

STUDIES ON THE MANAGEMENT OF SWEETPOTATO WHITEFLY, *BEMISIA TABACI*,  
AND TOMATO YELLOW LEAF CURL VIRUS IN TOMATO

by

MEREDITH M. DEMPSEY

(Under the Direction of David G. Riley)

ABSTRACT

A field crop tunnel experiment was conducted to study viruliferous whitefly, *Bemisia tabaci* and *Tomato yellow leaf curl virus* (TYLCV) spread across virus-susceptible tomatoes as mitigated by insecticide. Both whitefly presence and viral presence were distributed in close proximity to the source plant with very minor impact of insecticide treatments. A split-split plot experiment was used to examine the effects of TYLCV-resistant cultivars, new insecticides, and reflective mulch treatments efficacy on reducing whitefly incidence and TYLCV spread. Results showed that reflective mulches significantly reduced whitefly incidence and presence of TYLCV symptoms. Reflective mulch treatments trended toward greater yields in comparison to the non reflective mulch. The sub-treatment of different chemicals showed that the two insecticide treatments suppressed whitefly populations, but there was no significant effect on TYLCV incidence compared with the check. Virus-resistant tomato cultivars did not impact whitefly incidence, but showed the strongest reduction in virus disease incidence compared with the check. Host plant resistant tomato and reflective mulches provided the bulk of the protection against TYLC disease incidence and damage in these studies.

INDEX WORDS: whitefly, *Begomovirus*, virus transmission, IPM

STUDIES ON THE MANAGEMENT OF SWEETPOTATO WHITEFLY, *BEMISIA TABACI*,  
AND TOMATO YELLOW LEAF CURL VIRUS IN TOMATO

by

MEREDITH M. DEMPSEY

Bachelor of Science, University of Delaware, 2013

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment  
of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2015

© 2015

MEREDITH M. DEMPSEY

All Rights Reserved

STUDIES ON THE MANAGEMENT OF SWEETPOTATO WHITEFLY, BEMISIA TABACI,  
AND TOMATO YELLOW LEAF CURL VIRUS IN TOMATO

by

MEREDITH M. DEMPSEY

Major Professor: David G. Riley

Committee: Rajagopalbabu Srinivasan

Alton “Stormy” Sparks, Jr.

Electronic Version Approved:

Suzanne Barbour  
Dean of the Graduate School  
University of Georgia  
August 2015

## DEDICATION

I would like to dedicate this to my parents Jayne and Kevin Dempsey; without them I would not be where I am now. I would also like to dedicate this to my sister Erin who motivates me to struggle through the hard things. Lastly, I would like to thank all of the friends I have made along the way and my dogs that have made this experience less lonely and more enjoyable.

## ACKNOWLEDGEMENTS

I would like to acknowledge Dr. David Riley and Dr. Rajagopalbabu Srinivasan for presenting me with this opportunity and guidance they have provided. I would also like to acknowledge Mr. Stan Diffie, Saioa Legarrea, Anita Shrestha, Pin-Chu Lai, Nan Bostick, Julia Kitchens, Simmy McKeown, Nikki Bowman, Jenna Kicklighter, Abby Applewhite, Gordon MacQuirter, Cassidy Long and Donnie Cook for all the help they gave me.

## TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS.....	v
LIST OF TABLES .....	viii
LIST OF FIGURES .....	x
CHAPTER	
1 INTRODUCTION .....	1
2 LITERATURE REVIEW .....	10
<i>Bemisia tabaci</i> Biology .....	10
<i>Tomato yellow leaf curl virus</i> (TYLCV) Biology.....	14
Integrated Management of <i>Bemisia tabaci</i> and <i>Tomato yellow leaf curl</i> <i>virus</i> .....	23
References .....	33
3 INSECTICIDE AND PROXIMITY EFFECTS ON THE SPREAD OF TOMATO YELLOW LEAF CURL VIRUS AND WHITEFLIES .....	57
Introduction .....	59
Materials and Methods .....	61
Results and Discussion .....	64
Conclusion.....	69
References Cited.....	73

4	INTEGRATED MANAGEMENT TACTICS FOR BEMISIA TABACI AND TOMATO YELLOW LEAF CURL VIRUS .....	93
	Introduction .....	97
	Materials and Methods.....	100
	Results and Discussion.....	102
	Conclusion .....	112
	References .....	116
5	SUMMARY.....	136

## LIST OF TABLES

	Page
Table 3.1: Effects of treatments and their interactions on whiteflies and TYLCV incidence on tomatoes under all treatments in 2013 and 2014 .....	77
Table 3.2: Effects of treatments and their interactions on marketable and unmarketable yield on all treatments in 2013 and 2014 .....	78
Table 3.3: Effects of chemical and tunnel presence on whitefly and TYLCV incidence under all treatments in 2013 and 2014 .....	79
Table 3.4: Distance from source plant effect on whitefly and TYLCV incidence in 2013 and 2014.....	80
Table 3.5: Date effect on whitefly and TYLCV incidence in 2013 .....	81
Table 4.1: Effects of treatments and their interactions on whitefly incidence, TYLCV symptom and yield in 2013 .....	119
Table 4.2: Effects of treatment and their interactions on whitefly incidence, TYLCV symptom and yield in 2014 .....	120
Table 4.3: Effects of treatment and their interactions on mean immatures in 2013 and 2014 ...	121
Table 4.4: Effects of treatment and their interactions on whitefly incidence and TYLCV rating in 2013 and 2014 .....	122
Table 4.5: Effects of treatment and their interactions on immatures in 2013 .....	123
Table 4.6: Effects of treatment and their interactions on immatures in 2014.....	124

Table 4.7: Effects of treatment and their interactions on unmarketable and marketable yield in  
2013 and 2014 .....125

## LIST OF FIGURES

	Page
Figure 2.1: <i>Tomato yellow leaf curl virus</i> genome .....	17
Figure 2.2: Temporal movement of TYLCV incidence through insect vector <i>Bemisia tabaci</i> .....	22
Figure 3.1: Cross-section of the tunnel used in this study .....	83
Figure 3.2: Overall means of whitefly incidence under tunneled treatments only in 2013.....	84
Figure 3.3: Overall mean percentages of TYLCV symptomatic plants under tunneled treatments in 2013 .....	85
Figure 3.4: Overall mean whitefly incidence and TYLCV symptom severity rating under tunneled treatments in 2014.....	86
Figure 3.5: Overall average whitefly incidence by distance from source plant under tunneled treatments only in 2013 (a) ad 2014 (b) .....	87, 88
Figure 3.6: Overall average TYLCV symptom severity rating by plant number under tunneled treatments only in 2013 (a) and 2014 (b). .....	89, 90
Figure 3.7 Marketable fruit weight yield by plant number under tunneled treatments only in 2013(a) and 2014(b). .....	91, 92
Figure 3.8: Marketable fruit weight under tunneled treatments only in 2013 (a) and 2014 (b)	93, 94
Figure 4.1. Mulch treatment effect on mean whitefly incidence for 2013 trial (a) and 2014 trial (b) with dates with significant treatment effects indicated by an “*” (P < 0.05)	127,

Figure 4.2. Insecticide treatment effect on mean whitefly incidence for 2013 trial (a) and 2014 trial (b) with dates with significant treatment effects indicated by an “\*” (P < 0.05) 129, 130

Figure 4.3 Cultivar treatment effect on mean whitefly incidence for 2013 trial (a) and 2014 trial (b) with dates with significant treatment effects indicated by an “\*” (P < 0.05) 131, 132

Figure 4.4. Mulch effect on TYLCV ratings by date in 2014 with dates with significant treatment effects indicated by an “\*” (P < .05).....133

Figure 4.5. Insecticide effect on TYLCV ratings by date in and 2014 with dates with significant treatment effects indicated by an “\*” (P < 0.05) .....134

Figure 4.6 Cultivar effect on TYLCV ratings by date in 2014 with dates with significant treatment effects indicated by an “\*” (P < 0.05) .....135

## CHAPTER 1

### INTRODUCTION

#### ***Tomato yellow leaf curl disease history and economic impact***

*Tomato yellow leaf curl virus* (TYLCV), principally transmitted by biotype B sweetpotato whitefly, *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae), is a common virus that causes disease of tomato crops in the southeastern United States. TYLCV is a member of the genus *Begomovirus* of family *Geminiviridae* (Fauquet et al. 2000). TYLCV was first reported in Israel in the late 1930s (Pico et al. 1996) in the 1950s in Jordan and soon spread to Middle East, Central Asia, North and West Africa, Southeast Europe, the Caribbean Islands and Mexico (Czosnek 2007). The first report of TYLCV in Georgia occurred in 1998 (Momol et al., 1999). Tomato is an important crop for the southeastern USA region. Over 46,000 acres are planted in the Southeast and valued at upwards of \$850 million annually (USDA 2012). Florida alone produces 33% of the U.S. tomatoes (USDA 2012). Tomato production in Georgia specifically, has decreased by approximately 21% from years 2007 to 2012 (USDA 2012). This decrease was partially contributed to by the presence of whitefly-transmitted viruses such as TYLCV, but the USA salmonella outbreak of 2008 contributed to the major, abrupt decline of Georgia tomato production in 2009 (Riley, D., personal communication). TYLCV affects all the southeastern tomato producing states, but traditionally, TYLCV is the most severe in Florida compared to other states, including Georgia.

TYLCV is a monopartite *begomovirus* and depends on its capsid protein (CP) for whitefly transmission and host plant acquisition (Rybicki et al. 2000, Caciagli et al. 2009). It is postulated that capsid proteins facilitate virion assembly required for systemic infection

(Ghanim et al. 2001). Capsid proteins interact with different receptors in whitefly tissues; CPs involvement in receptor binding creates specificity in a vector's ability to facilitate certain strains of TYLCV (Czosnek and Ghanim 2012). Endosymbiotic bacteria, GroEL homologue, binds to TYLCV CP to protect virion particles from degradation in acidic hemolymph when crossing through tissues (Morin et al. 1999). Studies found that whitefly mutants not containing GroEL homologue protein were unable to transmit TYLCV as efficiently as non-mutants (Morin et al. 1999). TYLCV has coevolved with its whitefly vector to develop endosymbiotic chaperonins and CPs that better fit with whitefly biotypes that have more complimentary receptors (Czosnek et al. 2012). As a result of this coevolution, transmissibility is more efficient among vectors and virus strains belonging to the same geographic region (McGrath and Harrison 1995).

### **Vector *Bemisia tabaci***

*Bemisia tabaci* has been reported on over 600 plant species, half of which belong to one of seven common vegetable families: *Fabaceae*, *Asteraceae*, *Malvaceae*, *Solanaceae*, *Euphorbiaceae* (Mound and Hasley, 1978) *brassicaceae* and *cucurbitaceae* (McAuslane, H. and Smith, H.A., 2000). In addition to vegetable crop hosts, *B. tabaci* has many weed hosts (Simmons et al. 2000, Oliveira et al. 2001). The weed host families that have been documented in America include: *Cleomaceae*, *Fabaceae*, *Rubiaceae*, *Sterculiaceae*, *Verbenaceae*, *Solanaceae*, *Malvaceae*, *Rubiaceae*, *Euphorbiaceae* (Oliveira et al. 2000b), *Hypericaceae*, *Valerianaceae* and *Asteraceae* (Simmons et al. 2000). *Bemisia tabaci* is a species complex comprised of several different biotypes commonly differentiated with molecular techniques and associated with host plants and geographical location (Frolich et al. 1999, Kirk et al. 2000, Brown 2000, de Barro et al., 2000, 2005). Of these biotypes B is the most efficient at

transmitting TYLCV because of its larger host range in comparison to other biotypes (Rybicki and Pietersen 1999).

### **Crop Damage and Control Methods**

Characteristic TYLCV symptoms include upward leaf curling, yellowing of young leaves, chlorosis on outward leaf margins, stunting and flower death (Moriones 2000). Plants typically develop symptoms 2 to 3 weeks after being inoculated. Not all infected plants will show symptom development. In heavy infestations, yield losses can reach up to a 100% (Pico et al. 1996).

The short acquisition and inoculation period (10 to 20 minutes), and latency period (24 hours) (Ghanim et al. 2001) make it challenging to determine the best time to apply chemical sprays effectively. Control of virus and vector has historically been reliant upon chemical control tactics and resistant varieties, but within the recent decade, increased resistance to commonly used insecticides such as neonicotinoids, pyrethroids and insect growth regulators has occurred (Ma et al. 2007, Nauen and Denholm 2005, Cahill et al. 1996, and Horowitz and Ishaaya 1994). As a result, the viral disease has continued to damage the southeastern US tomato industry primarily in southern Florida. A new IPM strategy for effective disease management is needed.

### **Purpose of the Study**

Whitefly populations can develop in a vegetable field in two ways. First, there can be a single source overwintering population which can build up over 2-3 whitefly generations, enough to reach damaging levels in the field. Another large source can be whiteflies can migrate in large numbers from another host plant and quickly overwhelm a vegetable crop in a single generation time. What we observed in 2013 was that the first scenario may be more critical in

local whitefly/TYLCV outbreaks in Georgia than previously thought. However, small, virus infested plots carried over from the spring were observed to be more important for causing localized virus outbreaks than the large whitefly migration events. In order to generate data on how whitefly populations from localized sources progress to a TYLCV epidemic and what insecticides might be effective in reducing this, we used a technique called tunnel studies. Tunnel studies can control whitefly and virus movement events under near field conditions. This was critical timing for this work because the new diamide and butenolide (related to neonic) insecticides, Verimark (Dupont) and Sivanto (Bayer), respectively, were recently labeled (<http://www.cdms.net/labelsmsds/lmdefault.aspx>) as excellent whitefly materials that may reduce the incidence of virus. In order to provide an unbiased assessment of the potential for these chemistries to reduce both whitefly populations and virus transmission, a controlled tunnel study was conducted. Also, in order to assess the efficacy and interactions of traditional integrated pest management tactics, including host plant resistance, reflective mulch and insecticides, a splitsplit plot designed field experiment was conducted. These studies were conducted to support integrated TYLCV management for commercial tomato production in the southeastern USA.

### **Hypothesis and Experiments**

First, I hypothesized that the spread of whiteflies and TYLCV will be suppressed under insecticidal drench treatments of cyantraniliprole or imidacloprid when compared with untreated control under equally infested tomato crop tunnels and that all of these treatments will have significantly more whiteflies and TYLCV than an uninfested, untreated control tomato crop tunnel. The important, specific hypothesis to test is as follows.

H-1<sub>o</sub>: Cyantraniliprole and imidacloprid will have no effect on whitefly population levels and TYLC disease incidence compared with non-treated, infested control treatment.

H-1<sub>a</sub>: Cyantraniliprole and imidacloprid will significantly reduce whitefly population levels and TYLC disease incidence when compared with non-treated, infested control treatment.

Secondly, I hypothesized that the whitefly population levels and TYLC disease incidence in field grown tomatoes will be significantly reduced by cultural and chemical control tactics compared to industry standard practices. These management tactics were: the use of metallic silver mulch, the use of TYLCV-resistant cultivars (Shanty, Tygress and Security) and the use of insecticides (imidacloprid, cyantraniliprole) relative to a white standard mulch, a susceptible tomato (FL47) cultivar, and a no whitefly-insecticide treatment check, respectively.

H-2<sub>o</sub>: There will be no significant difference in whitefly population levels and TYLC disease incidence in plants planted in white or silver mulch, plants of susceptible or TYLCV-resistant tomato cultivars or plants treated with insecticide or not treated with insecticide.

H-2<sub>a</sub>: There will be a significantly higher whitefly population levels and TYLC disease incidence in plants planted in white mulch, susceptible cultivars and plants not treated with whitefly insecticides than plants planted in silver mulch, with resistance genes and treated with insecticides.

## References

- Brown, J.K., Perring, T.M., Cooper, A.D., Bedford, I.D., Markham, P.G. 2000. Genetic analysis of *Bemisia* (Hemiptera: Aleyrodidae) populations by isoelectric focusing electrophoresis. *Biochem. Genet.* 38: 13 - 25.
- Caciagli, P., V. Medina Piles, D. Marian, M. Vecchiati, V. Masenga, G. Mason, T. Falcioni, and E. Noris. 2009. Virion stability is important for the circulative transmission of tomato yellow leaf curl sardinia virus by *Bemisia tabaci*, but virion access to salivary glands does not guarantee transmissibility. *J. Virol.* 83: 5784 - 5795.
- Cahill, M., Gorman, K., Day, S., Denholm, I., Elbert, A., and Nauen, R. 1996. Baseline determination of resistance to imidacloprid in *Bemisia tabaci* (Homoptera: Aleyrodidae). *B. Entomol. Res.* 86: 343 - 349.
- Czosnek, H. 2007. Tomato Yellow Leaf Curl Virus. The Hebrew University of Jerusalem, Rehovot, Israel.
- Czosnek, H., and M. Ghanim. 2012. Back to Basics: Are Begomoviruses Whitefly Pathogens? *Journal of Integrative Agriculture* 11: 225-234.
- De Barro, P.J., Driver, F., Trueman, J.W.H., and Curran, J. 2000. Phylogenetic relationships of world populations of *Bemisia tabaci* (Gennadius) using ribosomal ITS1. *Molec. Phylogenetics Evol.* 16: 29 - 36.
- De Barro, P.J., Trueman, J.W., and Frohlich, D.R. 2005. *Bemisia argentifolii* is a race of *B. tabaci* (Hemiptera; Aleyrodidae): the molecular genetic differentiation of *B. tabaci* populations around the world. *B. Entomol. Res.* 95: 193 - 203.

- Fauquet, C.M., Maxwell, D.P., Gronenborn, B., and Stanley, J. 2000. Revised proposal for naming geminiviruses. *Virology Division News* 8-145: 1744 - 1761.
- Frohlich, D.R., Torres-Jerez, I.I., Bedford, I.D., Markham, P.G., and Brown, J.K.A. 1999. Phylogeographical analysis of the *Bemisia tabaci* species complex based on mitochondrial DNA markers. *Mol. Ecol.* 8: 1683 - 1691.
- Ghanim, M., S. Morin, and H. Czosnek. 2001. Rate of Tomato yellow leaf curl virus translocation in the circulative transmission pathway of its vector, the whitefly *Bemisia tabaci*. *Phytopathology* 91: 188-196.
- Horowitz, A.R. and Ishaaya, I. 1994. Managing resistance to insect growth regulators in the sweetpotato whitefly (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 87: 866 - 871.
- Kirk, A.A., lacey, L.A., Brown, J.K., Ciomperlik, M.A., Goolsby, J.A., Vacek, D.C., Wendel, L.E., Napompeth, B. 2000. Variation in the *Bemisia tabaci* s.l. species complex (Hemiptera: Aleyrodidae) and its natural enemies leading to successful biological control of *Bemisia* biotype B in the USA. *B. Entomol. Res.* 90: 317 - 327.
- McGrath, P.F. and Harrison, B.D. 1995. Transmission of tomato yellow leaf curl geminiviruses by *Bemisia tabaci*: effects of virus isolate and vector biotype. *Ann. Appl. Biol.* 126: 307 - 316.
- Ma, D., K. Gorman, G. Devine, W. Luo, and I. Denholm. 2007. The biotype and insecticideresistance status of whiteflies, *Bemisia tabaci* (Hemiptera: Aleyrodidae), invading cropping systems in Xinjiang Uygur Autonomous Region, northwestern China. *Crop Prot.* 26: 612 - 617.
- McAuslane, H.J. and Smith, H.A. 2000. *Bemisia tabaci* (Gennadius) (Insecta: Hemiptera: Aleyrodidae). University of Florida IFAS, EENY-129.

- Momol, M.T., Simone, G.W., Dankers, W., Sprengel, R.K., Olson, S.M., Momol, E.A., Polston, J.E. and Hiebert, E. 1999. First report of *Tomato yellow leaf curl virus* in tomato in south Georgia. *Plant Disease*. 83: 487.
- Morin, S., Ghanim, M., Zeidan, M., Czosnek, H. Verbeek, M., and Johannes, F. 1999. A GroEL homologue from endosymbiotic bacteria of the whitefly *Bemisia tabaci* is implicated in the circulative transmission of tomato yellow leaf curl virus. *Virology* 256: 75 - 84.
- Moriones, E., and Navas – Castillo, J. 2000. Tomato yellow leaf curl virus, an emerging virus complex causing epidemics worldwide. *Virus Res.* 71: 123-134.
- Mound, L.A. and Hasley, S.H. 1978. Whitefly of the World: a Systematic Catalogue of the Aleyrodidae (Homoptera) with Host Plant and Natural Enemy Data. Wiley, New York, 340pp.
- Nauen, R. and Denholm, I. 2005. Resistance of insect pests to neonicotinoid insecticides: current status and future prospects. *Arch. Insect Biochem.* 58: 200 - 215.
- Oliveira, M. R. V., T. J. Henneberry, and P. Anderson. 2001. History, current status, and collaborative research projects for *Bemisia tabaci*. *Crop Prot.* 20: 709 - 723.
- Oliveira, M. R. V., Icuma, I. M., and Lira, G. S. 2000b. Avaliação de surtos de mosca-branca em áreas do Sistema produtivo de melão, soja e feijão. Embrapa Recursos Genéticos e Biotecnologia, Comunicado Técnico, No 29, 10pp.
- Papayiannis, L.C., Katis, N.I., Idris, A.M., and Brown, J.K. 2011. Identification of weed hosts of *Tomato yellow leaf curl virus* in Cyprus. *Plant Dis.* 95: 120 - 125.
- Picó, B., M. J. Díez, and F. Nuez. 1996. Viral diseases causing the greatest economic losses to the tomato crop. II. The *Tomato yellow leaf curl virus* — a review. *Scientia Horticulturae* 67: 151-196.

- Rubinstein, G., and Czosnek, H. 1997. Long-term association of tomato yellow leaf curl virus (TYLCV) with its whitefly vector *Bemisia tabaci*: Effect on the insect transmission capacity, longevity and fecundity. *J. Gen. Virol.* 78: 2683 - 2689.
- Rybicki, E.P., and Pietersen, G. 1999. Plant virus problems in the developing world. *Adv. Virus Res.* 53: 127-175.
- Rybicki, E.P., Briddon, R.W., Brown, J.K., Fauquet, C.M., Maxwell, D.P., Stanley, J., Harrison, B.D., Markham, P.G., Bisaro, D.M., Robinson, D. 2000. Family Geminiviridae. In M.H.V. Van Regenmortel, C.M. Fauquet, D.H.L. Bishop, E. Carstens, M. Estes, S. Lemon, J. Manlioff, M.A. Mayo, D. McGeoch, C. Pringle, and R. Wickner (eds.), *Proceedings, Symposium: Virus Taxonomy. Seventh Report of the International Committee on Taxonomy of Viruses.* pp. 285 - 297. Academic Press, New York.
- Simmons, A. M., G. S. McCutcheon, R. J. Dufault, R. L. Hassell, and J. W. Rushing. 2000. *Bemisia argentifolii* (Homoptera: Aleyrodidae) attacking species of medicinal herbal plants. *Ann. Entomol. Soc. Am.* 93: 856 - 861.
- Srinivasan, R., Riley, D., Diffie, S., Sparks, A. and Adkins, S. 2012. Whitefly population dynamics and evaluation of whitefly-transmitted tomato yellow leaf curl virus (TYLCV) resistant tomato genotypes as whitefly and TYLCV reservoirs. *J. Econ. Entomol.* 105: 1447 - 1456.
- (USDA) U.S. Department of Agriculture. 2012. 2012 Census of Agriculture – State Data South Carolina.

## Chapter 2

### Literature Review

#### ***Bemisia tabaci* Biology**

Whiteflies belong to the order Hemiptera, suborder Sternorrhyncha, a taxonomic group notorious for their efficiency at transmitting plant viruses. *B. tabaci* transmits known distinct virus groups: geminiviruses, closteroviruses, carlaviruses and potyviruses (Duffus 1987, 1996). Of the six known virus groups, the most economically important are Geminiviruses belonging to the family *Geminiviridae*: Genus *Begomovirus* (Oliveira et al. 2001). Viruses belonging to *Geminiviridae* family are the most rampant and destructive to tomato production worldwide (Oliveira et al. 2001). TYLCV's severe destructive capability is due in part to the *B. tabaci* vector's efficient transmission of the virus.

*Bemisia tabaci* is thought to have originated from the Indian subcontinent (Brown et al. 1995). Its polyphagous nature allowed this species to invade tropical and subtropical regions around the world (Bosco et al. 2004). Their geographical spread cultivated different populations of the species that utilized different host plants; these populations are defined as biotypes (Bedford et al. 1994, Guirao et al. 1997). The variability between biotypes was so strong that a description of a new species *Bemisia argentifolii* was developed (Bellows et al. 1994). However, the new species name never separated itself from the original *Bemisia tabaci* species name.

Instead, *B. argentifolii* is used to describe *B. tabaci* biotype B (Perring 2001).

*B. tabaci* is best described as a species complex because it consists of 35 different biotypes are mostly differentiated by host range (Frohlich et al. 1999, DeBarro et al. 2011, Liu et al. 2012, Firdaus et al. 2013, Ghanim 2014). Of all the biotypes, biotype B, the Middle East Asia Minor species (MEAM1) and biotype Q, the Mediterranean (MED) species cause the most damage (Brown et al. 1995, Frohlich et al. 1999, Brown 2007a, b, Dinsdale et al. 2010). Biotype b is better at thriving in dry, irrigated open field farm systems, transmitting old and new world begomoviruses and is capable of inducing phytotoxic symptoms on plants after feeding (Gottlieb et al. 2010, Gotz et al. 2012, Costa and Brown 1991, Brown et al. 1995). Biotype Q is better at thriving in greenhouse environments and developing insecticide resistance (Horowitz et al. 2005, Dennehy et al. 2006, 2010).

Unlike other hemipterans (with the exception of Coccoidea) whiteflies have larviform stages and a sessile nymphal stage (Cranston and Gullan 2009). *B. tabaci* females can reproduce parthenogenically to make haploid males or sexually to make diploid females or males (McAuslane 2000). Fecundity is related to plant host characteristics (Byrne 1991). Females choose suitable landing sites by looking at plant color and by tasting the plant's chemical composition by using chemoreceptors on their mouthparts (McAuslane 2000). Oviposition behavior varies among different species of whiteflies. *B. tabaci* lays eggs individually and randomly on the underside of the leaf (Byrne and Bellows 1991). When eggs are first laid, they are a creamy white color but become dark brown in color as eclosion approaches. They are on average 0.21 mm long and 0.096 mm wide (McAuslane 2000). Eggs are oval in shape, and have a pedicel attached to them (Byrne and Bellows 1991). Pedicels are extensions of the corion so they act as a good structural integrity component (Byrne and Bellows 1991). Females will use their ovipositor to help fasten the pedicel of the egg into leaf tissue through the stomata or

through a laceration she makes (Byrne and Bellows 1991). The pedicel may play a role in water absorption (Weber 1931, Wigglesworth 1965 and Hinton 1981). *B. tabaci* further cements eggs to the ovipositioning site by excreting a glue like substance from their mouth (Gameel 1974). Within six to seven days at 25°C, eggs will hatch into first instars called crawlers (McAuslane 2000). Crawlers exit the egg shell and crawl away from their egg using their 3 segmented legs (Byrne and Bellows 1991). Crawlers rarely move onto a different leaf, instead they stay on the same leaf moving a small amount from their hatch site (Summers et al. 1996). Once centered above a leaf vein, the crawler uses its piercing sucking mouthpart to penetrate the leaf epidermis to immediately start feeding (Byrne and Bellows 1991). Crawlers are generally 0.27 mm long and 0.14 mm wide (McAuslane 2000). They have a very low profile, lying flat against the leaf surface. Crawlers are ovoid in shape and have a whitish green appearance. Two yellow spots can easily be seen through the exoskeleton, these yellow spots contain endosymbiotic bacteria and are called mycetomes (McAuslane 2000). The legs are only functional in the first instar. The first instar experiences the highest mortality rate of all life stages (Horowitz 1986). In the second, third and fourth instar, the legs reduce to being only 1 segmented (Gill 1990). Within two to three days, the first instar will molt into the second instar (McAuslane 2000). Like the first instar, the second and third instar are flattened and ovoid in shape and have a white green color with visible mycetomes. Instars grow from 0.365 mm at the second instar to 0.662 mm at the fourth instar (McAuslane 2000). These instars are sessile and they secrete a white waxy substance along the margins of their body to further aid in sealing them onto the leaf surface (McAuslane 2000). The fourth nymphal instar is also called the pupal instar. This instar is what differentiates whiteflies from other hemipterans. There is some reorganization of the morphology during this stage. The fourth instar feeds during this stage so it cannot be

considered as a true pupae (Gill 1990). The fourth instar is more opaque than previous instars and the red eyes become more prominent. The last part of the 4<sup>th</sup> instar, where apolysis has already taken place, could be considered a pupa since there is no feeding occurring. Adult eclosion is sensitive to light and temperature. A light intensity similar to dawn light (a photoperiod of 14:10 LD) and a temperature of 29.5°C is the ideal environment for eclosion (Hoffman and Byrne 1986). Soon after emergence, *B. tabaci* adults take their first flight and mate within 1 to 8 hours of eclosion (Byrne and von Bretzel 1987, Mau and Kessing 2007, Byrne 1991). Adult whiteflies live for 6 to 55 days depending on the temperature (Mau and Kessing 2007). In the southeast, adults live for 10 to 15 days during the warmer summer season (Mau and Kessing, 2007).

Hemipterans are characterized by their long needle-like stylet that penetrates plant cells. This feeding style allows them to feed on plant phloem. It also makes it easier for bacterial and viral pathogens to enter the plant system and cause systemic infection. Whitefly mouthparts consist of a labrum, labium and a stylet bundle (Rosell et al. 1995). The stylet bundle has 2 mandibular stylets and 2 maxillary stylets that curve inward to maximize the ability to cut and anchor into plant tissue (Rosell et al. 1995). Within the maxillary stylets, a food canal and a salivary canal exists; this is where the exchange of whitefly and plant fluid and virus particles occurs (Rosell et al. 1995). Whiteflies make efficient virus vectors because their stylet mouthparts are able to pass between plant cells and reach directly into the phloem and penetrate it without doing much cell damage (Ferreles and Moreno 2009).

Whiteflies select their host plant by using visual and olfactory cues. *B. tabaci* cues itself to land to feed when it recognizes host plant color. The ideal color is one that reflects 550 nm of visual wavelength (Byrne 1991). A wavelength of 550 nm is reflected off of most

yellow/green pigmented plants (Byrne 1991). Color is the main visual cue whiteflies use to select a plant host; leaf shape and size was not shown to influence host plant selection (van Lenteren and Woets 1977, Woets and van Lenteren 1976). Whiteflies use their cribriform organ to taste the phloem of the potential host plant (Guillot et al. 1979, Hargreaves 1915). Sensilla on the labium may have a chemosensory function (Walker and Gordh 1990). These sensilla may test plant surface prior to stylet penetration suggesting that whiteflies may be able to discern host plant suitability without having to probe the plant surface (Walker and Gordh 1990, Walker and Aitken 1987). Whiteflies prefer to settle on the abaxial part of the leaves (Calabrese and Edwards 1976).

### ***Tomato yellow leaf curl virus (TYLCV) Biology***

TYLCV was first recognized as a tomato disease in Israel in the late 1930s (Cohen and Nitzany 1966, Cohen and Antignus 1994, Czosnek and Laterrot 1997). By the late 1980s TYLCV had spread to Asia, Middle and Far East Africa, Europe, the Caribbean, North America (Bedford et al. 1994), Japan (Kato et al. 1998) Mexico (Ascencio – Ibanez et al. 1999) and specifically in Florida and south Georgia in 1998 (Momol et al. 1999). Several TYLCV species and strains exist, separated by differences in the N- terminus of the CP gene (Moriones and Navas – Castillo 2000). Viruses with a nucleotide sequence homology greater than 89% are considered strains of the same species; viruses with less than 89% homology of a nucleotide sequences are considered different species (Czosnek 2007). Recombination of DNA by different species is relatively common (Czosnek 2007). Different species and strains are found in different geographical locations (Moriones and Navas – Castillo 2000). The spread of TYLCV was largely facilitated by the B biotype of *B. tabaci* (Rybicki and Pietersen 1999). Biotype B has a larger host range than other *B. tabaci* biotypes (Rybicki and Pietersen 1999).

Host plants act as reservoirs of virus inoculum. *B. tabaci* is known to utilize both vegetable plants and weed plants (Moriones and Navas – Castillo 2000). In a study conducted in the Dominican Republic, positive TYLCV results were found in crop and weed families: *Acanthaceae*, *Caparidaceae*, *Compositae*, *Cucurbitaceae*, *Cyanastraceae*, *Euphoriaceae*, *Leguminosae*, *Malvaceae*, *Nyctaginaceae*, and *Solanaceae* (Salati et al. 2002). In Israel, the perennial weed, *Colchicum acutum* and annual weed, *Malva parviflora* were large TYLCV inoculum sources (Cohen et al. 1988). Different TYLCV species infect different host plants (Moriones and Navas – Castillo 2000). Often times, it is difficult to identify alternate virus hosts because the plants will be asymptomatic. Despite the large alternate host range that TYLCV has in Florida, the most common reservoir for reinfection are old tomato plants left in a field (Polston and Lapidot 2007). Whiteflies will move from an old field into a newer field up to 7 km away (Byrne and Bellows 1991, Cohen et al. 1988). In addition to host plants, *B. tabaci* may serve as a reservoir (Moriones and Castillo 2000) for TYLCV because of the capability of copulation and transovarial viral transmission (Ghanim et al. 1998, Ghanim and Czosnek 2000).

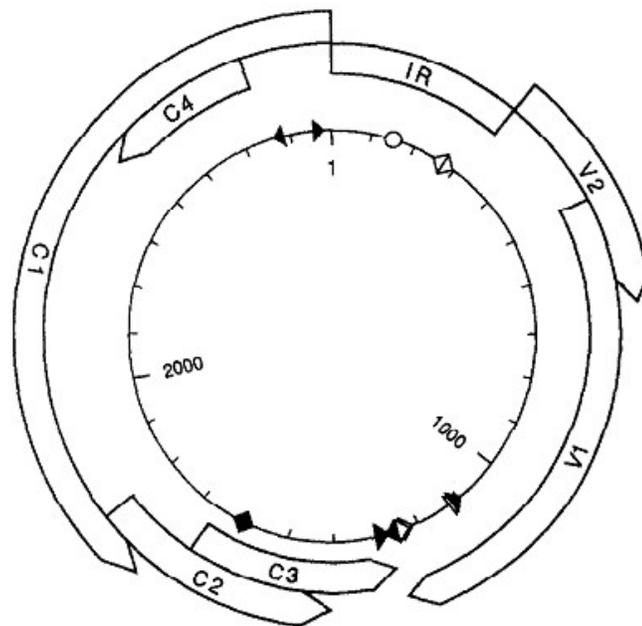
Begomovirus presence was mapped in the Latin Americas (Mexico, Central America, the Caribbean and South America) to occur between latitude 35°N to latitude 30°S and longitude 115°W to 35°E (Morales and Jones 2004). Temperature heavily influences *B. tabaci* population dynamics (Morales and Jones 2004). In tropical regions, temperatures average at 28°C and range from 15-33°C (Van Lenteren and Noldus 1990). *B. tabaci* also prefers relative humidity above 60% and less frequent, light rain events (Singh and Butler 1984). Morales and Jones were able to devise a recipe for optimum *B. tabaci* environment: 4 months of less than 80 mm of rainfall and a mean temperature no less than 21° in the warmest month. The areas at the highest risk for TYLCV and *B. tabaci* outbreaks are farmed areas of land that stay relatively dry and

warm for most of the year (Morales and Jones 2004). Symptoms occur on infected plants within 2 to 3 weeks of inoculation (Czosnek 2007). Symptoms include: growth stunting, inward cupping of leaflets, leaf margin yellowing and reduced fruit set (Czosnek 2007). Once disease is present in a field, incidence increases rapidly causing up to 100% yield loss (Czosnek 2007).

