borisoy et al. (1978) found that when greenhouse tomatoes were pruned to two stems rather than one, yield/area increased 10% to 15%. Plants can be clipped or wrapped around a support string, then topped once plants reach the support wire or, for long seasons, plants can be lowered and laid to one side as they get to be 35 ft long. Since large tomato grades are most marketable, growers want to maximize fruit size without negatively affecting overall yield. This can be partly accomplished by cluster thinning, which is the removal of flowers to avoid competition by high fruit set which causes poor fruit weight, shape, quality, and uniformity (Hochmuth, 1991). There are many recommendations of how severely to thin clusters. Koske et al (2005) recommended leaving three to four fruit per cluster for most tomato varieties. Hochmuth (1991) suggests thinning large fruiting cultivars to three or four fruit and medium fruiting cultivars to four or five fruit, but warned to never exceed five for any variety. Snyder (2007) advises thinning to three, four, or five fruit per cluster. According to Papadopoulos (1991), the first two clusters should be pruned to three fruits and subsequent clusters to four fruits. Hanna (2009) found that thinning clusters to three fruit instead of four fruit reduced cull yield and increased fruit weight, as well as total marketable yield. Moreover, Cockshull and Ho (1995) found that removing 30% of fruit from the first three clusters resulted in increased fruit weight and reduced culls. Hurd et al. (1979) saw a decrease in number of fruit when 2/3 of the flowers were removed. However, this reduction in fruit number did not greatly affect total yield, as it was almost entirely compensated by the increase in mean fruit. Cultivar and growing conditions are important factors to consider when cluster thinning as they greatly affect yield fruit size as well.

Tomato flowers are perfect with both male and female parts. Fertilization is usually accomplished from the pollen and ovary within the same flower. Tomato pollen is shed during anthesis when there is a vibrating force that shakes the plant (Snyder, 2007). In field conditions this is accomplished mostly by wind. To get good fruit set and size in greenhouse conditions, tomato flowers have to be mechanically vibrated to release pollen. The optimum temperature for pollination is between 70 and 82 ^{o}F. In ideal conditions fertilization occurs 48 hours after pollination (Snyder, 2007). There are a few mechanisms for pollination. Large greenhouse growers use hives of lab-reared bumblebees for the most effective and efficient pollination (Morgan, 2000) and spend up to $2,000/acre on them (Selina, 2002). For very small growers (<1000 plants), bee hives are not feasible because they don't have provide a sufficient number of flowers open at one time to supply the bees with enough pollen. This results in damaged flowers and female organs as the bees revisit open flowers (Hanna, 2004). Electric vibrators are just as effective at pollinating as bumblebees are and is most practical for small growers. Due to the labor involved with electric vibrators it is most economical for growers >2500 plants to use bumblebees (Snyder, 1995). The use of air-blowers in small greenhouses has been investigated to reduce the time and labor involved in manual pollination. But Hanna (2004) concluded that the yield loss from using air-blowers did not offset the savings in operating costs.

In greenhouse crop production, the indoor climate is manipulated to provide the appropriate environmental conditions for off-season or year round production (Bot, 2001). The environmental conditions of most concern are temperature, and relative humidity. Heating in the winter and cooling in the summer requires a lot of energy, which emits greenhouse gases and can be very expensive. Energy consumption is the largest expense for growers, heating greenhouses in Canada costs on average $130,000/ha (Statistics Canada, 2005). Ideal temperatures for optimal tomato plant growth are 70 to 82 ^{o}F for day and 62 to 64 ^{o}F for night (Snyder, 2007). This ideal temperature is determined by long-term averages rather than instantaneous temperatures (De Koning, 1990). Periods of low temperature can be compensated for by periods of high temperature, keeping the long-term averages in the optimal range for growth (Zhang, 2010). This concept has been studied as a practical way to conserve energy. Increasing temperatures when energy cost is lower and decreasing temperatures when energy cost is higher can maintain optimal long-term averages while reducing heating costs by 10% to 20% (Chalabi et al.,1996; Pollet et al., 2009). This practice, known as temperature integration (TI), can be successful as long as low and high temperature thresholds are not exceeded for long periods of time, which will hinder growth and production. Temperatures below 60 ^{o}F can cause nutrient deficiencies; one or two nights of 56 to 58 ^{o}F can cause rough fruit; temperatures above 86 ^{o}F hampers lycopene production, and above 90 ^{o}F causes fruit splitting (Snyder, 2007). Pre-night and pre-morning periods are usually the periods of highest energy consumption. Zhang (2010) found that the optimum low pre-night temperature for some cultivars was between 53.6 ^{o}F and 58.8 ^{o}F, and that using these lower than normal pre-night temperatures can improve early fruit yield and energy efficiency. Hao (2011) found that reducing pre-morning temperatures to 56.3 ^{o}F increased fruit yield and reduced energy consumption by 6% to 8% from March to May.

The optimal relative humidity levels for greenhouse tomatoes are between 60% and 70%. Relative humidity (RH) affects the transpiration rate of plants, and therefore affects uptake of water and nutrients, mainly nutrients transported through xylem like calcium and potassium. High humidity significantly reduces the hourly and daily transpiration rates and reduces crop yield (Jolliet et al.,1993; Trigiu et al.,1995). High humidity causes a reduction in leaf area and Ca and K deficiency (Adams, 1991; Bakker, 1990). Relative humidity in the greenhouse is also directly correlated to disease incidence as condensation on plant occurs at high levels of relative humidity. Diseases, like leaf mold, grey mold, and powdery mildew are most common in fall, early winter, and spring when RH is high and continuous heating is not necessary (Novak et al., 2010). Leaf mold infections are most severe at 65% to 82% RH (Novak et al., 2010). Powdery mildew infections are most severe at RH humidity levels of 60% to 90% (Jacob et al., 2008). Dehumidification is typically accomplished by heating and ventilating.

Combinations of high temperatures and low RH helps reduce disease severity in greenhouse tomatoes (Jacob et al., 2008).

Greenhouse production in the southeast has been growing in recent years as small farms are looking for ways to diversify and provide a supplemental income. Tomatoes are a high demand and high value crop that can be successfully grown in greenhouses all year long. There is a plethora of information for greenhouse tomato growers on extension websites and grower handbooks providing growing tips and guidelines. The overall objective of this work was to provide data on the critical points of greenhouse tomato production, by using commonly suggested practices and scientifically studying them to provide growers with specific production guidelines. Three separate studies were conducted between Fall 2008 and Spring 2010 in Knoxville and Crossville Tennessee. The purpose of the first and second studies were to evaluate yield and fruit weight of 'Trust' tomatoes at five different plant spacings, determine the effect of pruning production systems on yield and fruit weight, and evaluate the effect of cluster thinning on yield and fruit weight. The third study was conducted to compare the effectiveness of chemical pest control and biological pest control.

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CHAPTER I

OPTIMIZING PLANT DENSITY AND PRODUCTION SYSTEMS TO MAXIMIZE YIELD OF GREENHOUSE GROWN ‘TRUST’ TOMATOES

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Abstract

Plant spacing and production systems are important factors for maximizing production of greenhouse grown tomatoes (*Solanum lycopersicum*). Two studies were conducted simultaneously and independently, each in a 33 x 96-ft greenhouse in Fall 2008 and Spring 2009 using perlite soilless bag culture. The purpose of the first study was to evaluate yield and fruit weight of 'Trust' tomatoes spaced 12, 16, 20, 24, or 28 inches in-row. The second study was conducted to determine the effect of pruning production systems on yield and fruit weight. The first system is pruning two plants per bag each to a single leader and the second is pruning one plant per bag to double leader. A plant spacing of 28 inches resulted in significantly more tomato fruit per plant than the 12 inch plant spacing. However, yield per area (lb/ft^2) decreased with wider plant spacings. Plants spaced 12 inches apart in-row produced 2.8 and 3.8 lb/ft^2 total yield in the fall and spring, respectively, compared to plants spaced 28 inches apart that produced 1.7 and 2.2 lb/ft^2 in the fall and spring. Using a production system with one plant per bag pruned to a double leader increased yield by 6.4 lb/plant in the fall and 15.7 lb/plant in the spring. On a per bag basis, pruning two tomato plants to one leader increased total yield by 2.6 lb/bag and was more

economical in the fall; whereas, in the spring the double leader production system did not affect yield but was more economical.

Introduction

In 2003, U.S. greenhouse growers produced approximately 175,996 tons of tomatoes (*Solanum lycopersicum*); however, imports still exceeded domestic production, with 282,323 tons from Canada and Mexico alone (Cook and Calvin, 2005). This factor provides opportunities for growers to increase U.S. greenhouse tomato production. As of 2003, large (40+ acres) and medium (7-40 acres) operations accounted for 62% and 15%, respectively, of total U.S. greenhouse tomato productivity (Cook and Calvin, 2005). Over time, the largest U.S. greenhouse firms have shifted locations to align production with the most profitable market windows and utilize the warmer winter climates while simultaneously targeting the high-priced winter season (Cook and Calvin, 2005). While this shift allows profitable production all year-long, it also increased transportation expenses. This, according to Hanna (2009), accounts for a substantial part of tomato production expenses, and usually mandates growers to cut costs and/or increase yield.

Small greenhouse tomato operations are still prevalent in the U.S. and focus mainly on local sales on the premises, or to farmer's markets and retailers (Cook and Calvin, 2005; Korevaar, 2007). In order for these small family farms to compete in the market, they must either tap into a niche market, such as heirlooms or cherry tomatoes, or reduce production costs and increase plant yield (Korevaar, 2007; Hanna, 2009). In short, despite the size of operation or location, growers are always pursuing ways to increase yield.

Greenhouse tomato production requires many environmental, cultural, and biological practices to optimize production and fruit quality. Plant density and pruning methods are two important cultural approaches to increase yield. It has been recommended by Snyder (2007) and the Louisiana State University AgCenter (2011) that each tomato plant should receive 4 – 4.3-ft^2 growing area, with approximately a 13.7 – 15.7-inch spacing between plants, and 4 ft between rows. Previous tomato studies, grown in both field and greenhouse conditions, have demonstrated various responses to plant density. With greenhouse grown cherry tomatoes, Charlo et al. (2007) found that increasing plant spacing from 11.8 to 19.7 inches resulted in greater yield per plant but lowered productivity (lb/ft^2), while decreasing plant density resulted in greater yield per area but smaller more non-marketable fruit. Similarly, Saglam and Yazgan (1995) reported that tomatoes grown in unheated greenhouses saw overall yield (lb/ft^2) increase with an increased density. Kemble et al. (1994) found no yield differences between in-row spacing of 12 and 30 inches in field grown tomatoes. However, Santos et al. (2010) determined that higher yields of field grown tomatoes were obtained by using smaller in-row spacing.

