# THE DISTRIBUTION OF, RELATIONSHIP BETWEEN, AND FACTORS INFLUENCING THE ABUNDANCE OF *BEMISIA TABACI* AND THE INCIDENCE OF *TOMATO YELLOW LEAF CURL VIRUS* IN SOUTHERN FLORIDA TOMATO

By

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# THE DISTRIBUTION OF, RELATIONSHIP BETWEEN, AND FACTORS INFLUENCING THE ABUNDANCE OF *BEMISIA TABACI* AND THE INCIDENCE OF *TOMATO YELLOW LEAF CURL VIRUS* IN SOUTHERN FLORIDA TOMATO

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Biotype B of the sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), also known as the silverleaf whitefly, *B. argentifolii* Bellows and Perring, is a serious pest of many agricultural crops around the world. In Florida, *B. tabaci* has become a limiting pest species in tomato due to its ability to vector *Tomato yellow leaf curl virus* (TYLCV) (family *Geminiviridae,* genus *Begomovirus*). TYLCV is vectored in a persistent circulative manner and symptoms of infection in tomato include upward curling of leaflet margins, reduction of leaflet area, yellowing of young leaves, abscission of flowers, and stunting of plants.

The sampling of adult *B. tabaci* and TYLCV across commercial Florida tomato farms in four seasons from fall 2007 through spring 2009 combined with mapping of their distribution by Geographical Information Systems (GIS) and analyses by Spatial Analysis by Distance IndicEs (SADIE) and classification and regression tree (CART) analysis have produced a much more detailed explanation of in-field distribution, vector/disease relationship and influencing factors than previously reported. *B. tabaci* is a mobile pest and has been shown in the present study to have varying aggregation in

both space and time. Distributions of *B. tabaci* were significantly aggregated in every season but spring 2009, when the population of whitefly was very low. Weekly fluctuations throughout the study area suggest that, within the earlier sampling dates of each season, whiteflies were more likely to be aggregated. Inverse distance weighted (IDW) maps created by a GIS program, showed that populations of *B. tabaci* and incidence of plants with symptoms of TYLCV infection were associated more closely with the edges of tomato fields. Early fall season and late spring season populations of adult *B. tabaci* had stronger correlations to incidence of symptomatic TYLCV infected plants. SADIE spatial association tests indicated similar conclusions. There were indications that *B. tabaci* may have migrated from areas in which possible whitefly hosts were destroyed or disturbed. CART analysis confirmed the assumptions that environmental variables such as temperature, wind speed and wind direction influence populations of *B. tabaci* and TYLCV incidence. Geographical variables such as buffer distance and block size also influence populations of *B. tabaci* and TYLCV. Shorter buffer distances and smaller block sizes had consistently larger counts of *B. tabaci* and higher incidence of TYLCV. Rainfall and cropping factor variables such as mulch type and tomato type did not have as much influence as previously thought.

# CHAPTER 1
# INTRODUCTION

## Overview

Biotype B of the sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), also known as *B. argentifolii* Bellows and Perring (Bellows et al. 1994), is an important economic pest in tropical and subtropical climates around the world (Perring et al. 1993). The nomenclature of *Bemisia* spp. has been widely discussed and current research suggests there are multiple unique species worldwide (Dinsdale et al. 2010). The wide host range of over 600 plant species (Mound and Halsey 1978, Greathead 1986, Secker et al. 1998), including weed hosts that vary in their importance, depending on the cropping system, makes management even more challenging (Cohen et al. 1988, Schuster et al. 1992, Ucko et al. 1998, Bezerra et al. 2004). The polyphagous nature of the sweetpotato whitefly leads to management problems and could be associated with its high value pest status in many commodities (Naranjo and Ellsworth 2001). The sweetpotato whitefly produces direct feeding damage in tomato. Feeding by nymphs can cause irregular ripening of fruit (Maynard and Cantliffe 1989, Schuster et al. 1990) and inhibition of fruit softening (Hanif-Khan et al. 1999, McCollum et al. 2004) along with general reduction in plant vigor. The sweetpotato whitefly causes considerable yield loss in many areas of the world due to its capability of vectoring plant viruses (Markham et al. 1996, Naranjo and Ellsworth 2001).