TYLCV belongs to the family *Geminiviridae* which are characterized as being unipartite or bipartite DNA viruses that have single stranded DNA arranged in a circle (Moriones and Navas – Castillo 2000). Begomoviruses usually have a bipartite genome (Moriones and NavasCastillo 2000). In the bipartite genome, there are two genomic parts: DNA A and DNA B (Navot et al. 1991). Each genomic component is 2.5 – 2.8 kb in size (Lazarowitz 1992). TYLCV species are unique in comparison to other begomovirus species because they have a monopartite genome (Rochester et al. 1994). In bipartite begomoviruses, DNA A and B are required for replication and systemic infection but in TYLCV, DNA A is the only DNA component required for replication and systemic infection (Navot et al. 1991). The TYLCV genome has six overlapping open reading frames with two transcriptional units, the virion-sense strand and the complementary-sense strand, that run in opposing directions and differentiated by an intergenic region of 300 nucleotides (Rybicki et al. 2000). There is one gene on the virion sense strand and four on the complimentary sense strand (Lazarowitz 1992). The single gene (AV1) on the virion sense strand encodes for the coat protein (CP) (Elmer et al. 1988). The first gene on the complimentary sense strand (AC1) encodes the protein (Rep) the replicationassociated protein (Elmer et al. 1988). The second gene on the complimentary sense strand (AC2) encodes protein (TrAP), the transcriptional activator protein that activates the expression of the CP gene (Sunter and Bisaro 1991). The third gene on the complimentary strand (AC3) encodes (Ren) the replicator enhancer protein which monitors replication rate by

controlling the genes responsible for DNA synthesis (Azzam et al. 1994). The fourth gene on the complimentary sense strand (AC4) encodes the protein responsible for symptom expression (Rigden et al. 1994). Lastly, the intergenic region is utilized for replication and transcription (Moroinés and Navas – Castillo 2000).

The Geminivirus genus consists of three genera: Mastreviruses, Curtoviruses and Begomoviruses (Power 2000). Geminivirus genomes are monopartite or bipartite single



**Figure 2.1** Structure of *Tomato yellow leaf curl virus* from Navot et al. (1991). V1 and V2 are overlapping open reading frame virion sense strands. C1, C2, C3 and C4 are overlapping open reading frame complimentary sense strands. IR is the intergenic region.

Stranded DNA viruses and are transmitted in a persistent, circulative, non-propogative manner by one species vector (Power 2000). Within the species *B. tabaci*, several different biotypes exist. Different biotypes derive from *B. tabaci* populations in different geographical regions (Perring, 2001). Of all the biotypes, biotype B is the most efficient at transmitting TYLCV (Power 2000). Biotype B's efficiency as a vector is largely due to its wide host range allowing

it to transmit TYLCV to plants that could previously not become infected (Brown et al. 1995). In addition to broadening the host range, biotype B's highly polyphagous nature creates the possibility for new strains of the virus to develop through recombination events on different host plants (Zhou et al. 1997, Brown et al. 1999). When a TYLCV strain is from the same region that its whitefly vector biotype is from, transmission is more efficient (Götz et al. 2012). When insect vectors broaden their host range, the host range of the virus the insect vector transmits widens (Harrison and Robinson 1999, Goldbach and Peters 1994). Viruses can have a small vector host range but a broad plant host range because of their vector's wide plant host range (Power 2000). It is therefore postulated that there is some specificity of compatibility between vector and virus to transmit efficiently (Power 2000). This specificity is gained through co-evolution of vector and virus (Power 2000). Biotype B is thought to be the most efficient TYLCV vector because their coevolution has created a less volatile dynamic when compared to biotype b's interaction with younger similar viruses like *Squash leaf curl virus* (SLCV), a bipartite begomovirus (Brown 2010, Czosnek and Ghanim 2002). The variability in transmission efficiency among biotypes may also be caused by differences in symbiotic gut flora (Moriones and Navas – Castillo 2000). TYLCV is a phloem-restricted virus (Feres and Moreno, 2009) transmitted in a persistent circulative manner (Cohen and Nitzany 1966, Rubinstein and Czosnek 1997). In order for transmission to occur tomato yellow leaf curl virions must cross selective barriers: midgut/hindgut apical and basal plasmalemma, accessory gland basal lamina and accessory gland basal plasmalemma (Gildow and Gray 1993, Gray and Gildow 2003) to reach the salivary glands (Medina et al. 2006). Cohen and Nitzany (1966) claim that females are better at transmitting TYLCV than males, but Ghanim et al. (2001) demonstrated that there was no difference in the amount of time it took TYLCV to reach the

salivary glands. Cohen and Nitzany may have found females are better at transmission because a higher virus titer is accumulated in female salivary glands (Ghanim et al. 2001). Acquisition access periods (AAP) and inoculation access periods (IAP) were measured to be approximately 10 to 20 minutes (Ghanim et al. 2001) and a latency period of 8 (Ghanim et al. 2001) to 21 hours (Cohen and Nitzany 1966). Ghanim et al. (2001) attempted to determine the velocity TYLCV travels through its whitefly vector. They found that it took only 10 minutes of feeding to see presence in the head of the whitefly vector. The virus was already in the midgut within 30 minutes. They postulated that the reason for such a quick journey from head to midgut is due to the lack of selective barriers the virus has to pass through. Within 90 minutes of the initial feeding, the virus was located within the hemolymph. Passage of the virus through the gut wall to the hemolymph is crucial to virus transmission so that virus particles can accumulate in the salivary glands. To avoid being broken down by enzymes in the hemolymph, virus particles may bind to chaperonin proteins (Morin et al. 1999). Within 7 hours of the initial feeding, the virus was detected in the salivary glands.

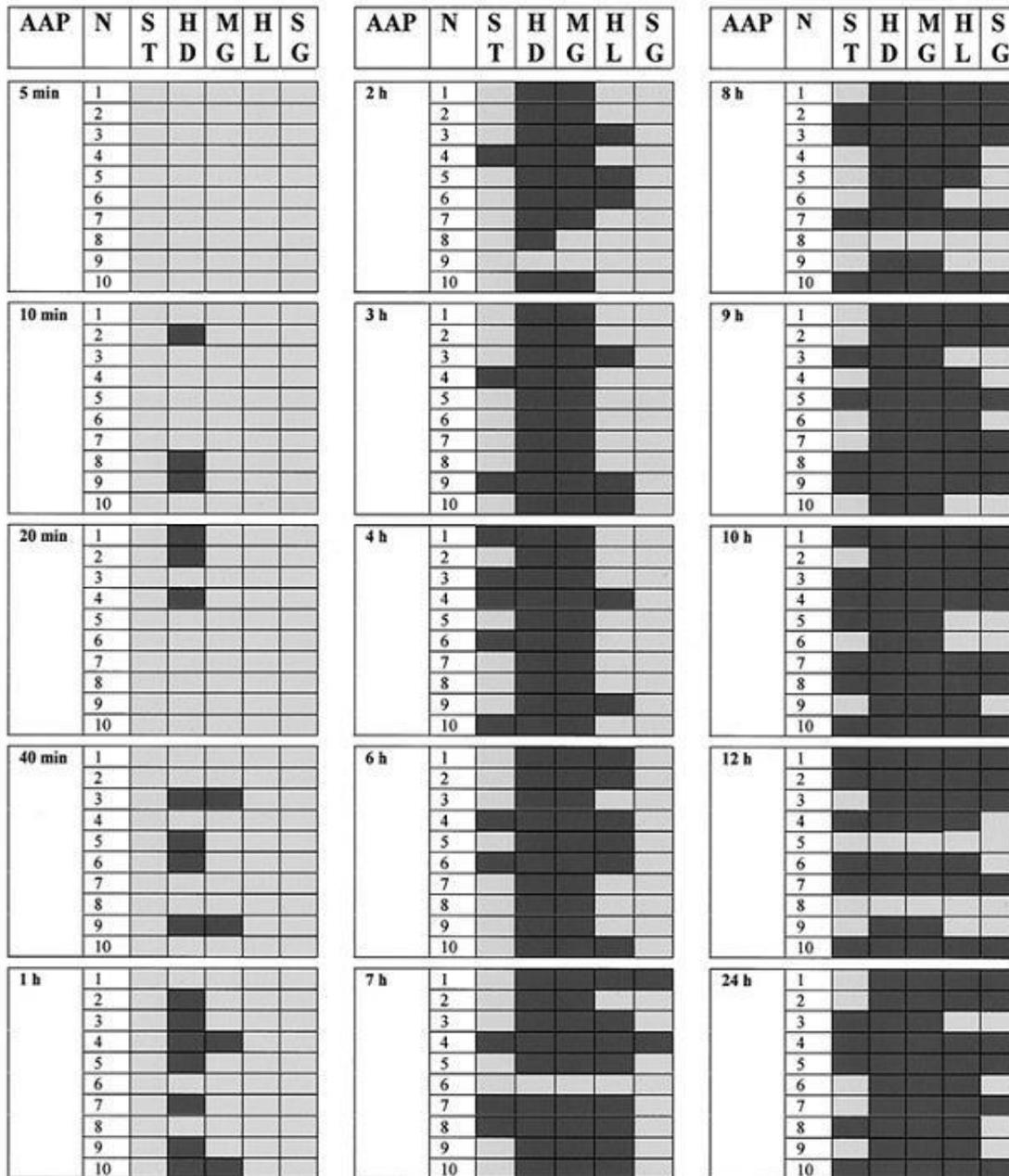
Once in the salivary glands, the virus was measured to be placed into plant tissue within an hour.

A viral coat protein (CP) and a GroEL homologue are needed for successful TYLCV transmission (Ghanim et al. 2001, Morin et al. 1999). The CP allows the virion to bind to receptors in the whitefly midgut where through endocytosis, the virus particle is taken into the hemolymph (Czosnek et al. 2002). Two proteins are implicated in providing virion transport through the insect vector body: GroEL chaperone protein and heat shock 70 (HSP70) protein. GroEL chaperone protein binds to the TYLCV and CP particle to protect it from the whitefly's internal environment during translocation (Czosnek et al. 2002). GroEL chaperone proteins are produced by a secondary endosymbiont, *Hamiltonella* (Gottlieb et al. 2010). When whiteflies

were fed an anti-GroEL antiserum, transmission of TYLCV was reduced by 80%, implicating this proteins heavy involvement in transmission efficiency (Gotz et al. 2012). In addition to the anti-GroEL antiserum, a study was done by Gottlieb et al. (2010) comparing the difference in transmission efficiency between *B. tabaci* biotype B and Q. They found that biotype B transmitted more efficiently than biotype Q because biotype Q lacked the secondary endosymbiont, *Hamiltonella*. Heat shock 70 gene is the only gene upregulated by *B. tabaci* infected with TYLCV (Gotz 2012). The *hsp70* proteins have been found to be associated with protein transport and translocation across membranes (Pishvaei et al. 2000, Pratt et al. 1999, Tsai et al. 2000). HSP70s and TYLCV were found in the filter chamber and the midgut suggesting that this may be where HSP70s bind to TYLCV particles (Gotz 2012). HSP70s may help to move the virus particles through the midgut epithelium without disturbing adjacent insect tissues (Gotz 2012). If this is true, the insect vector would favor this and place selective pressure on *hsp70* to upregulate upon TYLCV infection to prevent damage to other tissue areas which can cause losses in fecundity and longevity (Czosnek and Ghanim 2002, Rubinstein and Czosnek 1997). Most literature asserts that TYLCV is not capable of propagating within its host. This virus vector relationship is not common because it detracts from vector host's vigor (Hull 2002).

Often viruses that are able to propagate within their vector are similar to an insect pathogen (Ghanim et al. 2001). Bosco et al. (2004) investigated the ability for TYLCV to propagate within *B. tabaci* by analyzing transovarial inheritance. When TYLCV CP receptors are saturated, excess virions strip themselves of their CP and their GroEL protein and invade adjacent tissues where they bind to other proteins so that they can maintain their integrity (Czosnek et al. 2002). However, because the sequestered virus particles are stripped of the CP

and GroEL protein, they are no longer capable of translocation or surviving in insect hemolymph, so they are no longer infective (Bosco et al. 2004). Therefore, if uncoated TYLCV particles are inherited by progeny, progeny will not be functionally viruliferous (Bosco et al. 2004). Bosco et al. (2004) found that eggs and nymphs of viruliferous mothers had higher virus titer than adults. They speculate that the decrease in titer with age was due to the degradation of tissue that held the mother's uncoated virus particles. However, other studies contradict Bosco et al.'s results. Ghanim et al. (1998) found that adult progeny of viruliferous mothers were able to transmit TYLCV effectively to healthy tomato plants. This would indicate that functional virion particles were successfully transmitted from mothers to progeny. Despite the conflicting study, Bosco et al. (2004) asserts that *B. tabaci* cannot act as a reservoir for TYLCV and is therefore not a propagative virus. But, they do mention the oddity of the ability for the virus to be present in eggs and ovaries, in addition to viruliferous whiteflies having decreased fecundity and longevity, to indicate that TYLCV may be an artifact of an old whitefly pathogen. If TYLCV is a remnant of a whitefly pathogen it is more likely that this virus can propagate within its host.



**Figure 2.2** Ghanim et al. (2000)'s rate of *Tomato yellow leaf curl virus* translocation in the circulative transmission pathway of its vector, the whitefly *Bemisia tabaci*. Temporal movement of TYLCV through insect vector: stylets (ST), head (HD), midgut (MG), hemolymph (HL) and salivary glands (SG). 10 whiteflies were sampled for each time period. White box represents viral DNA not being detected by PCR, black boxes represent viral DNA being detected.

## **Integrated Management of *Bemisia tabaci* and Tomato yellow leaf curl virus**

TYLCV was traditionally managed by using insecticide treatments (Moriones and Navas – Castillo 2000). Insecticide treatments may not be the most efficient control agent for TYLCV because it is hard to achieve such a high and rapid kill rate of vectors to effectively suppress virus transmission. In addition, there is significant environmental pollution associated with applications, and a high risk of target pests developing insecticide resistance (Moriones and Navas Castillo 2000, Byrne et al. 1994, Cahill et al. 1996a, b, respectively).

Insecticidal control of *B. tabaci* was historically accomplished through the use of chlorinated hydrocarbons and organophosphates and pyrethroids (Sharaf 1986) and later neonicotinoids and pyridine-azomethines (Polston and Lapidot 2007). In addition to conventional chemicals, insecticidal soaps, oils and insect growth regulators (IGRs) are also used (Polston and Lapidot 2007). Of all of the classes of insecticides used, neonicotinoids (thiomethoxam, imidacloprid and dinotefuron) are the most frequently used to suppress TYLCV (Ahmed et al. 2001, Cahill et al. 1996a, Polston and Anderson 1997).

Pyrethroids are usually applied as a synergized mix of high levels of pyrethroids with moderate levels of other chemistries like organophosphates, carbamates, formamidines and cyclodienes (Palumbo et al. 2001). Synergized pyrethroids are efficient because they combine chemistries together that by themselves would not be able to provide as effective of a control (Dittrich et al. 1990, Denholm et al. 1998). In populations resistant to pyrethroids, susceptibility may be created again by adding an esterase inhibitor to the mixture (Ishaaya and Ascher 1983, 1984). Some of the synergized pyrethroids used for control in solanaceous vegetable crops include pyrethroids fenpropathrin or bifenthrin mixed with acephate, methamidophos, oxamyl, or endosulfan (Schuster 1994, 1995a, b, Stansly and Cawley 1994a, Stansly and Conner 1995).

Synergized pyrethroids are a contact poison and applied as a foliar spray (Horowitz and Ishaaya 1996). The combination of foliar application and contact poison, makes adult whiteflies more susceptible to synergized pyrethroids than sessile nymphs that reside on the abaxial leaf surface (Palumbo and Coates 1996). Control is achieved by killing adult females before they are able to oviposit (Palumbo et al. 2001). Because pyrethroids are a contact poison, they require frequent sprayings to control each whitefly population that settles into a field; residual activity can be masked by new whiteflies constantly immigrating into the field (Berlinger et al. 1993, Schuster et al. 1996). Contact poison's efficiency is highly relative to the efficiency of its application. Comprehensive spray coverage and deposition on target plants is crucial to synergized pyrethroid's efficiency (Palumbo et al. 2001). Timing of insecticide application is also crucial to maximize the poison's efficiency and minimize environmental degradation (Palumbo et al. 2001).

Nicotinoids are derived from naturally occurring nicotine compounds that block postsynaptic nicotinic acetylcholine receptors (Bai et al. 1991, Liu and Casida 1993). This class of insecticide are also known as nitroguanidines, nitromethylenes, chloronicotinylns and neonicotinoid (Yamamoto et al. 1995). Nicotinoids have low mammalian toxicity, minimum non target species effects and have a broad range of efficacy (Wollweber and Tietjen 1999). Nicotinoids are good at controlling phloem feeding insects because of their high water solubility and good residual activity, which makes them great systemic insecticides (Kagabu 1999, Yamada et al. 1999, Maienfisch et al. 2001).

Imidacloprid was the first nicotinoid used to control whiteflies (Elbert et al. 1990, Mullins and Engle 1993). Trade names manufactured by Bayer AG Company for this chemistry include: Admire®, Confidor®, Gaucho®, Merit®, Marathon®, and Pravado® (Palumbo et al.

2001). Imidacloprid is commonly applied as a systemic treatment by soil drench to control whiteflies (Chandler and Sumner 1994, Palumbo et al. 1996b, Horowitz et al. 1998a, Hernandez et al. 1999, Schuster 2000a). The chemical kills adults and nymphs upon ingestion but also repels whiteflies before landing (Nauen and Elbert 1997, Nauen et al. 1998b). Residual activity can last between 1 to 10 weeks (Palumbo et al. 2001). For tomatoes, treating with a soil drench while still in the greenhouse or soon after planting is most effective (Schuster 2000a, b). Prophylactic applications of imidacloprid through drip lines has been shown to decrease early *B. tabaci* and TYLCV outbreaks in tomato (Ahmed et al. 2001, Stansly and Conner 2000). However, in a study done by Rubinstein et al. in 1999, Imidacloprid was not shown to inhibit the transmission of TYLCV to a healthy host plant.

The following chemicals: thiamethoxam, acetamiprid, nitenpyram and thiacloprid belong to a class of insecticides called second generation nicotinoids, which have a mode of action similar to nicotinoids but can function as a foliar spray because of its increased translaminar activity (Palumbo et al. 2001). Thiamethoxam has a high water solubility factor which makes it a great systemic insecticide like imidacloprid (Maienfisch et al. 2001). It moves faster in the soil than imidacloprid so it is commonly used as a side drench, post emergent treatment (Palumbo et al. 2000b). Trade names for thiamethoxam products produced by Syngenta Crop Protection include: Platinum®, Actara®, Centric®, Adage® and Cruiser® (Palumbo et al. 2001). Acetamiprid has a high water solubility factor, which allows for rapid plant uptake translaminarily through foliar applications (Palumbo et al. 2001). When compared with imidacloprid, acetamiprid is more effective when applied as a foliar treatment instead of a soil treatment (Horowitz et al. 1998a). Trade names for acetamiprid products produced by Nippon

Soda Co. include: Mospilan®, Rescate® and Assail® (Palumbo et al. 2001). Nitenpyram has a high water solubility factor and is utilized as a soil treatment (Palumbo et al., 2001). Studies show that it has a very high residual systemic activity against whiteflies on tomatoes (Akayama and Miniamida 1999). The trade name for nitenpyram product produced by Takeda Chemical is Bestgurad® (Palumbo et al. 2001). Thiacloprid has a high water solubility factor which allows it to have great translaminar activity when applied as a foliar spray (Palumbo 2001, Palumbo et al. 2001). In recent studies on insecticide efficacy for whitefly control in ornamental crops the active ingredients that provided good to excellent control of B and Q biotype whiteflies over multiple experiments were cyantraniliprole, flonicamid, abamectin, acetamiprid, azadirachtin, thiamethoxam, sulfoxaflor, spinoteram+sulfoxaflor, spiromesifen, spirotetramat, pyrifluquinazon, dinotefuran, pyridaben, and petroleum oil (Vea and Palmer 2014).

Insect growth regulators (IGRs) have a non-neurotoxic mode of action (Horowitz and Ishaaya 1999); they interfere with an insect's ability to molt into its adult stage. IGRs rely on its vapor phase to effectively enter whiteflies, so it is commonly applied as a foliar spray (Palumbo et al. 2001). Additionally, IGR chemistries are not effective against all life stages, so timing of application must also coincide with the period of time in which susceptible life stages are most abundant (Wilson and Anema 1988, Horowitz and Ishaaya 1996, Ellsworth 1998, Naranjo et al. 1998). Common IGRs used against whiteflies include buprofezin and pyriproxyfen (Palumbo et al. 2001).

Buprofezin is a thiadiazine chitin synthesis inhibitor that prevents N-acetyl-[D-H<sup>3</sup>] glucosamine interacting chitin which impedes cuticle formation (Kanno et al. 1981). It is applied as a contact poison foliar spray because it has bad soil systemic activity and translaminar movement (Palumbo et al. 2001). Buprofezin controls whitefly populations by killing nymphs

during ecdysis (Yasui et al. 1987, Ishaaya et al. 1988), specifically crawlers and second instars (Beevi and Balasubramanian 1991). When nymphs inhale the volatiles or come into direct contact via the epidermis they become poisoned (De Cock et al. 1990). The trade name for the buprofezin product manufactured by Nihon-Nohyahu Co. is Applaud® (Palumbo et al. 2001).

Pyriproxyfen controls whitefly populations by disrupting the juvenile hormone balance (Horowitz et al. 1999b). This compound is toxic to eggs and juvenile forms (Ishaaya and Horowitz 1995). Eggs and juveniles that have come into contact with the poison experience suppression of embryogenesis, metamorphosis and adult formation (Ascher and Eliyahu 1988, Ishaaya and Horowitz 1992, 1995). Trade names for pyriproxyfen products manufactured by Sumitomo Chemical Company include: Knack®, Tiger®, Admiral®, Distance®, Sumilarv® and Epingle® (Palumbo et al. 2001).

### ***Bemisia tabaci* Insecticide Resistance**

Reports of whitefly resistance to synergized pyrethroids began in the mid 1990s (Palumbo et al. 2001). By 1995, whitefly resistance to this specific synergized pyrethroid combination was well documented (Dennehy et al. 1997, Dennehey and Williams 1997). After resistance to these compounds was widely believed, they were restrictively applied for several years, this allowed for modern whitefly populations to remain susceptible (Ellsworth et al. 1996a, Ellsworth 1998, Agnew and Baker 2001, Ellsworth and Jones 2001, Frisvold et al. 2000). However, in a paper by Ma et al. (2007), *B. tabaci* biotype B was found to have resistance to pyrethroids (cypermethrin and bifenthrin) >1000 – fold. Ma et al. (2007) elaborate on the significant resistance by saying “by far the worst affected compounds of those tested are the pyrethroids, which are very unlikely to exert any control of *B. tabaci*.” In addition to an

esterase resistance mechanism, Ma et al. suggests that *B. tabaci* biotype B has developed a knock down mechanism for resistance to pyrethroids.

Target pests have a higher propensity to develop resistance to nicotinoids because of its widespread use, and its application as a systemic insecticide (Palumbo et al. 2001, Taylor and Georghiou 1982). In a lab test, rapid resistance to imidacloprid by *B. tabaci* was demonstrated where under continuous exposure, there was a 9-fold resistance in the F<sub>5</sub> generation and a greater than 80-fold resistance in the F<sub>24</sub> generation (Prabhaker et al. 1997). Cross resistance to imidacloprid, acetamiprid and thiamethoxam has been observed in a bioassay test done by Li et al. (2001). However, in a study that investigated the efficacy of imidacloprid, on controlling whiteflies on lettuce crops over the course of 7 years (1993 – 2000) no decrease in efficacy over the course of time was observed (Palumbo et al. 2001). However, this result may be confounded by the influences of more integrated cropping systems and traditional integration of other insecticides with different modes of action (Palumbo et al. 2001). In a study done by Ma et al. in 2006, *B. tabaci* biotype B was found to have 4 to 15 – fold resistance against imidacloprid. Additionally, in a recent study done by Caballero et al. (2013), wide spread whitefly resistance to imidacloprid in Florida was observed.

In field settings, developed resistance has been more delayed, probably due to the restriction of 1 application per year (Palumbo et al. 2001). There was observation of a decrease of efficiency of whitefly suppression in Israel during the mid 1990s (Horowitz et al. 1999a). A ten fold reduction in efficacy was reported in 2000 in cotton fields of Arizona (Li et al. 2001).

Resistance to pyriproxyfen was documented in an Israeli greenhouse in 1992 to levels exceeding 500 – fold (Horowitz and Ishaaya 1994). In field settings where application is limited to once a season, resistance was less pronounced (Horowitz et al. 1999b). Since then,

susceptibility has waivered from year to year (Palumbo et al. 2001). In a more recent study done by Ma et al. (2007), *B. tabaci* biotype B was found to have 22 – 37 fold resistance to pyriproxyfen.

### **Cultural Control Tactics**

In conjunction with chemical control, cultural control should also be implemented to help maintain susceptibility to chemicals and alleviate environmental degradation. Cultural control tactics for TYLCV and *B. tabaci* include: use of resistant or tolerant cultivars, avoidance, plastic mulches, using clean transplants, maintaining crop free periods, practicing good sanitation, managing weeds and rouging (Polston and Lapidot 2007).

Development of TYLCV resistant cultivars is the best means of controlling TYLCV (Fargette et al. 1996). Resistant cultivars are developed through interbreeding of marketable tomato cultivars with wild *Lycopersicum* species (Moriones and Navas – Castillo 2000). Resistant cultivars have been developed: *Lycopersicum peruvianum* (Rom et al. 1993, Friedman et al. 1998), *Lycopersicum chilense* (Michelson et al. 1994), *Lycopersicum pimpinellifolium* (Vidavsky et al. 1998) and *Lycopersicum hirsutum* (now known as *L. habrochaites* (Czosnek 2007)) (Vidavsky and Czosnek 1998). Five loci (*Ty-1 through Ty-5*) on chromosome 6 of *Solanum* species have been found to be associated with TYLCV resistance (Czosnek 2007, Anbinder et al. 2009). *S. peruvianum* resistance is conferred by three to five recessive genes (*Ty5*) (Anbinder et al. 2009); *S. chilense* resistance is conferred by semidominant genes and minor genes (*Ty – 3, Ty – 4*) (Agrama and Scott 2006, Ji et al. 2007b, 2008); *S. habrochaites* resistance is conferred by a major dominant locus (*Ty – 2*) (Czosnek 2008, Hanson et al. 2006, Ji et al. 2007b). Genetically engineered tomato plants that have some kind of expression of a functional or dysfunctional Rep or CP protein is being investigated as a control tactic (Czosnek

2007). Rep gene tomato plants had proteins revised in the NTP-binding site which is needed for replication; viruses in plants with this gene were unable to replicate (Czosnek 2007). Using an antisense sequence of the viral Rep gene can also interfere with viral replication (Czosnek 2007). When utilizing genetics to create resistant cultivars, it is best to pyramid genes (Vidavski et al. 2008). Most TYLCV resistant cultivars lose efficiency under high vector population pressure, so other control tactics need to be employed to augment resistant varieties (Polston and Lapidot 2007).

Whiteflies discriminate host plants with physical contact (Hussey and Gurney 1959, Vaishampayan et al. 1975). It is thought that *B. tabaci* has to pierce and probe the plant surface before it is able to determine the plant's suitability as a host plant (Berlinger 1985). A whitefly may deem a plant unsuitable based on a number of morphological and chemical characteristics (Berlinger 1985); such as glabrous or pubescent leaf surfaces (Mound 1965), presence or absence of glandular leaf hairs (Williams et al. 1980, Berlinger and Dahan 1985), pH of plant (Harr et al. 1980), and secondary metabolites (Tingey and Gibson 1978, Raman et al. 1979). Any of these morphological and chemical characteristics may be bred into a cultivar to make them less attractive to *B. tabaci*. Whitefly resistant tomato cultivars have not been widely used by growers due to the perceived lack of marketable phenotypes.

Temporal and spatial avoidance can decrease whitefly presence and TYLCV incidence. Temporal avoidance is simply not planting tomatoes during the same time high whitefly populations are expected and spatial avoidance is not planting a new tomato crop next to an old or existing field planted in a TYLCV susceptible crop (Polston and Lapidot 2007). In addition to low resistance pressure, this tactic limits the need of heavy input of other control tactics which

saves money (Polston and Lapidot 2007). In the southeastern US, whitefly populations peak in the late Summer and early Fall (Riley et al., 2007).

Specialized plasticulture is another available cultural control tactic for TYLCV. The most effective plastic mulches for TYLCV suppression are aluminum reflective mulches (Polston and Lapidot 2007). The light reflected off of the mulch surface interferes with the whitefly's ability to perceive visible and UV light disrupting their landing cue signals (Polston and Lapidot 2007). This tactic is effective under high whitefly populations, but effectiveness decreases with dense plant canopy (Polston and Lapidot 2007). Yellow mulch is also effective at providing TYLCV control (Polston and Lapidot 2007). Instead of repelling and disorienting whiteflies to land, yellow mulch attracts the whiteflies so intensely that they fly to the mulch surface and die from contact because of the mulch's high surface temperature (Cohen 1982). In a study that investigated yellow mulch efficacy in Israel, yellow mulch protected tomato transplants up to 30 days after transplanting (Cohen and Melamed-Madjar 1978). Protection likely faded when the plant canopy became denser (Polston and Lapidot 2007). Still, 38 days after transplanting, 10% of the plants planted in the yellow mulch had TYLCV while the control plot had 100% infection. These results were not able to be replicated in Florida where the humidity is higher (Csizinsky et al. 1996, 1999). The higher humidity prevents whiteflies from desiccating at the high rate that they desiccate on yellow mulches in Israel (Polston and Lapidot 2007). The use of yellow mulch in a high humidity environment like Florida may actually attract whiteflies to tomato crops instead of repelling or killing them (Polston and Lapidot 2007).

Transplants should be purchased from a grow house that practices proper sanitation so that transplants are disease free (Polston and Lapidot 2007). The farther a tomato transplant house is from tomato fields and fields planted in an alternate host, the lower the chances of

purchasing infected transplants (Polston and Lapidot 2007). Additionally, a treatment with an antifeedant chemical on the transplants on the greenhouse should reduce the amount of transmission by any viruliferous whiteflies that may be present (Polston and Lapidot 2007). An application of a neonicotinoid to field grown tomato transplants is also recommended for protection for up to 8 weeks (Polston and Lapidot 2007).

Practicing field sanitation is another cultural control tactic for TYLCV management. Getting rid of all the old tomato plants in a field or any volunteer tomato plants will decrease the amount of inoculum reservoirs (Polston and Lapidot 2007). Whiteflies on old tomato plants will likely migrate to fresh new growth of adjacent fields planted in a newer tomato crop and spread the virus (Polston and Lapidot 2007). In addition to crop residues and volunteer tomatoes, weeds within the field should also be managed because of their potential as another virus reservoir or alternate host (Polston and Lapidot 2007). Rouging of symptomatic plants in the field may help decrease the amount of secondary spread (Polston and Lapidot 2007).

Implementing a regular scouting program can help with inputs on when to apply chemical controls (Polston and Lapidot 2007). Scouting thresholds for viruliferous whiteflies are usually 0%, so once one whitefly is spotted in the field, the field gets sprayed with insecticide (Polston and Lapidot 2007).

Destroying reservoirs for the disease is critical for maintaining control of TYLCV. Identifying alternate TYLCV hosts is difficult when hosts are asymptomatic (Polston and Lapidot 2007). Although TYLCV can be harbored in different neighboring plant species, the most common source of reinfection is from old tomato crops left in a field (Polston and Lapidot 2007).

## References

- Ahmed, N.E., Kanan, H.O., Sugimoto, Y., Ma, Y.Q. and Inanaga, S. 2001. Effect of imidacloprid on incidence of tomato yellow leaf curl virus. *J. Plant. Dis. Protect* 85: 84 – 87.
- Agnew, G.K. and Baker, P.B. 2001. Pest and pesticide usage patterns in Arizona cotton: final 2000 data. *In: Silvertooth, J.C. (Eds.), Cotton, A College of Agriculture Report, Series P-124. University of Arizona, College of Agriculture, Tuscon, AZ. pp. 216 – 234. URL: <http://ag.arizona.edu/pubs/crops/az1224/az12247b.pdf>.*
- Agrama, H.A. and Scott, J.W. 2006. Quantitative trait loci for *Tomato yellow leaf curl virus* and *Tomato mottle virus* resistance in tomato. *J. Hortic. Sci.* 131: 267 – 272.
- Akayama, A. and Minamida, I. 1999. Discovery of a new systemic insecticide, nitenpyram and its insecticidal properties, pp. 127 – 148. *In Yamamoto, I., Casida, J.E. (Eds.), Nicotinoid Insecticides and the Nicotinic Acetylcholine Receptor. Springer, Tokyo.*
- Anbinder I., Reuveni, M., Azari, R., Paran, I. and Nahon, S. et al. 2009. Molecular dissection of *Tomato yellow leaf curl virus* resistance in tomato line TY172 derived from *Solanum peruvianum*. *Theor. Appl. Genet.* 119: 519 – 530.
- Antignus, M., Gidonia, Y., Pilowsky, M. and Choen, S. 1993. Accumulation of *tomato yellow leaf curl virus* DNA in tolerant and susceptible tomato lines. *Plant Dis.* 77: 253 – 257.
- Ascher, K.R.S. and Eliyahu, M. 1988. The ovicidal properties of the juvenile hormone mimic Sumitomo S-31183 (SK-591) to insects. *Phytoparasitica* 16: 15 – 21.
- Ascencio\_Ibanez, J.T., Diaz – Plaza, R., Mendez – Lozano, J., Monsaive-Fonnegra, Z.I., Arguello-Astorga, G.R. and Rivera-Bustamante, R.F. 1999.

- Azzam, O., Frazer, J., De-La-Rosa, D., Beaver, J.S., Ahlquist, P. and Maxwell, D.P. 1994. Whitefly transmission and efficient ssDNA accumulation of bean golden mosaic geminivirus require functional coat protein. *Virology* 204: 289 – 296.
- Bai, D., Lummis, S.C.R., Leicht, W., Breer, H. and Stelle, D.B. 1991. Action of imidacloprid and a related nitromethylene on cholinergic receptors of an identified insect motor neurone. *Pestic. Sci.* 33: 197 – 204.
- Bedford, I.D., Briddon, R.W., Brown, J.K., Rosell, R.C. and Markham, P.G. 1994. Geminivirus transmission and biological characterization of *Bemisia tabaci* (Gennadius) biotypes from different geographic regions. *Ann. Appl. Biol.* 125: 311-325.
- Beevi, S.P. and Balasubramanian, M. 1991. Effect of buprofezin on adult life span, oviposition, egg hatch and progeny production of the cotton whitefly, *Bemisia tabaci*. *Phytoparasitica* 19: 33 – 47.
- Bellows, T.S., Perring, T.M., Gill, R.J. and Headrick, D.H. 1994. Description of a species *Bemisia* (Homoptera: Aleyrodidae). *Ann. Entomol. Soc. Am.* 87: 195 – 206.
- Berlinger, M.J. 1985. Host plant resistance to *Bemisia tabaci*. *Agriculture, Ecosystems and Environment*. 17: 69 – 82.
- Berlinger, M.J. and Dahan, R. 1987. Breeding for resistance to virus transmission by whiteflies in tomaotes. Special Issue of “Insect Science and its Application.” *Int. J. Trop. Insect Sci.*
- Berlinger, M.J., Dahan, R. and Cohen, S. 1983. Greenhouse tomato pests and their control in Israel. *Bulletin SROP*. 6: 7 – 11.
- Berlinger, M.J., Leibush-Mordechai, S., Mor, N. and Fridja, D. 1993. Insecticide efficiency in controlling the whitefly *Bemisia tabaci* and the tomato yellow leaf curl virus. *Phytoparasitica* 21: 176.