Franco et al. (2009) stated that choosing a proper pruning system was important to keep a balance in the relationship’s source/sink and the carbon/nitrogen (C/N) ratio. There are several reports that confirm the benefits of pruning on tomato yields. Cockshull et al. (2001) found a tendency for side shoots to reduce the yield of marketable fruit produced on each cluster in greenhouse production.

Pruning needs differ depending on the growth habit of the cultivar, but typically it is recommended that indeterminate greenhouse tomatoes be pruned to one stem by removing all side shoots (Snyder, 2007). However, literature indicates that productivity per area increases when pruning tomatoes to two stems. Aung (1999) reported that greater marketable yield/area was obtained by pruning indeterminate field tomatoes to two stems rather than one stem. Borisoy et al. (1978) found that greenhouse tomato yield/area increased 10% to 15% when pruned to two stems rather than one. Common pruning studies compare one plant with one leader and one plant with two leaders. This study was designed to compare two production systems, one using one plant per grow bag pruned to a double leader, the other using two plants per grow bag each pruned to single leaders. Growers are exploring ways to decrease production costs by cutting back on the number of transplants needed by using one plant with two leaders per 5-gal grow bag instead of two plants with one leader per grow bag. However, there is not adequate data to support the yield benefits and possible cost savings to support this practice. The objective of this study was to evaluate different plant densities and pruning production systems to maximize yield and fruit size for indeterminate tomatoes grown hydroponically under greenhouse conditions.

Materials and Methods

Two studies were conducted simultaneously and independently in Fall 2008 and Spring 2009 at the University of Tennessee Plateau Research and Education Center in Crossville, TN (lat. 35°56′N). Each study was performed in a 33 x 96-ft double layer polyethylene covered greenhouse using ‘Trust’ tomatoes (DeRuiter Seeds, Columbus, OH). Tomatoes were seeded into plastic germination trays filled with soilless germination mix comprised of peat moss, perlite, and vermiculite (BM2; Berger Peat Moss, Saint-Modeste, QC, Canada) on 27 June 2008 for fall crop and 26 Dec. 2008 for spring crop. Ten days later, seedlings were transplanted into 38-cell plastic trays containing all-purpose soilless mix comprised of peat moss, perlite, vermiculite, and starter fertilizer (BM1; Berger Peat Moss, Saint-Modeste, QC, Canada). Transplants were grown for approximately six weeks before transplanting at the fourth to fifth true leaf stage into white 3-gal (spacing study) or 5-gal (pruning study) grow bags containing perlite. Fall transplanting occurred on 22 Aug. 2008 and spring transplanting occurred on 7 Feb. 2009. Fall temperatures averaged 83^{o} F for the daytime and 62^{o} F for the nighttime. Spring temperatures averaged 85^{o}F for the daytime and 64^{o} F for the nighttime. For both experiments, plants were clipped to a string supported by an overhead wire and grown to the 10th flower cluster before being topped. Flower clusters were thinned to four or five fruit per cluster to remove excess fruit and flowers and to optimize fruit size. Pollination was done by bumblebees (*Bombus impatiens)* (Koppert Biological Systems, Romulus, MI). The fertilizer solution, made up of TotalGro Tomato Special 3N-5.7P-24.1K

(TotalGro, Winnsboro, LA), Magnesium sulfate ($Mg(SO_4)_2$), Potassium nitrate (KNO_3), Calcium nitrate ($Ca(NO_3)_2$), and Calcium chloride (CaCl) at a 100% strength supplied nutrients in the following concentrations (mg/L^{-1}): N (190); P (50); K (324); Ca (187); Mg (65); Fe (3). The fertilizer schedule followed recommendations based on Snyder (2007). Fall harvest began on 3 Nov. 2008, and ended on 20 Jan. 2009. Spring harvest began on 20 Apr. 2009, and ended on 2 July 2009. Tomatoes from each treatment/replication were harvested at the pink stage once weekly for 12 weeks. Unmarketable fruit (culls or small fruit) were discarded, and the remaining fruit were graded as follows: jumbo (>3.0 inches), extra-large (2.75 - 3.0 inches), large (2.5 – 2.75 inches), and medium (2.25 – 2.5 inches) (U.S. Dept. Agr., 2007). Weight and number of fruit in each grade were recorded for each treatment/replication, and total marketable yield was determined by combining all grades.

Experiment 1

The first study was designed to evaluate the effect of plant spacing on yield. One plant was transplanted into each 3-gal bag and spaced on-center according to its designated treatment. A row spacing of 4 ft remained constant and different plant densities were achieved by varying in-row spacing. Treatments were as follows: 12 in (0.25 plants/ft^2), 16 in (0.19 plants/ft^2), 20 in (0.16 plants/ft^2), 24 in (0.13 plants/ft^2), and 28 in (0.11 plants/ft^2). The experiment was arranged in a randomized complete block design with three replications of five treatments and 20 plants per experimental unit. The experimental layout consisted of five double rows (18 inches apart on-center) spanning the length of the greenhouse with north/south orientation. The center three rows were the experimental rows and the outer two rows were borders. Plants were pruned to a single leader. Simple linear regression was used to study changes in fruit yield associated with increases in plant spacing by partitioning the sums of squares into components that were associated with linear terms with SAS (version 9.2; SAS Institute, Cary, NC).

Experiment 2

The second study compared production systems: two plants with one leader and one plant with two leaders. Depending on the treatment, either one or two plants were transplanted into 5-gal bags which were spaced 18 inches on-center in rows 5 ft apart. The experiment was designed as a randomized complete block with four replications of two treatments and five bags per experimental unit, equaling five plants per experimental unit for the two-leader treatment and 10 plants per experimental unit for the one-leader. The two treatments consisted of either one plant per bag pruned to a double leader, or two plants per bag pruned to a single leader each. For single leaders, all suckers were removed. For double leaders, the sucker just below the first flower cluster was left to remain as the second leader. Yield data was analyzed using analysis of variance mixed models with SAS (version 9.2; SAS Institute, Cary, NC). Blocks, or replications, were considered random, and treatments were considered fixed. Significance of main effects was determined by F-test.

Results and Discussion

Experiment 1

Plant spacing affected greenhouse tomato total yield, yield of jumbo sized fruit, and average fruit weight per plant as well as per area (Tables 1.1 and 1.2). A positive linear trend showed that total yield/plant, jumbo yield/plant, and fruit weight increased with every increased increment in spacing. The highest 'Trust' yield of jumbo fruits produced per plant were obtained by an in-row spacing treatment of 28 inches in both seasons. In the fall, plants at a 28-inch spacing produced 4.5 lb more jumbos per plant than those spaced 12 inches apart (Table 1.1) and 6.3 lb more jumbos per plant in the spring (Table 1.2). When compared to plants spaced 12 inches apart, a plant spacing of 28 inches resulted in a total yield increase of 4.3 lb/plant in the fall and 4.8 lb/plant in the spring. Wider plant spacing also resulted in increasing the average fruit weight per plant, from 0.48 lb with the 12-inch spacing treatment to 0.57 lb with the 24 and 28-inch spacing treatments. In this experiment, increasing in-row spacing by 1 inch linearly increased total yield per plant by 0.27 lb/plant in the fall and 0.29 lb/plant in the spring and increased jumbo fruit yield by 0.28 lb/plant in the fall and 0.45 lb/plant in the spring. Lower plant densities produced more tomatoes per plant; however, with less plants being grown due to larger in-row spacing, total yield per area (lb/ft^2) was lower (Tables 1.1 and 1.2). There was a negative linear correlation between wider in-row plant spacing and total yield/area and jumbo yield/area. With every increase in plant spacing, yield per area decreased. Per area, plants in the 12-inch spacing resulted in a total yield of 2.8 lb/ft^2 in the fall and 3.8 lb/ft^2

in the spring, whereas plants in the 28-inch spacing only yielded 1.7 lb/ft^2 in the fall and 2.2 lb/ft^2 in the spring, an increase of approximately 40%. Similarly, the amount of jumbo tomatoes produced per area increased with closer spacings. The 12-inch spacing resulted in 1.7 lb/ft^2 and 2.4 lb/ft^2 of jumbo tomatoes in the fall and spring, respectively. The 28-inch spacing resulted in only 1.2 lb/ft^2 and 1.8 lb/ft^2 in the fall and spring, respectively, equaling a 30% increase of jumbo yield. Although yield per area increased with the smaller spacing it is not necessarily desirable for growers since the fruit produced were smaller, 0.48 lb with the 12-inch spacing compared to 0.57 lb and 0.60 lb with the 28-inch spacing (Tables 1.1 and 1.2). By increasing in-row plant spacing by 1 inch, overall yield per area decreased linearly by 0.07 lb/ft^2 in the fall and 0.10 lb/ft^2 in the spring and jumbo yield decreased by 0.03 lb/ft^2 in the fall and 0.037 lb/ft^2 spring, and increased average fruit weight by 0.009 lb.

These findings correspond to the findings of Papadoulos and Ormrod (1990). They found that with a narrow plant spacing, yield per plant declined but yield per area increased. This can be explained by the increased inter-plant and intra-plant competition that is imposed with higher plant densities (Fery and Janick, 1970; Rodriguez and Lambeth, 1975). They also attribute this to the fact that with lower plant densities (wider spacing) there is increased photosynthetically active radiation interception to the plant canopy, specifically the lower basal leaves, resulting in higher carbon dioxide (CO_2) fixation which ultimately increases yield per plant and fruit size (Papadopoulos and Ormrod 1990).

Closer cropping increases yield per area, but decreases yield per plant and fruit weight, while increasing the risk for diseases and pests. High plant densities are best used in situations with high light or where fruit size is not of great concern.