One important sweetpotato whitefly vectored virus is *Tomato yellow leaf curl virus* (TYLCV: genus *Begomovirus*, family *Geminiviridae*) (Polston et al. 1999). It is vectored in a persistent, circulative manner and causes extensive damage to tomato worldwide (Czosnek and Laterrot 1997). TYLCV can cause yield losses of up to 100% in tropical

and subtropical regions and in some regions is the limiting factor in commercial tomato production (Czosnek and Laterrot 1997). TYLCV was first recorded in the Middle East, North and Central Africa, and Southeast Asia, and has recently spread to Europe (Czosnek et al. 1990, Moriones and Navas-Castillo 2000). It has also been recorded in the Caribbean (Nakhla et al. 1994) and Mexico (Ascencio-Ibanes et al. 1999). In 1999, it was reported in the United States in Florida (Polston et al. 1999) and Georgia (Momol et al. 1999) and in 2001 in Louisiana (Valverde et al. 2001). Symptoms include leaf curling, chlorosis of leaf margins, reduction of leaf size, mottling, flower abscission, plant stunting and yield reduction (Polston et al. 1999, Mohamed 2010). TYLCV symptoms appear 2-3 weeks after infection and the virus can be acquired by the adult whitefly in 15-30 minutes (Cohen and Nitzany 1966, Rom et al. 1993). During symptom expression there is considerable loss in plant vigor and significant yield loss, particularly if plants are infected during early growth. Management of TYLCV is difficult and requires a multi-faceted approach (Momol et al. 2001). Unfortunately, growers often rely heavily on the use of insecticides to control TYLCV by targeting the whitefly vector, and insecticide resistance is widespread in *B. tabaci* (Palumbo et al. 2001, Horowitz et al. 2007).

Geographic information systems (GIS) and global positioning systems (GPS) might be useful in monitoring and predicting the distribution of whiteflies and TYLCV. GIS are software tools which allow for storage, analysis, synthesis, and output of spatial data (Bolstad 2005). Historically, applications of GIS in entomology have been limited to forest and rangeland entomology (Kemp et al. 1989, Schotzko and O'Keeffe 1989). Recently, it has been applied to study insect pests in agricultural systems (Barnes et al.

1999, Park and Obrycki 2004, Carriere et al. 2006, Garcia 2006, Reay-Jones et al. 2010). Spatial dependence in insects shows that there can be value at interpolating counts at un-sampled locations (Borth and Huber 1987, Schotzko and O'Keeffe 1989, Setzer 1995). Spatial interpolation methods include nearest neighbor, inverse distance weighting and spatial prediction models that include kriging (Bolstad 2005). Some insects, including whiteflies, are able to migrate over large areas; therefore, monitoring movement on a regional or area-wide scale could be beneficial (Sonka et al. 1997). GIS and geostatistics have also been used to implement management plans for plant viruses (Nelson et al. 1994, Barnes et al. 1999, Nelson et al. 1999) and to analyze spatial patterns of plant diseases (Fargette et al. 1985, Chellemi et al. 1988). Other statistical programs such as Spatial Analysis by Distance IndicEs (SADIE) have been developed to quantify spatial patterns of organisms (Perry 1998). SADIE measures the degree of aggregation in spatially-referenced data and is based on discrete count data (Xu and Madden 2004). Classification and regression tree (CART) analysis was designed to explore and model ecological data and can deal with nonlinear, complex and missing data values (Breiman et al. 1984). CART based models can handle categorical and continuous data. CART analysis uses trees to explain variation of target variables by repeatedly splitting the data into homogeneous partitions.

## Purpose of the Study

Current management tactics for sweetpotato whitefly and TYLCV in Florida include the use of a crop free summer period, virus free transplants, resistant cultivars, ultraviolet reflective mulch, chemical control of whiteflies, sanitation or roguing of TYLCV infected plants and removal of old plant material (Polston et al. 1999, Schuster et al. 2007a). The use of GIS can lead to a more thorough understanding of the

dispersal of the sweetpotato whitefly and of the whitefly and virus reservoirs at both the field and regional level. SADIE analysis of *B. tabaci* adult counts and symptomatic TYLCV infected tomato plants can express the nature of the distribution of the populations. Using CART analysis, environmental, geographical and cropping factor variables can be evaluated for their importance in influencing *B. tabaci* and TYLCV. With a greater understanding of the distribution of *B. tabaci* and TYLCV, their relationship, and variables influencing populations, results may lead to the development of new management recommendations.