- Bosco, D., Mason, G., and Accotto, G.P. 2004. TYLCSV DNA, but not infectivity, can be transovarially inherited by the progeny of the whitefly vector *Bemisia tabaci* (Gennadius). *Virology* 323: 276 – 283.
- Brown, J.K. 2007a. The *Bemisia tabaci* species complex: genotypic and phenotypic variation and relevance to TYLCV-vector interactions, pp. 25-56. *In* H. Czosnek (eds.), *Tomato Yellow Leaf Curl Virus Disease: Management, Molecular Biology, Breeding for resistance*. Springer, Dordrech.
- Brown, J.K. 2007b. The *Bemisia tabaci* species complex: genotypic and phenotypic variation and relevance to TYLCV vector interactions, pp. 25-55, 447. *In* *Tomato Yellow Leaf Curl Virus Disease*. Springer, New York and Tokyo.
- Brown, J.K. 2010. Phylogenetic biology of the *Bemisia tabaci* sibling species group, pp. 31-67. *In* P.A. Stansley and S.E. Naranjo (eds.), *Bemisia: bionomics and management of a global pest*. Springer, New York, NY.
- Brown, J.K., Frolich, D.R., and Rosell, R.C. 1995. The sweetpotato or silverleaf whiteflies: biotypes of *bemisia tabaci* or a species complex? *Annu. Rev. Entomol.* 40: 511-534.
- Brown, J.K., Ostrow, K.M., Idris, A.M. and Stenger, D.C. 1999. Biotic, molecular, and phylogenetic characterization of bean calico mosaic virus, a distinct Begomovirus species with affiliation in the squash leaf curl virus cluster. *Phytopathology* 89: 273 – 280.un
- Brunetti, A., Tavazza, M., Noris, E., Tavazza, R., Caciagli, P., Ancora, G., Crespi, S. and Accotto, G.P. 1997. High expression of truncated viral Rep protein confers resistance to tomato yellow leaf curl virus in transgenic tomato plants. *Mol. Plant Microbe In.* 10: 571 – 579.

- Byrne, D.N. and Bellows Jr., T.S. 1991. Whitefly biology. *Annu. Rev. Entomol.* 36: 431 – 457.
- Byrne, D.N., Cahill, M., Denholm, I. and Devonshire, A.L. 1994. A biochemical and tokiological study of the role of insensitive acetylcholinesterase in organophosphorous resistant *Bemisia tabaci* (Homoptera: Aleyrodidae) from Israel. *B. Entomol. Res.* 84: 179 – 184.
- Byrne, D.N. and Devonshire, A.L. 1993. Insensitive acetylcholinesterase and esterase polymorphism in susceptible and resistant populations of the tobacco whitefly, *Bemisia tabaci*. *Pestic. Biochem. Phys.* 45: 34 – 42.
- Byrne, D.N. and von Bretzel, P.K. 1987. Similarity in flight activity rhythm in coexisting species of Aleyrodidae, *Bemisia tabaci* and *Trialeurodes abutilonea*. *Entomol. Exp. Appl.* 43: 215 – 219.
- Caballero, R., Cyman, S. and Schuster, D.J. 2013. Monitoring insecticide resistance in biotype b of *Bemisia tabaci* (Hemiptera: Aleyrodidae) in Florida. *Fla. Entomol.* 96: 1243 – 1256.
- Cahill, M., Denholm, I., Byrne, F.J. and Devonshire, A.L. 1996a. Insecticide resistance in *Bemisia tabaci* – current status and implications for management. pp. 75 – 80. *In Brighton Crop Protection Conference: Pests and Diseases. British Crop Protection Council, Brighton, UK.*
- Cahill, M., Gorman, K., Day, S., Denholm, J., Elbert, A., and Naven, R. 1996b. Baseline determination and detection of resistance to imidacloprid in *Bemisia tabaci* (Homoptera: Aleyrodidae). *B. Entomol. Res.* 86: 343 – 349.
- Cahill, M., Jarvis, W., Gorman, K., and Denholm, J. 1996c. Resolution of baseline responses and documentation of resistance to buprofezin in *Bemisia tabaci* (Homoptera: Aleyrodidae). *B. Entomol. Res.* 86: 117 – 122.

- Calabrese, E.J. and Edwards, L.J. 1976. Light and gravity in leaf side selection by the green peach aphid, *Myzus persicae*. Ann. Entomol. Soc. Am. 69: 1145 – 1146.
- Chandler, L.D. and Sumner, H.R. 1994. Evaluation of insecticides for control of sweetpotato whitefly (SPWF) on peanut, 1992. Arthropod Manage. Tests 19: 246.
- Cohen, S. 1982. Control of whitefly vectors of viruses by r mulches. pp. 46 – 56. In K.F. Harris and K. Maramorosch (Eds.), Pathogens, Vectors and Plant Diseases, Approaches to Control. New York: Academic Press.
- Cohen, S. and Antignus, Y. 1994. Tomato yellow leaf curl virus (TYLCV) a whitefly-borne geminivirus of tomatoes. Adv. Dis. Vector Res. 10: 259 – 288.
- Cohen, S. and Melamed-Madjar, V. 1978. Prevention by soil mulching of the spread of tomato yellow leaf curl virus transmitted by *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) in Israel. B Entomol. Res. 63: 465-470.
- Cohen, S. and Nitzany, F.E. 1966. Transmission and host range of the tomato yellow leaf curl virus. Phytopathology 56: 1127 – 1131.
- Cohen, S., Kern, J., Harpaz, I., and Ben – Joseph, R. 1988. Epidemiological studies of the tomato yellow leaf curl virus (TYLCV) in the Jordan Valley, Israel. Phytoparasitica 16: 259 – 270.
- Costa, H.S. and Brown, J.K. 1991. Variation in biological characteristics and in esterase patterns among populations of *Bemisia tabaci* (Genn.) and the association of one population with silverleaf symptom development. Entomol. Exp. Appl. 61: 211 – 219.
- Cranston, P.S. and Gullan, P.J. 2009. Phylogeny of Insects. pp. 780-793. In: V.H. Resh and R.T. Carde (eds.), Encyclopedia of Insects, 2<sup>nd</sup> edn. Elsevier, San Diego.

- Csizinsky, A.A., Schuster, D.J. and Kring, J.B. 1997. Evaluation of color mulches and oil sprays for yield and for control of silverleaf whitefly, *Bemisia argentifolii* (Bellows and Perring) on tomatoes. *Crop Prot.* 16: 475-481.
- Csizinsky, A.A., Schuster, D.J. and Polston, J.E. 1999. Effects of ultraviolet-reflective mulches on tomato yields and on the silverleaf whitefly. *HortScience* 34: 911-914.
- Czosnek, H. 2007. Tomato Yellow Leaf Curl Virus. The Hebrew University of Jerusalem, Rehovot, Israel.
- Czosnek, H., Ghanim, M., Morin, S., Rubinstein, G., Fridman, V. and Zeidan, M. 2001. Whiteflies: vectors – or victims? – of Geminiviruses. pp. 291 – 322. *In* K. Maramorosch (eds.), *Adv. Virus Res.*, vol. 57. Academic Press, New York, NY.
- Czosnek, H. and Ghanim, M. 2002. Circulative pathway of begomoviruses in the white vector *Bemisia tabaci* – insights from studies with *Tomato yellow leaf curl virus*. *Ann. Appl. Biol.* 140: 215 – 231.
- Czosnek, H. and Laterrot, H. 1997. A world-wide survey of tomato yellow leaf curl virus. *Arch. Virol.* 142: 1391 – 1406.
- DeBarro, P.J., Liu, S.S., Boykin, L.M. and Dinsdale, A.B. 2011. *Bemisia tabaci*: a statement of species status. *Annu. Rev. Entomol.* 56: 1 – 19.
- DeCock, A., Ishaaya, I., Degheele, D., and Veierov, D. 1990. Vapor toxicity and concentration dependent persistence of buprofezin applied to cotton foliage for controlling the sweetpotato whitefly (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 84: 1254 – 1260.
- Denholm, I., Cahill, M., Dennehy, T.J. and Horowitz, A.R. 1998. Challenges with managing insecticide resistance in agricultural pests, exemplified by the whitefly *Bemisia tabaci*. *Philos. T. R. Soc. Lon. B* 353: 1757 – 1767.

- Dennehy, T.J., DeGain, B., Harpold, G., Brown, J.K., Byrne, F., Morin, S. and Nichols, R.L. 2006. First new world report of Q biotype of *Bemisia tabaci* (Gennadius) reveals high levels of resistance to insecticides. RPM Newsletter 5: 18 – 19.
- Dennehy, T.J., DeGain, B.A., Harpold, V.S., Zaborac, M., Morin, S., Fabrik, J.A., Nichols, R.L., Brown, J.K., Byrne, F.J. and Li, X. 2010. Extraordinary resistance to insecticides reveals exotic Q biotype of *Bemisia tabaci* (Gennadius) in the New World. J. Econ. Entomol. 103: 2174 – 2186.
- Dennehy, T.J. and Williams, L. 1997. Management of resistance in *Bemisia* in Arizona cotton. Pestic. Sci. 51: 398 – 406.
- Dennehy, T.J., Williams, L. III, Li, X., Wigert, M. and Birdwell, E. 1997. Status of whitefly resistance to insecticides in Arizona cotton. pp. 232 – 253. In Silvertooth, J.C. (ed.), Cotton, A college of Agriculture Report, Series P-108. University of Arizona, College of Agriculture, Tuscon, AZ.
- Dinsdale, A.B., Cook, L., Riginos, C., Buckley, Y.M. and DeBarro, P. 2010. Refined global analysis of *Bemisia tabaci* (Hemiptera: Sternorrhyncha: Aleyrodidae) mitochondrial cytochrome oxidase I to identify species level genetic boundaries. Ann. Entomol. Soc. Am. 103: 196 – 208.
- Dittrich, V., Uk, S., and Ernst, G.H. 1990. Chemical control and insecticide resistance of whiteflies pp. 263 – 286. In Gerling, D. (Ed.), Whiteflies: their Bionomics, Pest Status and Management. Intercept, Andover, UK.
- Duffus, J.E., 1987. Whitefly transmission of plant viruses. Curr. Top. Vector Res. 4: 73-91.
- Duffus, J.E., 1996. Whitefly borne viruses. In Gerling, D., Mayer, R.T. (Eds). Proceedings: *Bemisia*: 1995 Taxonomy, Biology, Damage, Control and Management. pp. 255-263.

- Intercept, UK.
- Elbert, A., Overbeck, H., Iwaya, H. and Tsuboi, S. 1990. Imidacloprid, a novel systemic nitromethylene analogue insecticide for crop protection, pp. 21 – 28. *In Proc. Brighton Crop Brighton, England.*
- Ellsworth, P.C. 1998. Whitefly management in Arizona: a decade of research, implementation & education. *In Silvertooth, J.C. (Ed.), Cotton, A College of Agriculture Report, Series P – 124. University of Arizona, College of Agriculture, Tucson, AZ, URL: <http://ag.arizona.edu/pubs/crops/az1224/az12247a.pdf>*
- Ellsworth, P.C. and Jones, J.S. 2001. Cotton IPM in Arizona: a decade of research, implementation and education. *In: Silvertooth, J.C. (Eds.), Cotton, A College of Agriculture Report, Series P-124. University of Arizona, College of Agriculture, Tucson, AZ, URL: <http://ag.arizona.edu/pubs/crops/az1224/az12247a.pdf>.*
- Ellsworth, P.C., Dennehy, T.J. and Nichols, R.L. 1996a. Whitefly management in Arizona cotton, 1996, IPM Series No. 3. The University of Arizona, Cooperative Extension, Publication #196004, Tucson, AZ. pp. 2. URL: <http://ag.arizona.edu/crops/cotton/insects/wf.cibroch.html>.
- Elmer, J.S., Brand, L., Sunter, G., Gardiner, W.E., Bisaro, D.M. and Rogers, S.G. 1988. Genetic analysis of the tomato golden mosaic virus. II. The product of the AL1 coding sequence is required for replication. *Nucleic Acids Res.* 16: 7043 – 7060.
- Fargette, D., Leslie, M. and Harrison, B.D. 1996. Serological studies on the accumulation and localization of three tomato leaf curl Geminiviruses in resistant and susceptible *Lycopersicum* species and tomato cultivars. *Ann. Appl. Biol.* 128: 317 – 328.
- Fereres, A. and Moreno, A. 2009. Behavioral aspects influencing plant virus transmission by homopteran insects. *Virus Res.* 141: 158 – 168.

- Fridaus, S., Vosman, B., Hidayati, N., Supena, E.D.J., Visser, R.G.F. and van Heusden, A.W. 2013. The *Bemisia tabaci* species complex: additions from different parts of the world. *Insect Science*, <http://dx.doi.org/10.1111/1744-7917.12001>.
- Friedman, M., Lapidot, M., Cohen, S., and Pilowsky, M. 1998. A novel source of resistance to tomato yellow leaf curl virus exhibiting a symptomless reaction to viral infection. *J. Am. Soc. Hort. Sci.* 123: 1004 – 1007.
- Frisvold, G., Tronstad, R. and Mortensen, J. 2000. Economic impact of Bt cotton adoption: a national and regional assessment. *In: Silvertooth, J.C. (Eds.), Cotton, A College of Agriculture Report, Series P-121. University of Arizona, College of Agriculture, Tucson, AZ. pp. 367 – 375.*
- Frohlich, D., Torres-Jerez, I., Bedford, I.D., Markham, P.G. and Brown, J.K. 1999. A phylogeographic analysis of the *Bemisia tabaci* species complex based on mitochondrial DNA markers. *Mol. Ecol.* 8: 1593 – 1602.
- Gameel, O.I. 1974. Some aspects of the mating and oviposition behavior of the cotton whitefly *Bemisia tabaci* (Genn.). *Rev. Zool. Afr.* 88: 784 – 788.
- Ghanim, M. 2014. A review of mechanisms and components that determine the transmission efficiency of *Tomato yellow leaf curl virus* (Geminiviridae; *Begomovirus*) by its whitefly vector. *Virus Res.* 186: 47 – 54.
- Ghanim, M., and Czosnek, H. 2000. Tomato yellow leaf curl geminivirus (TYLCV-Is) is transmitted among whiteflies (*Bemisia tabaci*) in a sex-related manner. *J. Virol.* 74: 4735 – 4745.

- Ghanim, M., Morin, S. and Czosnek, H. 2000. Rate of *Tomato Yellow Leaf Curl Virus* (TYLCSV) translocation in the circulative transmission pathway of its vector, the whitefly *Bemisia tabaci*. *Phytopathology* 91: 188-196.
- Ghanim, M., Morin, S., Zeidan, M., and Czosnek, H.G. 1998. Evidence for transovarial transmission of tomato yellow leaf curl virus by its vector, the whitefly *Bemisia tabaci*. *Virology* 240: 295 – 303.
- Gildow, F.E. and Grey, S.M. 1993. The aphid salivary gland basal lamina as a selective barrier associated with vector-specific transmission of barley yellow dwarf luteovirus. *Phytopathology* 83: 1293 – 1302.
- Gill, R.J. 1990. The morphology of whiteflies. Whiteflies: their Bionomics, Pest Status and Management. pp. 13 – 46. In Gerling D. (ed.) Intercept, Andover.
- Goldbach, R. and Peters, D. 1994. Possible causes of the emergence of tospovirus diseases. *Semin. Virol.* 5: 113 – 120.
- Gottlieb, Y., Zchori-Fein, E., Mozes – Daube, N., Kontsedalov, S., Skaljac, M., Brumin, M., Sobol, I., Czosnek, H., Vavre, F., Fleury, F. and Ghanim, M. 2010. The Transmission Efficiency of *Tomato Yellow Leaf Curl Virus* by the Whitefly *Bemisia tabaci* is Correlated with the Presence of a Specific Symbiotic Bacterium Species. *J. Virol.* 84: 9310 – 9317.
- Götz, M., Popovski, S., Kollenberg, M., Gorovits, R., Brown, J.K., Cicero, J.M., Czosnek, H., Winter, S., and Ghanim, M. 2012. Implication of *Bemisia tabaci* Heat Shock Protein 70 in Begomovirus – Whitefly Interactions. *J. Virol.* 86: 13241 – 13252.
- Gray, S. and Gildow, F.E. 2003. Luteovirus aphid interactions. *Annu. Rev. Phytopathology* 41: 539 – 566.
- Guillot, F.S., Droste, T. and Hart, W. 1979. Egg attachment of citrus blackfly *Aleurocanthus woglumi* Ashby to citrus leaves. *Southwest. Entomol.* 4: 167 – 169.

- Guirao, P., Beitia, F. and Cenis, J.L. 1997. Biotype determination in Spanish populations of *Bemisia tabaci* (Hemiptera: Aleyrodidae). *B. Entomol. Res.* 87: 587 – 593.
- Hargreaves, E. 1915. The life-history and habits of the greenhouse white fly (*Aleyrodes vaporariorum* Westd.). *Ann. Appl. Biol.* 1: 303 – 334.
- Harr, J., Guggenheim, R., Boller, T. and Oertli, J.J. 1980. High pH-values on the leaf surface of commercial cotton varieties. *Cotton Fibres Trop.* 35: 379 – 384.
- Harrison, B.D. and Robinson, D.J. 1999. Natural genomic and antigenic variation in whiteflytransmitted Geminiviruses (Begomoviruses). *Annu. Rev. Phytopathol.* 37: 369 – 398.
- Hansen, P.M., Green, S.K. and Kuo, G. 2006. Ty-2, a gene on chromosome 11 conditioning geminivirus resistance in tomato. *Tomato Genet. Crop Rep.* 56: 17 – 18.
- Hassen, I.M., Lapidot, M. and Thomma, B.P.H. 2010. Emerging viral diseases of tomato crops. *Mol. Plant Microbe In.* 23: 539 – 548.
- Hernandez, D., Mansanet, V. and Puiggroc Jove, J.M. 1999. Use of Confidor 200SL in vegetable cultivation in Spain. *Pflanzenschutz-Nachri. Bayer* 52, 364-375.
- Hinton, H.E., 1981. *Biology of Insect Eggs*, vol. 1, 2. Pergamon, New York, NY.
- Hoffman, C.J. and Byrne, D.N. 1986. Effects of temperature and photoperiod upon adult eclosion of sweetpotato whiteflies. *Entomol. Exp. Appl.* 42: 139-143.
- Horowitz, A.R. and Ishaaya, I. 1994. Managing resistance to insect growth regulators in the sweetpotato whitefly (Homoptera: aleyrodidae). *J. Econ. Entomol.* 87: 866 – 871.
- Horowitz, A.R. and Ishaaya, I. 1996. Chemical control of *Bemisia* – management and application. *In: D. Gerling and R.T. Mayer. (Eds.), pp. 537 0 556. Bemisia: 1995 Taxonomy, Biology, Damage, Control and Management. Intercept Ltd. Andover, Hants,*

UK

- Horowitz, A.R., Kontsedalov, S., Khasdan, V. and Ishaaya, I. 2005. Biotypes B and Q of *Bemisia tabaci* and their relevance to neonicotinoid and pyriproxyfen resistance. Arch. Insect Biochem. 58: 216 – 225.
- Horowitz, A.R., Medelson, Z., Weintraub, P.G. and Ishaaya, I. 1998a. Comparative toxicity of foliar and systemic applications of acetamiprid and imidacloprid against the cotton whitefly, *Bemisia tabaci* (Hemiptera: Aleyrodidae). B. Entomol. Res. 88: 437-442.
- Horowitz, A.R., Denholm, I., Groman, K. and Ishaaya, I. 1999a. Insecticide resistance in whiteflies: current status and implication for management. pp. 8996 – 8998. In: Denholm, I., Ioannidis, P. (Eds.), Proceedings of an ENMARIA Symposium: Combatting Insecticide Resistance, Thessalonikis, Greece, May 1999.
- Horowitz, A.R., Mendelson, Z., Cahill, M., Denholm, I. and Ishaaya, I. 1999b. Managing resistance to the insect growth regulator, pyriproxyfen in *Bemisia tabaci*. Pestic. Sci. 55: 272 – 276.
- Hussey, N.W. and Gurney, B. 1957. Greenhouse whitefly (*Trialeurodes vaporariorum* Westwood). Ann. Rep. Glasshouse Crops Res. Station. 134 – 137.
- Hull, R. 2002. Matthews' Plant Virology. (4<sup>th</sup> ed.). Academic Press, San Diego.
- Ishaaya, I. and Ascher, K.R.S. 1983. Synergized pyrethroids against *Bemisia tabaci*. Phytoparasitica 11: 67.
- Ishaaya, I. and Ascher, K.R.S. 1984. Synergized cypermethrin for controlling the whitefly, *Bemisia tabaci* in cotton. Phytoparasitica 12: 139 – 140.
- Ishaaya, I. and Horowitz, A.R. 1992. Novel phenoxy juvenile hormone analog (pyriproxyfen) suppresses embryogenesis and adult emergence of sweetpotato whitefly (Homoptera,

- Aleryrodidae). *J. Econ. Entomol.* 85: 2113 – 2117.
- Ishaaya, I. and Horowitz, A.R. 1995. Pyriproxyfen, a novel insect growth regulator for controlling whiteflies: mechanisms and resistance management. *Pestic. Sci.* 43: 227 – 232.
- Ishaaya, I., Mendelson, Z., Ascher, K.R.S. and Casida, J.E. 1987. Cypermethrin synergism by pyrethroid esterase inhibitors in adults of the whitefly *Bemisia tabaci*. *Pestic. Biochem. Phys.* 28: 155 – 162.
- Ishaaya, I., Mendelson, Z. and Melamed-Madjar, V. 1988. Effect of buprofezin on embryogenesis and progeny formation of sweetpotato whitefly (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 81: 781 – 784.
- Ioannu, N. 1987. Cultural management of tomato yellow leaf curl disease in Cyprus. *Plant Pathol.* 36: 367 – 373.
- Ioannu, N. and Iordanou, N. 1985. Epidemiology of tomato yellow leaf curl virus in relation to the population density of its whitefly vector *Bemisia tabaci* (Gennadius). Technical Bulletin No. 71. Agricultural Research Institute, Ministry of Agricultural and Natural Resources, Nicosia, Cyprus, 7 pp.
- Ji, Y., Scott, J.W., Hanson, P., Graham, E. and Maxwell, D.P. 2007b. Sources of resistance, inheritance and location of genetic loci conferring resistance to members of the tomato infecting begomoviruses. pp. 343 – 362. *In* H. Czosnek (Eds.), *Tomato Yellow Leaf Curl Virus Disease. Management, Molecular Biology, Breeding for Resistance*. Springer, Dordrecht, The Netherlands.
- Ji, Y., Scott, J.W., Maxwell, D.P. and Schuster, D.J. 2008. Ty-4, a *Tomato yellow leaf curl virus* resistance gene on chromosome 3 of tomato. *Rep. Tomato Genet. Coop.* 58: 29-31.

- Kagabu, S. 1999. Studies on the synthesis and insecticidal activity of neonicotinoid compounds. *Pestic. Sci.* 21: 231 – 239.
- Kanno, H.K., Asi, T. and Maekawa, S. 1981. 2-tert-butylimino-3-isopropyl-perhydo-1,3,5thaidiazon-4-one (NNI 750), a new insecticide. pp. 56-69. *In Proc Brighton Crop, Brighton, England.*
- Kato, K., Onuki, M., Fuji, S. and Hanada, K. 1998. The first occurrence of *tomato yellow leaf curl virus* in tomato (*Lycopersicon esculentum* Mill.) in Japan. *Ann. Phytopath. Soc. Japan* 64: 552 – 559.
- Lazarowitz, S.G. 1992. Geminiviruses: Genome structure and gene function. *CRC CR. Rev. Plant Sci.* 11: 327 – 349.
- Li, A.Y., Dennehy, T.J., Li, S., Wigert, M.E., Zarborac, M. and Nichols, R.L. 2001. Sustaining Arizona's fragile success in whitefly resistance management. pp. 1108 – 1114. *In P. Dugger and D. Richter. (eds.), Proceedings: Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.*
- Liu, M.Y. and Casida, J.E. 1993. High affinity binding of [<sup>3</sup>H] imidacloprid in the insect acetylcholine receptor. *Pestic. Biochem. Phys.* 46: 40 – 46.
- Liu, S.S., Colvin, J. and DeBarro, P.J. 2012. Species concepts as applied to the whitefly *Bemisia tabaci* systematics: how many species are there? *J. Integr. Agr.* 11: 176 – 186.
- Ma, D., Gorman, K, Divine, G., Luo, W. and Denholm, I. 2007. The biotype and insecticideresistance status of whiteflies, *Bemisia tabaci* (Hemiptera: Aleyrodidae), invading cropping systems in Xinjiang Uygur Autonomous Region, northwestern China. *Crop Prot.* 26: 612 – 617.

- Maienfisch, P., Brandt, F., Kobel, W., Rindlisbacher, A. and Senn, R. 1999. CGA293'343: a novel, broad-spectrum neonicotinoid insecticide. pp. 177 – 209. *In* I. Yamamoto and J.E. Casida (Eds.), *Nicotinoid Insecticides and the Nicotinic Acetylcholine Receptor*. Springer, Tokyo.
- Maienfisch, P., Huerlimann, H., Rindlisbacher, A., Gsell, L., Dettwiler, H., Haettenschwiler, J., Sieger, E. and Walti, M. 2001. The discovery of thiamethoxam: a second generation neonicotinoid. *Pestic. Sci.* 57: 165 – 176.
- Mason, G., Rancati, M. and Bosco, D. 2000. The effect of thiamethoxam, a second generation neonicotinoid insecticide, in preventing transmission of tomato yellow leaf curl geminivirus (TYLCV) by the whitefly *Bemisia tabaci* (Gennadius). *Crop Prot.* 19: 473 – 479.
- Mau, R.F.L. and Kessing, J.L.M. 2007. *Bemisia tabaci* (Gennadius).  
[http://www.extento.hawaii.edu/kbase/crop/type/b\\_tabaci.htm](http://www.extento.hawaii.edu/kbase/crop/type/b_tabaci.htm)
- McAuslane, H.J. 2000. Sweetpotato whitlefy B Biotype of Silverleaf whitefly, *Bemisia tabaci* (Gennadius) or *Bemisia argentifolii* Bellows & Perring (Insecta: Hemiptera: Aleyrodidae). University of Florida, IFAS Extension EENY 129.
- Medina, V., Pinner, M.S., Bedford, L.D., Achon, M.A., Gemeno, C. and Markham, P.G. 2006. Immunolocalization of *Tomato yellow leaf curl sardine virus* in natural host plants and its vector *Bemisia tabaci*. *J. Plant Pathol.* 88: 299 – 308.
- Michelson, I., Zamir, D. and Czosnek, H. 1994. Accumulation and translocation of tomato yellow leaf curl virus (TYLCV) in a *Lycopersicon esculentum* breeding line containing the *L.chilense* TYLCV tolerance gene Ty-1. *Phytopathology* 84: 928 – 933.

- Moralesm F.J. and Jones, P.G. 2004. The ecology and epidemiology of whitefly-transmitted viruses in Latin America. *Virus Res.* 1: 57 – 65.
- Morin, S., Ghanim, M., Zeidan, M. Czosnek, H., Verbeek, M. and van den Heuvel, J.F.J.M., 1999. A GroEL Homologue from Endosymbiotic Bacteria of the Whitefly *Bemisia tabaci* Is Implicated in the Circulative Transmission of *Tomato yellow leaf curl virus*. *Virology* 30: 75-84.
- Moriones, E. and Navas – Castillo, J. 2000. Tomato yellow leaf curl virus, an emerging virus complex causing epidemics worldwide. *Virus Res.* 71: 123 – 134.
- Mound, L.A. 1965. Studies on the olfaction and colour sensitivity of *Bemisia tabaci* (GENN.) (Homoptera: Aleyrodidae). *Entomol. Exp. Appl.* 5: 99 – 104.
- Mullins, J.W. and Engle, C.E. 1993. Imidacloprid (BAY NTN 33893): a novel chemistry for sweetpotato whitefly control in cotton. pp. 719 – 720. *In* D.J. Herber and D.A. Richter (Eds.), *Proceedings, Symposium: Beltwide Cotton Conferences*. National Cotton Council, Memphis, TN.
- Naranjo, S.E., Ellsworth, P.C., Chu, C.C., Henneberry, T.J., Riley, D.G., Watson, T.F. and Nichols, R.L. 1998. Action thresholds for the management of *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton. *J. Econ. Entomol.* 91: 1415 – 1426.
- Nauen, R. and Elbert, A. 1997. Apparent tolerance of a field-collected strain of *Myzus persicae* to imidacloprid due to strong anti-feeding responses. *Pestic. Sci.* 49: 252 – 258.
- Nauen, R., Tietjen, K., Wagner, K. and Elber, A. 1998a. Efficacy of plant metabolites of imidacloprid against *Myzus persicae* and *Aphis gossypii* (Homoptera: Aphididae). *Pestic. Sci.* 52: 53 – 57.

- Nauen, R., Koob, B. and Elbert, A. 1998b. Antifeedant effects of sublethal doses of imidacloprid on *Bemisia tabaci*. Entomol. Exp. Appl. 88: 287 – 293.
- Nauen, R., Reckmann, U., Armbrorst, S., Stupp, H.P. and Elbery, A. 1999. Whitefly active metabolites of imidacloprid: biological efficacy and translocation in cotton plants. Pestic. Sci. 55: 265 – 271.
- Nault, L.R. 1997. Arthropod transmission of plant viruses: a new synthesis. Ann. Entomol. Soc. Am. 90: 521 – 541.
- Navot, N, Pichersky, E., Zeidan, M, Zamir, D. and Czosnek, H. 1991. Tomato Yellow Leaf Curl Virus: A Whitefly-Transmitted Geminivirus with a Single Genomic Component. Virology 185: 151-161.
- Noris, E., Accotto, G.P., Tavazza, R., Brunetti, A., Crespi S. and Tavazza, M. 1996. Resistance to tomato yellow leaf curl geminivirus in *Nicotiana benthamiana* plants transformed with a truncated viral C1 gene. Virology 224: 130 – 138.
- Oliveria, M., Hennerberry, T. and Anderson, P. 2001. History, current status, and collaborative research projects for *Bemisia tabaci*. Crop Prot. 20: 709 – 723.
- Omran, H.H. and El Khidir, E. 1978. Über die Bevorzugung von Blatthaaren zur Eiablage bei *Bemisia tabaci* (Genn.) (Hom., Aleyrodidae). Anz. Schaedlingskde. Pflanz. Umweltschutz, 51: 175.
- Palumbo, J.C. 2001. Residual efficacy of foliar chloronicotinyls against silver leaf whiteflies on melons, 2000. Athropod Manage. Tests 26: E21.
- Palumbo, J.C. and Coates, W.E. 1996. Air-assited electrostatic application of pyrethroid and endosulfan mixtures for sweetpotato whitefly (Homoptera: Aleyrodidae) control and spray depostion in cauliflower. J. Econ. Entomol. 89: 970 – 980.

- Palumbo, J.C., Horowitz, A.R. and Prabhaker, N. 2001. Insecticidal control and resistance management for *Bemisia tabaci*. *Crop Prot.* 20: 739 – 765.
- Palumbo, J.C., Kerns, D.L., Engle, C.E., Sanchez, C.A. and Wilcox, M. 1996b. Imidacloprid formation and soil placement effects on colonization by sweetpotato whitefly (Homoptera: Aleyrodidae): head size and incidence of chlorosis in lettuce. *J. Econ. Entomol.* 89: 735 – 742.
- Palumbo, J.C., Mullis Jr., C.H., Reyes, F.J., Amaya, A., Ledesma, L. and Carey, L. 2000b. Comparison of neonicotinoid use patterns for silverleaf whitefly management in melons and broccoli. pp. 22-34. *In* D.N. Byrne and P. Baciewicz. (Eds.), 2000 Vegetable Report, University of Arizona, College of Agriculture and Life Sciences, Tuscon, AZ.
- Palumbo, J.C., Mullis Jr., C.H. and Reyes, F.J. 2001. Residual efficacy and field performance of thiacloprid (Calypso) against silverleaf whitefly in melons. pp. 43 – 52. *In* D.N. Byrne and P. Baciewicz (Eds.), 2001 Vegetable Report, University of Arizona, College of Agriculture and Life Sciences, Tuscon, AZ.
- Perring, T.M. 2001. The *Bemisia tabaci* species complex. *Crop. Prot.* 20: 725 – 737.
- Pishvaei, B., Costaguta, G., Yeung, B.G., Ryazantsev, S., Greener, T., Eisenberg, E., McCaffery, J.M., and Payne, G.S. 2000. A yeast DNA J protein required for uncoating of clathrin – coated vesicles in vivo. *Nat. Cell Biol.* 2: 958 – 963.
- Polston, J.E. and Anderson, P.K. 1997. The emergence of whitefly-transmitted geminiviruses in tomato in the Western Hemisphere. *Plant Dis.* 81: 1358 – 1369.
- Polston, J.E. and Lapidot, M. 2007. Management of Tomato yellow leaf curl virus: US and Israel Perspectives. pp. 251 – 262. *In* H. Czosnek (Eds.), *Tomato Yellow Leaf Curl Disease*. Springer, Netherlands.

- Power, A.G. 2000. Insect transmission of plant viruses: a constraint on virus variability. *Curr. Opin. Plant Biol.* 3: 336 – 340.
- Prabhaker, N., Coudriet, D.L. and Toscano, N.C. 1988. Effect of synergists on organophosphate and permethrin resistance in sweetpotato whitefly (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 81: 34 – 39.
- Prabhaker, N., Toscano, N.C., Castle, S.J. and Henneberry, T.J. 1997. Selection for imidacloprid resistance in silverleaf whiteflies from the imperial valley and development of a hydroponic bioassay for resistance monitoring. *Pestic. Sci.* 51: 419 – 428.
- Pratt, W.B., Silverstein, A.M., and Galigniana, M.D. 1999. A model for the cytoplasmic trafficking of signalling proteins involving the hsp90-binding immunophilins and p50. *Cell Signal.* 11: 839-851.
- Raman, K.V., Tingey, W.M. and Geogry, P. 1979. Potato glycoalkaloids: effect on survival and feeding behavior of the potato leafhopper. *J. Econ. Entomol.* 72: 337 – 341.
- Rigden, J.E., Krake, L.R., Rezaian, M.A. and Dry, I.B. 1994. ORF C4 of tomato yellow leaf curl virus is a determinant of symptom severity. *Virology* 204: 847 – 850.
- Rochester, D.E., DePaulo, J.J., Fauquet, C.M. and Beachy, R.N. 1994. Complete nucleotide sequence of the geminivirus tomato yellow leaf curl virus, Thailand isolate. *J. Gen. Virol.* 75: 477 – 485.
- Riley, D, Culpepper, S., Kelley, T., Keinath, A.P., Langston, D., Powell-Smith, J. and Sparks, S. 2007. Insect Pest-by-Pest Profile. pp. 22. *In* Workshop at Savannah Conference Center: Pest Management Strategic Plan for Tomato in Georgia and South Carolina, Savannah, GA, USA.

- Rosell, R.C., Lichty, J.E., and Brown, J.K. 1995. Ultrastructure of the mouthparts of adult sweetpotato whitefly, *Bemisia tabaci*. *Int. J. Insect Morphol.* 24: 297 – 306.
- Rubinstein, G. and Czosnek, H. 1997. Long-term association of tomato yellow leaf curl virus (TYLCV) with its whitefly vector *Bemisia tabaci*: effect on the insect transmission capacity, longevity and fecundity. *J. Gen. Virol.* 78: 2683 – 2689.
- Rubinstein, G., Morin, S. and Czosnek, H. 1999. Transmission of tomato yellow leaf curl geminivirus to imidacloprid treated tomato plants by the whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 92: 685 – 662.
- Rybicki, E.P., Briddon, R.W., Brown, J.K., Fauquet, C.M., Maxwell, D.P., Stanley, J., Harrison, B.D., Markham, P.G., Bisaro, D.M., Robinson, D. 2000. Family Geminiviridae. *In* M.H.V. Van Regenmortel, C.M. Fauquet, D.H.L. Bishop, E. Carstens, M. Estes, S. Lemon, J. Manlioff, M.A. Mayo, D. McGeoch, C. Pringle, and R. Wickner (eds.), *Proceedings, Symposium: Virus Taxonomy. Seventh Report of the International Committee on Taxonomy of Viruses.* pp. 285 - 297. Academic Press, New York.
- Rybicki, E.P. and Pietersen, G. 1999. Plant virus problems in the developing world. *Adv. Virus Res.* 53: 127 – 175.
- Salati, R., Nahkla, M.K., Rojas, M.R., Guzman, P., Jaquez, J., Maxwell, D.P. and Gilbertson, R.L. 2002. *Tomato yellow leaf curl virus* in the Dominican Republic: Characterization of an Infectious Clone, Virus Monitoring in Whiteflies, and Identification of Reservoir Hosts. *Virology* 92: 487 – 496.
- Schuster, D.J. 1994. Insect control on fresh market tomatoes in west-central Florida, spring 1993. *Arthropod Manage. Tests* 19: 150 – 152.
- Schuster, D.J. 1995a. Control of insects on fresh market tomatoes in west-central Florida, spring 1994. *Arthropod Manage. Tests* 20: 134 – 136.