Experiment 2

In the production systems study, the treatment effect significantly affected yields (Tables 1.3 and 1.4). The production system of one plant/ 5-gallon bag pruned to a double leader resulted in more total fruit/plant and extra-large yield/plant than two plants/5-gallon bag pruned to single leaders. The double leader system produced significantly higher total yields during fall and spring seasons, 15.4 and 29.1 lb/plant respectively, compared to the single leader system with 9 lb and 13.4 lb/plant during the fall and spring, respectively (Tables 1.3 and 1.4). The one plant with two leader system produced, 6.4 and 15.7 lb more fruit per plant during the fall and spring than two plants with single leaders. While yield/plant is interesting from a physiological standpoint, it is yield/bag that is most pertinent to growers trying to decrease production cost while not sacrificing yield. On a per bag basis, two plants with one leader yielded more fruit for the fall crop, 18 lb/bag (9 lb/plant each) compared to 15.4 lb/bag of a single plant with double leaders (Table 1.3). During the spring crop, the two systems produced comparable yields (Table 1.4). So, by using the same floor space, water, and fertilizer, one would have higher yields in the fall by having two plants each with a single leader, as the double leader plant produces 15.5 lb/bag of tomatoes, and the two single leader plants together produce 18 lb/bag of tomatoes. However, in the spring it would be more beneficial to use the double leader system than the single leader system as it decreases input costs of seeds and transplants without reducing yield. Maintenance and labor inputs were equal for both pruning systems, except seeding and planting, theoretically, would take half as much time when using the double leader system. Using the double leader production system would be beneficial if the cost of using twice as many plants (as for the one leader system) outweighs the possible profits achieved by the increased yield. However, a cost analysis (Table 1.5) calculating the projected gross income for one 3000-ft^2 house using 4 ft^2 growing area per grow bag shows that the yield increase of a single leader system outweighs the increased seed cost in the fall but not in the spring. Estimates show an increase in profit of $2925.00 by pruning two plants per bag to a single leader in the fall; whereas in the spring the opposite holds true, pruning one plant per bag to a double leader will be $2587.50 more profitable. A disadvantage of the double leader production system is that when diseases, such as *Botrytis cinerea*, are present there is a greater chance of losing the whole plant, whereas if there are two plants per bag it may affect one plant but not the other. This factor may partly explain why the single leader system was more effective in the fall when greenhouse disease pressure is greatest in Tennessee.

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Appendix A

Table 1.1. Regression analysis of fruit size and yield per plant and per area of greenhouse 'Trust' tomato fruit grown in double rows spaced 18 inches on-center with 4 ft. between rows. Different plant densities were achieved with various in-row spacing treatments in Fall 2008.

Plant spacing (inches)^y	Plant spacing (plants/ft^2)	Fruit yield (lb/plant)		Fruit yield (lb/ft^2)^z		Mean fruit wt (lb)^w
		Jumbo^x	Total	Jumbo	Total	
12	0.25	7.0	11.1	1.7	2.8	0.48
16	0.19	8.7	12.6	1.6	2.4	0.52
20	0.16	9.6	13.4	1.5	2.1	0.54
24	0.13	10.9	14.6	1.4	1.8	0.57
28	0.11	11.5	15.4	1.2	1.7	0.57
Linear^v		<0.0001	0.0005	0.0006	<.0001	<.0001

^{z}1.0 lb/ft^2 = 4.8824 kg·m-2.
^{y}1 inch = 2.54 cm.
^{x}Jumbo is categorized as any tomato >3.0 inch diameter.
^{w}1.0 lb = 0.4536 kg.
^{v}Fruit yield in response to plant spacings described as the following linear regression equations: jumbo/plant: y = 3.89 + .28x; total/plant: y = 8.09 + .27x; jumbo/ft^2: y = 2.14 - .03x; total/ft^2: y = 3.53 - .07x; fruit weight: y = .29 + .02x.

Table 1.2. Regression analysis of fruit size and yield per plant and per area of greenhouse 'Trust' tomato fruit grown in double rows spaced 18 inches on-center with 4 ft. between rows. Different plant densities were achieved with various in-row spacing treatments in Spring 2009.

Plant spacing (inches)^y	Plant spacing (plants/ft^2)	Fruit yield (lb/plant)		Fruit yield (lb/ft^2)^z		Mean fruit wt (lb)^w
		Jumbo^x	Total	Jumbo	Total	
12	0.25	9.8	15.2	2.4	3.8	0.48
16	0.19	12.0	17.3	2.3	3.2	0.51
20	0.16	14.7	18.9	2.3	3.0	0.54
24	0.13	16.1	19.5	2.0	2.4	0.57
28	0.11	16.8	20.0	1.8	2.2	0.60
Linear^v		<0.0001	0.0005	0.01	<0.0001	<0.0001

^{z}1.0 lb/ft^2 = 4.8824 kg·m-2.
^{y}1 inch = 2.54 cm.
^{x}Jumbo is categorized as any tomato >3.0 inch diameter.
^{w}1.0 lb = 0.4536 kg.

[v] Fruit yield in response to plant spacings described as the following linear regression equations: jumbo/plant: $y = 4.7 + .45x$; total/plant: y $y = 12.2 + .29x$; jumbo/ft^2: $y = 2.9 - .037x$; total/ft^2: $y = 4.9 - .10x$; fruit weight: $y = .38 + .009x$.

Table 1.3. Yield of greenhouse 'Trust' tomato grown in two production systems: two plants per bag with one leader each or one plant per bag with two leaders in Fall 2008.

Treatment	Fruit yield (lb/plant)[z]			Fruit yield (lb/ft^2)[y]		
	Extra large[x]	Jumbo[w]	Total	Extra large	Jumbo	Total
1 leader, 2 plants/bag	1.9 b[v]	5.7 a	9.0 b	4.0 a	11.5 a	18.0 a
2 leaders, 1 plant/bag	4.1 a	7.8 a	15.4 a	4.1 a	7.8 b	15.4 b
P value	0.002	NS[u]	0.0003	NS	0.025	0.02

[z]1.0 lb = 0.4536 kg.
[y]1.0 lb/ft^2 = 4.8824 kg·m-2.
[x]Extra-Large is categorized as any tomato between 2.75 - 3 inch diameter.
[w]Jumbo is categorized as any tomato >3.0 inch diameter.
[v] Means within columns followed by the same letter are not significantly different at $P < 0.05$ by least significant difference (LSD).
[u]Not statistically significant.

Table 1.4. Yield of greenhouse 'Trust' tomato grown in two production systems: two plants per bag with one leader each or one plant per bag with two leaders in Spring 2009.

Treatment	Fruit yield (lb/plant)[z]			Fruit yield (lb/ft^2)[y]		
	Extra large[x]	Jumbo[w]	Total	Extra large	Jumbo	Total
1 leader, 2 plants/bag	2.5 b[v]	10.1 a	13.4 b	6.4 a	20.3 a	26.8 a
2 leaders, 1 plant/bag	6.4 a	21.0 a	29.1 a	5.0 a	21.0 a	29.1 a
P value	0.016	NS[u]	0.05	NS	NS	NS

[z]1.0 lb = 0.4536 kg.
[y]1.0 lb/ft^2 = 4.8824 kg·m-2.
[x]Extra-Large is categorized as any tomato between 2.75 - 3 inch diameter.
[w]Jumbo is categorized as any tomato >3.0 inch diameter.
[v] Means within columns followed by the same letter are not significantly different at $P < 0.05$ by least significant difference (LSD).
[u]Not statistically significant.

Table 1.5. Cost analysis of single leader versus double leader training systems in one 3000-ft^2 (278.7 m^2) greenhouse using 4 ft^2 (0.37 m^2) growing area per grow bag for ‘Trust’ tomato.

Treatment	Transplant costs^z	Fall yield (lb)^y	Spring yield (lb)	Tomato price ($/lb)^x	Fall gross income	Spring gross income
1 leader, 2 plants	$750	13,500	20,100	$1.50	$20,250	$30,150
2 leaders, 1 plant	$375	11,550	21,825	$1.50	$17,325	$32,737

^{z}Transplant costs are only expense differences as production costs for media, water, fertilizer and other resources remain the same for each system.
^{y}1.0 lb = 0.4536 kg.
^{x}$1.00/lb = $2.2046/kg.

Chapter II

Evaluating Effect of Cluster Thinning On Greenhouse-Grown 'Trust' Tomatoes

Abstract

Cluster thinning is a common practice among greenhouse tomato (*Solanum lycopersicum*) growers that has great potential to maximize fruit size. This study was conducted over two growing seasons, Fall 2009 and Spring 2010, in two 33 x 96-ft. greenhouses using perlite soilless bag culture. The objective was to evaluate marketable yield, fruit weight, and cull production of 'Trust' tomatoes thinned to three, four, five, or six fruit/cluster or not thinned at all (control). For fall production, thinning to three or four fruit/cluster resulted in more jumbo tomatoes than the control or treatments thinned to five or six fruit/cluster. Total marketable yield was greater when plants were not thinned or thinned to six fruit/cluster, but average fruit weight decreased. For spring production, cluster thinning did not affect marketable yield, percentage of culls, or fruit weight.

Introduction

Large tomato (*Solanum lycopersicum*) grades are often sought after by consumers, specifically the jumbo grades. It is advantageous for growers to maximize fruit weight and yield in order to receive a premium price for these larger tomato grades. This is done through an array of environmental controls and maintenance techniques, one of which is cluster thinning. Tomatoes can produce as many as 12 flowers per flower cluster. Under ideal conditions as many as eight of these flowers can form fruit (Hochmuth, 1991). However, such high fruit set leads to poor fruit weight, shape, quality, and uniformity for most cultivars (Hochmuth, 1991). This can be avoided by fruit thinning (or pruning), which reduces competition by limiting the number of fruit each cluster bears.

The degree to which clusters should be thinned is dependent on cultivar and growing conditions. Thinning recommendations are abundant and varied in extension publications and tomato crop handbooks; however, they are often not supported by data. To maximize fruit weight without sacrificing yield, Koske et al (2005) recommended leaving three to four fruit per cluster for most tomato varieties. Hochmuth (1991) suggests thinning large fruiting cultivars to three or four fruit and medium fruiting cultivars to four or five fruit, but warns to never exceed five for any variety. Snyder (2007) advises thinning to three, four, or five fruit per cluster. According to Papadopoulos (1991), the first two clusters should be pruned to three fruits and subsequent clusters to four fruits.

In refereed literature, Hanna (2009) found that thinning clusters to three fruit instead of four fruit reduced cull yield and increased fruit weight, as well as total marketable yield. Moreover, Cockshull and Ho (1995) found that removing 30% of fruit from the first three clusters resulted in increased fruit weight and reduced culls. Hurd et al. (1979) saw a decrease in number of fruit when 2/3 of the flowers were removed. However, this reduction in fruit number did not greatly affect total yield, as it was almost entirely compensated by the increase in mean fruit weight from 2.2 oz to 3.8 oz and 2.1 oz to 3.4 oz over two growing periods. In order to provide information on fruit thinning to tomato growers in the mid-south region, the objective of this study was to evaluate the yield and fruit weight of ‘Trust’ tomatoes thinned to three, four, five, or six fruit/cluster compared to unthinned clusters (control).