The specific objectives for research were:

1) To evaluate seasonal abundance of *B. tabaci* and incidence of TYLCV in Florida tomatoes
2) To investigate the spatial and temporal distribution of *B. tabaci* adults and TYLCV infected plants in Florida tomatoes
3) To investigate the relationship between the abundance of *B. tabaci* and incidence of TYLCV in Florida tomatoes
4) To investigate the environmental, geographical, and cropping factor variables influencing the abundance of *B. tabaci* and incidence of TYLCV in Florida tomatoes

The overall hypothesis for this research was that non-tomato hosts in west central Florida can influence populations of *B. tabaci* and subsequent incidence of TYLCV in tomato.

CHAPTER 2
REVIEW OF LITERATURE

## *Bemisia tabaci* (Gennadius)

### Taxonomy

The B biotype of the sweetpotato whitefly, *Bemisia tabaci*, also known as the silverleaf whitefly, *B. argentifolii* (Bellows and Perring), was first described as *Aleyrodes tabaci* by Gennadius (1889) in Greece. It was first recorded in the United States in 1897 (Russell 1957, Mound and Halsey 1978). There has been confusion in the literature on the nomenclature of this insect, as Mound and Halsey (1978) listed 22 synonyms for *B. tabaci.* Gill (1992) suggested that the A (cotton biotype) and the B (poinsettia biotype) of the sweetpotato whitefly were two distinct species. Perring et al. (1993) suggested a common name of silverleaf whitefly for the introduced sweetpotato B biotype and concluded that there were two distinct species based on the absence of interbiotype copulation along with genotypic and phenotypic differences. Based on light microscopy (Bedford et al. 1994) and transmission electron microscopy inspections of *B. tabaci*, no distinctive characteristics were found to determine differences in *Bemisia* spp. (Rosell et al. 1997). These examinations, along with similarities in morphological characters and evidence of biotic and genetic polymorphism (Costa and Brown 1991, Burban et al. 1992, Perring et al. 1993, Bedford et al. 1994, Brown et al. 1995, De Barro and Driver 1997), have led some researchers to hypothesize that *B. tabaci* is a cryptic species or species complex (Bedford et al. 1994, Brown et al. 1995, Rosell et al. 1997, Frohlich et al. 1999, Brown et al. 2000). Perring (2001) reviewed the species complex and hypothesized that there are seven groups within the *B. tabaci* species. Dinsdale et al. (2010) examined mitochondrial cytochrome oxidase 1 to determine species

differentiation among *B. tabaci* and concluded that at >3.5% divergence there could be up to 24 species worldwide. The designation of this insect as multiple unique species is not universally accepted, so *B. tabaci*, B biotype (= *B. argentifolii*), sweetpotato whitefly will be used in the present treatise.

**Biology**

*B. tabaci* (Hemiptera: Aleyrodidae) is a cosmopolitan polyphagous pest and has become one of the most important pests of world agriculture (Naranjo and Ellsworth 2001). There are approximately 150 whitefly species in the United States and over 1500 species worldwide (Miller et al. 2001). General whitefly biology was reviewed by Byrne and Bellows (1991). Whiteflies are plant feeders with piercing, sucking mouthparts and undergo incomplete metamorphosis (Byrne and Bellows 1991). Whitefly adults are small insects 2-3 mm in length and range from pale to completely pigmented in color (Miller et al. 2001). *B. tabaci* adults are approximately 2mm in length (Byrne and Bellows 1991). *B. tabaci* produce offspring based on haplodiploidy, i.e. males are produced from unfertilized, haploid eggs, and females are produced from fertilized, diploid eggs (Denholm et al. 1998, Klowden 2002). Whitefly eggs are usually attached to the underside of the leaves, may be smooth or sculptured, and can be laid in patterns or scattered over the leaf (Byrne and Bellows 1991). *B. tabaci* eggs possess a pedicel, are elliptical in shape and are laid indiscriminately (Byrne and Bellows 1991). Oviposition rates vary greatly and are dependent on environmental conditions and host plants (Powell and Bellows 1992, Muniz 2000, Gruenhagen and Perring 2001, Omondi et al. 2005). There are four immature stages between the egg and adult, with the first three being larval instars and the fourth stage labeled the pupae stage or puparium (Byrne and Bellows 1991). The first immature stage is called the crawler because it is

the only mobile immature stage. The second and third instars are oval in shape and are sessile. The fourth stage is elliptical in shape, is the most common stage to identify species differentiation, and is characterized by the pair of eyes which show up as red spots in *B. tabaci* (Lopez-Avila 1986). Emergence of adult whiteflies takes 5-15 minutes. Wing expansion occurs on or near the pupal case and takes approximately 40-50 minutes (Azeb et al. 1972).