- Schuster, D.J. 1995b. Control of insects on bell pepper in west-central Florida, spring 1994. *Arthropod Manage. Tests* 20: 103 – 104.
- Schuster, D.J. 2000a. Insecticides applied on demand for managing the silverleaf whitefly on fresh market tomatoes in spring 1998. *Arthropod Manage. Tests* 25: 100.
- Schuster, D.J. 2000b. Insecticides applied on demand for managing the silverleaf whitefly on fresh market tomatoes in fall 1998. *Arthropod Manage. Tests* 25: 101.
- Schuster, D.J., Stansly, P.A. and Polston, J.E. 1996. Expressions of plant damage by *Bemisia*. Pp. 153 – 165. *In* D. Gerling and R.T. Mayer. (Eds.), *Bemisia: 1995 Taxonomy, Biology, Damage, Control and Management*. Intercept Ltd., Andover, Hants, UK.
- Sharaf, N. 1986. Chemical control of *Bemisia tabaci*. *Agric. Ecosyst. Environ.* 17: 111 – 127.
- Singh, J. and Buttler, N.S. 1984. Influence of climatic factors on the buildup of whitefly *Bemisia tabaci* on cotton. *Indian J. Entomol.* 47: 359 – 360.
- Sinisterra, X.H., McKenzie, C.L., Hunter, W.B., Powell, C.A. and Shatters Jr., R.J. 2005. Differential transcriptional activity of plant pathogenic begomoviruses in their whitefly vector (*Bemisia tabaci*, Gennadius: Hemiptera Aleyrodidae). *J. Gen. Virol.* 86: 1525 – 1532.
- Stansly, P.A. and Cawly, B.M. 1994a. Control of adult sweetpotato whitefly (SPWF) and tomato mottle geminivirus (TMoV) transmission on staked tomato, spring, 1992. *Arthropod Manage. Tests* 19: 156.
- Stansly, P.A. and Conner, J.M. 1995. Control of silverleaf whitefly and tomato pinworm on staked tomato with chemical and biological insecticides, spring 1994. *Arthropod Manage. Tests* 20: 145 – 146.
- Stansly, P.A. and Conner, J.M. 2000. Impact of insecticides on silverleaf whitefly and tomato yellow leaf curl virus on staked tomato, 1999. *Arthropod Manage. Tests* 25: 104.

- Sunter, G. and Bisaro, D.M. 1991. Transactivation in a geminivirus: AL2 gene product is needed for coat protein expression. *Virology* 180: 416 – 419.
- Taylor, C.E. and Georghiou, G.P. 1982. Influence of pesticide persistence in evolution of resistance. *Environ. Entomol.* 11: 746 – 750.
- Tingey, W.M. and Gibson, R.W. 1978. Feeding and mobility of the potato leafhopper impaired by glandular trichomes of *Solanum berthaultii* and *S. polyadenium*. *J. Econ. Entomol.* 71: 856 – 858.
- Tsai, M.Y., Morfini, G., Szebenyi, G., and Brady, S.T. 2000. Release of kinesin from vesicles by hsc70 and regulation of fast axonal transport. *Mol. Biol. Cell* 11: 2161 – 2173.
- Vaishampayan, S.M., Waldbauer, G.P. and Kogan, M. 1975. Visual and olfactory responses in orientation to plants by the greenhouse whitefly *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae). *Entomol. Exp. Appl.* 18: 412 – 422.
- Van Lenteren, J.C. and Noldus, P.J.J. 1990. Plant relationships: behavioral and ecological aspects, pp. 348. *In* D. Gerling (eds.), *Whiteflies: Their Bionomics, Pest Status and Management*. Intercept, Wimborne, UK.
- van Lenteren, J.C., and Woets, J. 1977. Development and establishment of biological control of some glasshouse pests in the Netherlands, pp. 81 – 87. *In* F.F. Smith and R.E. Webb (eds.), *Pest Management in Protected Culture Crops*.
- Vea, E. and C. Palmer. 2014. IR-4 Ornamental Horticulture Program - whitefly efficacy. <http://ir4.rutgers.edu/Ornamental/SummaryReports/WhiteflyDataSummary2014.pdf>
- Vidavsky, F., and Czosnek, H. 1998. Tomato breeding lines resistant and tolerant to tomato yellow leaf curl virus issued from *Lycopersicon esculentum*. *Phytopathology* 88: 910 – 914.

- Vidavsky, F., Czosnek, H., Gazit, S., Levy, D. and Lapidot, M. 2008. Pyramiding of genes conferring resistance to *Tomato yellow leaf curl virus* from different wild tomato species. *Plant Breeding* 127: 625 – 631.
- Vidavsky, F., Leviatov, S., Milo, J., Rabinowitch, H.D., Kedar, N. and Czosnek, H. 1998. Response of tolerant breeding lines of tomato, *Lycopersicum esculentum*, originating from three different sources (*L. peruvianum*, *L. pimpinellifolium*, and *L. chilense*) to early controlled inoculation by tomato yellow leaf curl viruses (TYLCV). *Plant Breeding* 117: 165 – 169.
- Walker, G.P. and Aitken, D.C.G. 1985. Oviposition and Survival of Bayberry Whitefly, *Parabemisia myricae* (Homoptera: Aleyrodidae) on Lemons as a Function of Leaf Age. *Environ. Ecol.* 14: 254-257.
- Walker, G.P. and Gordh, G. 1990. The occurrence of apical labial sensilla in the Aleyrodidae and evidence for a contact chemosensory function. *Entomol. Exp. Appl.* 51: 215 – 224.
- Weber, H. 1931. Lebensweise und Umweltbeziehungen von *Trialeurodes vaporariorum* (Westwood) (Homoptera: Aleurodina). *Zeitschrift fuer Morphologie und Oekologie der Tiere* 23: 575 – 753.
- Wigglesworth, V.B., 1965. *The Principles of Insect Physiology*. 6<sup>th</sup> ed. pp. 827. Chapman and Hall, England.
- Williams, W.G., Kennedy, G.G., Yamamoto, R.T., Thacker, J.D. and Bordner, J. 1980. 2Tridecanone: A naturally occurring insecticide from the wild tomato *Lycopersicon hirsutum* f. *glabratum*. *Science* 207: 888 – 889.
- Wilson, D. and Anema, B.P. 1988. Development of buprofezin for control of whitefly *Trialeurodes vaporariorum* and *Bemisia tabaci* on glasshouse crops in the Netherlands and the UK. pp. 175 – 180. *In Proc. Brighton Crop. British Crop Protection Council*,

Thornton Heath, UK.

- Woets, J. and van Lenteren, J.C. 1976. The parasite-host relationship between *Sucaisia Formosa* (Hymenoptera: Aphelinidae) and *Trialeurodes vap* (Homoptera: Aleyrodidae) VI. The influence of the host plant on the greenhouse whitefly and its parasite *Encarsia Formosa*. B. OILB/SROP 4: 151 – 164.
- Woolweber, D. and Tietjen, K. 1999. Chloronicotynyl insecticides: a success of the new chemistry. pp. 106 – 126. *In* I. Yamamoto and J.E. Casdia (Eds.), *Nicotinoid Insecticides and the Nicotinic Acetylcholine Receptor*. Springer, Tokyo.
- Yamada, T., Takahashi, H. and Hatano, R. 1999. A novel insecticide, acetamiprid. pp. 149 – 176. *In* I. Yamamoto and J.E. Casdia (Eds.), *Nicotinoid Insecticides and the Nicotinic Acetylcholine Receptor*, Springer, Tokyo.
- Yamamoto, I., Yabuta, G., Tomizawa, M., Saito, T., Miyamoto, T. and Kagabu, S. 1995. Molecular mechanisms for selective toxicity of nicotinoids and neonicotinoids. *J. Pestic. Sci.* 20: 33 – 40.
- Yasui, M., Fakuda, M. and Maekawa. 1987. Effects of buprofezin on reproduction of the greenhouse whitefly, *Trialeurodes vaporarium* (Westwood) (Homoptera: Aleyrodidae). *Appl. Entomol. Zool.* 22: 266 – 271.
- Zhou, X., Liu, Y., Calvert, L., Munoz, C. and Otim – Nape, G.W. 1997. Evidence that DNA-A of geminivirus associated with severe cassava mosaic disease in Uganda has arisen by interspecific recombination. *J. Gen. Virol.* 78: 2101 – 2111.

## Chapter 3

### INSECTICIDE AND PROXIMITY EFFECTS ON THE SPREAD OF TOMATO YELLOW

### LEAF CURL VIRUS AND WHITEFLIES<sup>1</sup>

---

<sup>1</sup> Dempsey, Meredith M. To be submitted to the Journal of Integrated Pest Management

## **Abstract**

A field crop tunnel experiment was conducted to study viruliferous whitefly, *Bemisia tabaci*, movement and *Tomato yellow leaf curl virus* (TYLCV) spread across virus-susceptible tomatoes as mitigated by insecticide treatments. TYLCV infected and *Bemisia tabaci* infested source plants were planted at the beginning of tunneled rows to serve as inoculum source so that movement of whiteflies and TYLCV symptoms could be tracked down the length of the tunnel over time. Results showed that insecticide treated rows suppressed whitefly incidence and slowed TYLCV movement in comparison to check tunnels. Tomato plants planted closer to the infested, infected source plant had higher incidence of whiteflies and TYLCV infection. This implies that the proximity of tomato plant to the inoculum source increases whitefly incidence and TYLCV symptoms. Presence of whiteflies positively correlated with TYLCV presence in all treatments. Whitefly distribution and TYLCV incidence were influenced more by spatial proximity to the inoculum source rather than by insecticide treatments.

**Key words:** TYLCV, *Bemisia tabaci*, population dynamics, insecticide, epidemiology

## Introduction

*Bemisia tabaci* is a severe pest on tomato in the southeastern United States because they transmit a debilitating plant virus called *Tomato yellow leaf curl virus* (TYLCV). TYLCV is in the family *Geminiviridae*, characterized as being unipartite or bipartite DNA viruses that have single stranded DNA arranged in a circle (Moriones and Navas – Castillo 2000). When a nonviruliferous whitefly feeds on an infected plant, the virus passes through the midgut, into the hemolymph and into the salivary glands where it persists until the whitefly can inoculate a healthy plant upon feeding. Whitefly stylets penetrate through the leaf epidermis and enter into plant cells to feed on phloem sap (Feres and Moreno 2009). Once the virus has been transmitted to the phloem via infected whitefly saliva, the plant typically experiences a systemic infection (Moriones and Navas – Castillo 2000). Tomato plants infected with TYLCV become stunted and have low to no yield (Czosnek 2008). Where viruliferous whitefly populations are dense, there can be up to 100% yield loss (Czosnek 2008). TYLCV is difficult to control because *B. tabaci* transmits the virus in a persistent manner. Additionally, adults only need to feed for a minimum of 15 minutes to successfully inoculate a host plant (Ghanim et al. 2001), making them difficult to kill before they can inoculate a tomato plant. For this reason, chemical controls are commonly applied prophylactically at periods in the year that viruliferous whitefly populations are expected and not triggered by adult action thresholds.

Prophylactic insecticide treatments are usually applied as a soil drench immediately before transplanting. Systemic insecticides of the neonicotinoid class is the standard insecticide for whitefly control (Ahmed et al. 2001, Cahill et al. 1996, Polston and Anderson 1997). Neonicotinoids block postsynaptic nicotinic acetylcholine receptors (Bai et al. 1991, Liu and

Casida 1993). This class of insecticide is good at providing control for phloem feeding insects because it has a high water solubility factor which allows it to move systemically throughout the plant's vascular system (Kagabu 1999, Yamada et al. 1999, Maienfisch et al. 2001).

Imidacloprid is commonly applied as a systemic treatment by soil drench to suppress whiteflies (Chandler and Sumner 1994, Palumbo et al. 1996b, Horowitz et al. 1998a, Hernandez et al. 1999, Schuster 2000a). The chemical kills adults and nymphs upon ingestion of treated plant sap, but also repels whiteflies before landing (Nauen and Elbert 1997, Nauen et al. 1998b).

Residual activity can last between 1 to 10 weeks (Palumbo et al. 2001). For tomatoes, treating with a soil drench while still in the greenhouse or soon after planting is most effective (Schuster 2000a, b). Prophylactic applications of imidacloprid through drip lines has been shown to decrease early *B. tabaci* and TYLCV outbreaks in tomato (Ahmad et al. 2001, Stansly and Conner 2000). However, imidacloprid was not shown to inhibit the transmission of TYLCV to a healthy tomato host plant under controlled conditions (Rubinstein et al. 1999). Thus, there is a need to further investigate insecticide effects on the spread of the virus.

In addition to traditional systemic neonicotinoids, new chemistries have been developed for *B. tabaci* control. One of these new insecticides belongs to a new insecticide class, the diamide class. Diamides act antagonistically on the ryanodine receptor modulator and kills the insect within 72 hours through muscle paralysis (Andaloro et al. 2010). Some diamides can act systemically via a soil drench application or a foliar spray (Smith 2013). Three diamide insecticides are labeled for tomato: chlorantraniliprole, cyantraniliprole and flubendiamide (Smith 2014). Chlorantraniliprole and cyantraniliprole are used for *B. tabaci* control (Smith

2014). Cyantraniliprole may provide protection against viruliferous whiteflies and suppress TYLCV (Smith 2013). Cyantraniliprole trade names include Verimark® or Cyazypyr® (soil) and Exirel® (foliar) (Smith 2013).

Chemical control of whitefly vectors of TYLCV is most effective when used in conjunction with vector population dynamic information versus preventative applications. This avoids unnecessary overuse of the chemistry which helps to maintain susceptibility of the target pest to the pesticide. A TYLCV epidemic can occur slowly through a point source or rapidly from a large scale source of whitefly vectors resulting in large scale primary spread. The more obvious way is through primary spread from large whitefly migrations typically seen in late July and August in southern Georgia (Srinivasan et al. 2012). The less obvious way is through the gradual build-up of whiteflies from a few virus infected plants that have resided in small virus infected plots. In the South Georgia epidemic that was observed in 2013, secondary spread seemed to play a larger role in facilitating the TYLCV epidemic than the large whitefly migrations, because epidemics were localized (D. Langston, personal communication).

Our study investigated the effect of the diamide insecticide, cyantraniliprole and the neonicotinoid insecticide, imidacloprid, on spread of TYLCV. Spread of both the vector and virus were contained to the plants planted underneath fabric row tunnels and originated from a TYLCV positive, whitefly infested source plant planted at the beginning of each row. The null hypothesis was that insecticide treated (imidacloprid or cyantraniliprole) rows would have a reduced observed whitefly and virus symptom spread as compared to untreated rows.

### **Materials and Methods**

This experiment was conducted at the Coastal Plains Research Station in Tifton, GA at the Lang-Rigdon Farm location during the summers of 2013 and 2014. The experiment was a

complete randomized block design. Each trial had four replicates and four treatments within each replicate. The whole experiment was replicated twice, but only the TYLCV positive check under the tunnel and cyantraniliprole treated tunnel treatments were consistent across years.

After turn plowing the field, 24.4 m long treatment beds were formed and covered in white plastic mulch. Holes were punched in the plastic 46 cm apart. The framing for the hoop structures was constructed using rebar and aluminum conduit hoops as seen in Figure 3.1. Three foot sections of rebar were hammered approximately one foot into the ground so that 3.05 meter curved aluminum conduit could slide on top of exposed rebar. Hoops were placed at 3.05 m intervals down a 24.4 m treatment row. Each row was divided by 9 hoops. Hoop frames were covered with a heavy-duty fabric row cover material (Row Cover Supreme®, Greenhouse Megastore, Danville, IL) and anchored down on sides with dirt. At every 3.05 m in the tunnel fabric, a hole was cut to allow access for sampling as seen in Figure 3.1. Tomato seedlings were purchased from Lewis Taylor farms in Tifton, GA. Transplants were a TYLCV-susceptible cultivar, FL-47. Prior to transplanting, holes were drenched with a chemical treatment or with water as a control treatment. Tomatoes were irrigated using 30.5 cm emitter interval drip tape placed underneath the plastic mulch.

In 2013, whiteflies were sampled at 5 sections along the tunnel, approximately every 20 plants, every other hoop, or at 0, 6.1, 12.2, 18.3 and 24.4 m distances from the source plant (DSP). Whitefly incidence was measured once a week by vacuuming out adult whiteflies on plants adjacent to sample holes. The vacuum used was a #2820B DC Insect Vacuum issued by BioQuip Products, Inc. In this trial there were four treatments and 4 replicates. Treatment 1 tomatoes were underneath row cover fabric, treated with a water drench, and at the beginning of each row, a 7-week old TYLCV positive source plant was planted. Treatment 2 tomatoes were

underneath row fabric, treated with a water drench, and at the beginning of the row, no TYLCV source plant was planted. Treatment 3 tomatoes were planted underneath row cover, treated with a Verimark® (cyantraniliprole (DuPont, Newark, DE)) drench applied at 13.5 liters product per hectare, and a TYLCV positive source plant was planted at the beginning of each row. Treatment 4 tomatoes were not planted underneath row cover fabric, treated with a water drench and a TYLCV positive source plant was planted at the beginning of each row. Infected source plants underneath tunneled treatments had approximately 100 whiteflies released near them. At the end of the study, tunnel fabric was removed so that all plants were revealed. Plants were rated individually for TYLCV symptom severity on a 4 point scale with a 0 being non symptomatic and a 4 being very symptomatic.

In 2014, whiteflies were sampled at 9 sections along the tunnel, approximately every 10 plants, every hoop, or at 0, 3.05, 6.1, 9.15, 12.2, 15.25, 18.3, 21.35 and 24.4 m distances from the source plant (DSP). Symptom severity and disease incidence was measured by visually assessing each plant adjacent to sample holes. Symptom severity was measured at the end of the experiment using a 4 point scale. Treatment 1 tomatoes were underneath row cover fabric, treated with a water drench, and at the beginning of each row, a TYLCV positive source plant was planted. Treatment 2 tomatoes were underneath row fabric, treated with an imidacloprid (Admire Pro®, Bayer Crop Protection, Pittsburgh, PA) drench at a rate of 10.5 liters of product per hectare, and at the beginning of the row, a TYLCV positive source plant was planted. Treatment 3 tomatoes were planted underneath row cover, treated with a cyantraniliprole (DuPont, Newark, DE) drench applied at 13.5 liters of product per hectare, and a TYLCV positive source plant was planted at the beginning of each row. Treatment 4 tomatoes were not covered in row cover fabric, treated with a water drench and no TYLCV positive source plant

was planted at the beginning of each row. Infected source plants underneath tunneled treatments had approximately 100 whiteflies released by the source plant. At the end of the study, tunnel fabric was removed so that all plants were revealed. Plants were rated individually for TYLCV symptom severity on a 4 point scale with a 0 being non symptomatic and a 4 being very symptomatic.

At the end of the study, tunnel fabric was removed to reveal all plants. Each plant had all tomato fruit harvested. Fruit was categorized as being bad fruit or good fruit based on assessment of basic marketable qualities like blemishes and discoloration. All fruit from each plant was weighed and counted. Yield was sampled in the same way in 2013 and 2014 trials.

All data were subjected to an analysis of variance (ANOVA) using Proc GLIMMIX in SAS (SAS Institute, Cary, NC) first with all tunneled treatments, then with tunnel only treatments. Plot means and within plot sections down the tunnel were analyzed for overall treatment effects on whitefly and TYLCV symptoms both averaged and distributed down the tunnel. A simple log regression using Excel (Microsoft Corporation, Redmond, WA) was used to describe the distribution of whiteflies and TYLCV symptoms down the length of the tunnel from the source plant.

## **Results and Discussion**

### ***Treatment Effect and Treatment Interaction Effect on Adult Whitefly Counts Overall***

#### ***Treatments***

There was not a significant insecticide treatment effect in 2013 ( $F = 2.96$ ,  $df = 3, 9$ ,  $P = 0.089$ ) on whitefly adults (Table 3.1). However, there was a significant distance from source plant (DSP) effect ( $F = 11.4$ ,  $df = 4, 311$ ,  $P < 0.0001$ ) on whitefly adult counts. In the 2014 trial, there was an insecticide treatment effect on whitefly adults ( $F = 18.4$ ,  $df = 3, 9$ ,  $P = 0.0004$ ).

The 2014 trials also had a significant DSP effect for whitefly presence ( $F = 10.1$ ,  $df = 8$ ,  $295$ ,  $P < 0.0001$ ). There is also a significant treatment and DSP interaction effect for 2013 and 2014 adult whitefly counts, ( $F = 4.34$ ,  $df = 12$ ,  $295$ ,  $P < 0.0001$ ), ( $F = 1.65$ ,  $df = 24$ ,  $72$ ,  $P < 0.05$ ).

### ***Treatment Effect and Treatment Interaction Effect on Adult Whitefly Counts on Tunneled Treatments Only***

There was a significant treatment effect on adult whitefly counts in 2013 and 2014 trials (Table 3.3). In 2013, cyantraniliprole had the highest mean whiteflies in comparison to blank and check treatments. Mean adult whitefly counts in cyantraniliprole treated rows was not different from mean adult whitefly counts in the tunnel check. The tunneled check with no source plant and the no tunnel check were the only treatments that provided a mean adult whitefly counts significantly lower than the tunneled cyantraniliprole treatment and the tunneled control treatment. In 2014, the no tunnel check had a significantly higher mean adult whitefly counts than all other treatments. The tunneled check treatment, tunneled cyantraniliprole treatment and the imidacloprid treatment did not have means significantly different than each other (Table 3.3).

In 2013, plants 6.1 meters away from the source plant, had mean adult whitefly counts significantly higher in comparison to all other DSP increments. In 2014, plants, 3.05 meters from the source plant, had a mean adult whitefly count significantly higher than all other DSP increments. Plants beyond 6.1 meters from the source plant in 2013 and plants beyond 3.05 meters from the source plant in 2014 were not significantly different from each other in mean adult whitefly counts. (Table 3.4.)

In 2013 when just the tunneled treatments were considered in the analysis of variance, there were significant differences between treatments. The infested check ( $3.89 \pm 11.15$ ) did not

have a significantly different mean adult whitefly counts than the blank check ( $0.12 \pm 0.44$ ) or cyantraniliprole treatment ( $6.67 \pm 29.37$ ) (Figure 3.2). However, the cyantraniliprole treatment ( $6.67 \pm 29.37$ ) did have a significantly higher mean adult whitefly counts than the blank treatment ( $6.67 \pm 29.37$ ) (Figure 3.2). In the 2014 trial when excluding the non-tunneled treatment from analysis, the check ( $0.11 \pm 0.47$ ) has a significantly higher mean average adult whitefly counts than imidacloprid treatment ( $0.03 \pm 0.23$ ) (Figure 3.4). Cyantraniliprole treatments did not have a significantly lower mean adult whitefly counts than the check or a significantly higher mean adult whitefly counts than the imidacloprid treatments ( $0.06 \pm 0.30$ ).

### ***Treatment Effect and Treatment Interaction Effect on TYLC Disease Incidence Overall***

#### ***Treatments***

There was a significant chemical treatment effect in 2013 on percent of TYLCV symptom presence ( $F = 125$ ,  $df = 3, 9$ ,  $P < 0.0001$ ) and DSP effect on percent TYLCV symptom presence ( $F = 3.16$ ,  $df = 3, 219$ ,  $P = 0.025$ ). In the 2014 trial, there was an insecticide treatment effect on TYLCV symptom severity ( $F = 12.5$ ,  $df = 3, 9$ ,  $P < 0.0001$ ) and DSP effect on TYLCV symptom severity rating ( $F = 19.4$ ,  $df = 8, 295$ ,  $P < 0.0001$ ). In 2013, there was no significant treatment and DSP interaction effect on TYLCV symptoms ( $F = 0.36$ ,  $df = 9, 295$ ,  $P = 0.9525$ ). But, in 2014, there was also a significant treatment and DSP interaction on TYLCV rating ( $F = 4.93$ ,  $df = 24, 72$ ,  $P < 0.0001$ ).

### ***Treatment Effect and Treatment Interaction Effect on TYLC Disease Incidence on Tunneled***

#### ***Treatments Only***

There was a significant treatment effect on TYLCV presence means in 2013 and 2014 trials (Table 3.3). The no tunnel check treatment had the significantly highest mean TYLCV symptom severity ratings in comparison to all other treatments indicating that the tunnels

reduced the overall intensity of TYLCV compared to ambient infection levels. The tunneled control and the tunneled cyantraniliprole treatment had similar mean TYLCV presence (Table 3.3). In 2015, the tunnel blank treatment had a significantly lower mean TYLCV symptom presence than all other treatments. The no tunnel check had a significantly higher mean TYLCV rating than all other treatments. The tunnel check, cyantraniliprole and imidacloprid treatments were not significantly different from each other (Table 3.3).

In 2013, plants 6.1 meters away from the source plant had TYLCV presence mean significantly higher in comparison to all other DSP increments. In 2014, plants, 3.05 meters from the source plant, had a mean TYLCV symptom severity rating significantly higher than all other DSP increments. Plants beyond 6.1 meters from the source plant in 2013 and plants beyond 3.05 meters from the source plant in 2014 were not significantly different from each other in TYLCV presence, 2013, and TYLCV symptom severity rating, 2014. (Table 3.4.)

In the 2013 trial when excluding the non tunneled treatment from analysis, the check ( $0.095 \pm 0.206$ ) and cyantraniliprole treatments ( $0.09 \pm 0.167$ ) did not have significantly different mean percentage of TYLCV symptomatic plants from each other, but they were both significantly higher than the blank treatments ( $0.013 \pm 0.067$ ) (Figure 3.3). In 2014, TYLCV symptom severity rating, the check ( $0.26 \pm 0.76$ ), imidacloprid ( $0.15 \pm 0.56$ ) and cyantraniliprole ( $0.059 \pm 0.340$ ) treatments do not have significantly different mean severity ratings (Figure 3.4).

#### ***Treatment Effect and Treatment Interaction Effect on Marketable and Unmarketable Yield***

There was not a significant chemical treatment effect on marketable weight in 2013 ( $F = 2.94$ ,  $df = 3, 9$ ,  $P = 0.0916$ ) or 2014 ( $F = 0.90$ ,  $df = 3, 9$ ,  $P = 0.48$ ) trials (Table 3.2). Similarly, there was no significant chemical treatment effect on unmarketable yield in the 2013 trial ( $F =$

0.15,  $df = 3, 9$ ,  $P = 0.9300$ ) or in the 2014 trial ( $F = 1.15$ ,  $df = 3, 9$ ,  $P = 0.38$ ). Plant number had a significant treatment effect on marketable ( $F = 1.93$ ,  $df = 42, 295$ ,  $P = 0.0009$ ) and unmarketable weight ( $F = 2.35$ ,  $df = 42, 295$ ,  $P < 0.0001$ ) in the 2013 trial, but in the 2014 trial, there was no significant effect observed on marketable ( $F = 0.72$ ,  $df = 52, 352$ ,  $P = 0.92$ ) or unmarketable yield ( $F = 0.85$ ,  $df = 52, 353$ ,  $P = 0.76$ ). There was an observed treatment and plant number interaction effect on yield for the 2013 trial for marketable yield ( $F = 2.03$ ,  $df = 99, 295$ ,  $P < 0.0001$ ), but not for unmarketable yield ( $F = 1.04$ ,  $df = 99, 295$ ,  $P = 0.40$ ). No significant interaction effect was observed in the 2014 trial for marketable yield ( $F = 0.89$ ,  $df = 147, 352$ ,  $P = 0.79$ ) or unmarketable yield ( $F = 0.93$ ,  $df = 147, 353$ ,  $P = 0.69$ ).

Treatment effects on mean marketable and unmarketable yield weight were not consistent for 2013 and 2014 trials (Table 3.5). In 2013, the blank treatment and the cyantraniliprole treatment had a significantly higher mean marketable weight than the no tunnel check. The tunneled check source plant treatment mean marketable weight was not significantly different than other treatments. In 2013, unmarketable weight yields were not significantly different from each other for any treatments. In 2014, there was no significant difference between any treatments for their influence on marketable or unmarketable yield (Table 3.5).

The marketable, i.e. good, fruit weight yield down row from source plant when excluding non tunneled treatment from analysis for 2013 and 2014 trials is presented in Figure 3.7 (a) and (b), respectively. In 2013, the blank treatment had the highest mean good fruit weight ( $34.7 \pm 116$ ), cyantraniliprole had the second highest mean ( $24.4 \pm 0.04$ ) and the infested check had the lowest mean ( $20.6 \pm 71.6$ ). Logarithmic trend lines indicate that there was a relatively flat response in good fruit weight for plants down the tunnel for most treatments, not a

slowly increasing trend line in good fruit weight as plants get farther from source plant that we hoped to demonstrate. Figure 3.7 (b) illustrates that imidacloprid had the highest mean good fruit weight ( $117.6 \pm 137.5$ ), check had the second highest mean ( $58.2 \pm 162$ ) and cyantraniliprole had the lowest mean ( $53.9 \pm 90.4$ ). Logarithmic trend lines were not significant, but tended to a slow incline in good fruit weight as plants get farther from the source plant. Finally, Figure 3.8 (a) and (b) illustrate mean good fruit mean yields for 2013 and 2014 trials, respectively. Figure 3.8 (a) and (b) demonstrates that there was no significant difference in means of any treatment for producing good fruit weight in either year.

### **Conclusion**

The insecticide treatment for the 2013 trial did not provide significantly better whitefly or TYLCV control in comparison to the tunneled check. All tunneled treatments provided better TYLCV presence suppression than the non tunnel check, but the chemical treatment measured no better at suppressing TYLCV presence than the no chemical treatments. Thus, the mechanical barrier of the floating row cover was the most consistent mitigator of TYLCV incidence in the field. In 2014, all tunneled treatments provided better whitefly and TYLCV incidence suppression than the non-tunneled check. Chemical treatments did not measure better than the no chemical check treatment at suppressing whitefly and TYLCV incidence. There was also a significant distance from source plant and chemical treatment interaction effect on adult whitefly counts for both years, and in 2014, TYLCV symptom severity ratings.

The closest sample position to the source plant had significantly higher adult whitefly counts and TYLCV presence and rating for both years. These results indicate that the distribution of whiteflies and TYLC disease is biased towards the source plant's location even in

the short tunnel distance of 24 m. Source plants planted at the beginning of each tunnel caused a higher amount of whitefly presence and TYLC disease presence at the top of each tunnel where some significant difference in treatments could be observed. Of all the treatment interactions, treatment and hoop were significant for 2013 adult whitefly counts and 2014 adult whitefly counts and 2014 TYLCV rating. Unfortunately, cyantraniliprole was not consistent in its effect between years. In 2014, imidacloprid had the strongest effect on whitefly adults in the proximity position closest to the source plant.

In the 2013 trial, there was no significant difference between any treatments' influence on unmarketable weight. Tunneled blank and cyantraniliprole treatments produced more mean marketable weight than non tunneled treatment and the tunneled check. Cyantraniliprole chemical treatment did not produce significantly more yield than the covered check or blank. In 2014, no treatments proved better than each other at positively influencing marketable or unmarketable yield. Plant number had a significant impact on marketable weight in 2013, but was not significant in 2014. This could be because the adult whitefly counts that we were able to establish under the tunnels was greater in 2013 than 2014. Likewise, there was a treatment and plant number interaction effect on marketable yield for 2013 but not for 2014. This indicates that it is important to take into account the proximity of plants to a whitefly and TYLCV source when evaluating insecticide treatment effects on mitigating TYLCV epidemics.

The results from this experiment did not support the hypothesis that chemical treatments alone would suppress adult whitefly counts and disease severity under any TYLCV severity situation. Distance from the whitefly TYLCV source plant played a more important role than chemical control. Even when excluding non tunneled treatments, chemical treatments were not effective at suppressing adult whitefly counts or disease severity averaged over the entire length

of the tunnel. In addition to understanding chemical treatments influence on whitefly and disease spread, we were also able to ascertain the approximate distance whiteflies and disease spread. TYLCV ratings were measured to be highest in plants within the first 3.05 m of the source plant and the disease incidence was observed to decline in plants at the end of the 24 m row. The TYLCV severity distribution tends to decline with distance from the source plant at a fairly rapid rate when excluding migrating adults and restricting whitefly movement to mostly plant-to-plant movement. A large population of whiteflies have been illustrated to correspond with high disease incidence, but high population densities are not required to have disease incidence. The circulative persistent manner TYLCV is transmitted allows the virus to be spread to multiple plants by just one whitefly. Whiteflies move from plant to plant by wind or by flight. It is likely that whiteflies from plants closer to the source plant actively flew down the tunnel to plants farthest from the source plant and transmitted TYLCV as they began to feed at a lower rate than on plants adjacent to the source plant. What this study did show is that floating row tunnel covers can help to study plant to plant movement of both whitefly and TYLC disease incidence.

## **Acknowledgements**

The authors thank Nikki Bowman, Jenna Kicklighter, Abby Applewhite, Gordon MacQuirter, Cassidy Long and Donnie Cook for their assistance with experiment maintenance and sampling. This project was partially funded by a USDA AFRI Grant and the Coastal Plain Experiment Station.

## References

- Ahmad, N.E., Kanan, H.O., Inanaga, S., Ma, Y.Q. and Sugimoto, Y. 2001. Impact of pesticide seed treatments on aphid control and yield of wheat in the Sudan. *Crop Protect.* 20: 929 – 934.
- Andaloro, J.T., Veronica Company, Porter, A., Slater, R., Senn, R., Chisholm, K., Teixeira, L., and Marcon, P. The Mode of Action of Diamides and Other Lepidopteran Insecticides and General Rotation Recommendations. *In Proceedings, 6<sup>th</sup> Annual DBM Conference, March 2010.*
- Bai, D.L., Lummis, S.C.R., Leicht, W., Breer, H. and Sattelle, D.B. 1991. Actions of Imidacloprid and a related nitromethylene on cholinergic receptors of an indentified insect motor neurone. *Pestic. Sci.* 33: 197 – 204. Andaloro, J.T., Veronica Company, Porter, A., Slater, R., Senn, R., Chisholm, K., Teixeira, L., and Marcon, P. The Mode of Action of Diamides and Other Lepidopteran Insecticides and General Rotation Recommendations. *In Proceedings, 6<sup>th</sup> Annual DBM Conference, March 2010.*
- Cahill, M., Gorman, K., Day, S., Denholm, I. Elbert, A. and Nauen, R. 1996. Baseline determination of resistance to imidacloprid in *Bemisia tabaci* (Homoptera: Aleyrodidae). *Bull. of Entomol. Res.* 86: 343-349.
- Chandler, L.D. and Sumner, H.R. 1994. Evaluation of insecticides for control of sweetpotato whitefly (SPWF) on peanut, 1992. *Arthropod Manage. Tests.* 19: 246.
- Czosnek, H. 2008. Tomato Yellow Leaf Curl Virus. The Hebrew University of Jerusalem, Rehovot, Israel.
- Elbert, A.B., Becker, J., Hartwig and Erdelen, C. 1990. Imidacloprid, a New Systemic Insecticide. *Pflanzenschutz-Nachrichten Bayer.* 44: 113 – 136.

- Fereres, A. and Moreno, A. 2009. Behavioral aspects influencing plant virus transmission by homopteran insects. *Virus Res.* 141: 158 – 168.
- Ghanim, M., Morin, S. and Czosnek, H. 2001. Rate of *Tomato Yellow Leaf Curl Virus* (TYLCV) translocation in the circulative transmission pathway of its vector, the whitefly *Bemisia tabaci*. *Phytopathology* 91: 188-196.
- Hernandez, D., Mansanet, V. and Puiggroc Jove, J.M. 1999. Use of Confidor 200SL in vegetable cultivation in Spain. *Pflanzenschutz-Nachricht. Bayer.* 52: 364 – 375.
- Horowitz, A.R., Mendelson, Z., Weintraub, P.G. and Ishaaya, I. 1998a. Comparative toxicity of foliar and systemic applications of acetamiprid and imidacloprid against the cotton whitefly, *Bemisia tabaci* (Hemiptera: Aleyrodidae). *Bull. Entomol. Res.* 88: 437 – 442.
- Kagabu, S. 1999. Discovery of chloronicotynyl insecticides. *In* Nicotinoid Insecticides and the Nicotinic Acetylcholine Receptor. Yamamoto, I. and Casida, J.E. (Eds.). pp. 91 – 106. Springer – Verlag, Tokyo.
- Liu, M.Y. and Casida, J.E. 1993. High affinity binding of [3H] Imidacloprid to the insect acetylcholine receptor. *Pestic. Biochem. Physiol.* 46: 40 – 46.
- Marcon, P. The Mode of Action of Diamides and Other Lepidopteran Insecticides and General Rotation Recommendations. *In* Proceedings, 6<sup>th</sup> Annual DBM Conference, March 2010.
- Maienfisch, P., Huerlimann, H., Rindlisbacher, A., Gsell, L., Dettwiler, H., Hattenschwiler, J., Sieger, E. and Walti, M. 2001. The discovery of thiamethoxam: a second-generation neonicotinoid. *Pestic. Sci.* 57: 165 – 176.
- Moriones, E. and Navas – Castillo, J. 2000. Tomato yellow leaf curl virus, an emerging virus complex causing epidemics worldwide. *Virus Res.* 71: 123 – 134.