Materials and Methods

This study was conducted over two short growing seasons, Fall 2009 and Spring 2010, at the Plateau Research and Education Center in Crossville, TN (35°56 N lat.). Studies were performed in 33 x 96-ft double layer polyethylene covered greenhouses using ‘Trust’ tomatoes (DeRuiter Seeds, Columbus, OH). Tomatoes were seeded into plastic germination trays filled with soilless germination mix of peat moss, perlite, and vermiculite (BM2; Berger Peat Moss, Saint-Modeste, QC, Canada) and grown for 1 week. Seedlings were then transplanted into 38-cell plastic trays containing all-purpose soilless mix comprised of peat moss, perlite, vermiculite, and starter fertilizer (BM1; Berger Peat Moss, Saint-Modeste, QC, Canada) and grown for six weeks before being transplanted into five-gal. grow bags containing perlite at the fourth to fifth true leaf stage.

Two plants were transplanted into each bag, with bags spaced 18 inches on-center. The experiment was arranged in a randomized complete block design with two blocks of five treatments with three replications each and ten plants per experimental unit. The experimental layout consisted of five rows spanning the length of the greenhouse with north/south orientation. The center three rows the experimental rows and the outer two rows were borders. Fruit clusters were thinned according to its assigned treatment as soon as all fruits on that cluster were visible. Clusters were thinned to fruits represented as: no thinning (control), three, four, five, or six fruit/cluster. At harvest, the actual number of fruit produced was recorded for each cluster on each plant, and the average number of fruit per cluster across each replication was calculated. Plants were pruned to a single leader and clipped to a string supported by an overhear wire and grown to the 10th flower cluster. Pollination was done by bumblebees (*Bombus impatiens) (*Koppert Biological Systems, Romulus, MI). The fertilizer solution, made up of TotalGro Tomato Special 3N-5.7P-24.1K (TotalGro, Winnsboro, LA), Magnesium sulfate ($Mg(SO_4)_2$), Potassium nitrate (KNO_3), Calcium nitrate ($Ca(NO_3)_2$), and Calcium chloride (CaCl) at a 100% strength supplied nutrients in the following concentrations (mg/L^{-1}): N (190); P (50); K (324); Ca (187); Mg (65); Fe (3). The fertilizer schedule followed recommendations by Snyder (2007). Tomatoes from each treatment/replication were harvested at the pink stage once weekly for 11 weeks. Fall harvest began on October 26, 2009, and ended on January 19, 2010. Spring harvest began on April 23, 2010, and ended on July 1, 2010.

Marketable fruit were graded as follows: jumbo (>3.0 inches), extra-large (2.75 - 3.0 inches), large (2.5 – 2.75 inches), and medium (2.25 – 2.5 inches) (U.S. Dept. Agr., 2007). Weight and number of fruit in each grade was recorded for each treatment replication, and total marketable yield was determined by combining all grades. Number and weight of unmarketable fruit were recorded for any fruit with visible defects or small size (<2.5 inches). Percent cull was determined by dividing the yield of culls by the total yield plus cull yield. Marketable yield refers to all yields from medium to jumbo grades. Average fruit weight was calculated by dividing the total weight by the total number of tomatoes produced. Data was analyzed by SAS (version 9.2; SAS Institute, Cary, NC). The relationship between yield and cluster thinning were determined by regression analysis. Orthogonal polynomials were used to study changes associated with fruit yield and size with varying cluster thinning practices by partitioning the sum of squares into components that were associated with linear and quadratic terms.

Results

In the fall planting (Table 2.1), thinning to three, four, five, or six fruit or not thinning did not drastically change the actual number of fruit produced per cluster. Actual fruit per cluster across all treatments ranged from 2.7 (3 fruit/cluster treatment) to 3.6 fruit (un-thinned control). However, this minor change in fruit/cluster did respond in a quadratic trend for all factors. Jumbo yield decreased as number of fruit/cluster increased (Fig 2.4). The greatest yield of jumbos was achieved by thinning clusters to three or four fruit, which resulted in 5.1 and 4.8 lb/plant, respectively, compared to 3.7 - 4.2 lb/plant when thinned to five or six fruit or not thinned. A quadratic trend indicated that total marketable yield increased as number of fruit/cluster increased (Fig 2.1). Marketable yield was improved by thinning clusters to four fruit (11.7 lb/plant) or six fruit (12.2 lb/plant) or not thinning (12.2 lb/plant) compared to thinning to three fruit (10.6 lb/plant). The percentage of culls produced is also described as a quadratic trend. Percent cull increased as number of fruit/cluster increased (Fig 2.2). Percent cull/plant declined from 9.3% to 6.8% when clusters were thinned to three fruit instead of six or not thinned at all. A quadratic trend showed that average fruit weight declined as number of fruit/cluster increased (Fig 2.3). Fruit weight was increased when clusters were thinned to three fruit (0.42 lb), compared to all other treatments that resulted in fruit weight of 0.37 lb and 0.34 lb.

In the spring planting (Table 2.2), the number of fruit each cluster actually produced was closer to the intended thinning treatment than that seen in the fall planting. The actual fruit number per cluster across treatments ranged from 3.0 (3 fruit/cluster treatment) to 5.4 fruit (unthinned control). Yet, this did not affect the yield of jumbos, total marketable yield, average fruit weight, or percent cull.

Discussion

In the fall planting, thinning clusters to three or four fruit resulted in significantly lower marketable yield, but resulted in a greater number of fruit of jumbo size. These results are similar to those reported by Gosselin (1996), who saw average fruit weight increase by 0.07 oz to 0.29 oz when thinning clusters to three or four fruit. These findings also partially correlate with Hanna (2009), who observed an increase of 0.7 oz in fruit weight when clusters were thinned from four to 3 fruit. When thinning to six fruit or not thinning at all there is greater marketable yield, but these tomatoes are smaller in size and plants have a tendency to produce a greater percentage of culls (Table 2.1). This result is in agreement with Hanna (2009), who saw 1.08 to 2.07 lb/plant more culls with four fruit/cluster than with three fruit/cluster. In the spring planting, thinning treatments did not influence marketable yield, jumbo yield, average fruit weight, or percent cull (Table 2).

There is a fine line between cluster thinning to maximize fruit weight and over-thinning, which may sacrifice yield. This balance was clearly demonstrated in Fall 09, where thinning to three fruit/cluster actually left an average of 2.7 fruit, thinning to four and five fruit/cluster actually averaged 3.2 fruit, thinning to six fruit/cluster averaged 3.4 fruit, and not thinning clusters averaged 3.6 fruit/cluster. Fruit can be lost after cluster thinning due to variables such as disease, physical disorders, or natural abscission. Therefore, if the intent is to thin to three fruit/cluster, it is likely an average of 2.7 fruits/cluster will mature. This can lead to over-thinning and decreased yield, as was seen in the fall planting through a decline in total yield of 1.6 lb/plant when comparing 3.4 actual fruit/cluster to 2.7 actual fruit/cluster. This concept was also demonstrated when comparing the yield differences between the two seasons. Whereas cluster thinning in the fall led to increased production of jumbo tomatoes, it did not affect yield or fruit weight in the spring. So, cluster thinning ‘Trust’ tomatoes in the spring the same way plants are thinned in the fall could possibly lead to over-thinning and decreased yield.

Fruit thinning to optimize the source-sink relationship is not the only factor that affects yield and fruit weight. Light, temperature, and CO_2 concentrations are important factors as well (Bertin, 1995). The seasonal variations in fruit thinning effects that were observed in the current study may be partially explained by differences in light levels. During low light periods (fall), competition among fruit is increased because of low photosynthate availability (Bertin, 1995, Cockshull and Ho, 1995; Ho and Hewitt, 1986) resulting in decreased marketable yield. In periods of high light (spring), flowering is hastened, and the canopy photosynthetic rate increases allowing for more photosynthate partitioning to fruit, thereby decreasing competition among developing fruit. This was seen by McAvoy and Janes (1984) and Gosselin (1996) where, by using supplemental lighting with PPF of 150 micromoles m^{-2} s^{-1} in low light periods, an improvement in plant growth and fruit yield was achieved. Gosselin (1996) found that with minimal to no thinning (five fruit/cluster), marketable yield increased by 0.84 lb/ft^2, and fruit weight was increased by 0.25 oz when supplemental lighting increased from 50 to 150.

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Appendix B

Table 2.1. Yield and fruit size of greenhouse-grown 'Trust' tomato (*Solanum lycopersicum*) thinned to various numbers of fruit per cluster in Fall 2009.

Cluster Thinning Treatment	Actual fruit/cluster	Fruit yield (lb/plant) Jumbo[z]	Fruit yield (lb/plant) Marketable[y]	Mean fruit wt (lb)[x]	Cull (%)
3	2.7	5.1	10.6	0.42	6.8
4	3.2	4.8	11.7	0.37	7.4
5	3.2	3.7	11.1	0.34	8.8
6	3.4	4.2	12.2	0.34	9.3
Control	3.6	4.1	12.2	0.34	9.1
Linear		0.57	0.54	0.70	0.78
Quadratic[w]		0.01	0.001	<.0001	0.01

[z]Jumbo is categorized as any tomato >3.0 inch diameter.
[y]Marketable yield is comprised of medium, large, extra large, and jumbo grades
[x]1.0 lb = 0.4536 kg.
[w]Fruit yield in response to cluster thinning practices described as the following regression equations: jumbo yield/plant y = 4.18 + 0.47(jumbo wt.) – 0.09(jumbo wt.^{2}); marketable yield/plant y = 12.15 – 0.8(marketable wt.) + 0.13(marketable wt.^{2}); percent cull/plant y = 9.0 – 1.41(% cull) + 0.25 (% cull^2); fruit weight/plant y = 0.34 + 0.04(fruit wt.) - .006(fruit wt.^{2}).

Table 2.2. Yield and fruit size of greenhouse-grown 'Trust' tomato (*Solanum lycopersicum*) thinned to various numbers of fruit per cluster in Spring 2010.

Cluster Thinning Treatment	Actual fruit/cluster	Fruit yield (lb/plant) Jumbo[z]	Fruit yield (lb/plant) Marketable[y]	Mean fruit wt (lb)[x]	Cull (%)
3	3.0	11.4	20.5	0.53	10.1
4	4.0	11.0	20.5	0.54	13.5
5	4.8	12.6	20.2	0.56	12.5
6	4.8	11.2	21.3	0.50	8.5
Control	5.4	11.9	20.5	0.53	11.9
Linear		0.84	0.68	0.79	0.22
Quadratic		0.76	0.58	0.40	0.10

[z]Jumbo is categorized as any tomato >3.0 inch diameter.
[y]Marketable yield is comprised of medium, large, extra large, and jumbo grades
[x]1.0 lb = 0.4536 kg.