The length of the *B. tabaci* life cycle can vary greatly depending on climatic and host plant conditions (Russell 1975, Coudriet et al. 1985). Under field conditions the life cycle can last from 14 to 75 days (Azeb et al. 1971). Coudriet et al. (1985) found *B. tabaci* development from egg to adult on tomato to be 27.3 ± 1.0 days at 26.7 ± 1.0ºC whereas Salas and Mendoza (1995) observed development on tomato to be 22.3 days at 25ºC and 65% R. H. Lopez-Avila (1986) determined development time on tomato was 23.5 days. On tomato at 25ºC and 65% R. H., egg incubation took an average of 7.3 ± 0.5 days (Salas and Mendoza 1995) and 7.3 days at 25ºC and 75% R. H (Lopez-Avila 1986). Egg incubation periods can vary from 3 to 33 days depending on temperature and humidity (Husain and Trehan 1933, Avidov 1956, Azeb et al. 1972, Butler et al. 1983, Powell and Bellows 1992, Liu and Stansly 1998). The first instar stage duration is approximately 4.0 ± 1.0 days; second instar 2.7 ± 1.1 days; third instar 2.5 ± 0.7 days; and fourth instar/pupa 5.8 ± 0.3 days on tomato (Salas and Mendoza 1995). In tropical field conditions there can be 10 to 16 generations per year (Avidov 1956, Azeb et al. 1972, Salas and Mendoza 1995).

**History**

The sweetpotato whitefly has been associated with many agricultural losses and is the limiting pest species in many field and vegetable crops around the world. It has

benefited from international trade movement and is now found on every continent except Antarctica (De Barro 1995, Martin et al. 2000). *B. tabaci* is a cosmopolitan pest that has been labeled “superbug” (Barinaga 1993). Sweetpotato whitefly B biotype is thought to have originated in the northeast Africa/Middle East/Arabian peninsula region (Frohlich et al. 1999, De Barro et al. 2000). Global outbreaks over recent years have been correlated with whitefly geminiviruses (Polston and Anderson 1997, Rubinstein et al. 1999). In the United States, *B. tabaci* has shown the potential to cause millions of dollars in crop damage and lost yields (Perring et al. 1993, Birdsall et al. 1995, Ellsworth et al. 1999). Since the introduction of the B biotype in 1986, the sweetpotato whitefly has become a problem in Florida (Price 1987). In a survey by McKenzie et al. (2004) in Florida, researchers concluded that the B biotype of *B. tabaci* has excluded the native non-B biotypes. *B. tabaci* has been linked to tomato irregular ripening disorder and squash silverleaf disorder (Schuster et al. 1990, Schuster et al. 1991) in Florida and has become a limiting pest species in tomato production due to its ability to transmit TYLCV (Polston et al. 1999).

**Hosts**

*B. tabaci* has a host range of over 600 plant species (Mound and Halsey 1978, Greathead 1986, Secker et al. 1998, Evans 2007). It has been suggested that *B. tabaci* has a much wider host range than other *Bemisia* biotypes indicating its success as a cosmopolitan pest is due to a large host range (Brown et al. 1995, Perring 2001). Weed hosts vary in their importance depending on the cropping system (Cohen et al. 1988, Schuster et al. 1992, Ucko et al. 1998, Bezerra et al. 2004). *B. tabaci* B biotype has been shown to be much better at developing and surviving on multiple hosts than a native biotype in China (Zang et al. 2006). This whitefly has shown the ability to quickly

acclimatize to alternative hosts which may give it advantages over non-B biotypes (Gerling and Kravechenko 1996).

Even though alternative host sources are important for insect pests including *B. tabaci,* most of the current research has focused on cultivated crops (Avidov 1956, Gerling 1984, Schuster et al. 1992, Muniz 2000, Simmons et al. 2008). There has been considerable research on *B. tabaci* survival (Costa et al. 1991, Tsai and Wang 1996, Liu and Stansly 1998, Omondi et al. 2005, Bayhan et al. 2006, Walker and Natwick 2006, Zang et al. 2006, Jindal et al. 2008, Mansaray and Sundufu 2009), developmental rates (Coudriet et al. 1985, Powell and Bellows 1992, Tsai and Wang 1996, Liu and Stansly 1998, Omondi et al. 2005, Bayhan et al. 2006, Zang et al. 2006, Jindal et al. 2008, Mansaray and Sundufu 2009, Baldin and Beneduzzi 2010) and fecundity (Costa et al. 1991, Chu et al. 1995, Tsai and Wang 1996, Liu and Stansly 1998, Toscano et al. 2002, Omondi et al. 2005, Bird and Kruger 2006, Walker and Natwick 2006, Zang et al. 2006, Boica Junior et al. 2007, Jindal et al. 2008, Mansaray and Sundufu 2009, Baldin and Beneduzzi 2010) on cultivated plant species. Until recently, research on weeds as hosts of *B. tabaci* has been relatively ignored in the literature even though weed hosts are considered important for its management (Gerling 1984, Cohen et al. 1988, Schuster et al. 1992, Hilje et al. 2001).