- Nauen, R. and Elbert, A. 1997. Apparent tolerance of a field-collected strain of *Myzus nicotianae* to imidacloprid due to strong antifeeding responses. *Pestic. Sci.* 49: 252 – 258.
- Nauen, R., Hungenberg, H., Tollo, B., Tietjen, K. and Elbert, A. 1998a. Antifeedant effect, biological efficacy and high affinity binding of imidacloprid to acetylcholine receptors in *Myzus persicae* and *Nyctotia nicotianae*. *Pestic. Sci.* 53: 133-140.
- Nauen, R., Hungenberg, H., Tollo, B., Tietjen, K. and Elbert, A. 1998a. Antifeedant effect, biological efficacy and high affinity binding of imidacloprid to acetylcholine receptors in *Myzus persicae* and *Myzus nicotianae*. *Pestic. Sci.*
- Nauen, R., Jeschke, P., Velten, R., Beck, M.E., Ebbinghaus – Kintscher, U., Theirlert, W., Wölfel, K., Haas, M., Kunz, K. and Raupach, G. 2014. Flupyradifurone: a brief profile of a new butenolide insecticide. pp. *Pest. Manag. Sci.*
- Nauen, R., Reckmann, U., Amborst, A., Stupp, H.P., and Elbert, A. 1999. Whitefly-active metabolites of imidacloprid: biological efficacy and translocation in cotton plants. *Pestic. Sci.* 55: 265 – 271.
- Palumbo, J.C., Horowitz, A.R. and Prabhaker, N. 2001. Insecticidal control and resistance management for *Bemisia tabaci*. *Crop Prot.* 20L 739 – 765.
- Palumbo, J.C., Kerns, D.L., Engle, C.E., Sanchez, C.A., and Wilcox, M. 1996b. Imidacloprid formation and soil placement effects on colonization by sweetpotato whitefly (Homoptera: Aleyrodidae): head size and incidence of chlorosis in lettuce. *J. Econ. Entomol.* 89: 735 – 742.
- Polston, J.E. and Anderson, P.K. 1997. The emergence of whitefly-transmitted geminiviruses in tomato in the Western Hemisphere. *Plant Dis.* 81: 1358 – 1369.

- Rubenstein, G., Morin, S. and Czosnek, H. 1999. Transmission of tomato yellow leaf curl geminivirus to imidacloprid treated tomato plants by the whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 92: 658 – 662.
- Schuster, D.J. 2000a. Insecticides applied on demand for managing the silverleaf whitefly on fresh market tomatoes in spring 1998. *Arthropod Manage. Tests* 25: 100.
- Schuster, D.J. 2000b. Insecticides applied on demand for managing the silverleaf whitefly on fresh market tomatoes in fall 1998. *Arthropod Manage. Tests* 25: 101.
- Stansly, P.A. and Conner, J.M. 2000. Impact of insecticides on silverleaf whitefly and tomato yellow leafcurl virus (TYLCV) on staked tomato, 1999. *Arthropod Manage. Tests* 25: 173-174.
- Smith, H.A. 2013. Managing Diamide Resistance in Florida Tomato. University of Florida IFAS Extension. ENY-867
- Smith, H.A. 2014. Susceptibility of Silverleaf Whitefly to Group 4 Insecticides. University of Florida IFAS Extension.
- Srinivasan, R., Riley, D., Diffie, S., Sparks, A. and Adkins, S. 2012. Whitefly population dynamics and evaluation of whitefly-transmitted tomato yellow leaf curl virus (TYLCV) resistant tomato genotypes as whitefly and TYLCV reservoirs. *J. of Econ. Entomol.* 105: 1447-1456.
- Yamada, T., Takashi, H., and Hatano, R. 1999. A novel insecticide, Acetamiprid. *In Nicotinoid Insecticides and the Nicotinic Acetylcholine Receptor*. I. Yamamoto and J.E. Casida (Eds.). pp. 149 – 176. Springer – Verlag, Tokyo.

**Table 3.1 Effects of treatments and their interactions on whiteflies and TYLCV incidence on tomatoes under all treatments in 2013 and 2014 at Tifton, GA Coastal Plains Research Station.**

	2013						2014					
	Adult Whitefly Counts			Percent TYLCV Symptomatic Plants			Adult Whitefly Counts			TYLCV Rating		
	DF	F	Pr>F	DF	F	Pr>F	DF	F	Pr>F	DF	F	Pr>F
Rep	3	2.80	0.0402	3	0.74	0.5317	3	0.18	0.9116	3	0.12	
	0.9498											
Treatment	3,9	2.96	0.0899	3,9	125.14	<0.0001	3,9	18.40	0.0004	3,9	12.51	
	0.0015											
DSP	4,311	11.42	<0.0001	3,219	3.16	0.0254	8,851	10.14	<0.0001	8,52	19.42	
	<0.0001											
Treatment*DSP	12,311	4.34	<0.0001	9,219	0.36	0.9525	24,851	1.65	0.0259	24,53	4.93	
	<0.0001											

\*Treatment effect considered significant if Pr>f is less than or equal to

<0.05. \*\* DSP = distance from source plant

**Table 3.2 Effects of treatments and their interactions on marketable and unmarketable yield on all treatments in 2013 and 2014 at Tifton, GA Coastal Plains Research Station.**

	<u>2013</u>						<u>2014</u>					
	<u>Marketable Weight</u>			<u>Unmarketable Weight</u>			<u>Marketable Weight</u>			<u>Unmarketable Weight</u>		
	DF	F Value	Pr>F Value	DF	F Value	Pr>F Value	DF	F Value	Pr>F Value	DF	F Value	Pr>F Value
Rep	3	4.67	0.0033	3	7.90	<0.0001	3	17.12	<0.0001	3	2.45	0.0631
Treatment	3,9	2.94	0.0916	3,9	0.15	0.9300	3,9	0.90	0.4793	3,9	1.15	0.3816
Plant Number	42,295	1.93	0.0009	42,295	2.35	<0.0001	52,352	0.72	0.9243	52,353	0.85	0.7620
<u>Trt*Plant Number</u>	<u>99,295</u>	<u>2.03</u>	<u>&lt;0.0001</u>	<u>99,295</u>	<u>1.04</u>	<u>0.3950</u>	<u>147,352</u>	<u>0.89</u>	<u>0.7932</u>	<u>147,353</u>	<u>0.93</u>	<u>0.6948</u>

\*Treatment effect considered significant if Pr>f is less than or equal to <0.05.

**Table 3.3 Effects of chemical and tunnel presence on whitefly and TYLCV incidence under all treatments in 2013 and 2014, Tifton, GA.**

Treatment	2013		Treatment	2014	
	Adult Whitefly Counts	Percent Symptomatic Plants		Adult Whitefly Counts	TYLCV Rating
Tunnel, Water Drench Check, Source Plant (Treatment 1)	3.894ab	9.52b	Tunnel, Water Drench Check, Source Plant (Treatment 1)	0.1063b	0.2625b
Tunnel, Water Drench Check, No Source Plant Check (Treatment 2)	0.122b	1.32c	Tunnel, AdmirePro, Source Plant Check (Treatment 2)	0.0324b	0.1526b
Tunnel, Verimark Drench, Source Plant (Treatment 3)	6.678a	9.04b	Tunnel, Verimark Drench, Source Plant (Treatment 3)	0.0629b	0.0596b
No Tunnel Check, Water Drench Check, Source Plant (Treatment 4)	0.622b	43.80a	No Tunnel Check, Water Drench Check, <b>No</b> source Plant (Treatment 4)	0.3132a	0.6341a

\*Means followed by different letters signify differences

\*\*TYLCV rating assessed on a 0 - 4 point scale of symptom severity with 0 being non symptomatic and 4 being very symptomatic.

**Table 3.4 Effect of DSP on adult whitefly counts and TYLCV disease presence (2013) and TYLCV symptom severity rating (2014) for all treatments in 2013 and 2014, Tifton, GA.**

DSP (m)	2013		2014	
	Whitefly Adult Counts	Percent Symptomatic Plants	Whitefly Adult Counts	TYLCV Rating
3.05	13.239a	-	0.4565a	0.9202a
6.10	-	25.18a	0.1181b	0.2834b
9.15	0.225b	-	0.0802b	0.2043b
12.20	-	13.72b	0.0857b	0.1857b
15.25	0.310b	-	0.0948b	0.1884b
18.30	-	12.81b	0.0579b	0.1884b
21.35	0.099b	-	0.1087b	0.2246b
24.40	-	11.97b	0.0895b	0.2246b
27.45	0.197b	-	0.0797b	0.1666b

\*Means followed after a different letter signify significant difference.

\*\*2013 trial measured TYLCV presence at approximately every 20 feet.

**Table 3.5 Effects of treatments and their interactions on unmarketable and marketable yield for all treatments at Tifton, GA Coastal Plains Research Station.**

Treatments	2013		Treatments	2014	
	Marketable Weight	Unmarketable Weight		Marketable Weight	Unmarketable Weight
Tunnel, Water Drench Check, Source Plant (Treatment 1)	20.56ab	20.06a	Tunnel, Water Drench Check, Source Plant (Treatment 1)	58.91a	69.84a
Tunnel, Water Drench Check, No Source Plant Check (Treatment 2)	34.71a	17.97a	Tunnel, AdmirePro, No Source Plant Check (Treatment 2)	117.65a	26.84a
Tunnel, Verimark Drench, Source Plant (Treatment 3)	24.37a	21.90a	Tunnel, Verimark Drench, Source Plant (Treatment 3)	53.91a	20.12a
No Tunnel Check, Water Drench Check, Source Plant (Treatment 4)	3.26b	24.88a	No Tunnel Check, Water Drench Check, <b>No</b> Source Plant (Treatment 4)	99.57a	83.08a

\*Treatment effect considered significant if Pr>f is less than or equal to <0.05.

\*\*Weight measured in grams.

### Figure Legends

- Figure 3.1.** Cross-section of the tunnel used in this study.
- Figure 3.2** Overall means of adult whitefly counts under tunneled treatments only in 2013.
- Figure 3.3** Overall mean percentages of TYLCV symptomatic plants under tunneled treatments only in 2013.
- Figure 3.4.** Overall mean adult whitefly counts and TYLCV symptom severity rating under tunneled treatments only in 2014.
- Figure 3.5.** Overall average adult whitefly counts by distance from source plant under tunneled treatments only in 2013(a) and 2014(b).
- Figure 3.6** Overall average TYLCV symptom severity rating by plant number under tunneled treatments only in 2013(a) and 2014(b).
- Figure 3.7** Good fruit weight yield by plant number under tunneled treatments only in 2013 (a) and 2014 (b).
- Figure 3.8** Good fruit weight yield under tunneled treatments only in 2013 (a) and 2014 (b).

Figure 3.1.

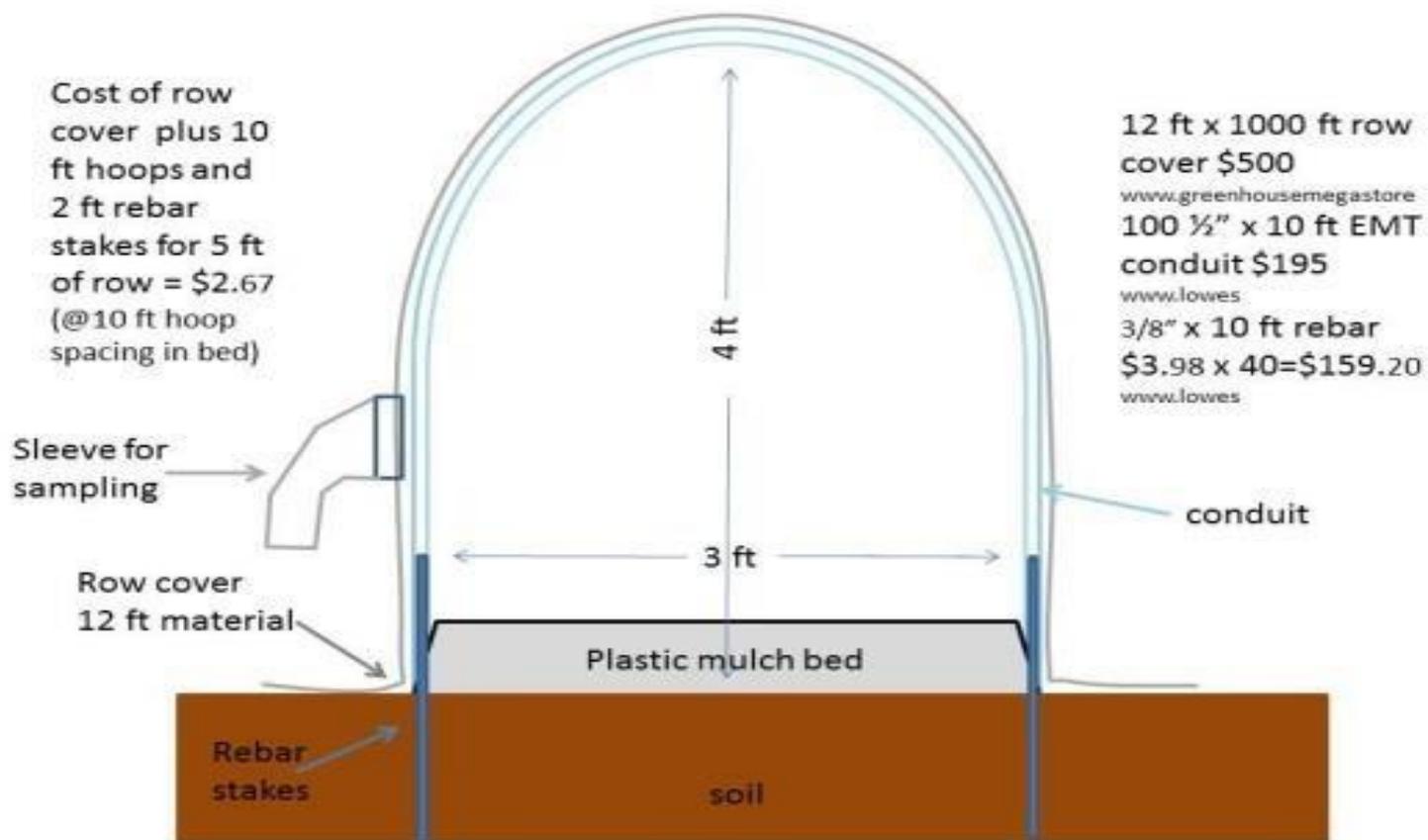
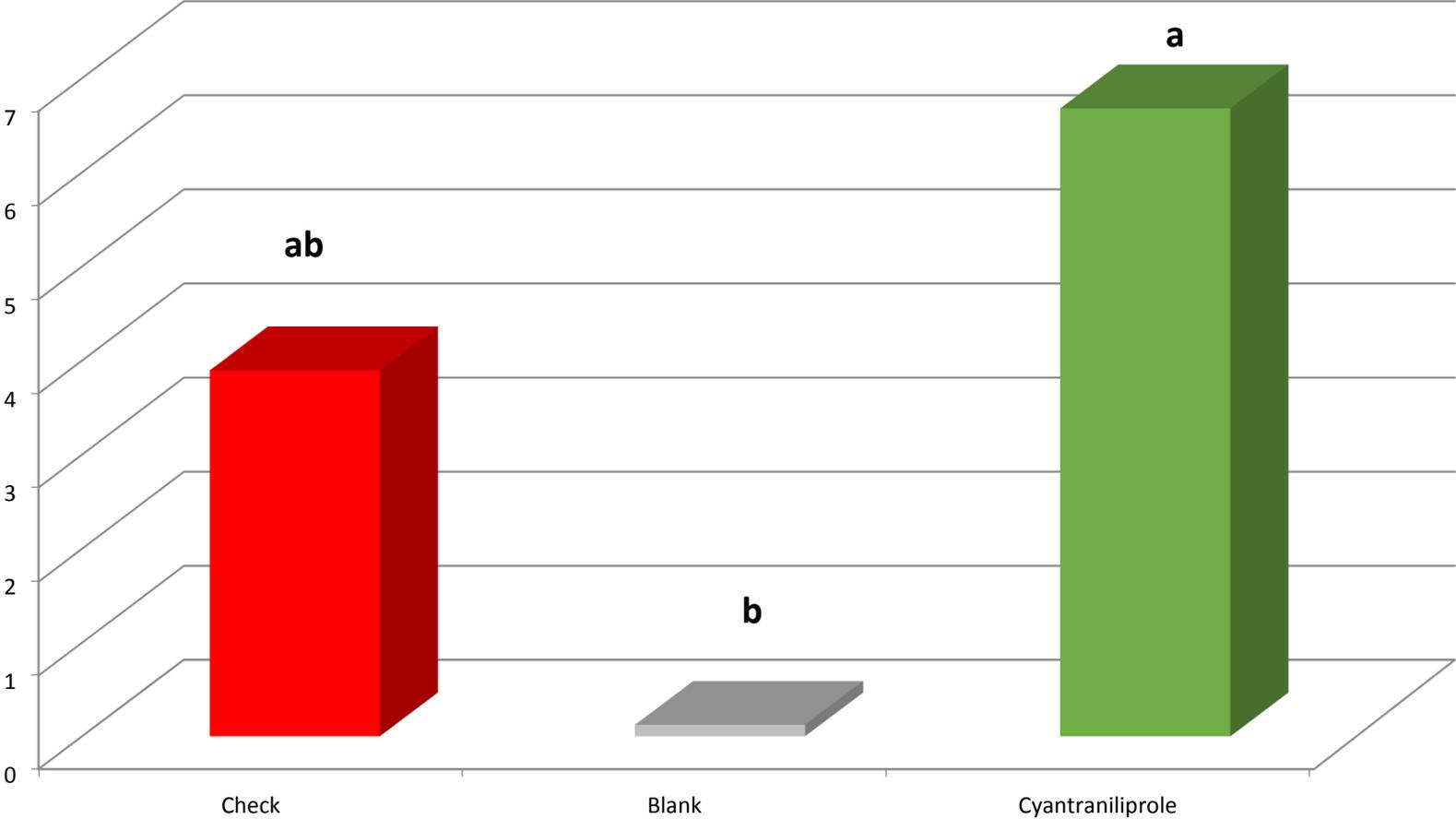


Figure 3.2

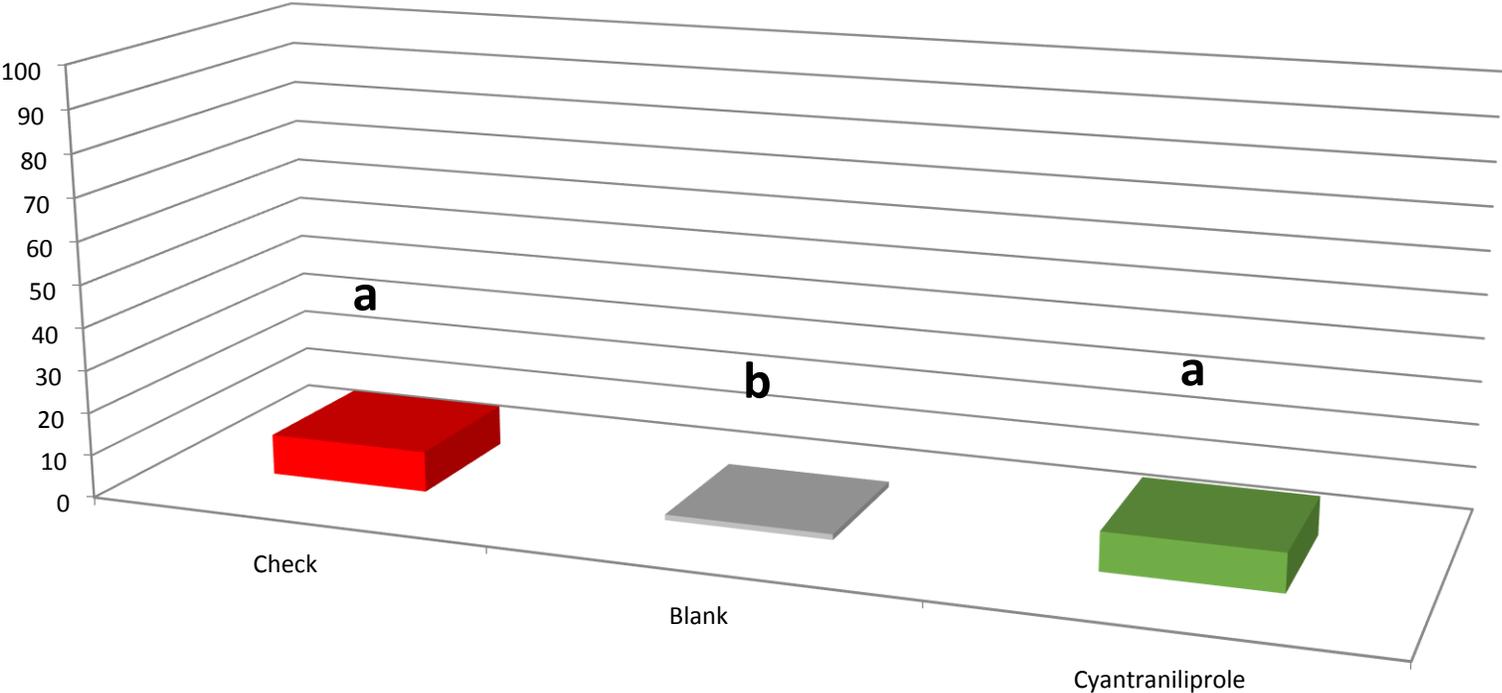
### 2013 Average Adult Whitefly Counts



\*Whitefly counts averaged over all time points.

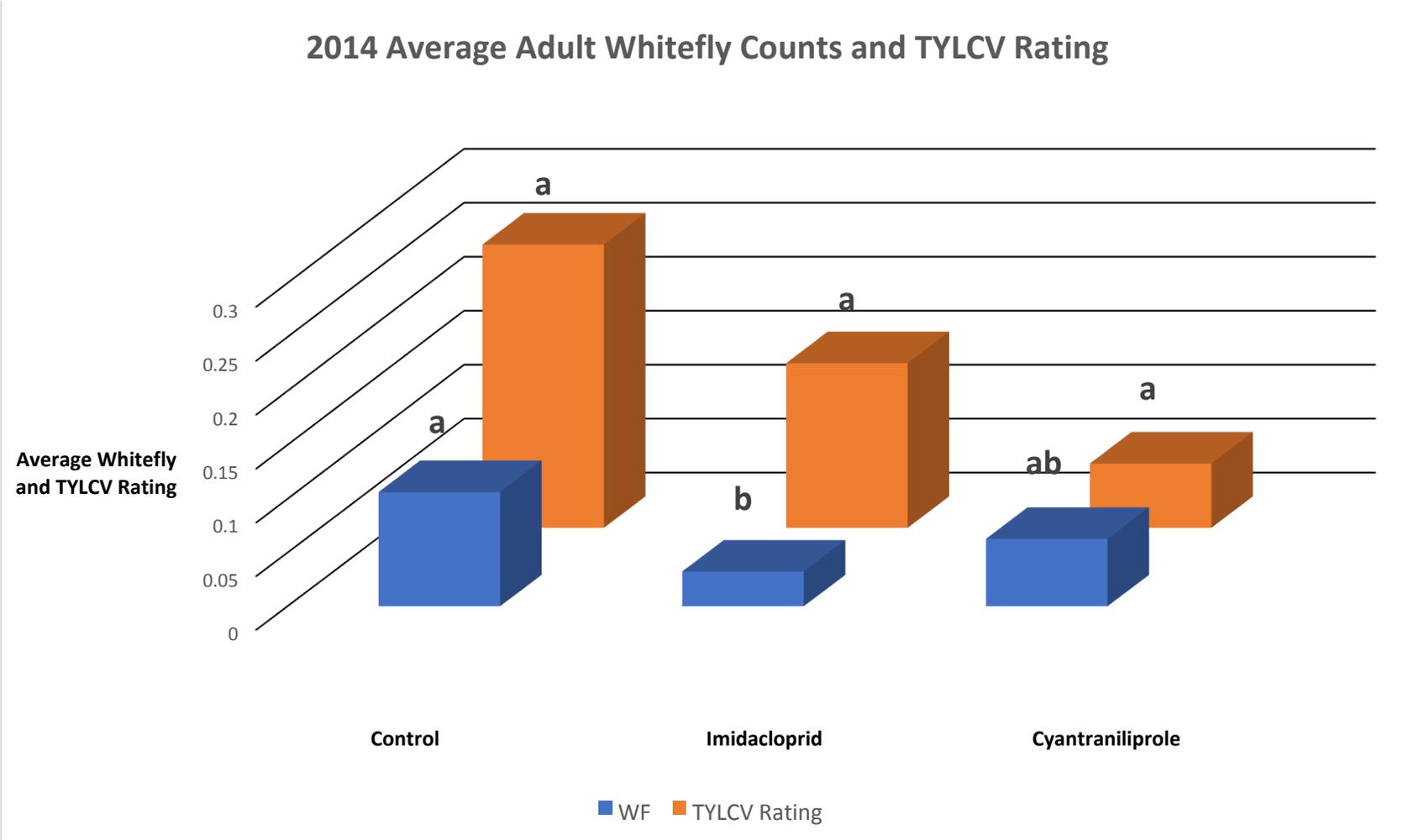
Figure 3.3

### 2013 Percentage of TYLCV Symptomatic Plants



\*Percentage of TYLCV symptomatic plants averaged over all time points.

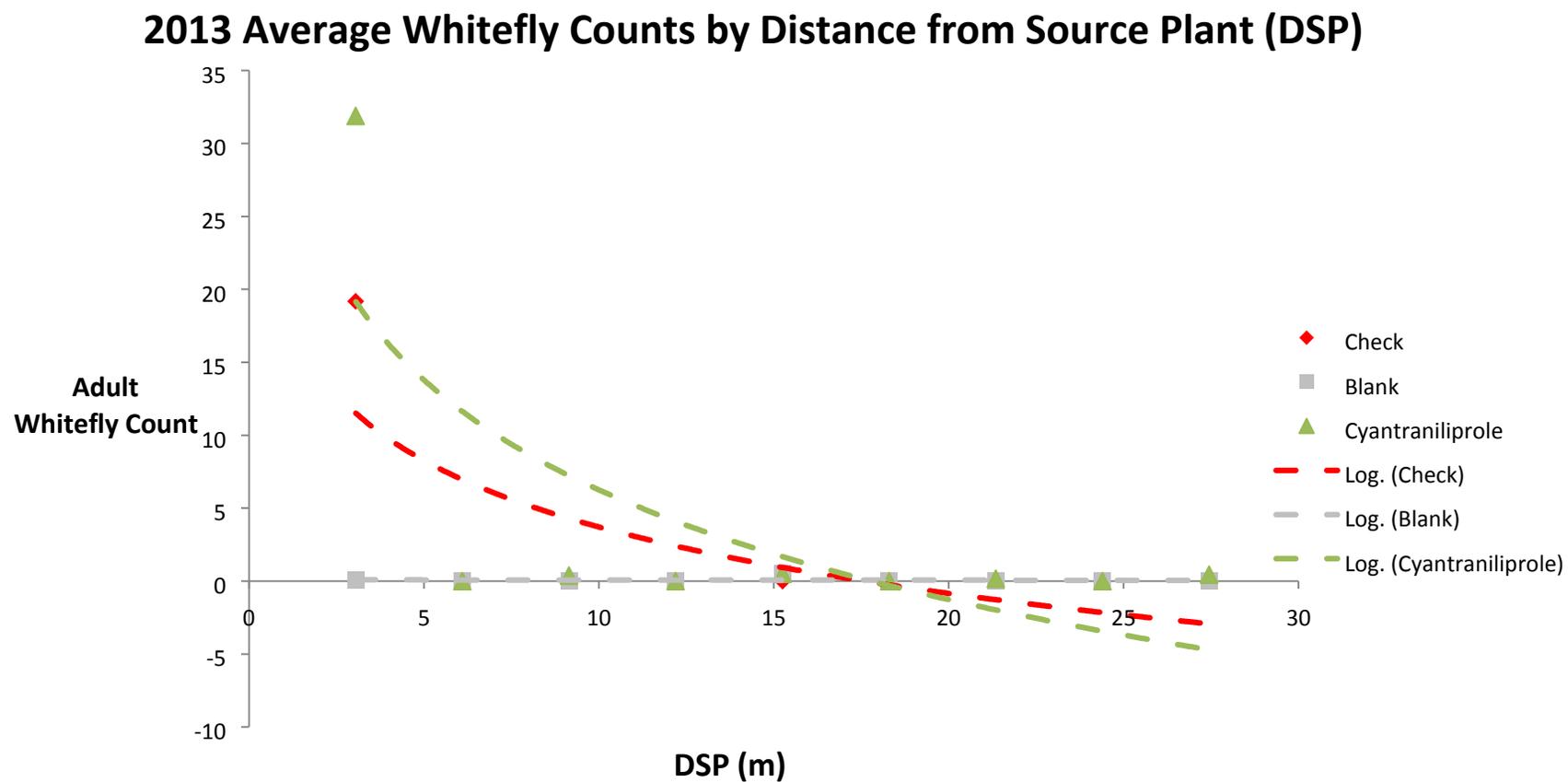
Figure 3.4



\*Whitefly counts averaged over all time points.

\*\*TYLCV rating averaged over all time points.

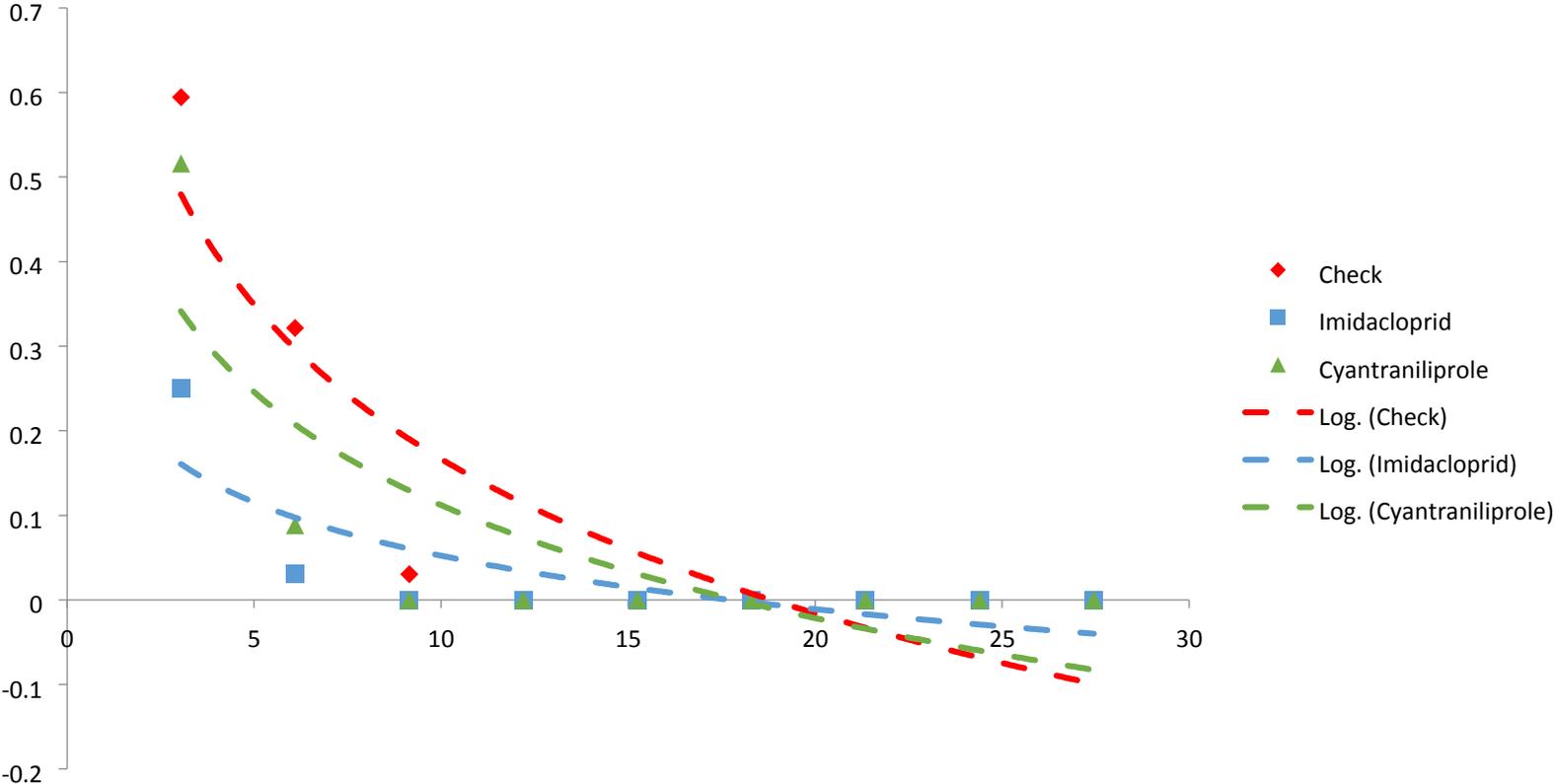
Figure 3.5 (a)



\*Whitefly counts averaged over all time points

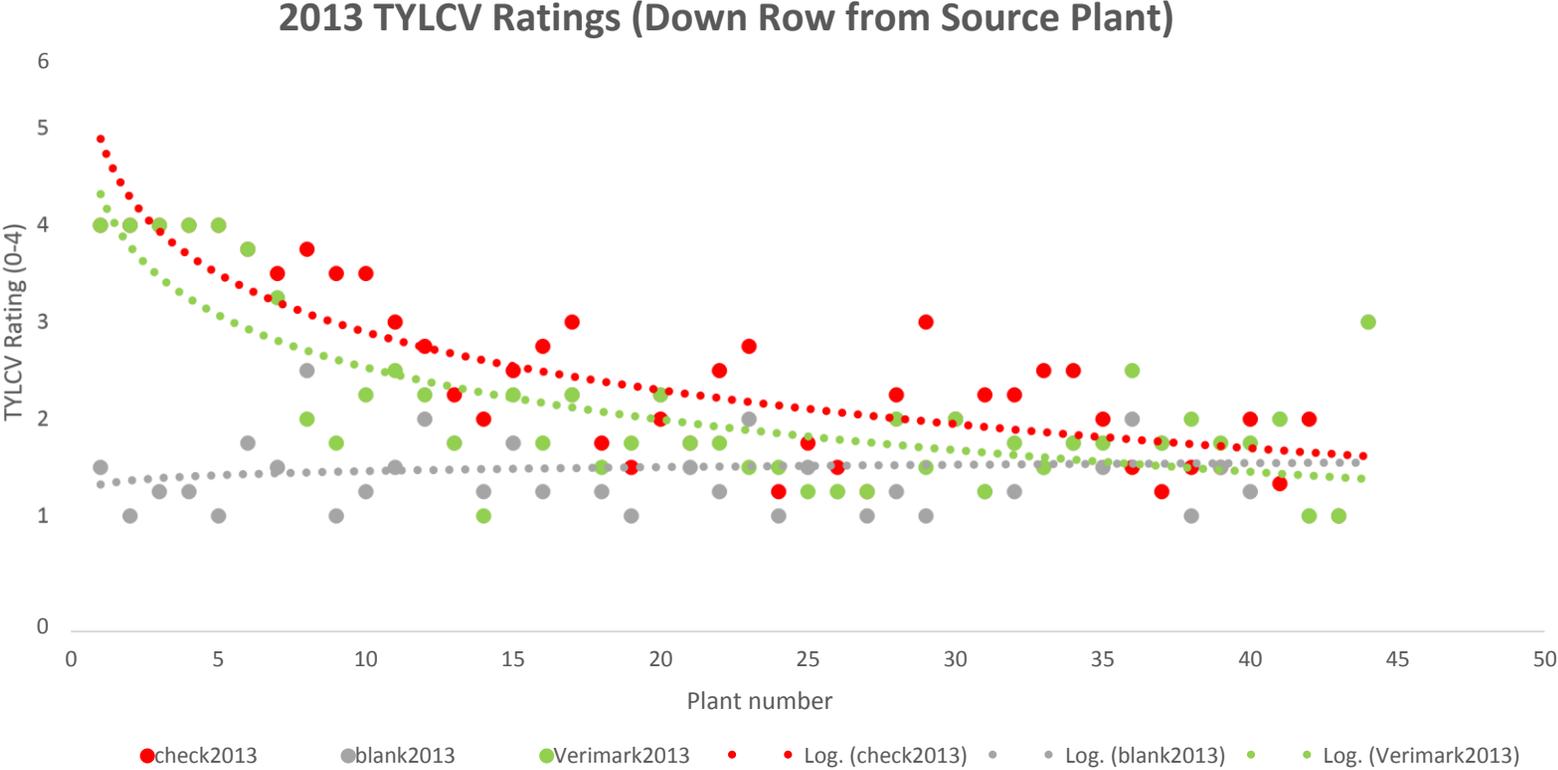
Figure 3.5(b).