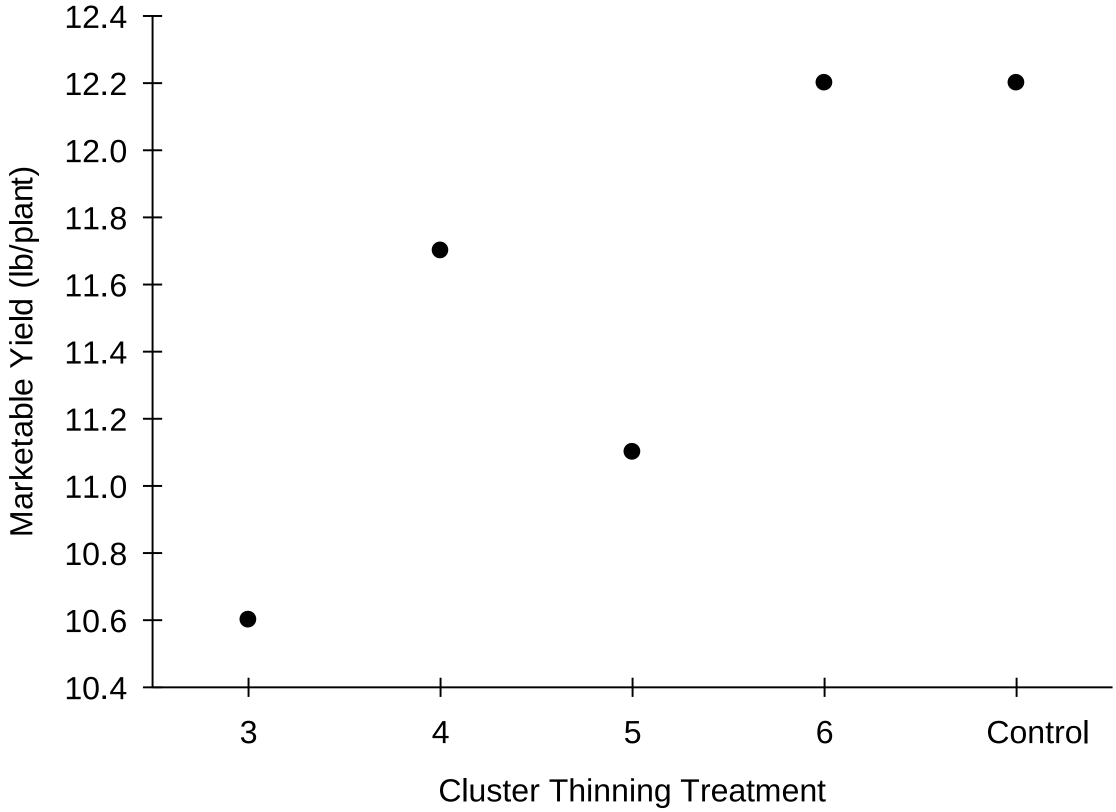

Figure 2.1. Quadratic response of marketable yield to cluster thinning treatments of 3, 4, 5, or 6, fruit per cluster and un-thinned control treatment in Fall 2009, described as the following regression equation y = 12.15 – 0.8(marketable wt.) + 0.13(marketable wt.^{2}).

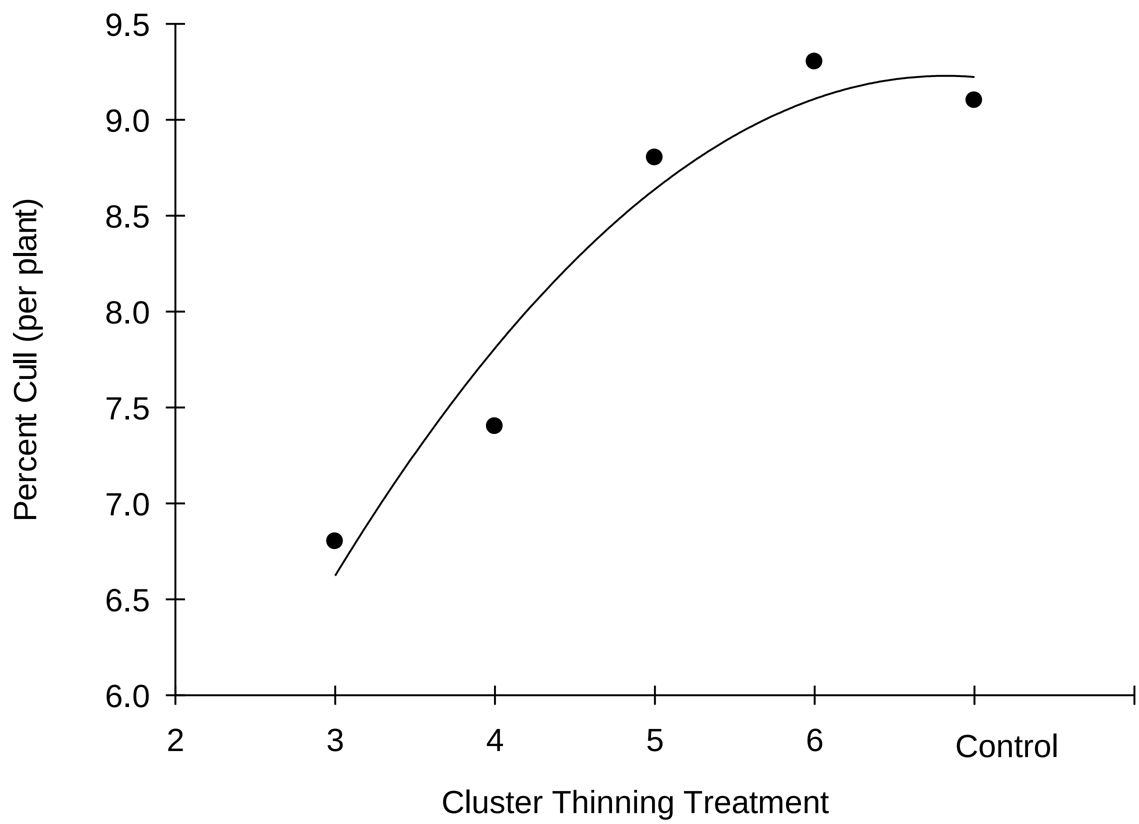

Figure 2.2. Quadratic response of percent cull to cluster thinning treatments of 3, 4, 5, or 6, fruit/cluster and un-thinned control treatment in Fall 2009, described as the regression equation y = 9.0 – 1.41(% cull) + 0.25 (% cull^2).

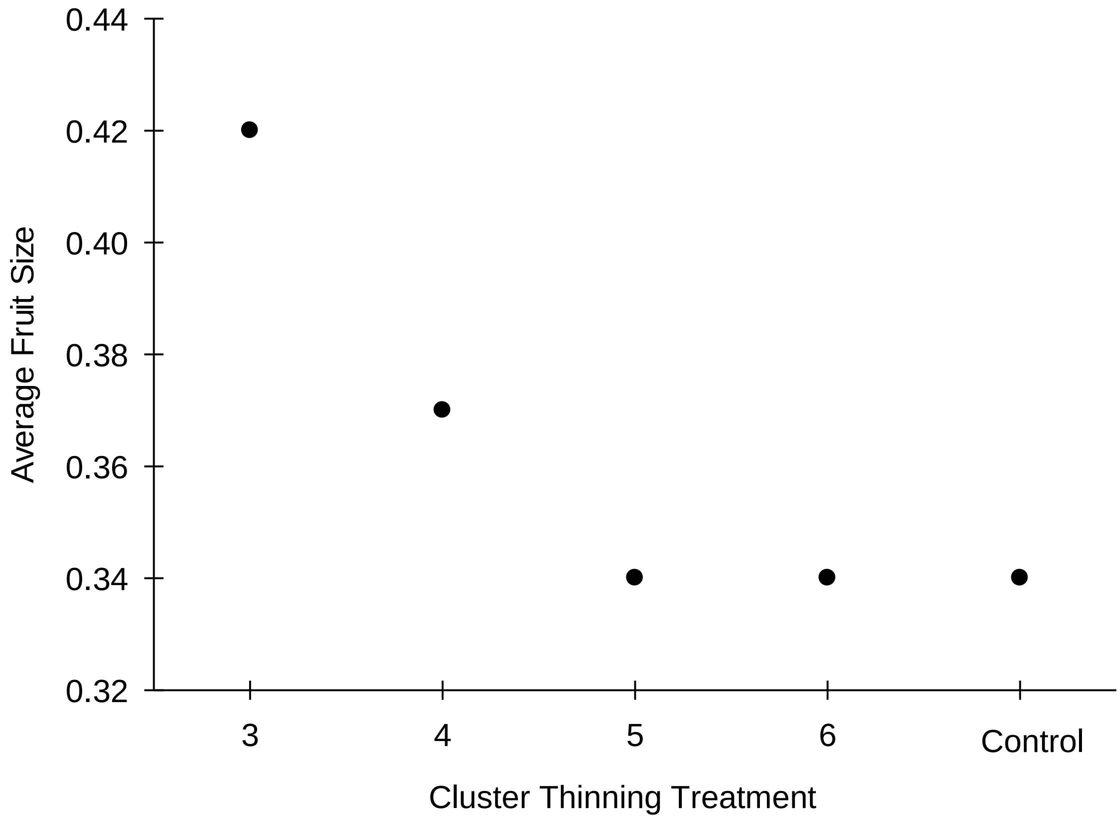

Figure 2.3. Quadratic response of marketable yield to cluster thinning treatments of 3, 4, 5, or 6, fruit per cluster and un-thinned control treatment in Fall 2009, described as the following regression equation y = 0.34 + 0.04(fruit wt.) - .006(fruit wt.^{2}).