Weeds can act as important reservoirs for whiteflies and their natural enemies and in some systems can be hosts for cultivated crop pathogens (Bezerra et al. 2004, Naveed et al. 2007). In Italy, Calvitti and Remotti (1998) examined developmental rates of *B. tabaci* biotype B under laboratory conditions on herbaceous weeds found around greenhouses. *Sonchus oleraceus* L. (sowthistle) and *Solanum nigrum* L. (black

nightshade) were found to be preferred hosts of *B. tabaci* and also had the highest intrinsic rate of increase (Calvitti and Remotti 1998). In Spain, Muniz (2000) concluded there were differences in composition and host suitability to the sweetpotato whitefly in overwintering and over summering host species. In winter weeds, *Malva parviflora* L. (cheeseweed), had significantly more eggs laid per female, higher numbers of pupae and greater percentages of adult emergence than *Capsella bursa-pastoris* (L.) Medik. (shepherd's purse), *Brassica kaber* (DC) (wild mustard), and *Lactuca serriola* L. (prickly lettuce) (Muniz 2000). Summer weeds *Datura stramonium* L. (jimsonweed) and *S. nigrum* were more suitable hosts in terms of numbers of infested plants and higher numbers of pupae and adults than *Amaranthus retroflexus* L. (amaranth), *Chenopodium album* L. (lambsquarters) and *Echinochloa crus-galli* (L.) P. Beauv. (barnyardgrass). Host suitability studies in Ghana demonstrated that *Desmodium tortuosum* (Sw.) DC. (Dixie ticktrefoil) and *Euphorbia heterophylla* (L.) (Mexican fireplant) were good hosts of *B. tabaci* based on fecundity and survival compared to *A. retroflexus*, *Chromolaena odorata* (L.) R. M. King and H. Rob. (jack in the bush) and *Malvastrum coromandelianum* (L.) Garcke (threelobe false mallow) (Gachoka et al. 2005). Field studies conducted in Brazil by Bezerra et al. (2004) found higher *B. tabaci* populations on *Ancanthospermum hispidum* ("carrapicho-de-burro") compared to other weeds: *Amaranthus deflexus* L. (largefruit amaranth), *D. stramonium* and *E. heterophylla*. In the presence of weeds, tomato infestations by *B. tabaci* were reduced (Bezerra et al. 2004), suggesting that there might have been a reduction of attractiveness of tomato by a phenomenon discussed by Bernays (1999). Bird and Kruger (2006) found similar

results to Bernays (1999) in a choice test of similar hosts of mixed cultivated crops and cultivars.

In the United States, understanding weed hosts is important for management of both *B. tabaci* and their associated viral epidemics (Schuster et al. 1992, Hilje et al. 2001). Florida weed hosts listed by Stansly and Schuster (1990) were similar in species composition to those listed by other researchers worldwide. Early work by Gerling (1967) found *B. tabaci* on *M. parviflora* in the Imperial Valley of California. Other Imperial Valley weeds were evaluated as hosts of *B. tabaci* by Coudriet et al. (1986). *L. serriola* (prickly lettuce) was the best host in terms of developmental time but *S. oleraceus* (sowthistle) and *S. asper* Hill were good hosts as well, although *M. parviflora* only differed in adult development time by 2 to 3 days from the best host (Coudriet et al. 1986). Crop plants in the Imperial Valley of California may have as much influence on overwintering whitefly populations as weed hosts (Coudriet et al. 1985, Coudriet et al. 1986). In southwest Florida, Stansly (1995) determined weeds were poor intermediate hosts for whiteflies during suggested crop-free periods in the summer. In another Florida study, *B. tabaci* populations in weeds paralleled those found in neighboring tomato fields (Schuster et al. 1992). Hence, the relationship of weeds to overall whitefly population dynamics is unclear.