### 2014 Average Adult Whitefly Counts by Distance from Source Plant (DSP)



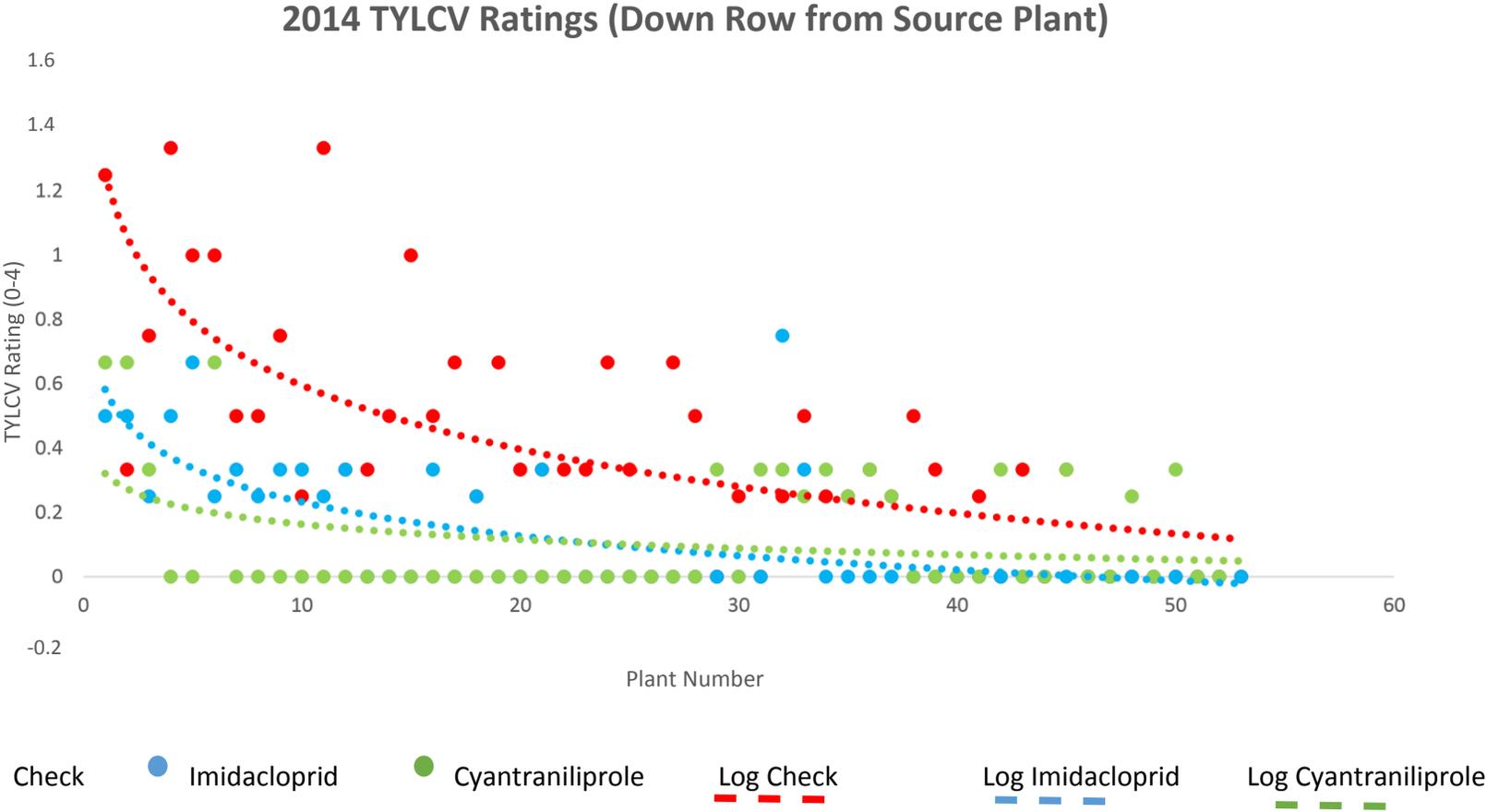
\*Whitefly counts averaged over all time points.

Figure 3.6(a).



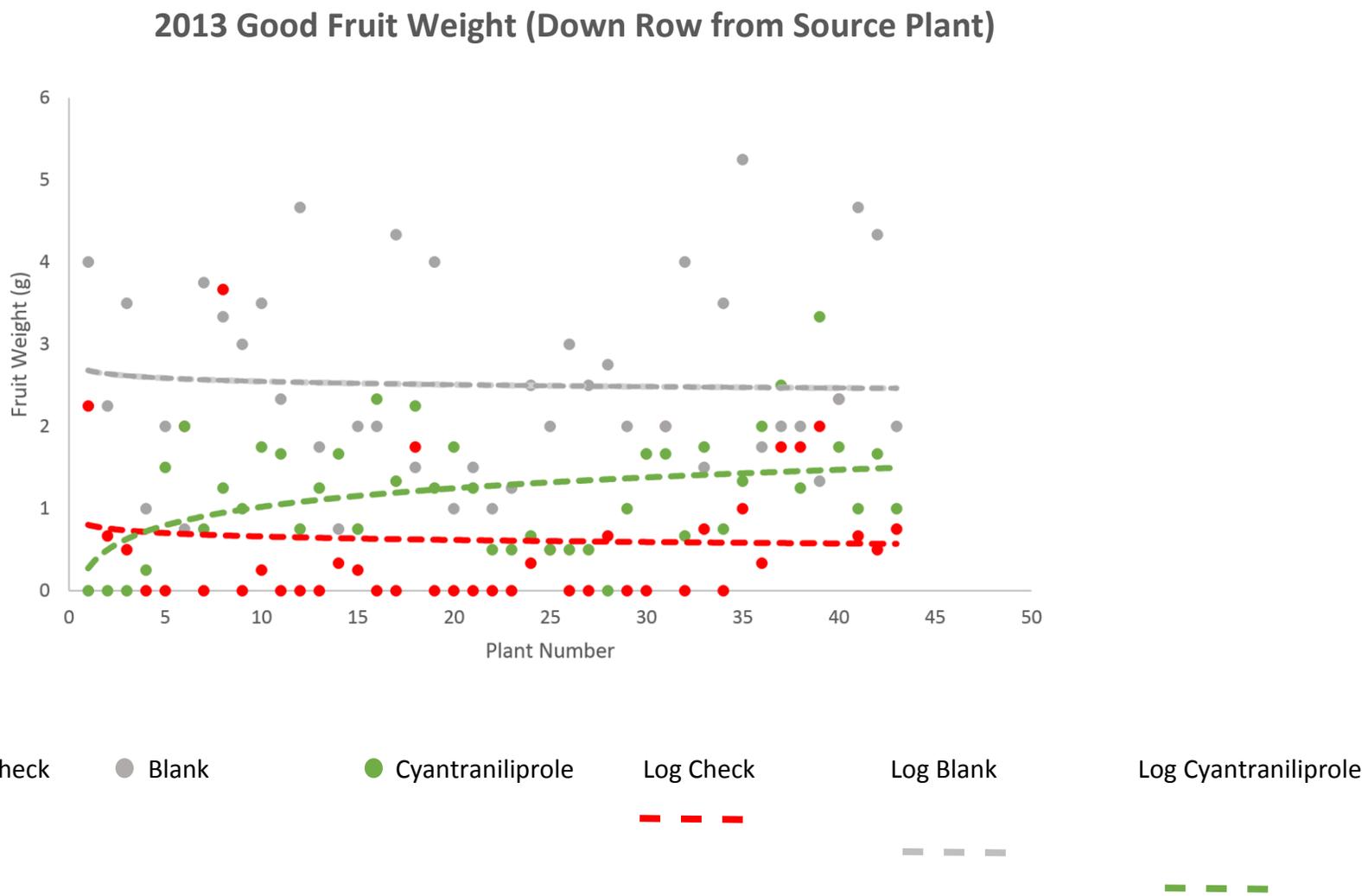
\*TYLCV ratings taken on one date

Figure 3.6(b)



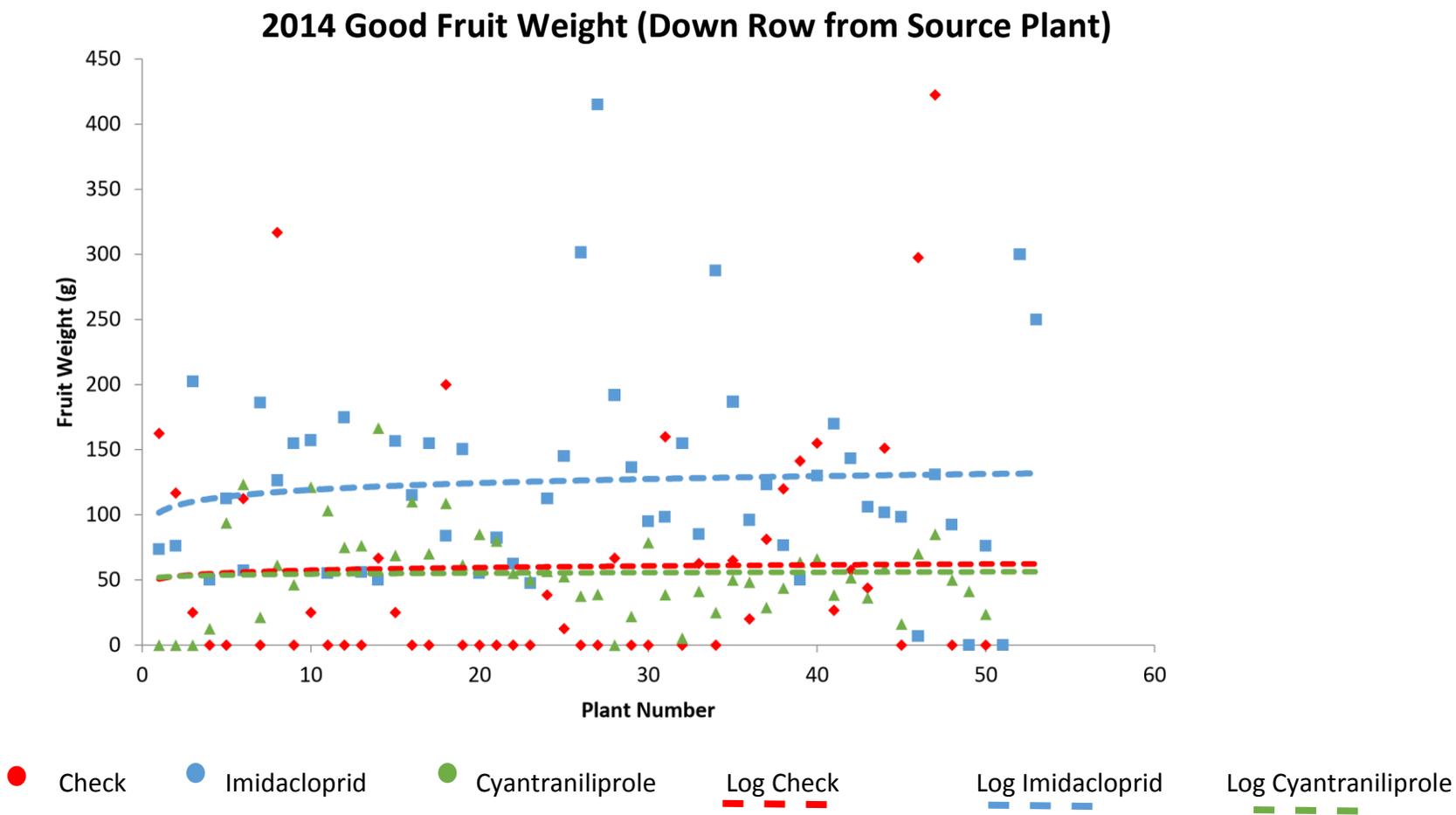
\*TYLCV ratings taken on one date

Figure 3.7(a).



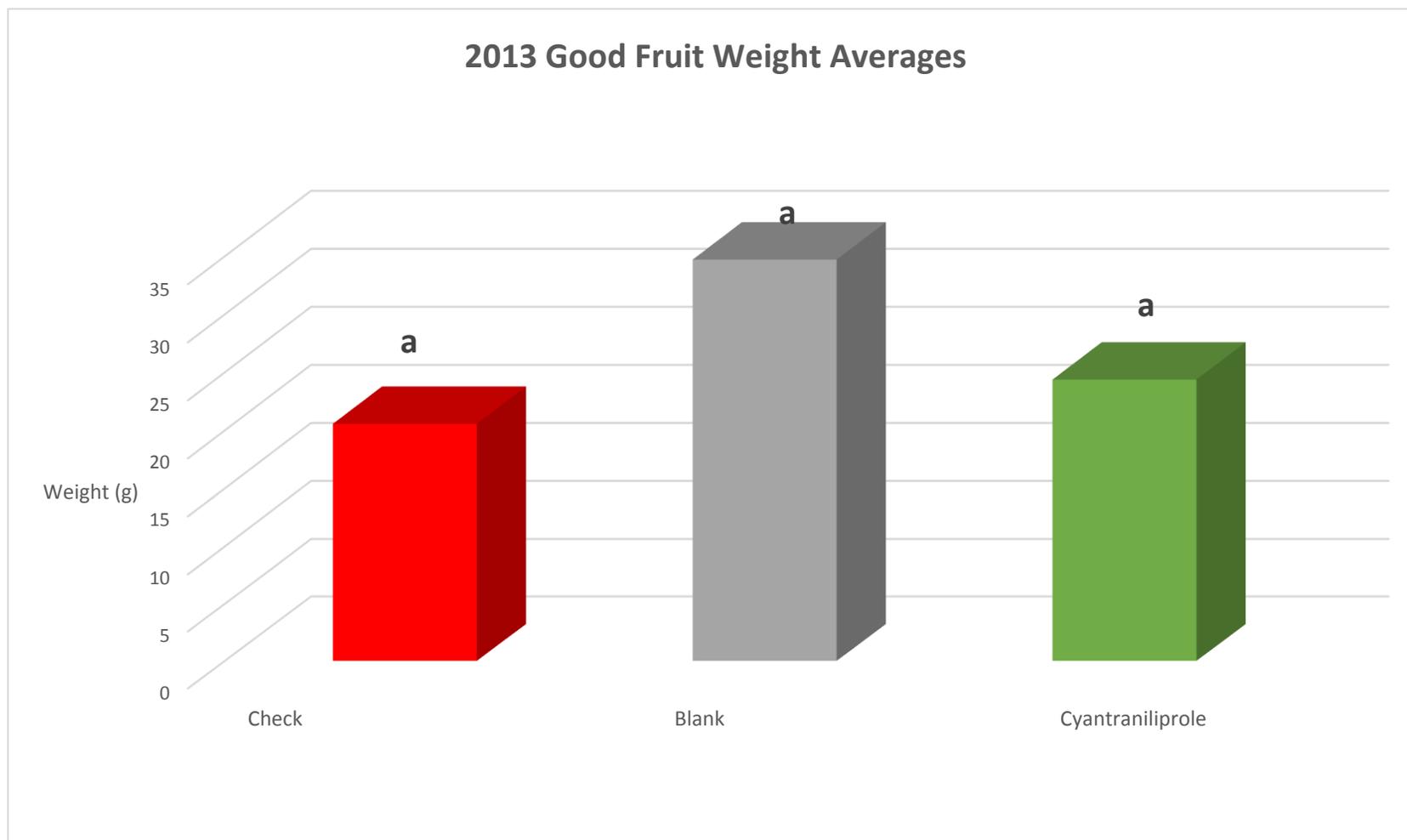
\*Yield data taken on one date

Figure 3.7(b).



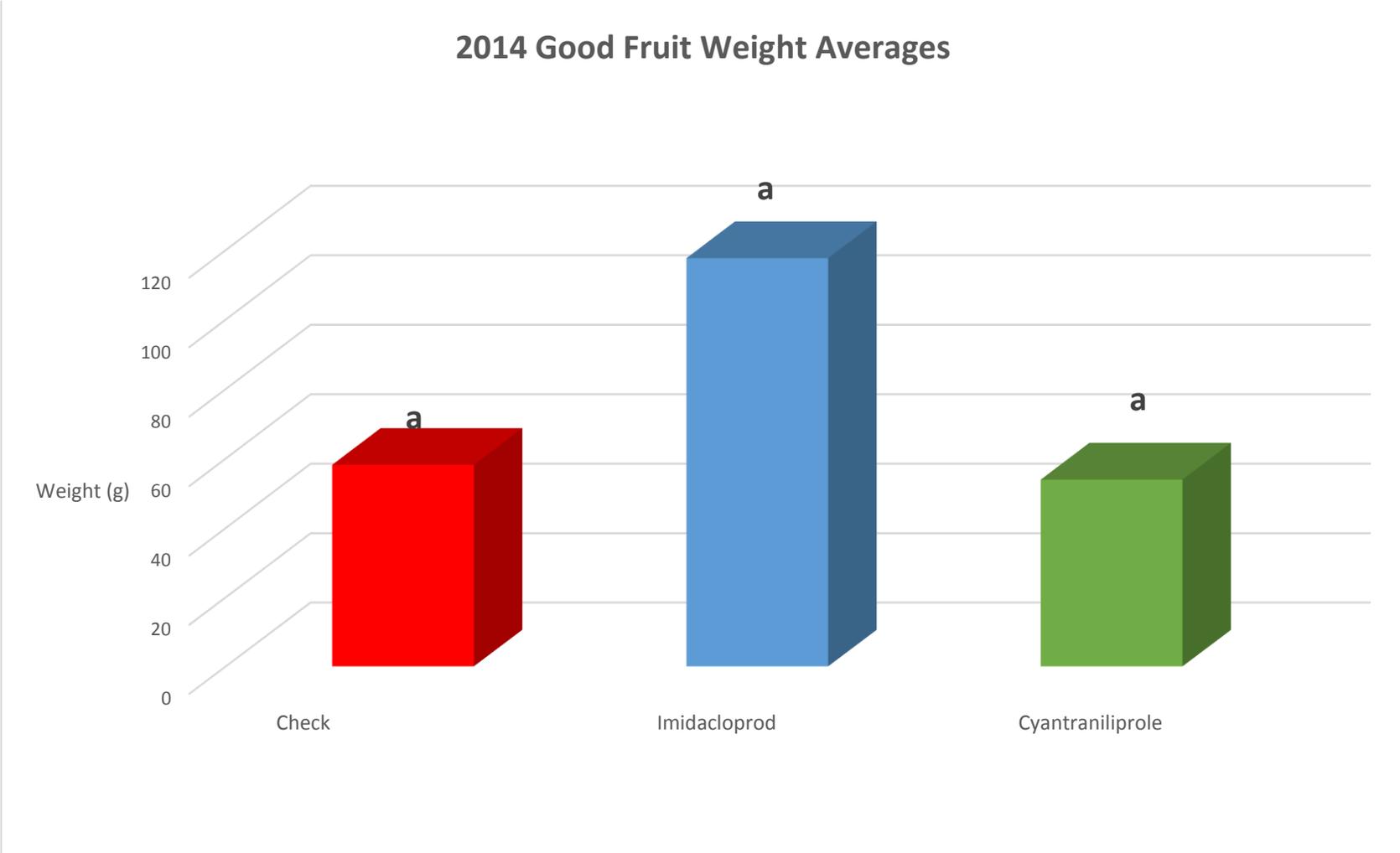
\*Yield data taken on one date

**Figure 3.8(a)**



**\*Yield data taken on one date.**

**Figure 3.8(b)**



**\*Yield data taken on one date.**

## **Chapter 4**

### INTEGRATED MANAGEMENT TACTICS FOR BEMISIA TABACI AND TOMATO

### YELLOW LEAF CURL VIRUS<sup>2</sup>

---

<sup>2</sup> Dempsey, Meredith M. To be submitted to the Journal of Integrated Pest Management

## Abstract

A split-split plot experiment was used to examine the effects of tomato yellow leaf curl virus (TYLCV) resistant cultivars, new insecticides, and reflective mulch on tomato yields. Results showed that reflective mulches significantly reduced whitefly incidence and TYLCV symptom severity. Reflective mulch treatments trended toward greater yield. The treatments of imidacloprid and cyantraniliprole showed that the two insecticide treatments reduced whitefly nymph establishment, but there was no significant effect on TYLCV symptoms compared with the check. Virus-resistant tomato cultivars did not impact whitefly incidence, but showed the strongest reduction in virus disease incidence. Host plant resistant tomato and reflective mulches provided the bulk of the protection against TYLCV incidence in these studies.

**Key words:** *tomato yellow leaf curl virus*, *tomato yellow leaf curl virus* resistant cultivars, reflective mulch, integrated pest management for tomato yellow leaf curl virus

## Introduction

The Florida tomato industry has been significantly impacted by *Tomato yellow leaf curl virus* (TYLCV) since the late 1990s (Polston et al., 1999). Since TYLCV's initial introduction to the Southeastern US, the disease's incidence has been an annual problem in lower subtropical Florida and Georgia. In response to the disease's economic impact, several control tactics have been derived over the past decade. Despite the availability of control tactics, the threat of insect transmitted viruses such as TYLCV continues to play a role in discouraging Georgia tomato production. Control tactics for TYLCV such as host plant resistance (HPR) and reflective mulch are not being employed by growers in Georgia presumably because of uncertainties about the cost and benefit of these tactics. If there is to be a decrease in TYLCV epidemics in Georgia, there needs to be an area wide implementation of preventative TYLCV management tactics (Srinivasan et al. 2012). This will not occur until growers are convinced of the economic viability of such tactics so that the misconception surrounding the benefits of intergrating tactics for control can be reversed.

Cultural and chemical control tactics fit well into integrated pest management programs because they are easily manipulated. TYLCV is transmitted in a persistent circulative manner (Czosnek et al. 2001). Suppression of persistently transmitted viral diseases is accomplished best by using host plant resistant (HPR) cultivars. Common tomato, *Solanum esculentum* L. cultivars are extremely susceptible to TYLCV (Moriones and Navas-Castillo 2000). Breeding for TYLCV resistance in this common cultivar was accomplished by investigating origins of potential resistance in wild cultivar lines: *Solanum peruvianum*, *Solanum chilense* and *Solanum babrochites* (Lapidot and Friedman 2002). From these wild cultivars, several TYLCV-resistant cultivars have been developed. These include: Shanty, Security, Tygress and Inbar. Resistance

originates largely from exploitation of the *Ty-1* semi-dominant gene. In addition to *Ty-1* gene, more recently developed resistant stock has been developed from *Ty-2*, *Ty-3*, *Ty-4* and *Ty-5* genes (Czosnek 2007, Anbinder et al. 2009). Though not immune to the TYLCV virus, these cultivars exhibit strong TYLCV resistance. Resistant plants will show mild symptoms or no symptoms at all. Even with mild symptom expression, resistant yields are much better than susceptible stock. Resistant TYLCV cultivars are reported to provide no whitefly suppression and can act as reservoirs for disease inoculum (Polston and Lapidot 2007). It has been observed that with outbreaks of high viruliferous whitefly population densities, resistance in resistant cultivars can be overcome (Polston and Lapidot 2007). The inability of resistant tomato germplasm to suppress whitefly populations can be detrimental to TYLCV management because uninhibited vector population growth can lead to such outbreaks. Therefore, augmentation of resistant cultivar control tactic with other whitefly control tactics like insecticides is recommended (Polston and Lapidot 2007). Less than 1/3 of all tomato acreage in the southeastern US is planted in TYLCV resistant tomato cultivars (Ozores-Hampton et al. 2010). This lack of planted resistant cultivars could interfere with area wide suppression of the disease. In order to provide more information on the utility of HPR for TYLCV management, regional work is needed to assess resistant cultivar's ability to suppress TYLCV disease symptoms, improve tomato quality and improve yield.

In addition to using resistant cultivars, the use of reflective mulch also provides effective cultural control of TYLCV (Csizinsky et al. 1995, Nyoike et al. 2008). Reflective mulch is also effective at suppressing TYLCV epidemics because it repels whiteflies by interfering with their visual cues to land on host plants (Polston and Lapidot 2007). Because it discourages whitefly landing and therefore, whitefly feeding, it also protects against whitefly virus transmission.

Unlike resistant cultivars, this control tactic is still effective under high whitefly population densities, its effectiveness only deteriorates with dense plant canopy because as the plant grows, more of the reflective mulch surface is covered (Polston and Lapidot 2007). Growers are hesitant to implement this control strategy because of its cost (approximately an additional \$247/ha) and they question the efficiency of this tactic in comparison to chemical control or HPR. What is needed is a replicated comparison of tactics for their ability to reduce whitefly and disease incidence. Because reflective mulch repels whiteflies (Csizinsky et al. 1995) and reduces soil temperature (Diaz and Batal 2002), this control strategy should work well in conjunction with resistant cultivars grown in the late summer in southern Georgia when both of these traits are very advantageous for tomato production.

Chemical control is often the preferred control tactic among tomato growers for any pest because of the ease of use. Insecticide classes, neonicotinoids, diamides, pyrethroids and insect growth regulators are recommended for whitefly population management. Of all the classes mentioned, neonicotinoids are the most frequently applied (Schuster et al. 2010). Application usually occurs in the greenhouse and at transplant as a systemic drench, and as a foliar spray throughout the growing season. Insecticide use alone has not been shown to effectively influence TYLCV epidemics in Florida under field conditions (Polston and Lapidot 2007). This may be because the high usage of these same insecticide classes has selected for resistance in the pest population. Whiteflies are known to be very efficient at detoxifying compounds in insecticides (Horowitz et al. 2005). There are already cases of resistance to neonicotinoids, imidacloprid and thiamethoxam in Georgia and Florida (Polston et al. 2007, Schuster et al. 2010). Some new chemicals have come on the market with novel chemistries, but their effectiveness at providing TYLCV and whitefly control in the field has not been verified. Thus,

an investigation into insecticide efficacy at suppressing whitefly and TYLCV incidence was merited. In addition to the chemicals' evaluation independently, an investigation into how they interact, possibly synergistically with resistant cultivars and reflective mulch was also of interest.

Thus, the initial hypothesis tested in this study was that the incidence of whitefly numbers and TYLCV incidence in field grown tomatoes would be significantly reduced by the aforementioned control tactics compared to an alternate standard practice. The three control tactics evaluated were the use of reflective mulch, HPR tomato cultivars and insecticides for whiteflies. A second hypothesis was that there would be significant interactions between tactics.

### **Materials and Methods**

This experiment was conducted at the Coastal Plains Research Station in Tifton, GA on the Horticulture Farm during the summers of 2013 and 2014. We specifically evaluated metallic silver mulch, the use of TYLCV-resistant cultivars and the use of the insecticides AdmirePro (imidacloprid) and Verimark (cyantraniliprole) relative to a white mulch, a TYLCV-susceptible tomato, and a no insecticide check, respectively. The experimental response variables measured were whitefly adult, immature and egg incidence, TYLCV symptom severity, and marketable yield. The experiments in both 2013 and 2014 were split-split plot designs with four replicates so that both main mulch treatment effects and treatment interactions could be compared relative to providing TYLCV and whitefly control. Mulch acted as the main effect, insecticides acted as the sub effect, and TYLCV resistant cultivars acted as the subsub effect. Each complete plot (complete plot defined as final section with all three layers of treatment: mulch, insecticide and variety) was planted in three rows. Tomato cultivars used included Shanty (Hazera, Coconut Creek, FL, USA), Security (Harris Moran, Rochester, NY, USA) and Tygress (Seminis

Vegetable Seeds, St. Louis, Missouri, USA) and the susceptible cultivar used was FL-47 (Reimer Seeds, Maryland, USA). Types of mulch used was reflective (Agricultural Metallized Mulch Film, Imaflex USA, Thomasville, NC) and a standard non-reflective white mulch (Intergro, Inc., Clearwater, FL). Insecticides used were cyantraniliprole (Verimark 20 SG, Dupont Crop Protection, Wilmington, DE) applied at 13.5 fl. oz. per acre, imidacloprid (AdmirePro 4.6F, Bayer CropScience, Monheim am Rhein Monheim, Germany Global Headquarters) at 10.5 fl. oz. per acre and water as a control. Each treatment was replicated 4 times.

Tomato transplants were purchased from Lewis Taylor Farms in Tifton, GA. Transplants were planted in raised beds 9.14 m by 1.83 m beds separated by a 1.52 m alleyway. Each main treatment plot had three adjacent subsections of four 9.14 m by 1.83 m beds. Reflective mulch was applied to all beds in the main treatment plots. White mulch effect was achieved by spray painting reflective mulch with white paint. For the sub plot insecticide treatments, holes were drenched with forementioned insecticide treatments in one of the three randomly selected subsections prior to transplant. The sub-subplot treatments were randomly assigned single beds in the subplots with each of the four forementioned tomato cultivars. Plants were irrigated with drip irrigation installed underneath the plastic beds and tomatoes were staked to maintain plant vigor. Fungicides were applied as needed throughout the course of the study.

Adult whitefly counts were taken by randomly selecting two leaves off of two randomly selected plants from within the middle row of three rows within a plot. Counts were taken on two leaflets. Immature whitefly counts were taken by randomly selecting one leaf from five randomly selected plants within the middle row of the three rows within a plot. Eggs and small and large nymphs were counted by looking at leaf underneath a microscope. Adult and

immature whitefly counts were done once a week for the duration of the study. TYLCV presence was assessed based on display of characteristic TYLCV symptoms. TYLCV rating was assessed by surveying every plant in the middle row of each plot for symptom severity. Rating was assigned on a scale of 0 to 5 with a 0 being an asymptomatic plant and a 5 being a very symptomatic plant. Yield data was taken at the end of the study. Over the course of several harvests throughout the season, fruit was graded, sorted into virus fruit and non virus fruit and weighed.

All data were subjected to an analysis of variance (ANOVA) by using Proc GLIMMIX in SAS using a split-split plot design. First, seasonal plot averages were compared for main effects and interactions, then whitefly counts and TYLCV ratings were compared on individual sampling dates. Means separation was evaluated with LSD tests ( $P < 0.05$ ) following a significant split-split-plot level effect ( $P < 0.05$ ).

### **Results and Discussion**

In 2013, metallic silver mulch had significantly lower adult whitefly count and TYLCV symptom severity rating means than white mulch (Table 4.1). Metallic silver mulch and white mulch means were not statistically significantly different in terms of marketable yield, but averaged 46% greater in the silver mulch plots. Cyantraniliprole treatment adult whitefly count means were significantly lower than imidacloprid and check means (Table 4.1). Chemical treatment means were not significantly different when measuring TYLCV symptom severity ratings. Cyantraniliprole had a lower mean unmarketable weight than the check, but not the imidacloprid treatment. The check had a significantly lower mean marketable weight than all other treatments. Imidacloprid had the second significantly highest mean marketable weight and

cyantraniliprole had the significantly highest mean marketable weight. The Shanty cultivar had the significantly lowest mean adult whitefly count in comparison to Tygress variety, but not Security or FL-47. Shanty had the lowest TYLCV symptom severity rating in comparison to all other cultivars. Security and Tygress were not significantly different from each other but had significantly lower TYLCV symptom severity ratings than FL-47. FL-47 had the significantly highest rating of all treatments. Shanty and Tygress had the lowest unmarketable weight. FL-47 had the second highest mean unmarketable weight and Security had the highest mean unmarketable weight. Shanty, Tygress and FL-47 did not have significantly different mean marketable weights (Table 4.1).

In 2014, silver mulch had significantly lower mean adult whitefly counts and mean TYLCV symptom severity ratings in comparison to white mulch (Table 4.2). Silver mulch produced a significantly higher unmarketable mean weight than white mulch. Silver mulch and white mulch mean marketable weights were not significantly different from each other, but silver averaged 16% more marketable fruit. Imidacloprid and cyantraniliprole were both significantly better at providing whitefly suppression in comparison to the check, they were not significantly different from each other. Cyantraniliprole did not have significantly lower mean TYLCV symptom severity ratings in comparison to the check or imidacloprid. Imidacloprid was not significantly better at providing lower mean TYLCV symptom severity ratings than the check or cyantraniliprole (Table 4.2). Cyantraniliprole was significantly better at producing more unmarketable and marketable yield than imidacloprid or the check treatments. Imidacloprid and the check treatment were not significantly different from each other at influencing unmarketable or marketable weight means. Tygress had significantly higher mean adult whitefly counts than all other varieties except Security. Shanty and Security were not

significantly better at providing whitefly suppression than FL-47. Varieties were not significantly different than each other at suppressing TYLCV symptom severity rating. Security and Shanty had the significantly highest unmarketable weight than Tygress, but were not significantly different from each other or FL-47 variety. Shanty had a significantly higher mean marketable weight than Tygress, but not Security or FL-47. Security and FL-47 were not significantly different from each other (Table 4.2).

Metallic silver mulch and white mulch were not significantly different from each other at suppressing whitefly immatures in 2013 (Table 4.3). In 2014, silver mulch was not significantly better at providing immature suppression in comparison to white mulch. Cyantraniliprole and imidacloprid were both significantly better at providing whitefly immature suppression in 2013 in comparison to the check, but were not significantly better than each other. In 2014, chemical treatments and check were not significantly different from each other at providing whitefly immature suppression. In 2013, resistant varieties did not provide significantly better suppression for whitefly immatures in comparison to the susceptible variety. In 2014, resistant variety Shanty provided significantly better suppression for small nymphs in comparison to FL-47 but not in comparison to other resistant varieties. Varieties were not significantly better at suppressing eggs or large nymphs (Table 4.3).

#### ***Treatment Effect and Treatment Interaction Effect on Adult Whitefly Counts***

Mulch had a significant treatment effect for adult whitefly in 2013 ( $F = 238$ ,  $df = 1, 3$ ,  $P = 0.0006$ ) and 2014 adult whitefly counts ( $F = 147$ ,  $df = 1, 3$ ,  $P = 0.0012$ ). Insecticide provided a significant treatment effect for adult whitefly counts in 2013 ( $F = 41.2$ ,  $df = 2, 12$ ,  $P$

= <0.0001) and 2014 ( $F = 21.7$ ,  $df = 2, 12$ ,  $P = 0.0001$ ). Cultivar provided a significant treatment effect for adult whitefly counts in 2013 ( $F = 4.6$ ,  $df = 3, 54$ ,  $P = 0.006$ ) and 2014 adult whitefly counts ( $F = 18.82$ ,  $df = 3, 52$ ,  $P < 0.0001$ ). . Mulch and cultivar interaction effect was significant on 2014 adult whitefly counts ( $F = 6.7$ ,  $df = 3, 52$ ,  $P = 0.0007$ ). Insecticide and cultivar interaction effect was significant on whitefly adult counts in 2013 ( $F = 2.33$ ,  $df = 6, 54$ ,  $P = 0.04$ ). Mulch and insecticide interaction effect and mulch and insecticide and cultivar interaction effect was not significant on influencing adult whitefly counts in 2013 or 2014.