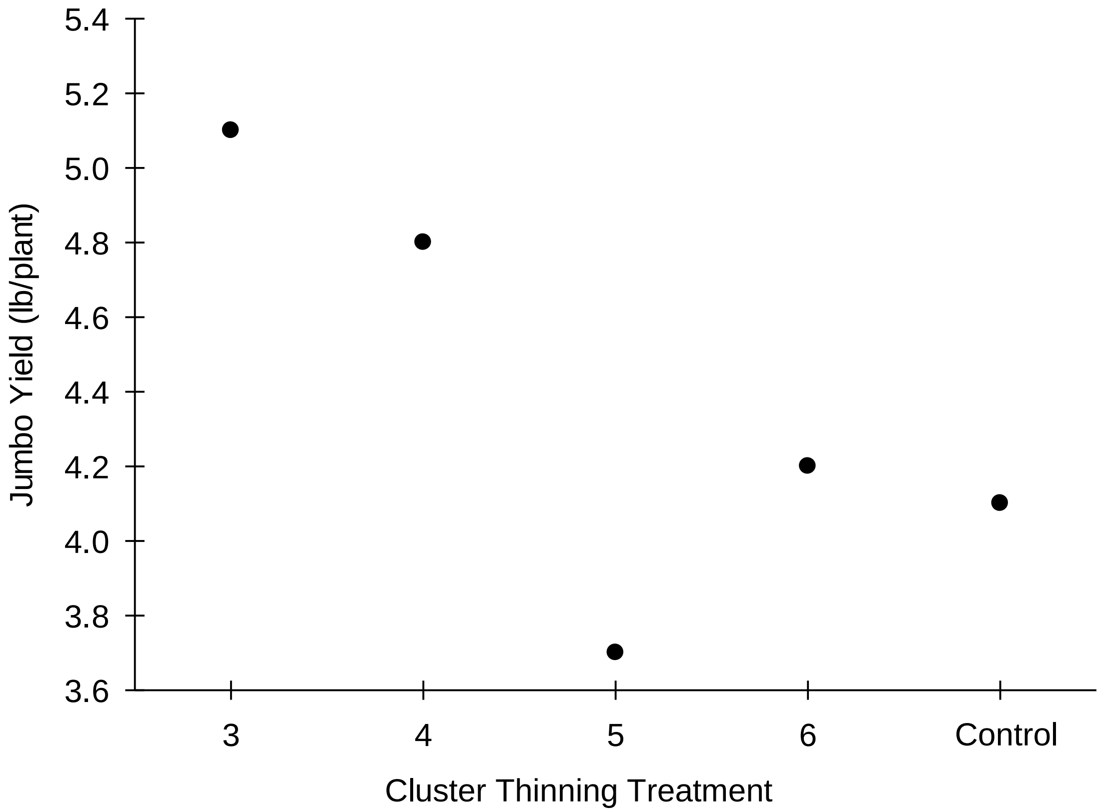

Figure 2.4. Quadratic response of marketable yield to cluster thinning treatments of 3, 4, 5, or 6, fruit per cluster and un-thinned control treatment in Fall 2009, described as the following regression equation $y = 4.18 + 0.47(\text{jumbo wt.}) - 0.09(\text{jumbo wt.}^2)$.

Chapter III

Comparison of biological and conventional pest control utilizing banker plant systems in greenhouse tomato production

Abstract

Concerns surrounding the use of chemical pest control in greenhouses is spurring growers to explore the possibilities of biological pest control (biocontrol). Issues slowing the adoption of these practices consist mostly of financial concerns and fear of failure. Banker plants are a new concept that strives to combat these biocontrol concerns by providing a habitat and alternative food source for natural enemies to sustain their populations and provide long-term pest supression. The objective of this study was to compare the effectiveness of chemical control and biological control on pest populations and evaluate the effectiveness of banker plants as an aid to biocontrol. Chemical pest control and biological pest control had comparable effects on whitefly (*Trialeurodes vaporariorum)* pest populations without affecting tomato yield. In the second study, marigold (*Tagetes patula* 'Janie Yellow') banker plants were successful in *Orius* reproduction, but thrips (*Frankliniella occidentalis*) populations were not affected by the presence of banker plants.

Introduction

Off-season tomato (*Solanum lycopersicum)* production in greenhouses in the Southeast is a small but growing industry. The incentive for producing tomatoes in the fall and winter months is due to growing year round consumer demand, and as a result, the grower receives a premium price for the out-of-season fruit (Kempler, 2004). Benefits of greenhouse production compared to field production include: reduced reliance on soil fumigation and use of methyl bromide; reduced pesticide usage; improved yields due to the control of light, temperature, humidity, irrigation, and fertility; and increased profit by harvesting during the time of year when market prices are highest. While greenhouses provide many benefits and an optimal growing environment for crop production they also provide an optimal environment for insects to quickly establish. Most European producers have already adopted IPM-biocontrols of greenhouse pests.

Two of the most economically important greenhouse pests are western flower thrips (*Frankliniella occidentalis;* WFT) and whiteflies (*Trialeurodes vaporariorum)*. Western flower thrips (WFT) are piercing-sucking insects that have been a major greenhouse problem since the 1980’s. Temperature is the main factor in determining population growth and increase is most rapid at 77 – 86 ^{o}F (Malais et al, 2003). Thrips prefer flowers, which leads to damaged unmarketable fruit even at low pest densities. In ideal conditions, one female thrips can lay 3 eggs and when pollen is available that number can be much higher, doubling populations in 4 days. Another threat of WFT is their ability to vector viruses, the tomato spotted wilt virus being of most concern. The predatory bug, *Orius insidiousus*, has been used to control WFT since 1991. Temperature, day length, and food supply are the main factors affecting their reproduction and development. If pollen is present, the rate of development and survival is greatly improved, although prey is necessary as *O. insidiosus* cannot survive on plant material alone. They are long-lived bugs, with a lifespan of 3 - 4 weeks. They are voracious feeders that feed on all stages of WFT and at high pest densities more WFT are killed than are needed for food. *Orius* are fast movers, fairly good flyers and easily move around to search out prey.

Whiteflies are piercing-sucking insects and are major pests of greenhouse vegetable and ornamental crops throughout the world. The key factors affecting whitefly population growth is temperature and host plant. Unlike most other pests, whiteflies are adapted to lower temperatures; populations have the best growth on tomatoes at temperatures around 68 – 77 ^{o}F. They experience a higher mortality rate at higher temperatures. Whitefly damage is mostly attributed to the excretion of honeydew that encourages sooty mold growth on leaves and fruit. Whitefly infestations are typically concentrated in a few places, as they typically stay close together until populations are too dense. For decades, *Encarsia formosa* has been used to control whiteflies. The parasitic wasps success is due to the fact that it develops faster than the whitefly and its population is made up mostly of females so mating is not necessary for reproduction (Malais et al, 2003). They also lay approximately 5 – 15 eggs a day averaging 150 eggs over its lifespan (Malais et al, 2003). They have a highly active searching ability and clustered whitefly infestations are quickly and easily located.

Chemical control measures are the most common pest control practice used in U.S greenhouses. However, the issues surrounding the use of chemical sprays are prompting growers to explore other control measures and are making biocontrol more attractive. The major concerns are: development of pest resistance due to the continued use of the same pesticides (Opit, 2009; McMahon, 1992); discontinuations of reliable pesticides (McMahon, 1992); limited pesticide options for greenhouse use since the enclosed area increases risks to human health; environmental concerns, exposure of the applicator to the chemicals, and consumer trends desiring chemical free produce. Another problem is that many growers act preventatively by applying pesticides on a set schedule regardless of pest presence. This practice often leads to unnecessary pesticide applications that magnify the problems of resistance, human exposure, and environmental concerns, as well as increase the cost of production (chemicals and labor), thereby reducing profitability (Opit, 2009). There is ample evidence to show that biological control can be a successful alternative or additive to chemical control in the greenhouse vegetable industry worldwide. Whitefly control by *E. formosa* on tomatoes was shown to be successful with nymph parasitism between 47 and 97% by the end of the tomato growing season depending on temperature, pest density, and biological release rates (Gu, 2008; Lopez, 2010; Tello, 2007; Vis, 2008). Biological control or integrated pest management using *Orius* spp. gave acceptable and comparable, if not better, control of thrips in comparison to chemical control (Santonicola, 1998; Vergara, 2009). Two releases of *Orius* spp. controlled thrips to acceptable levels with negligible damage to fruit (Choi, 2009). Spider mites were adequately controlled by *Phytoseiulus* spp. provided a high predator-prey ratio was maintained and pest control by *P. persimilis* was comparable to conventional chemical control (Choi, 2009; Ferrero, 2011; Mansour, 2010). Release of *Aphidius colemani* decreased aphid pest populations (Moon, 2011; Cota, 2009). Despite the demonstrated effectiveness of biocontrol, growers were described as reluctant to adopt these practices primarily because they have: 1) low threshold for pest damage; 2) limited information on how best to implement biocontrol, and 3) attitude that biocontrols were too expensive and impractical (Opit, 2009).

Biological control can be effective if conditions are ideal, but the system is not without hindrances. Success of biocontrol is highly dependent on timely intervention which requires careful scouting. If pest numbers are not detected in the earliest stages of invasion, natural enemies will have difficulty keeping populations under control, especially given the time lapse of ordering beneficial insects and waiting for shipments to arrive. Biocontrol also requires high predator populations for adequate control and often the crop may not be able to provide an ideal environment for predators to persist. Overnight shipping costs and the need for multiple releases of predators make biocontrol less cost effective. The use of banker plants is one approach to combating these costs and concerns. Banker plants are plants grown alongside a crop that provide prey to support the beneficial predators/parasitoids. By supplying the predators/parasitoids with a ready food source and reproduction site, the banker plants allow the population to maintain itself. Benefits of banker plants include economic rewards, minimal demand on grower's time, low risk of failure, easy and effective scouting, and reduced reliance on chemical controls. Banker plants such as barley (*Hordeum vulgare)*, corn (*Zea mays)*, marigolds (*Tagetes patula)*, lantana (*Lantana camera)*, and alyssum (*Lobularia maritime)* are generally inexpensive, easy to grow, and make initial start-up costs low. The ongoing investment is low as well, since ideally the beneficial population sustains itself, thereby reducing the costs of overnight shipping and repeated releases of lab-reared natural enemies. Also, the time normally spent on spraying pesticides in the greenhouse is reduced or eliminated. If pest populations become too high and are resulting in damage when using biocontrol, pesticides can be used to knock down populations. The established predators/parasitoids can be protected from chemicals by temporarily removing the banker plants from the greenhouse and replacing them once safe, thereby reducing the risk of failure. The banker plants allow significant advantages for scouting because they offer specific sites where insect presence can be accurately assessed, instead of patrolling the entire production area and perhaps inaccurately measuring pest numbers. Greenhouse pests are difficult to spot and if miscounted they may be allowed to establish and reach levels difficult to control. Having natural enemies already established permits early intervention when pest outbreaks occur. Opit (2009) concluded that predatory mites can be used effectively as long as they were applied soon after initial spidermite invasion of the crop. Pre-established banker plant/predator systems would assist in the success of biocontrol because, by the time the pest is observed, the predator/parasitoid is ordered and received, pest populations have often risen to infestation levels not as easily controlled biologically. With banker plants in place the predators/parasitoids are present before such outbreaks occur and can be controlled more efficiently. Thus, shifting from reactive controls to proactive controls and reducing or eliminating the need for chemical controls that can be harmful to the environment and human health.