There was a strong mulch treatment effect on mean adult whitefly counts over time for years 2013 and 2014 (Figures 4.1 (a) and (b), respectively). Figure 4.1 (a) demonstrates that in 2013 a peak in adult whitefly counts occurred on the 10<sup>th</sup> of September for reflective and white mulch, respectively  $45.29 \pm 20.95$ ,  $224.70 \pm 98.14$ , and the 8<sup>th</sup> of October  $162.79 \pm 80.89$ . Figure 4.1 (b) illustrates in 2014, peaks in adult whitefly counts occurred in silver and white mulch, respectively, on the 2<sup>nd</sup> of September ( $21.64 \pm 19.26$ ), ( $71.31 \pm 57.69$ ), the 16<sup>th</sup> of September ( $68.70 \pm 224.10$ ), ( $224.10 \pm 114.56$ ) and the 7<sup>th</sup> of October ( $85.14 \pm 49.08$ ), ( $201.29 \pm 83.69$ ). White mulch maintained a higher mean whitefly average for the duration of the study in comparison to silver mulch for both years.

The insecticide treatment effect on mean adult whitefly counts over time for years 2013 and 2014 (Figure 4.2 (a) and (b), respectively) was less dramatic than that seen with the mulch effect (Figure 4.1). In 2013, there were peaks of adult counts on the 10<sup>th</sup> of September for cyantraniliprole, imidacloprid and check treatments ( $133.25 \pm 109.43$ ,  $132.59 \pm 119.99$ ,  $139.28 \pm 117.43$ , respectively) and the 8<sup>th</sup> of October ( $332.00 \pm 139.97$ ,  $171.187 \pm 86.73$ ,  $303.625 \pm 174.24$ , respectively) (Figure 4.2 (a)). In 2014, there was a spike in population in imidacloprid and check treatments on 2<sup>nd</sup> of September ( $69.32 \pm 56.11$ ,  $56.65 \pm 50.82$ , respectively) and

spikes in population for imidacloprid, cyantraniliprole and check on the 16<sup>th</sup> of September ( $98.38 \pm 75.77$ ,  $162.24 \pm 130.35$ ,  $176.59 \pm 119.79$ , respectively) and the 7<sup>th</sup> of October ( $144.19 \pm 84.95$ ,  $114.18 \pm 71.89$ ,  $172.21 \pm 103.10$ , respectively) (Figure 4.2 (b)). The cultivar effect on mean adult whitefly counts over time for years 2013 and 2014 was even smaller (Figure 4.3 (a) and (b), respectively). In 2013 populations peaked on the 10<sup>th</sup> of September for Security, Shanty, Tygress and FL-47 cultivars respectively ( $132 \pm 101$ ), ( $103 \pm 82$ ), ( $170 \pm 153$ ), ( $135 \pm 108$ ), and the 8<sup>th</sup> of October ( $280 \pm 169$ ), ( $267 \pm 146$ ), ( $2889 \pm 149$ ), ( $241 \pm 157$ ) (Figure 4.3 (a)). Similarly in 2014, populations peaked on the 2<sup>nd</sup> of September for Security, Shanty, Tygress and FL-47 varieties respectively, ( $33.0 \pm 36.0$ ), ( $41.4 \pm 36.4$ ), ( $62.9 \pm 58.4$ ), ( $48.6 \pm 60.0$ ) the 16<sup>th</sup> of September ( $159 \pm 131$ ), ( $116 \pm 75$ ), ( $200 \pm 140$ ), ( $110 \pm 85.7$ ) and the 7<sup>th</sup> of October ( $160 \pm 107$ ), ( $144 \pm 78$ ), ( $147 \pm 87$ ), ( $126 \pm 86$ ) (Figure 4.3(b)).

The metallic silver mulch treatment provided the largest reduction of mean adult whitefly counts in 2013 and 2014 (Table 4.1 and 4.2). There was a chemical treatment effect on adult whitefly presence in 2013 (Table 4.1) and 2014 (Table 4.2). In 2013, cyantraniliprole provided superior suppression while imidacloprid was not significantly better at suppression than the check (Table 4.1). In 2014, cyantraniliprole and imidacloprid were both significantly better at adult whitefly suppression than the no chemical check but neither insecticide was significantly better than the other at suppression (Table 4.2).

The bottom line was that insecticide use of either imidacloprid or cyantraniliprole significantly reduced adult whitefly counts averaged over all dates in comparison to the control (Tables 4.1 and 4.2), but cannot be recommended for a stand alone treatment of virus incidence in the field. The cyantraniliprole treatment produced greater marketable yield in comparison to imidacloprid and the no insecticide control, with imidacloprid resulting in intermediate yield,

likely due to the presence of lepidopteran larvae (Tables 4.1 and 4.2). Shanty cultivar was significantly better at providing suppression for adult whitefly counts in 2013 (Table 4.1), but in 2014, Shanty was not significantly better than Security or FL-47, Tygress had the significantly highest mean adult whitefly counts (Table 4.2). FL-47, the susceptible cultivar, actually had the least amount of whiteflies in 2014 probably because of reduced plant vigor caused by TYLCV infection (Table 4.2).

All treatments were significant in reducing adult whitefly counts for both 2013 and 2014 (Table 4.4). Of the interaction of treatments, mulch and insecticide worked best together at providing whitefly suppression. Mulch and insecticide would have a stronger effect on adult whitefly counts in comparison to different cultivar treatment interactions because mulch and insecticides have repellent properties, resistant cultivars do not.

#### ***Treatment Effect and Treatment Interaction Effect on TYLCV Symptom Severity Rating***

Mulch had a significant treatment effect for TYLCV symptom severity rating in 2013 ( $F = 115$ ,  $df = 1, 3$ ,  $P = 0.0017$ ) and 2014 TYLCV symptom severity rating ( $F = 50.29$ ,  $df = 1, 3$ ,  $P = 0.0058$ ). Insecticide did not provide a significant treatment effect for TYLCV symptom severity rating in 2013 ( $F = 2.31$ ,  $df = 2, 12$ ,  $P = 0.1412$ ) or 2014 ( $F = 0.53$ ,  $df = 2, 12$ ,  $P = 0.599$ ). Cultivar provided a significant treatment effect for TYLCV symptom severity rating in 2013 ( $F = 72.96$ ,  $df = 3, 54$ ,  $P < 0.0001$ ) and 2014 rating ( $F = 54.02$ ,  $df = 3, 52$ ,  $P < 0.0001$ ).

Mulch and cultivar interaction effect was significant on TYLCV symptom severity rating in 2013 ( $F = 26$ ,  $df = 3, 54$ ,  $P < 0.0001$ ), and 2014 TYLCV symptom severity rating ( $F = 3.08$ ,  $df = 3, 52$ ,  $P = 0.035$ ). Mulch and insecticide interaction effect and mulch and insecticide

and cultivar interaction effect was not significant on influencing TYLCV symptom severity rating in 2013 or 2014.

Figures 4.4, 4.5 and 4.6 illustrate mulch, insecticide and variety effect on TYLCV symptom severity rating in 2014 over time. Neither mulch treatment had a significantly lower mean TYLCV symptoms severity rating. Despite, the mean number not being significantly different, there were lower ratings observed in silver mulch treatments than white mulch treatments. Insecticides showed no significant difference between each other at providing lower TYLCV symptom severity ratings. All resistant varieties did not have significantly lower TYLCV symptom severity rating in comparison to the susceptible variety. Despite, not being significantly different, there were lower TYLCV symptom severity ratings observed in resistant variety treatments.

The metallic silver mulch treatment provided the largest reduction of TYLCV symptom severity rating in 2013 and 2014 (Table 4.1 and 4.2). There was no significant chemical effect on TYLCV symptom severity rating compared with the check in 2013 (Table 4.1), but there was an effect on TYLCV symptom severity rating compared with the check in 2014 (Table 4.2). Cyantranilprole was significantly superior at reducing TYLCV symptom severity than imidacloprid and check (Table 4.2). In terms of TYLCV symptom expression, Shanty had a significantly lower mean rating, followed by Tygress and Security in 2013 and 2014 (Tables 4.1 and 4.2).

In terms of TYLCV symptom severity control, the mulch and cultivar interaction effect was the most significant in comparison to mulch and insecticide interaction or insecticide and cultivar interaction (Table 4.4). This makes sense because resistant cultivars are meant to maintain plant vigor despite TYLC infection. Mulch may have worked better in conjuncture

with cultivar instead of insecticide for TYLCV suppression because the mulch prevents feeding of whiteflies by discouraging whiteflies to land on the tomato plant. Insecticides require feeding, thereby inviting transmission, before it can provide any kind of control.

### ***Treatment Effect and Treatment Interaction Effect on Whitefly Immature Counts***

In 2013, insecticide had a significant treatment effect on whitefly immature counts, eggs, ( $F = 7.67$ ,  $df = 2, 12$ ,  $P = 0.0071$ ), small nymphs ( $F = 7.13$ ,  $df = 2, 12$ ,  $P = 0.0091$ ), and large nymphs ( $F = 4.84$ ,  $df = 2, 12$ ,  $P = 0.0287$ ) (Table 4.5). The main plot mulch effect was significant on only small nymph establishment ( $F = 126$ ,  $df = 1, 3$   $P = 0.0015$ ). Cultivar had significant impact on small nymph presence ( $F = 0.89$ ,  $df = 3, 54$ ,  $P = 0.4515$ ) but not egg or large nymph establishment. Mulch and insecticide interaction effect was significant on egg ( $F = 3.92$ ,  $df = 2, 12$   $P = 0.0489$ ) and small nymph counts ( $F = 5.06$ ,  $df = 2, 12$ ,  $P = 0.0255$ ), but not large nymph counts ( $F = 2.72$ ,  $df = 2, 12$ ,  $P = 0.1$ ). Mulch and cultivar interaction effect, insecticide and cultivar interaction effect and mulch and insecticide and cultivar interaction effect had no significant influence on immature presence. In 2014, there were no significant treatment effects or treatment interaction effects on immature presence (Table 4.5).

Silver mulch did not provide significant suppression for whitefly immatures in 2013 and 2014 (Table 4.3). The sub-treatment of different chemicals showed that the two insecticide treatments, imidacloprid and cyantraniliprole, were similar in efficacy in suppressing whitefly nymph establishment in 2013, but no difference to the no chemical check was observed in 2014 (Table 4.3).

Mulch and insecticide were consistent significant treatment effects for egg and nymph suppression in 2013 (Table 4.5). Cultivar was not significant. Mulch and insecticide interaction effect was the only interaction effect that provided a significant treatment effect in 2013. Strong treatment effect in the 2014 trial was not observed (Table 4.6). Mulch treatment effect on small nymphs and insecticide and cultivar interaction effect on eggs were the only significant treatment effects observed in 2014. The discrepancy between observed treatment effects in 2013 versus 2014 is unclear. When looking at 2013 results, they indicate that cultivar does not provide a significant influence on whitefly oviposition or nymph vigor. This makes sense because resistant cultivars are bred to express a genotype that aids with accommodating viral infection, not a phenotype that repels whitefly landing or feeding. Mulch however has a repellency effect that would deter females from landing on the plant and laying eggs. Insecticide has a repellency effect too, but has an even stronger toxicity effect. The repellency effect of insecticides may reduce oviposition rates of females on treated plants. Eggs laid on treated plants may die because of contact with the insecticide poison. Of the eggs that hatch, once the nymphs feed on the plant, the systemic insecticide will kill them. 2014 results indicate that mulch, insecticide and cultivar play no role in suppressing egg or nymph presence.

#### ***Treatment Effect and Treatment Interaction Effect on Yield***

The mulch effect was significant on influencing marketable yield in 2013 ( $F = 16.02$ ,  $df = 1, 3$ ,  $P = 0.0002$ ), but not unmarketable yield ( $F = 48.85$ ,  $df = 1, 3$ ,  $P = 0.18$ ) in 2014, there was no significant mulch effect on yield (Table 4.7). Insecticide significantly influenced marketable yield in 2013 ( $F = 7.02$ ,  $df = 2, 12$ ,  $P < 0.0001$ ), but not unmarketable yield ( $F = 79.83$ ,  $df = 2$ ,

12,  $P = 0.07$ ). In 2014, insecticide was significant on unmarketable ( $F = 4.38$ ,  $df = 2, 12$ ,  $P = 0.029$ ) and marketable yield ( $F = 5.11$ ,  $df = 2, 12$ ,  $P = 0.025$ ). Cultivar was significant on influencing unmarketable weight in 2013 ( $F = 4.30$ ,  $df = 3, 52$ ,  $P < 0.0001$ ), but not marketable weight ( $F = 31.21$ ,  $df = 3, 52$ ,  $P = 0.74$ ). In 2014, cultivars significantly influenced both unmarketable ( $F = 3.98$ ,  $df = 3, 54$ ,  $P = 0.009$ ) and marketable yield ( $F = 4.79$ ,  $df = 3, 54$ ,  $P = 0.003$ ). The mulch and insecticide interaction significantly influenced unmarketable yield ( $F = 6.80$ ,  $df = 2, 12$ ,  $P = 0.013$ ) but not marketable yield ( $F = 13.14$ ,  $df = 2, 12$ ,  $P = 0.13$ ) in 2013. Mulch and cultivar interaction effect, insecticide and cultivar interaction effect and mulch, insecticide and cultivar interaction effect had no significant impact on marketable or unmarketable yield in 2013. In 2014, mulch and insecticide interaction, mulch and cultivar interaction, insecticide and cultivar interaction and mulch, insecticide and cultivar interaction were not significance for any yield variables (Table 4.7).

Mulch treatments did not result in significantly different marketable yield in 2013, but did trend toward greater yields in 2013 (Table 4.1) and 2014 (Table 4.2). Cyantraniliprole produced the highest mean marketable yield in 2013 and 2014 in comparison to imidacloprid (Tables 4.1 and 4.2). Cyantraniliprole produced the significantly lowest mean unmarketable yield in 2013 (Table 4.1). Imidacloprid was an intermediate chemical control for pests resulting in unmarketable yield. Yet, cyantraniliprole produced the lowest significant mean unmarketable yield in 2014 (Table 4.2).

In terms of marketable yield in 2013, Security was the only cultivar that showed a significantly higher yield than the other cultivars (Table 4.1). Shanty, Tygress and FL 47 were not significantly different in terms of mean marketable yield (Table 4.1). However, in terms of amount of unmarketable yield all cultivars were significantly different from each other, Shanty produced the lowest mean yield, followed by Tygress, FL 47 and Security. Security was

obviously a more vigorous tomato cultivar, which resulted in both greater marketable and unmarketable yield. In 2014, Shanty, Security and FL-47 were the only cultivars that showed a significantly higher mean for unmarketable and marketable yield than Tygress (Table 4.2). The important take away message for tomato is that host plant resistant tomato and reflective mulches are providing the bulk of the protection against TYLC disease presence, however, there will likely be other insect pests that will need to be targeted with insecticides to maximize yields.

All treatments had a significant impact on unmarketable and marketable weight in 2013 trial. In the 2014 trial, mulch and insecticide were the only treatments that had significant impact on unmarketable weight, but for marketable weight, cultivar was the only treatment that had a significant impact (Table 4.7). Of all the treatments, cultivar should have the most impact on fruit yield. TYLC disease causes flower necrosis, so in resistant cultivars that suppress symptom onset, flower necrosis will not occur as frequently as in susceptible cultivars. Treatment interaction effects were only significant in the 2013 trial, but variation like this is typical in small plot studies. Mulch and insecticide treatment interaction effect was significant for unmarketable and marketable fruit weight (Table 4.7). Mulch and cultivar was significant at influencing marketable weight, but not unmarketable weight (Table 4.7). Insecticide and cultivar interaction effect was not significant in the 2013 trial at influencing marketable or unmarketable yield (Table 4.7).

### **Conclusion**

The results from this experiment did support the hypothesis that resistant tomato cultivars would mitigate TYLCV disease symptom severity, adult whitefly presence and yield. In

addition to resistant cultivars, there were observed significant treatment effects for mulch treatment for whitefly and TYLCV disease suppression and insecticide significant treatment effect for adult whitefly counts.

Of the three resistant cultivars, Shanty had the lowest adult whitefly counts, but was only significantly better than Fl-47. Security and Tygress were no different at whitefly suppression than Fl-47. This is because resistant cultivars were not bred for whitefly resistance, only TYLCV disease resistance. This is clear comparing FL-47 versus resistant cultivars in relation to TYLCV symptom severity. Shanty had the lowest symptom severity rating than all other resistant cultivars and all resistant cultivars had lower disease symptom severity ratings than FL47. Shanty's superior TYLCV resistance compared to Tygress and Security has not been previously reported for Georgia conditions.

Of the two mulch treatments, silver mulch had the lowest adult whitefly counts and disease severity rating than conventional white mulch for both years. Silver mulch is such a powerful control tactic because it has a strong repellency property. Whiteflies are unable to perceive host plants because their visual perception is distorted by light being reflected off of the reflective mulch. Because whiteflies are unable to see the host plant, they do not land, thus decreasing incidence. Because they do not land, they do not feed and therefore do not transmit the virus. Reflective mulch's efficacy is highly influenced by plant canopy density. If plant cover is so thick that foliage is covering most of the mulch surface, the reflective effect of the reflective mulch will be nullified, and whiteflies will be able to visually perceive the tomato plant in contrast to the ground. Later on in the season when plant canopy is dense, an increase in whitefly populations may be observed. Often times at that stage in the season, fruit has

already set, so the most vulnerable time for the plant to become negatively impacted by TYLCV has passed.

The two insecticides provided consistently better whitefly suppression than the no chemical check. In 2013, cyantraniliprole suppressed whiteflies significantly better than imidacloprid. In relation to TYLCV disease severity, the chemical treatments did not significantly suppress disease severity in comparison to the no chemical check. The generally poor insecticide protection from TYLCV disease incidence is likely because insecticides do not provide control of the vector before TYLCV transmission occurred. Target pests must ingest or come into contact with the poison before they are killed. In the time it takes for them to come into contact with the poison, they could be feeding and transmitting the virus. After they have fed or landed on a treated leaf surface they will die and a decrease in adult whitefly counts as observed.

## Acknowledgements

The authors thank Stan Diffie, Saioa Legarza, Anita Shrestha, Pin-Chu Lai, Nan Bostick, Julia Kitchens, Simmy McKeown, Nikki Bowman, Jenna Kicklighter, Abby Applewhite, Gordon MacQuirter, Cassidy Long and Donnie Cook for their assistance with experiment maintenance and sampling. This project was partially funded by a USDA AFRI Grant and the Coastal Plain Experiment Station.

## References

- Anbinder, I., Reuveni, M., Azari, R., Paran, I., Nahon, S., Shlomo, H., Chen, L., Lapidot, M. and Levin, I. 2009. Molecular dissection of tomato leaf curl virus resistance in tomato line TY172 derived from *Solanum peruvianum*. *Theor. Appl. Genet.* 119: 519 – 530.
- Bennett, S.D., K.W. Littrell, T.A. Hill, M. Mahovic, and C.B. Behravesh. 2015. Multistate foodborne disease outbreaks associated with raw tomatoes, United States, 1990-2010: a recurring public health problem. *Epidemiology and Infection* 143: 1352-1359.
- Csizinsky, A.A., Schuster, D.K. and Kring, J.B. 1995. Color mulches influence yield and insect pest populations in tomatoes. *J. Amer. Soc. Hort. Sci.* 120: 778 – 784.
- Czosnek, H. 2007. Tomato yellow leaf curl virus disease management. *In* *Molecular Biology, Breeding for Resistance*. Springer. Dordrecht, Netherlands.
- Czosnek, H. 2008. *Tomato Yellow Leaf Curl Virus*. The Hebrew University of Jerusalem, Rehovot, Israel.
- Czosnek, H., Ghanim, M., Morin, S., Rubinstein, G., Fridman, V. and Zeidan, M. 2001. Whiteflies: vectors – or victims? – of Geminiviruses. pp. 291 – 322. *In* K. Maramorosch (eds.), *Advances in virus research*, vol. 57. Academic Press, New York, NY.
- Díaz-Pérez, J. C., and K. D. Batal. 2002. Colored plastic film mulches affect tomato growth and yield via changes in root-zone temperature. *J. Am. Soc. Hortic. Sci.* 127: 127–136.
- Horowitz, A.R., Kontsedalov, S., Khasdan, V. and Ishaaya, I. 2005. Biotypes B and Q of *Bemisia tabaci* and their relevance to neonicotinoid and pyriproxyfen resistance. *Archives Insect Biochem. and Physiol.* 58: 216 – 225.
- Kumar, Y., V. Hallan, and A.A. Zaidi. 2010. Emerging Begomovirus problems in India, pp 105-128. *In* P. Sharma, R.K. Gaur, and M. Ikegami (Eds) *Emerging Geminiviral Diseases and*

- Their Management, Book Series: Botanical Research And Practices, Nova Science Publishers, Inc, Hauppauge, NY.
- Lapidot, M. and Friedmann, M. 2002. Breeding for resistance to whitefly-transmitted Geminiviruses. *Ann. App. Biol.* 140: 109 – 127.
- Nyoike, T.W., Liburd, O.E. and Webb, S.E. 2008. Suppression of whiteflies, *Bemisia tabaci* (Hemiptera: Aleyrodidae) and incidence of cucurbit leaf crumple virus, a whiteflytransmitted virus of zucchini squash new to Florida, with mulches and imidacloprid. *Fla. Entomol.* 91: 460 – 465.
- Ozores-Hampton, M., McAvoy, G., Lamberts, M. and Sui, D. 2010. A survey of the effectiveness of current methods used for the freeze protection of vegetables in South Florida. *Proc. Fla. State Hort. Soc.* 123: 128 – 133.
- Polston, J.E. and Lapidot, M. 2007. Management of Tomato yellow leaf curl virus: US and Israel Perspectives. pp. 251 – 262. *In* H. Czosnek (Eds.), *Tomato Yellow Leaf Curl Disease*. Springer, Netherlands.
- Polston, J.E., McGovern, R.J. and Brown, L.G. 1999. Introduction of Tomato yellow leaf curl virus in Florida and implications for the spread of this and other geminiviruses of tomato. *Plant Disease* 83:984-988
- Schuster, D.J., Mann, R.S., Toapanta, M., Cordero, R., Thompson, S., Spurgeon, S., Shurtleff, A. and Morris II, R.F. 2010. Monitoring neonicotinoid resistance in biotype B of *Bemisia tabaci* in Florida. *Pest Mgt. Sci.* 66: 186 – 195.
- Srinivasan, R., D. Riley, S. Diffie, A. Sparks, and S. Adkins. 2012. Whitefly population dynamics and evaluation of whitefly-transmitted Tomato yellow leaf curl virus (TYLCV)-resistant tomato genotypes as whitefly and TYLCV reservoirs. *J. Econ.*

Entomol. 105(4): 1447-1456

**Table 4.1** Effects of treatments and their interactions on whitefly incidence, TYLCV symptom and yield in 2013 at the Coastal Plain Experiment Station at Tifton, GA

Treatments by Main, Sub, and Sub-sub plot levels	Whitefly Incidence	TYLCV Symptoms	Unmarketable Weight	Marketable Weight
Main Plot – Mulch				
Silver Mulch	43.68b	1.75a	7.88a	23.15a
White Mulch	151.48a	2.55b	6.17a	15.86a
Subplot – Insecticide				
Imidacloprid 4.6F 10.5 floz/ac	105.99b	2.27a	7.28ab	20.56b
Cyantraniliprole 20SG 13.5 floz/ac	68.09c	2.23a	5.95b	23.50a
No insecticide check, water	118.66a	1.95a	7.86a	14.47c
Subsubplot – Cultivar				
Security (TYLCV resistant)	96.65ba	2.16b	9.87a	21.32a
Shanty (TYLCV + TSWV resistant)	86.78b	1.12c	4.39c	18.65a
Tygress (TYLCV = ToMV resistant)	107.06a	2.01b	5.93c	19.27a
FL-47 (virus susceptible)	99.83ba	3.31a	7.93b	18.79a

\* Means within columns followed by the same letter are not significantly different (LSD, P<0.05).

**Table 4.2** Effects of treatment and their interactions on whitefly incidence, TYLCV symptom and yield in 2014 at the Coastal Plain Experiment Station at Tifton, GA

Treatments by Main, Sub, and Sub-sub plot levels	Whitefly Incidence	TYLCV Symptoms	Unmarketable Weight	Marketable Weight
Main Plot – Mulch				
Silver Mulch	31.76a	1.14a	13.7208a	23.0858a
White Mulch	85.33b	2.07b	11.7845b	19.9861a
Subplot – Insecticide				
Imidacloprid 4.6F 10.5 floz/ac	55.09b	1.64a	11.8469b	19.8906b
Cyantraniliprole 20SG 13.5 floz/ac	47.23b	1.44a	14.4500a	24.4437a
No insecticide check, water	74.99a	1.72a	11.9611b	20.2736b
Subsubplot – Cultivar				
Security (TYLCV resistant)	61.92ab	1.01a	13.7198a	21.5488ab
Shanty (TYLCV + TSWV resistant)	54.33b	1.26a	13.7667a	25.0510a
Tygress (TYLCV = ToMV resistant)	71.70a	1.96a	10.9229b	19.0781b
FL-47 (virus susceptible)	48.78b	1.71a	12.6012ab	20.4660ab

\* Means within columns followed by the same letter are not significantly different (LSD, P<0.05).

**Table 4.3 Effects of treatment and their interactions on mean immatures in 2013 and 2014 at the Coastal Plain Experiment Station at Tifton, GA**

Treatments by Main, Sub, and Subsub plot levels	2013			2014		
	Eggs	Small	Large	Eggs	Small	Large
Main Plot – Mulch						
Silver Mulch	2.14a	0.27a	0.03a	25.93a	2.12a	1.32a
White Mulch	9.36a	1.95a	0.20a	22.42a	4.72a	2.01a
Subplot – Insecticide						
Imidacloprid 4.6F 10.5 floz/ac	5.75ab	0.96b	0.07b	22.02a	4.21a	0.97a
Cyantraniliprole 20SG 13.5 floz/ac	3.16b	0.65b	0.04b	28.43a	3.11a	2.20a
No insecticide check, water	8.21a	1.68a	0.22a	21.68a	2.89a	1.81a
Subsubplot – Cultivar						
Security (TYLCV resistant)	5.76a	1.11a	0.11a	25.82a	3.42ab	1.06a
Shanty (TYLCV + TSWV resistant)	6.61a	1.07a	0.10a	19.46a	1.97b	1.84a
Tygress (TYLCV = ToMV resistant)	5.21a	0.90a	0.072a	23.74a	2.95ab	1.44a
FL-47 (virus susceptible)	5.30a	1.32a	0.16a	27.24a	5.16a	2.30a

\* Means within columns followed by the same letter are not significantly different (LSD, P<0.05).

**Table 4.4 Effects of treatment and their interactions on whitefly incidence and TYLCV rating in 2013 and 2014 at the Coastal Plain Experiment Station at Tifton, GA**

	2013						2014					
	Whitefly Incidence			TYLCV Rating			Whitefly Incidence			TYLCV Rating		
	DF	F	Pr>F	DF	F	Pr>F	DF	F	Pr>F	DF	F	Pr>F
Rep	3	3.22	0.0298	3	6.06	0.0012	3	5.14	0.0035	3	9.46	<0.0001
Mulch	1,3	238.25	0.0006	1,3	115.40	0.0017	1,3	147.45	0.0012	1,3	50.29	0.0058
Insecticide	2,12	41.16	<0.0001	2,12	2.31	0.1412	2,12	21.67	0.0001	2,12	0.53	0.5993
Mulch*Insecticide	2,12	24.36	<0.0001	2,12	0.45	0.6499	2,12	3.79	0.0530	2,12	1.61	0.2403
Cultivar	3,54	4.60	0.0061	3,52	72.96	<0.0001	3,52	18.82	<0.0001	3,53	54.02	<0.0001
Mulch*Cultivar	3,54	1.90	0.1413	3,54	26.00	<0.0001	3,52	6.70	0.0007	3,53	3.08	0.0353
Insecticide*Cultivar	6,54	2.33	0.0450	6,54	0.62	0.7145	6,52	1.55	0.1813	6,53	1.11	0.3703
Mulch*Insecticide*Cultivar	6,54	2.22	0.0552	6,54	1.11	0.3704	6,52	0.73	0.6264	6,53	0.48	0.8182

\*Significant treatments defined as treatments with Pr>F value of 0.05 or less.

**Table 4.5** Effects of treatment and their interactions on immatures in 2013 at the Coastal Plain Experiment Station at Tifton, GA

	2013								
	Eggs			Small Nymphs			Large Nymphs		
	DF	F	Pr>F	DF	F	Pr>F	DF	F	Pr>F
Rep	3	30.02	<0.0001	3	0.65	0.5834	3	3.89	0.0138
Mulch	1,3	8.57	0.0611	1,3	126.52	0.0015	1,3	8.96	0.0580
Insecticide	2,12	7.67	0.0071	2,12	7.13	0.0091	2,12	4.84	0.0287
Cultivar	3,52	1.63	0.1937	3,52	0.89	0.4515	3,52	1.14	0.3405
Mulch*Insecticide	2,12	3.92	0.0489	2,12	5.06	0.0255	2,12	2.72	0.1061
Mulch*Cultivar	3,54	0.11	0.9517	3,54	0.82	0.4903	3,54	0.58	0.6283
Insecticide*Cultivar	6,54	0.29	0.9396	6,54	0.41	0.8158	6,54	0.36	0.9004
Mulch*Insecticide*Cultivar	6,54	0.52	0.7930	6,54	0.20	0.9759	6,54	0.18	0.9821

\*Significant treatments defined as treatments with Pr>F value of 0.05 or less.

**Table 4.6** Effects of treatment and their interactions on immatures in 2014 at the Coastal Plain Experiment Station at Tifton, GA

	2014								
	Eggs			Small Nymphs			Large Nymphs		
	DF	F	Pr>F	DF	F	Pr>F	DF	F	Pr>F
Rep	3	14.14	<0.0001	3	0.78	0.5125	3	5.09	0.0040
Mulch	1,3	0.10	0.7697	1,3	4.36	0.1279	1,3	0.49	0.5357
Insecticide	2,12	0.65	0.5379	2,12	0.67	0.5293	2,12	1.38	0.2878
Cultivar	2,12	0.35	0.7860	2,12	1.73	0.1749	2,12	0.92	0.4397
Mulch*Insecticide	3,52	0.20	0.8216	3,52	0.87	0.4451	3,52	0.98	0.4051
Mulch*Cultivar	3,52	0.31	0.8181	3,52	1.16	0.3348	3,52	0.84	0.4772
Insecticide*Cultivar	6,52	2.09	0.0726	6,52	1.10	0.3764	6,52	2.18	0.0662
Mulch*Insecticide*Cultivar	6,52	0.55	0.7698	6,52	0.66	0.6814	6,52	0.32	0.9228

\*Significant treatments defined as treatments with Pr>F value of 0.05 or less.

**Table 4.7** Effects of treatment and their interactions on unmarketable and marketable yield in 2013 and 2014 at the Coastal Plain Experiment Station at Tifton, GA

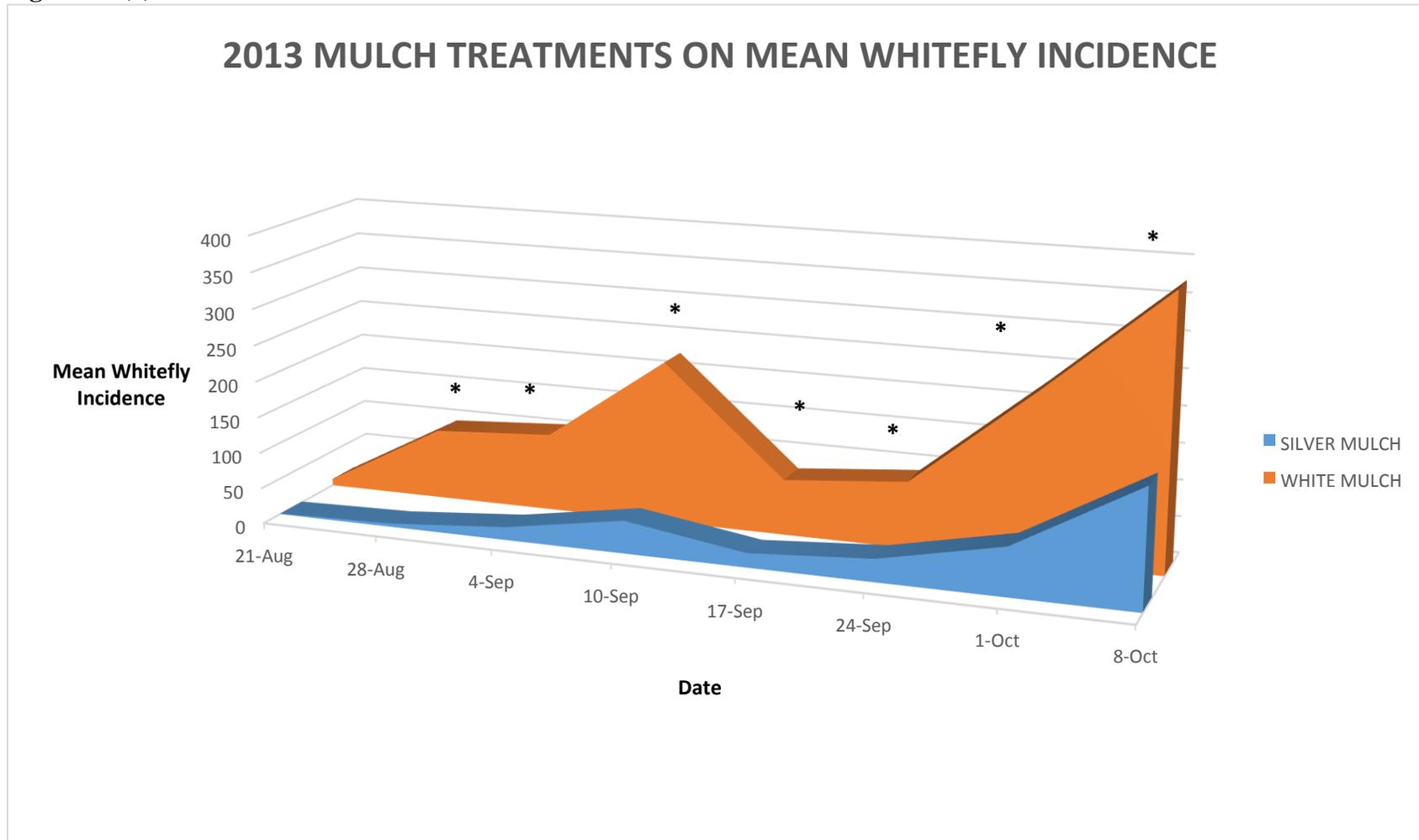
	2013						2014					
	Unmarketable Weight			Marketable Weight			Unmarketable Weight			Marketable Weight		
	DF	F	Pr>F	DF	F	Pr>F	DF	F	Pr>F	DF	F	Pr>F
Rep	3	5.94	0.0007	3	4.66	0.0038	3	34.19	<0.0001	3	55.88	<0.0001
Mulch	1,3	48.85	0.1843	1,3	50.65	0.0002	1,3	3.95	0.1412	1,3	3.62	0.1532
Insecticide	2,12	79.83	0.0679	2,6	28.05	<0.0001	2,12	4.83	0.0289	2,6	5.11	0.0248
Cultivar	3,52	4.30	<0.0001	2,6	0.41	0.7461	2,52	3.98	0.0091	2,6	4.79	0.0032
Mulch*Insecticide	2,12	6.80	0.0132	3,9	2.40	0.1324	3,12	0.61	0.5589	3,9	0.22	0.8073
Mulch*Cultivar	3,54	16.34	0.5063	3,9	1.56	0.2015	3,52	1.09	0.3552	3,9	1.44	0.2326
Insecticide*Cultivar	6,54	2.12	0.9712	6,18	0.20	0.9755	6,52	1.39	0.2210	6,18	1.53	0.1582
Mulch*Insecticide*Cultivar	6,54	0.72	0.6514	6,18	0.07	0.9987	6,52	1.25	0.2818	6,18	1.25	0.2858

\*Significant treatments defined as treatments with Pr>F value of 0.05 or less.