The great potential of *Orius insidiosus* for thrips control is hindered because it does not navigate the glandular hairs on tomatoes well (Malais et al,

2003) is expensive to release and is slow to establish (Bennison, 2011). Thrips are attracted to yellow flowers, making marigolds ideal banker plants because once there, they are easily attacked by an established *Orius* population that also prefers flower habitats. *Orius'* ability to feed on marigold pollen can help sustain populations until prey is present. Having a natural enemy population (via banker plant) in place before a pest outbreak occurs will be advantageous in controlling the damage.

In recent years, banker plant systems that support 19 natural enemies of 11 pest species have been studied in greenhouse and field environments on ornamentals and fruits and vegetables (Frank, 2010). Glenister et al. (2006) found that a floral banker plant consisting of marigolds, lantana, and alyssum served as both a reproduction site for *Orius* sp. and as a magnet for attracting thrips off the crop and onto the banker plant. However, there is still little definitive information available on optimal banker plant systems or how best to create, maintain, and implement them (Frank, 2010). Banker plant systems are complex relationships that require a certain amount of trial and error when planning a program that will work best for a specific crop and environment. Our objective is to evaluate a banker plant/predator system for control of thrips in greenhouse tomato production; and to compare effectiveness and cost efficiency of biocontrol versus chemical control.

Materials and Methods

The first study compared biocontrol to conventional chemical pest control. It was conducted at the Plateau Research and Extension Center in Crossville, TN in Fall 2009 and Spring 2010. Two isolated 33 x 96 ft polyethylene covered greenhouses containing hydroponic tomatoes were used. The first house functioned as the control with pests controlled by chemical means and the second house utilized biocontrol. The control house was chemically treated as needed. Pests were not that problematic in the fall the chemically treated house and had only two insecticide sprays of Admire pro (imidacloprid) and Lannate (methomyl) at a plant age of 9.5 and 19 weeks, respectively. The whitefly predator *Encarsia formosa* was released once on 1 Nov. 2009 when plants were 17 weeks old. Fall tomatoes were seeded on 6 July 2009 into plastic germination trays filled with soilless germination mix of peat moss, perlite, and vermiculite (BM2; Berger Peat Moss, Saint-Modeste, QC, Canada). On July 15, seedlings were transplanted into 38-cell plastic trays containing all-purpose soilless mix comprised of peat moss, perlite, vermiculite, and starter fertilizer (BM1; Berger Peat Moss, Saint-Modeste, QC, Canada). On August 11 when plants were at the fourth to fifth true leaf stage, tomatoes were transplanted into five-gal. grow bags containing perlite. In the spring, there were a total of nine releases of *Encarsia formosa*, beginning on 12 Feb. 2010 when plants were 6.5 weeks old. Insecticides used for control of whiteflies in the spring were Admire pro (imidacloprid), Spintor 2SC (spinosad), Asana XL (esfenvalerate), and Lannate (methomyl), for a total of ten treatments beginning on 3 Feb. 2010 when plants were five weeks old. The biocontrol house also received two chemical knockdown sprays near the end of the crop. On May 15th, safer soap was applied and on June 11th a combination of Endura and Asana was applied.

Spring seeding took place on 28 Dec. 2009, transplanting took place on 8 Jan. 2010, and planting in greenhouse was done on 1 Feb. 2010. Pests were scouted weekly for eight weeks in the fall and 16 weeks in the spring by two different methods; 1) yellow sticky cards; and 2) five leaves from four randomly selected tomato plants. Each greenhouse was divided into four quadrants. One quadrant contained two and a half rows with a total of 155 plants. One sticky card was placed at the top of the plant canopy in the center of each quadrant. Tomato plants were randomly chosen for sampling within each quadrant. The experimental design for the pests was a randomized complete block with replications in a split-split plot treatment design. The two seasons were analyzed as blocks, the two greenhouses as the main plot treatments, scouting date as the split plot, and there were four reps of two (whitefly) scouting methods as the split-split plot. The experimental design for biological insects differed from the pest's experimental design, since they were only present in one greenhouse. A randomized complete block design with replications and repeated measures treatment design was used, with seasons analyzed as blocks, four replications of scouting method as treatment, and scouting dates as the repeated measure. Insect counts were analyzed using analysis of variance mixed models with SAS software (version 9.2; SAS Institute, Cary, N.C). The analysis tested for season, treatment, scouting method, and scouting date by LSD mean separation; significance of main effects and interactions were determined by the F test with a P-value of 0.05.

Total marketable yield and percent cull yield data between both greenhouses was compared to determine affect of pest control methods on overall productivity. Tomatoes from each greenhouse were harvested at the pink stage once weekly. Marketable fruits were graded as follows: jumbo (>3.0 inch diameter), extra-large (2.75 - 3.0 inches), large (2.5 – 2.75 inches), and medium (2.25 – 2.5 inches) (U.S. Dept. Agr., 2007). Weight and number of fruit in each grade was recorded for each treatment replication, and total marketable yield was determined by combining all grades. Number and weight of unmarketable fruit (cull) was recorded for any fruit with visible defects or small size (<2.5 inches). Percent cull was determined by dividing the yield of culls by the total yield plus cull yield. Marketable yield refers to all fruit from medium to jumbo grades. Experimental design was a randomized complete block with replications. Yield data was analyzed by LSD mean separation using analysis of variance mixed models with SAS (version 9.2; SAS Institute, Cary, N.C). Significance of main effects was determined by the F test.

The second study was a smaller study to more closely evaluate the performance of banker plants in rearing predator populations compared to predator populations when bankers are not present. It was performed in two isolated 30 ft x 30 ft glass greenhouse bays in Spring 2010 at the University of Tennessee in Knoxville, TN. One bay functioned as the treated bay with a marigold banker plant/predator system and the second bay functioned as the control using biological control but with no banker plants. Both bays contained hydroponic ‘Trust’ tomatoes planted in composted pine bark (Sunshine Pro Pine

Soil Conditioner; Sun Gro Horticulture, Canada) on 16 Feb. 2010 at 7 weeks old. Marigolds were used as banker plants to supply pollen to maintain *Orius insidiosus* populations for control of WFT. Marigolds were seeded into 1-gallon pots containing 50% promix and 50% perlite. Once in bloom they were dispersed into biocontrol treated greenhouse at a rate of 1/11 ft^2. Shipments of *Orius insidiosus* were obtained from IPM Laboratories, Inc (Locke, NY).

Marigold plants were placed in greenhouse bays on 16 Mar 2010. Predators were released as needed in the control bay and according to the banker/predator system in the treated bay. On 10 Apr 2010 and 26 Apr 2010, approximately 250 *O. insidiosus* were distributed in each bay. On 16 May 2010, 500 *O. insidiosus* were released into the control bay, for a total of two releases in the treated bay and three releases in the control bay over an eight week period. Thrips and *Orius* were scouted every 7-10 days for eight weeks (a total of six occurrences) by three different methods: 1) yellow sticky cards; 2) five leaves from four randomly selected tomato plants, and 3) four randomly selected marigold plants (not applicable to the control bay). The experimental design for thrips was a randomized complete block with replications with a repeated measures treatment design. The two greenhouse bays analyzed as blocks, there were two (sticky cards) or four (banker or tomato plants) replications of three scouting methods in the main plot treatment, and the scouting days as the repeated measure. Insect counts were analyzed using analysis of variance mixed models with SAS software (version 9.2; SAS Institute, Cary, N.C). The analysis tested for greenhouse bays, scouting method, and scouting date by LSD mean separation; significance of main effects and interactions were determined by the F test with a P value of 0.05. For *O. insidiosus* counts a log transformation was done and the un-transformed means are reported along with the transformed P value.

Results and Discussion

Experiment 1

Pest populations during the fall and spring seasons did not differ statistically, thus their data was combined for further analysis. The whitefly pest populations did not differ between the biologically controlled greenhouse and the conventionally controlled greenhouse (Table 3.1). Over the 16 week period, whitefly numbers in the biological greenhouse averaged 60.9/week across both plant and sticky card scouting methods, whereas in the conventional greenhouse they averaged 63.3. Total marketable yield and percent cull yield of both houses did not differ (Table 3.4). In fall, the chemically treated house produced a marketable yield of 11.3 lb/plant with 9 % culls/plant, and the biocontrol house produced 11.7 lb/plant with 7.6 % culls/plant. In the spring, the chemically treated house produced a marketable yield of 20.6 lb/plant with 11.4 % culls/plant, and the biocontrol house produced 20.7 lb/plant with 11.1 % culls/plant. In the last few weeks of spring production, whitefly populations were very high and sooty mold was present resulting in a slightly higher percent cull than usual, however yield results indicate that *Encarsia formosa* was equally effective as chemical sprays in controlling them. The seasonal population trends of whiteflies showed that in fall the growth rates were very similar (Figure 3.1); however this time period only accounts for the first half of the season when insect pressure is relatively low. In spring, whitefly populations grew at a steady and slightly slower pace when controlled biologically compared to chemically controlled whitefly populations that grew in a series of peaks and falls that correlated with every spray incidence (Figure 3.2). Scouting dates differed significantly for whitefly populations (Table 3.2). Whitefly populations from June 9 to 29, ranging from 189.2 to 254.5, were significantly higher than populations from Feb 24 to May 26 where whitefly numbers only ranged from 0.16 to 49.4. Methods for scouting whiteflies were equal between yellow sticky card and tomato plants, 67.2 and 56.9, respectively.

What is significant in this experiment is that it indicated that biocontrol can work as well as chemical if predator/prey ratios are maintained and environment is conducive. The economical cost comparison between the chemically controlled house and the biologically controlled house showed that biological control was less expensive in the fall (which was only accounting for the first part of the season) and more expensive in the spring (Table 3.5). In the fall, labor hours were about equal with the chemical house taking 30 more minutes. The chemical supply costs (consisting of chemicals, sprayer, and protective clothing) outweighed the biological supply costs by $70. The total cost of control was greater in the chemical house by $73. However, this estimate only accounts for eight weeks of production. Labor to release biological insects took ten hours less than it took to mix and apply chemicals in the spring. Total cost for chemical control was approximately $100 less than that of biological control. The bulk of the biocontrol cost was shipping which totaled $215, while the cost of the natural enemies was only $161. These cost estimates are calculated for a 3000 ft^2 greenhouse. For larger greenhouses it is likely that the shipping costs would remain about the same, making the cost difference between chemical and biological control narrower. It is also possible that a higher selling price could be acquired for tomatoes grown chemical free, which would offset the higher biocontrol costs.