## Figure Legends

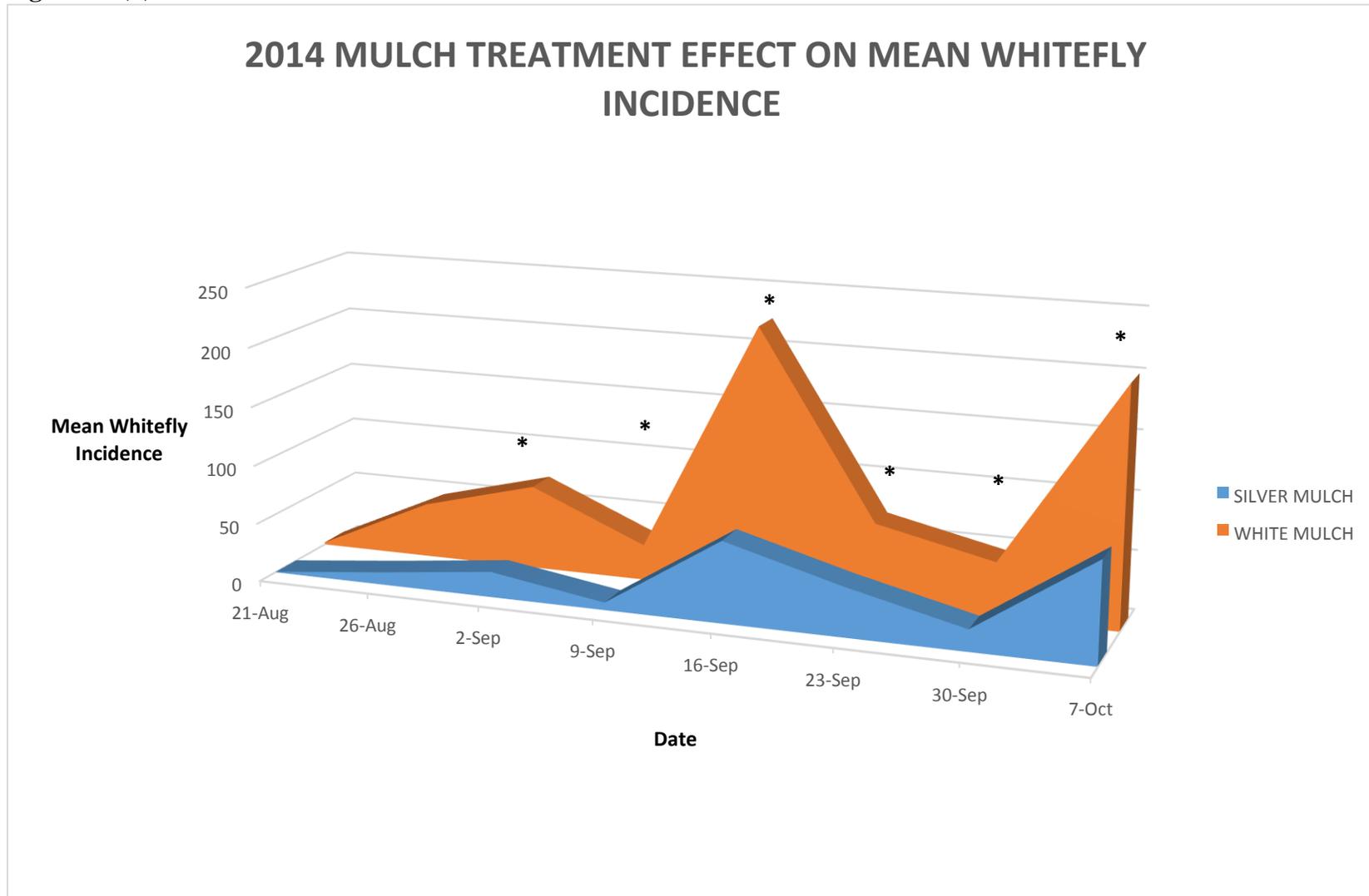
- Figure 4.1.** Mulch treatment effect on mean adult whitefly count for 2013 trial (a) and 2014 trial (b) with dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).
- Figure 4.2.** Insecticide treatment effect on mean adult whitefly count for 2013 trial (a) and 2014 trial (b) with dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).
- Figure 4.3.** Cultivar treatment effect on mean adult whitefly count for 2013 trial (a) and 2014 trial (b) with dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).
- Figure 4.4.** Mulch effect on TYLCV ratings by date in 2013 (a) and 2014 (b) with dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).
- Figure 4.5.** Insecticide effect on TYLCV ratings by date in 2013 (a) and 2014 (b) with dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).
- Figure 4.6.** Cultivar effect on TYLCV ratings by date in 2013 (a) and 2014 (b) with dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

Figure 4.1(a)



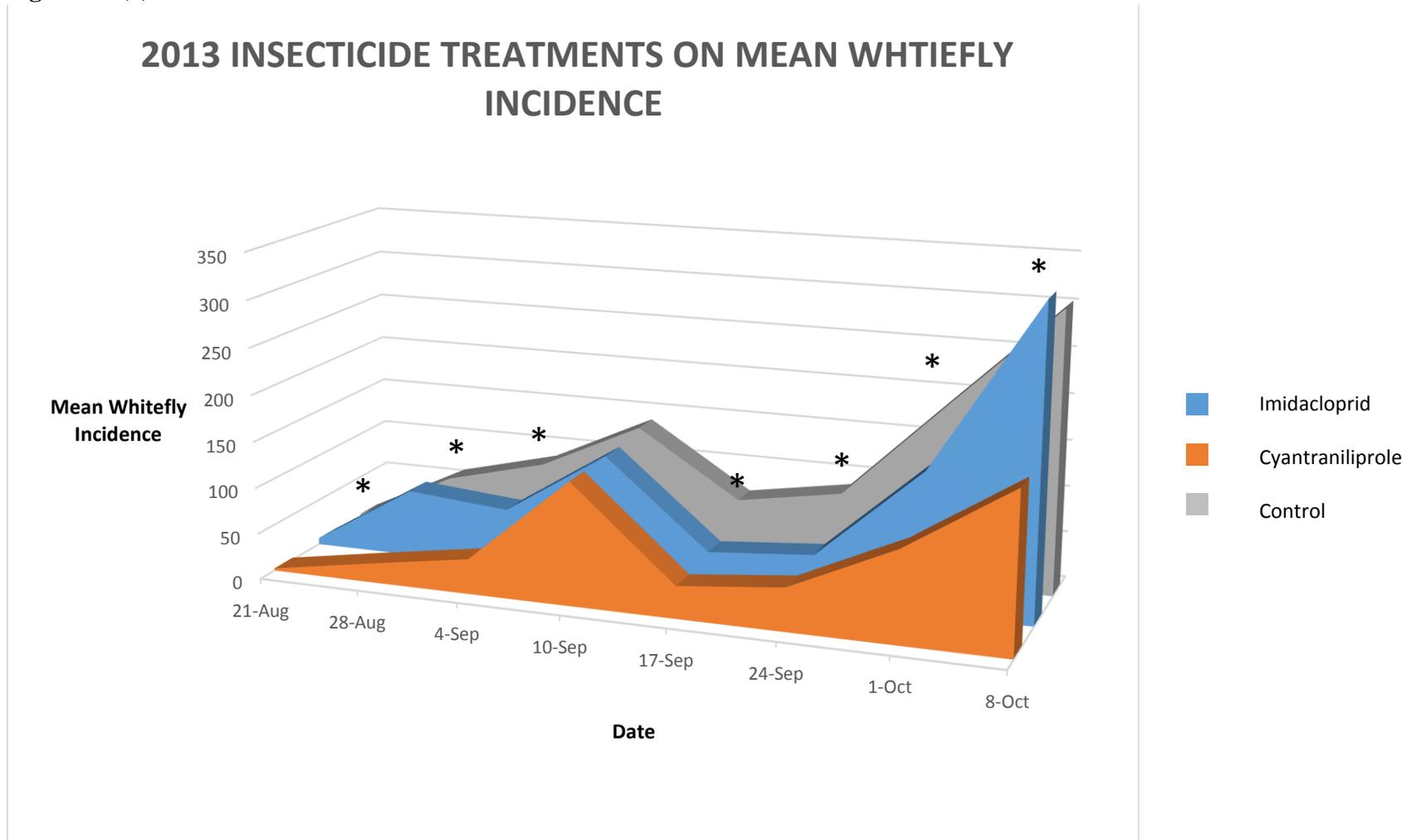
\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

Figure 4.1(b)



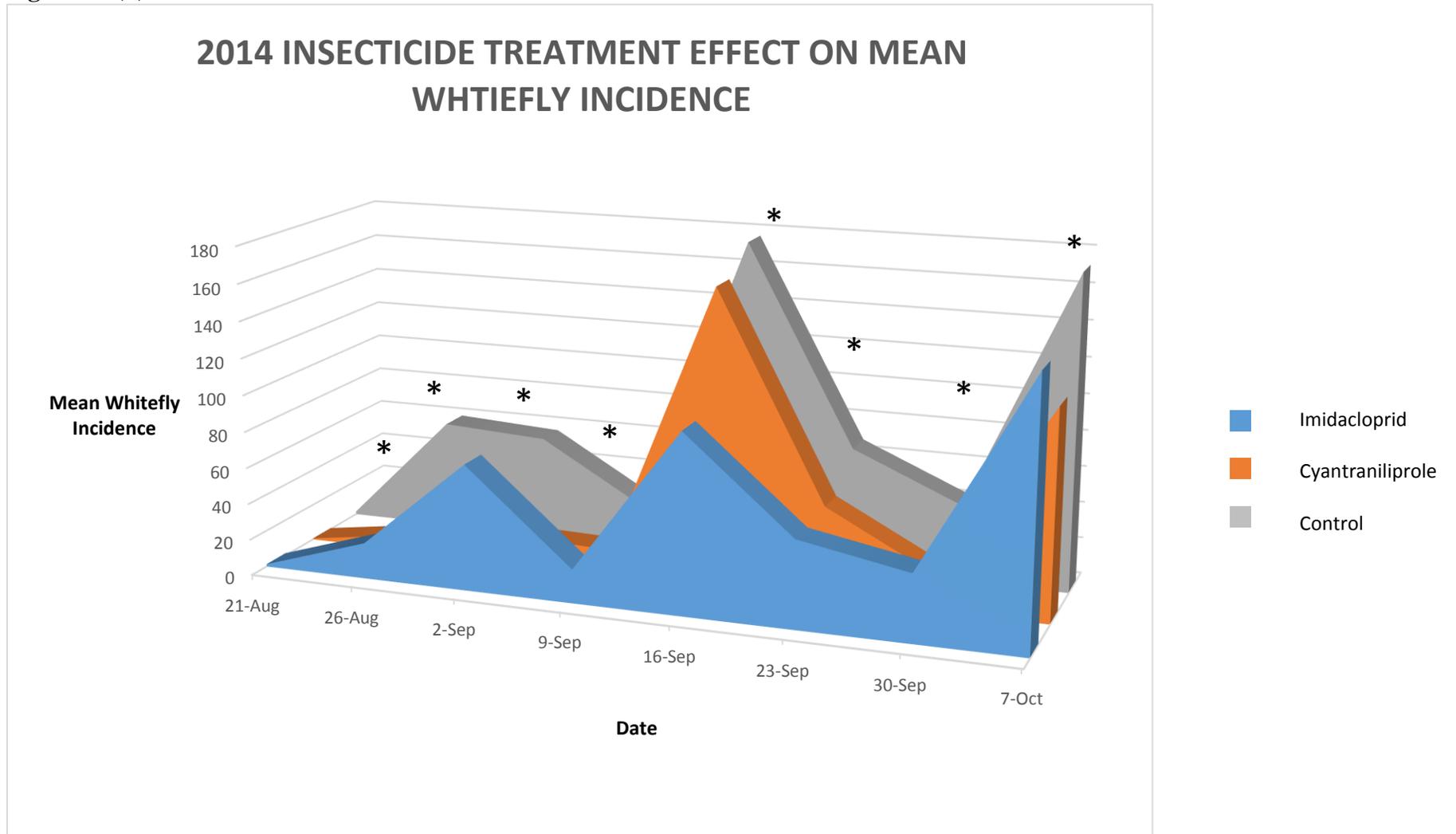
\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

Figure 4.2(a)



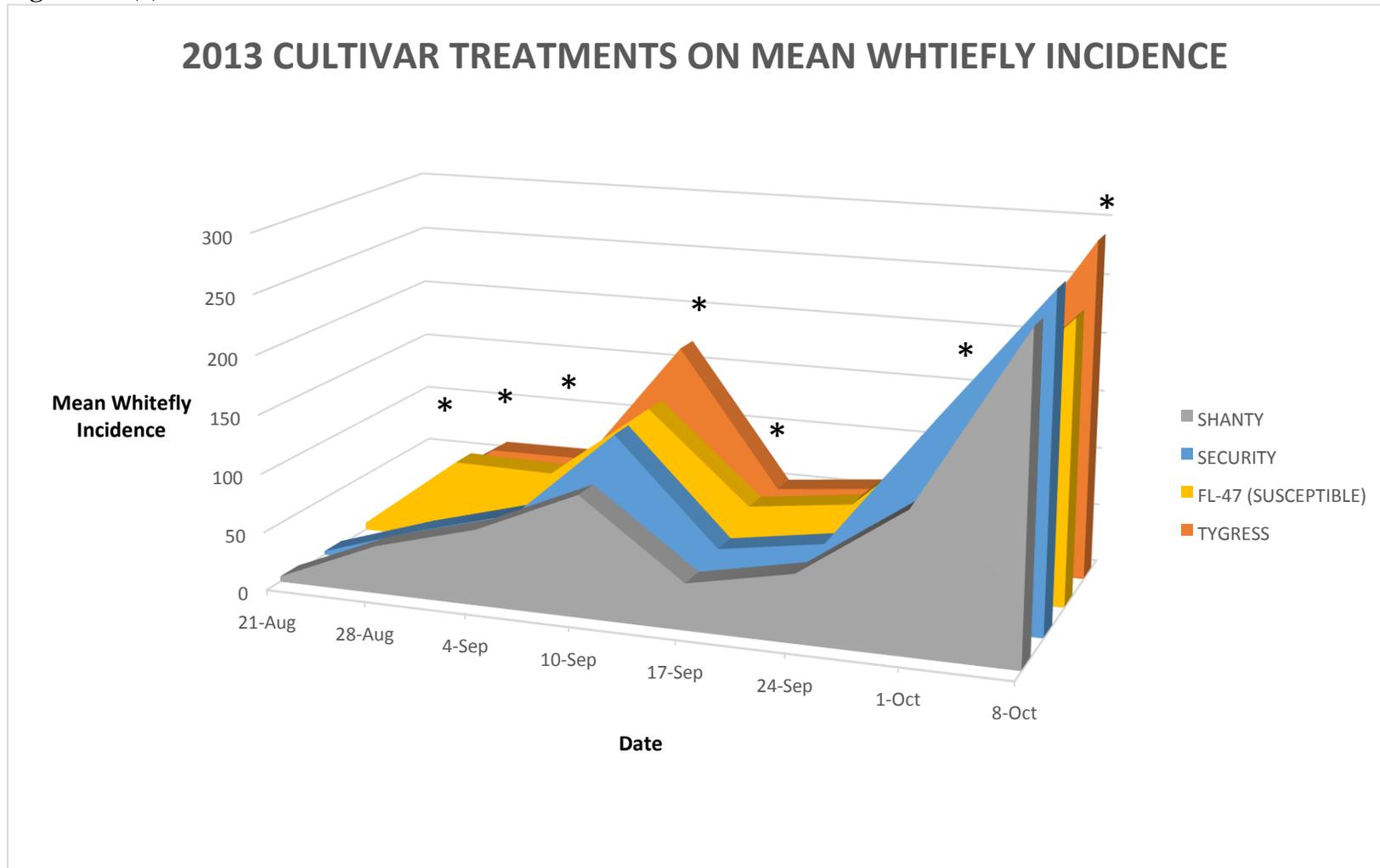
\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

Figure 4.2(b)



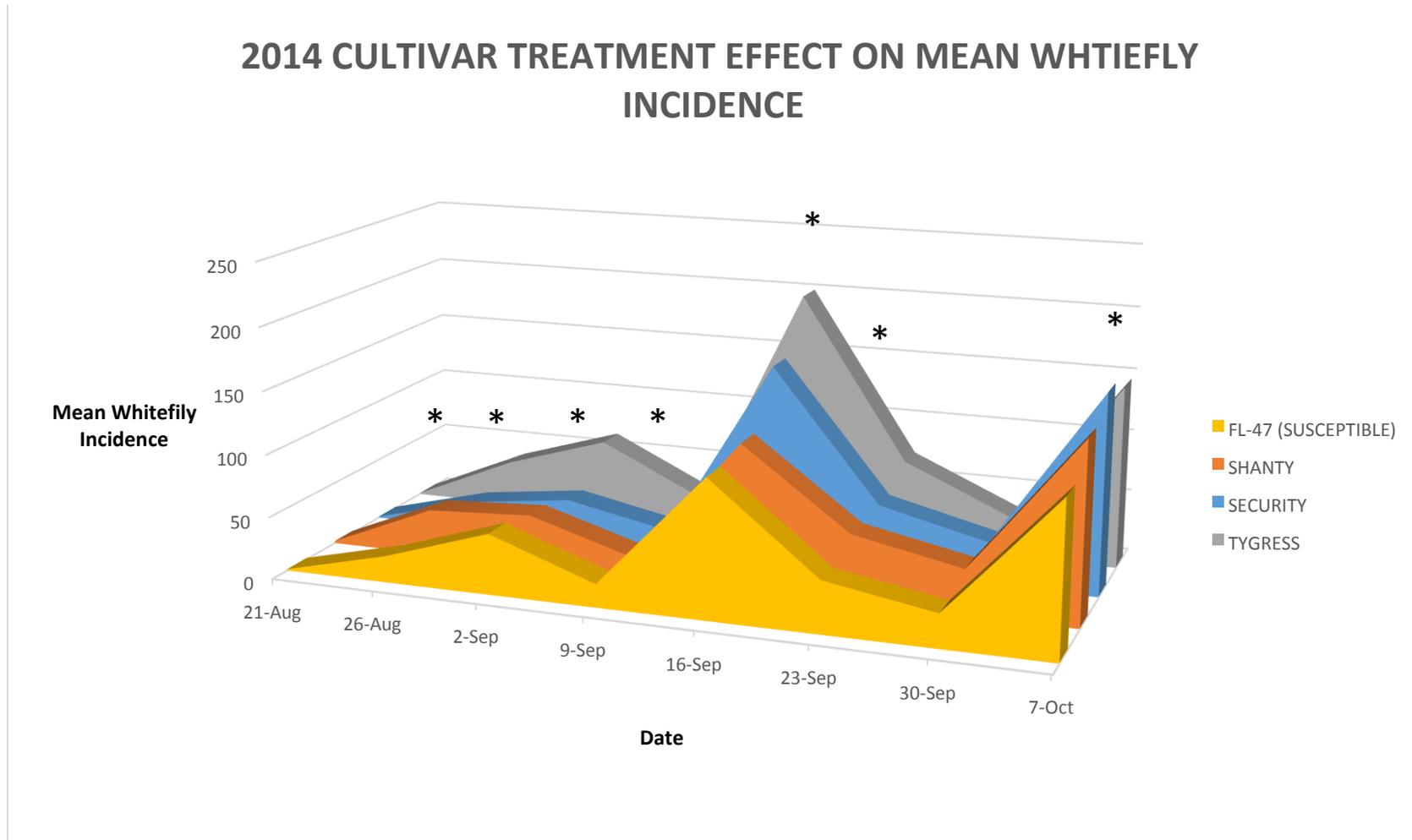
\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

Figure 4.3(a)



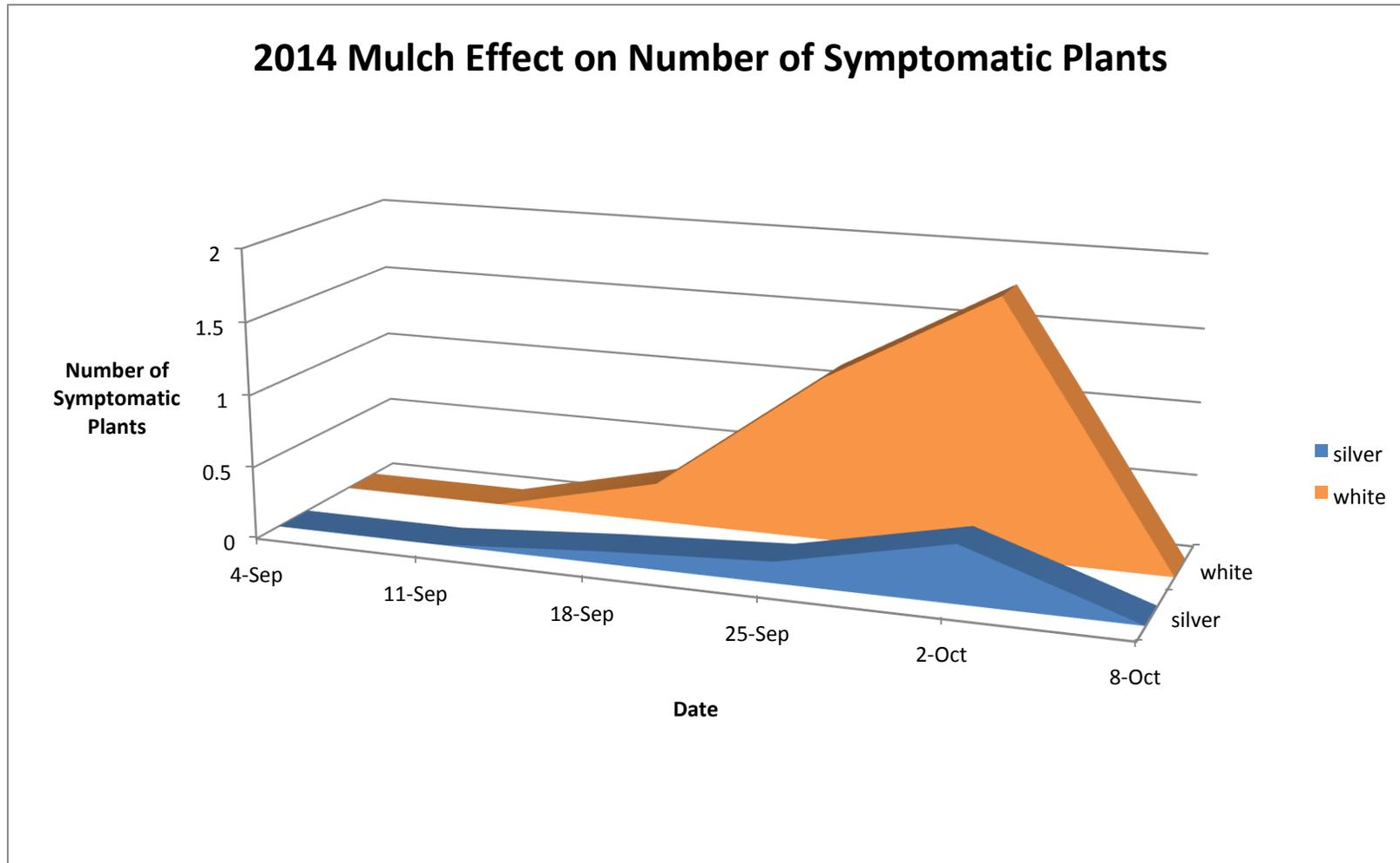
\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

Figure 4.3(b)



\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

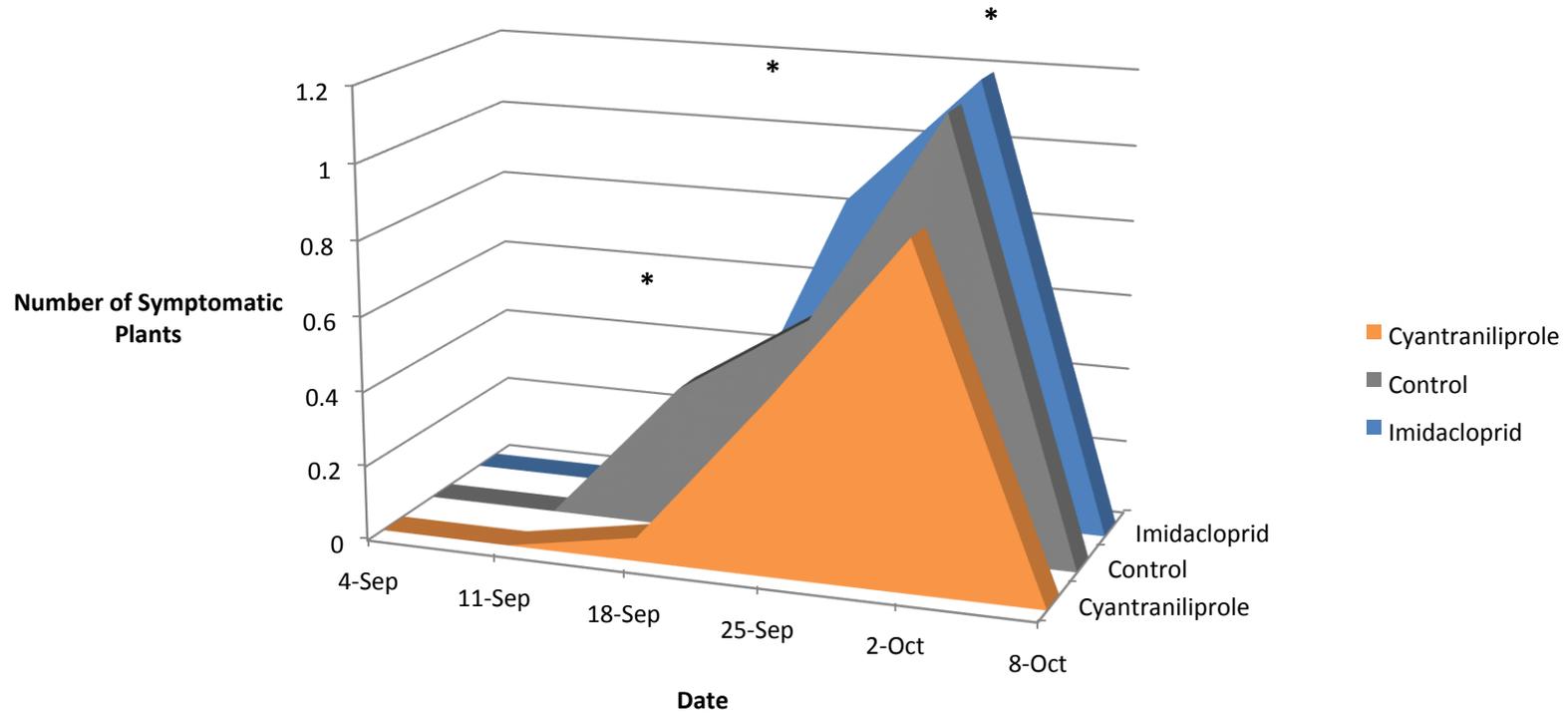
Figure 4.4



\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

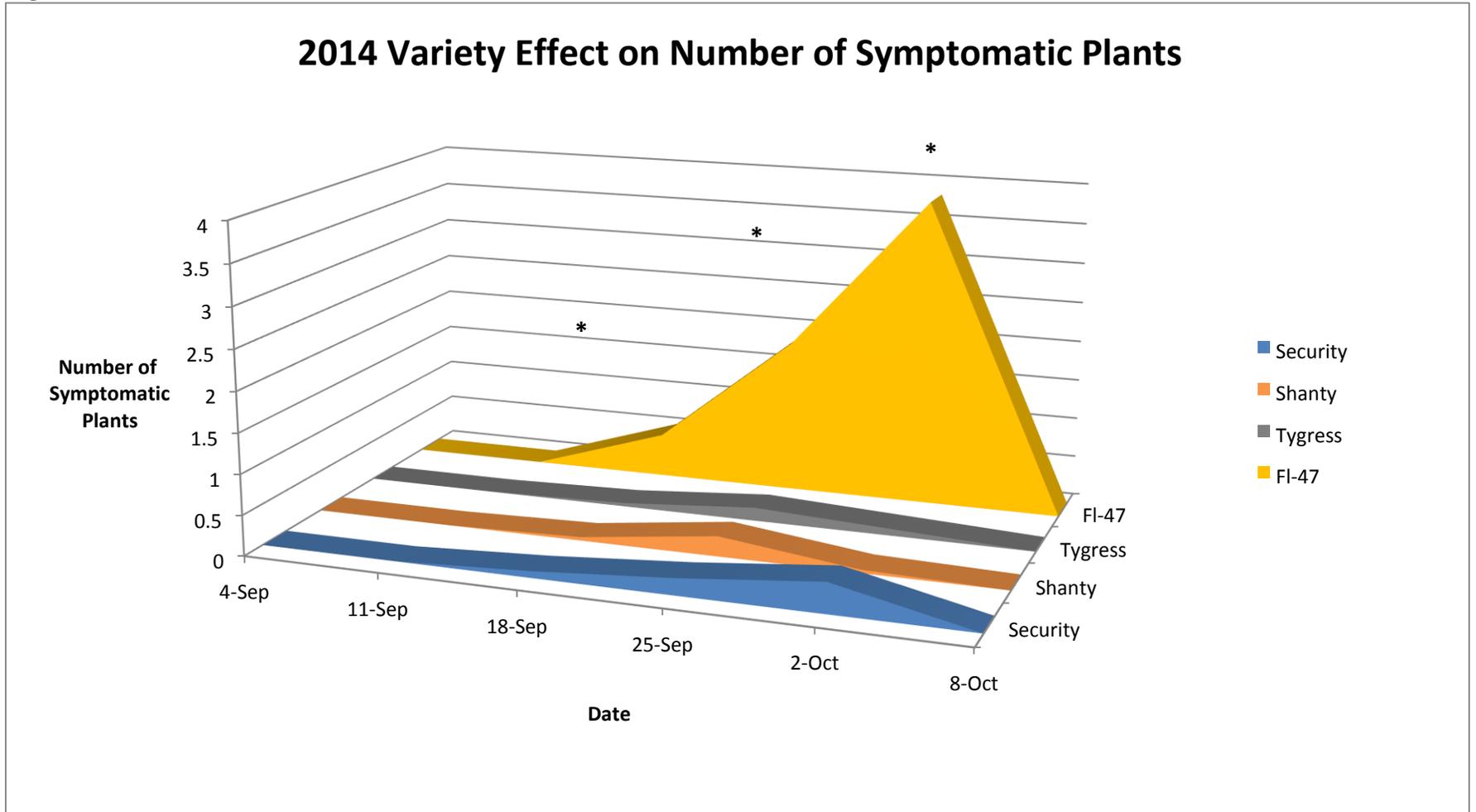
Figure 4.5

### 2014 Insecticide Effect on Number of Symptomatic Plants



\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

Figure 4.6



\*Dates with significant treatment effects indicated by an “\*” ( $P < 0.05$ ).

## Summary

Crop tunnel experiments and split-split plot IPM experiments were conducted to observe whitefly population spread and TYLC disease movement in response to various preventative treatments. The tunnel study also provided spatial and temporal patterns of TYLCV epidemiology along with its whitefly vector. The hypotheses of the two experiments both asserted that employing various tactics, whitefly and TYLCV incidence could be reduced in tomato. The results from both sets of experiments suggest that this assertion is generally true. In the tunnel experiment the chemical treatment and distance from an inoculation source did suppress whitefly populations and TYLCV disease incidence and severity, as did the chemical, mulch, and resistant cultivar control tactics in the IPM study. However, the largest effects on reducing TYLCV spread were not from insecticide treatments.

The epidemiological tunnel experiment illustrated temporal and spatial information for tunneled treatments with controlled whitefly populations. Temporal data showed that whitefly populations may flourish in late summer and early fall in southern Georgia if tunneled population dynamics mimic natural population dynamics. In accordance to measured variance in whitefly population per week, the date was found to have had a significant impact on whitefly presence and TYLCV presence and disease severity. Control for TYLCV should be administered prophylactically because of the extremely short time window with which TYLCV presence follows whitefly presence and the guarantee that with whitefly presence, there will be TYLCV presence. Spatial data showed that whitefly incidence and TYLCV presence and disease severity will be highest in plants in closer proximity to the source plant. This helps to elaborate on the movement that this disease may have through a field. Still, the movement of the disease in the field will depend the most on the way with which the whitefly population

arrives to the field. This experiment replicated the migration scenario where a relatively small overwintering population takes up residence on a volunteer virus positive tomato plant. New tomato plants planted closest to this infected and infested volunteer tomato plant will experience whitefly presence and TYLC disease first. With the infection of the new plants, a slow radiating spread may be observed throughout the whole field. The slow spread of the disease is linked with the slow spread of whiteflies. Whiteflies are poor fliers and will not move far from plant to plant, moreover, adult whiteflies may experience their whole life cycle on just one plant. Whiteflies generally only move from plant to plant when they deem their original host plant unsuitable because of a sustained severe infection or defoliation. Infestation patterns will be a slow, increasingly larger radial spread of the disease from one or more plants from outside of the field. This experiment did not focus on natural whitefly population migrating onto a field. The uncovered treatment was meant to provide a measure of the natural, ambient TYLCV/whitefly pressure. In this treatment we observed that all plants sustained TYLCV infection regardless of proximity to the source plant, but the intensity varied with year. This could illustrate situations where a whitefly population mass migrates into a field, TYLCV infection beginnings will not be easily defined by a singular source point.

Overall, chemical treatments provided more influence on whitefly populations than TYLCV presence and severity compared to the no chemical checks in both studies. Both experiments used AdmirePro, an imidacloprid chemical, and Verimark, a cyantraniliprole chemical. In both experiments, cyantraniliprole generally provided superior whitefly suppression, but not necessarily better reduction of TYLCV incidence. The better performance by cyantraniliprole may be due to cyantraniliprole's novel chemistry. Imidacloprid is the most widely used neonicotinoid so the pressure for whiteflies to develop resistance is very high.

Additionally, imidacloprids are an older chemistry than diamides. Cyantraniliprole was made available in 2013, so its chemistry has been subjected a lot less to the whitefly populations.

Whiteflies in the experiments may have been less susceptible to imidacloprid than cyantraniliprole causing cyantraniliprole's superior performance in whitefly population suppression.

Of all the resistant cultivars sampled in the IPM experiment, Shanty was superior in influencing whitefly incidence and TYLCV symptom severity. Security was the second best and Tygress was the poorest resistant cultivar. There was more of an observed cultivar effect when looking at TYLCV symptom severity rating than whitefly incidence. This is due to the resistant cultivars lack of any repellency properties. Cultivars do not discourage whiteflies from landing and feeding. They allow whiteflies to transmit the virus. Resistant cultivars are used as a control tactic because their genotype has been altered to host a resistance gene. The resistanceconferring gene manifests itself in the plants physiological ability to withstand viral infection. Resistant cultivars are able to produce more yield in spite of whitefly and viral presence in comparison to susceptible cultivars. The variability in performance among cultivars is likely due to phenotypic variability. The high performance of Shanty versus the other cultivars should be further investigated so that there can be a better explanation for its superiority.

Reflective mulch significantly reduced whitefly presence and TYLCV symptom severity in comparison to traditional white mulches. The light reflected off of the reflected mulch prevents whiteflies from being able to perceive contrast between the tomato plant and the ground. Because the whiteflies cannot see the tomato plant, they do not experience a cue to land

and feed or oviposit. Because the whitefly is not compelled to land, it never oviposits or feeds, therefore reducing whitefly population and TYLCV presence.

In terms of creating an integrated pest management program based upon the results of this study, I would advise beginning with resistant cultivars. Resistant cultivars should be evaluated on taste and appearance and be contrasted to popular susceptible cultivars. Upon completion of cost and benefit analysis and marketable characteristic evaluation of resistant cultivars, implementing this integrated control strategy should ameliorate negative impacts of TYLCV disease for South Georgia tomato growers. Also, applying cyantraniliprole drench treatments to seedlings in greenhouse and transplants in field at planting could be beneficial. In the months of August and September, regular applications of cyantraniliprole should be made to accommodate the natural high populations during this period of the year. Over the course of the whole planting season, the field should be monitored for whitefly presence. Both preventative and curative insecticide application will likely be needed to maintain the vector population as low as possible in a TYLCV prone tomato production region. In conjunction with chemical control, all plants should be transplanted into silver reflective mulch and all tomatoes should be of the best available resistant cultivar. Additionally, prior to planting, all volunteer tomato crops and crop residue should be cleared from the field. It would be optimum if the new tomato field could be planted far away from previous tomato fields and not in a field that previously had a tomato crop in it. In order to further persuade farmers to begin to employ the aforementioned integrated pest management strategy, there should be a cost and benefit analysis of these tactics. There should also be an investigation into the market acceptability of the resistant cultivars.