Experiment 2.

The population of thrips was not significantly affected by presence of marigold banker plants, and their numbers did not differ between scouting dates, or scouting method (data not shown). The thrips populations were not different between the two greenhouse bays, control and banker plant bays. This indicates that thrips were controlled just as well in the banker plant bay with only two releases of *O. insidiosus* as they were in the control bay with three releases in a time span of eight weeks. *O. insidiosus* populations were not significantly affected by the presence of banker plants; however, there was a tendency for their numbers to be higher when banker plants were available. *O. insidiosus* populations averaged 0.05 in the control bay and 1.3 in the treated bay (Table 3.3). *Orius insidiosus* nymphs were seen on two occasions in the marigold banker plants, indicating that reproduction was successful in the treated bay, whereas, nymphs were never seen in the control bay. Because of this, it could be speculated that if pest outbreaks had occurred earlier in the season, it is probable that more releases would have been needed in the control bay, where as the treated bay had successful reproduction of *O. insidiosus* in the banker plant allowing the population to sustain itself and maintain numbers even higher than those in the control with only two releases.

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Appendix C

Table 3.1. Number of whiteflies in chemical and biological pest control tomato greenhouses counted per week across both plant and sticky card scouting methods in Fall 2009 and Spring 2010.

Treatment	Whitefly
Biological	60.9 a[z]
Chemical	63.3 a
P-value	0.84

[z] Means within columns followed by the same letter are not significantly different at $P < 0.05$ by least significant difference (LSD).

Table 3.2. Number of whiteflies in greenhouse grown tomatoes scouted weekly over a 16 week period in Fall 09 and Spring 2010.

Scouting Week	Whitefly
1	0.16 e
2	0.06 e
3	0.03 e
4	0.47 e
5	0.31 e
6	0.22 e
7	1.40 e
8	2.60 e
9	3.70 de
10	25.10 de
11	49.40 de
12	78.60 cd
13	189.20 ab
14	149.40 bc
15	237.80 a
16	254.50 a
P value	<.0001

[z] Means within columns followed by the same letter are not significantly different at $P < 0.05$ by least significant difference (LSD).

Table 3.3. Number of thrips and *Orius* in greenhouse tomato production using biological control with and without banker plants in Spring 2010.

Treatment	Thrips	Orius
Greenhouse without banker plants	7.94 a	0.05 a
Greenhouse with banker plants	7.73 a	1.30 a
P value	0.48	0.50

[z] Means within columns followed by the same letter are not significantly different at $P < 0.05$ by least significant difference (LSD).

Table 3.4. Marketable yield and percent cull yield for chemically controlled and biologically controlled tomatoe greenhouses in Fall 2009 and Spring 2010.

Treatment	Fall 2009		Spring 2010	
	Total yield (lbs/plant)	Cull (%/plant)	Total yield (lbs/plant)	Cull (%/plant)
Chemical	11.3 a	9.0 a	20.6 a	11.4 a
Biocontrol	11.7 a	7.6 a	20.7 a	11.1 a
P value	0.37	0.29	0.39	0.41

[z] Means within columns followed by the same letter are not significantly different at $P < 0.05$ by least significant difference (LSD).

Table 3.5. Economic comparison of chemical pest control and biological pest control in greenhouse grown tomatoes in Fall 2009 and Spring 2010. Costs calculated for a 3000 ft^2 greenhouse.

	Fall 2009		Spring 2010	
Expenses	Chemical	Biological	Chemical	Biological
Labor hours	2.5	2.0	23.5	13.5
Labor cost	$21.3	$17.0	$199.8	$114.8
Chemical supplies[z]	$190.0	NA	$213.3	$19.0
Biocontrol supplies[y]	NA	$42.8	NA	$161.9
Shipping cost	NA	$78.0	NA	$215.9
Total cost	$211.3	$137.8	$413.1	$511.6

[z] Cost of labor given $8.50/hour. For chemical house these labor hours consist of mixing and applying sprays. For biological house, labor hours consist of releasing beneficial insects.

[y] Supplies for chemical house consist of chemicals used, sprayer, and protective clothing. Supplies for biological house consist of beneficial insects.

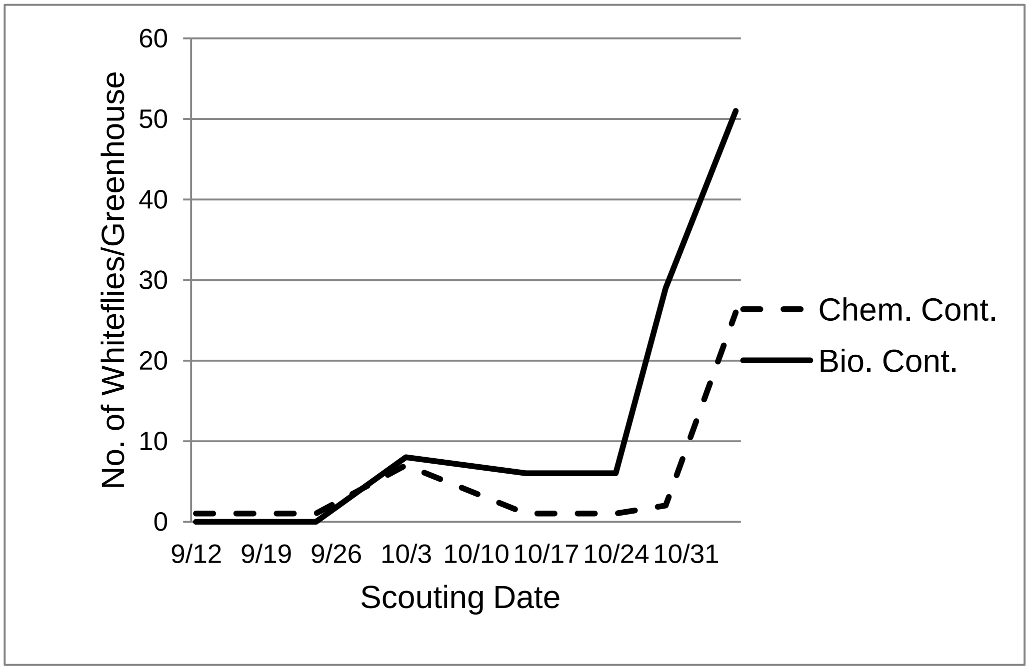

Figure 3.1. Total number of whiteflies on four sticky traps and four tomato plants in chemically controlled and biologically controlled tomato greenhouses on each insect scouting date in Fall 2009. Scouting began when plants were 9 weeks old.

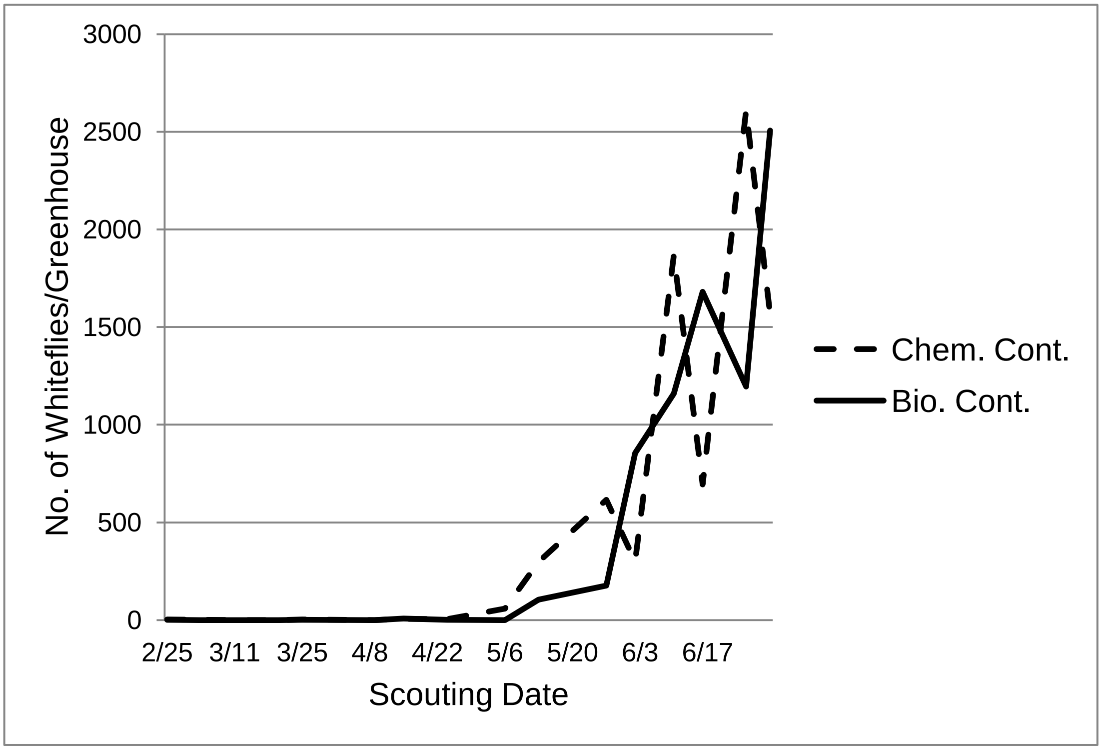

Figure 3.2. Total number of whiteflies on four sticky traps and four tomato plants in chemically controlled and biologically controlled tomato greenhouses on each insect scouting date in Spring 2010. Scouting began when plants were 8 weeks old.

Conclusions

Through these studies it can be concluded that an in-row spacing of 16 – 20 inches (18 inches being ideal) is recommended for 'Trust' tomato growers wanting to maximize greenhouse space without negatively affecting yield or fruit weight. A production system that prunes two plants per bag each to a single leader is most profitable in the fall; whereas, in the spring it is more profitable to prune one plant per bag to a double leader. For growers wanting to maximize fruit weight without sacrificing yield, it is recommended that greenhouse grown 'Trust' tomatoes be thinned to four fruit in the fall. In the spring, when light levels are greater, cluster thinning is not necessary as yields and fruit weight are not affected.

Chemical pest control and biological pest control had the same effect on whitefly populations without affecting tomato yield. However, the cost of weekly whitefly parasite introductions did outweigh the cost to control whiteflies chemically. In the second experiment, marigolds were successful in *Orius* reproduction, but thrips populations were not affected by the inclusion of banker plants. However, the reproduction of *Orius* on marigolds did allow for less predator applications in the biocontrol bay while maintaining the same level of thrips control.

VITA

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