To determine hosts, insects use both visual and olfactory cues (Visser 1988). Color plays a main role in visual determination of a host and *B. tabaci* is attracted most strongly to yellow/green in the range of 500 – 700 nm (Husain and Trehan 1940, Berlinger 1986). Olfactory cues are not considered key factors in host determination in *B. tabaci* (Berlinger 1986, Van Lenteren and Noldus 1990). Based on olfactory cues

from five different hosts Jing et al. (2003) found host plant preferences affected attraction of *B. tabaci*, but they were unsure of the B biotype label of their experimental colony. Although not much data suggests that olfaction plays a role in attraction of *B. tabaci* to hosts, there are current research projects to determine the roles of volatile semiochemicals (Bleeker et al. 2009) and ginger oil (Zhang et al. 2004) on repellency.

Once landed, whitefly adults determine host acceptance by contact cues, touch and taste (Berlinger 1986). If the plant is found unfavorable, the whitefly will leave or have reduced fecundity, which could be due to many factors such as leaf hairiness (Mound 1965, Butler and Henneberry 1984, McAuslane 1996, Gruenhagen and Perring 2001, Mansaray and Sundufu 2009, Baldin and Beneduzzi 2010), leaf age (Bentz et al. 1995c, Liu and Stansly 1995b, Cardoza et al. 2000), pH (Berlinger et al. 1983), secondary metabolites (Baldin and Beneduzzi 2010), nitrogen availability (Bentz et al. 1995a, Bentz et al. 1995c) and amino acid composition (Blackmer and Byrne 1999). Nitrogen availability in the host plant has been shown to affect *B. tabaci* populations on some crops including cotton (Blua and Toscano 1994, Bi et al. 2001).

**Management**

Successful control of the sweetpotato whitefly requires flexible management programs. Cultural control for sweetpotato whitefly has been reviewed by Hilje et al. (2001), Ellsworth and Martinez-Carrillo (2001) and Gerling and Mayer (1996). The most commonly used practice to control *B. tabaci* is chemical control and most whitefly control is dependent on insecticides (Palumbo et al. 2001). Therefore, resistance to many different insecticide classes has been documented (Palumbo et al. 2001). With the loss of efficacy of certain chemical classes and chemistries, research has been conducted on resistance management (Palumbo et al. 2001). Concurrent research has

been directed at evaluation of sampling methods (Ekbom and Rumei 1990, Naranjo 1996) and action thresholds (Ellsworth and Meade 1994, Riley and Palumbo 1995, Naranjo et al. 1998) for whitefly control. The widespread use of broad spectrum insecticides in many crops has limited the contribution of predators and parasitoids to control *B. tabaci*. With the increased use of selective insecticides and a greater adoption of Integrated Pest Management (IPM) practices, biological control for *B. tabaci* has had a growing interest in the literature (Naranjo 2001). IPM is the integration of multiple control tactics as part of an overall management plan. Unfortunately, IPM programs are based on local conditions and cropping systems so they are temporally and spatially relative, which complicates adoption on a large scale.

**Cultural control**

Cultural practices to control sweetpotato whitefly have been reviewed by Hilje et al. (2001). Hilje et al. (2001) designated four categories to define whitefly management strategies using cultural practices: avoidance in time or space, behavioral manipulation of the insect, host suitability and insect removal. Avoidance in time/space would consist of separating the crop from sources of the insect. Planting and termination date manipulation can be a useful control tactic for both individual growers and for regional control (Ellsworth and Martinez-Carrillo 2001). Crop-free periods have been used in multiple agricultural systems to reduce sweetpotato whitefly pressure (Stansly and Schuster 1990, Nuessly et al. 1994, Alvarez and Abud-Antun 1995, Ucko et al. 1998, Villar et al. 1998). Planting date manipulation has been used in multiple cropping systems to avoid *B. tabaci* problems (Patel and Patel 1966, Borah 1994, El-Gendi et al. 1997, Hernandez and Pacheco 1998, Mewally 1999). Spatially avoiding associated weed hosts of *B. tabaci* and vector reservoirs can reduce problems associated with both

(Cohen et al. 1988). Watson et al. (1992) determined that whitefly populations could be affected by disrupting spatial and temporal relationships of neighboring crops.

Physical exclusion of whiteflies from plant material has been used to reduce damage from whiteflies and could include greenhouse structures (Cohen and Berlinger 1986, Horowitz and Ishaaya 1994, Antignus et al. 1996, Berlinger and Lebiush-Mordechi 1996, Ausher 1997, Antignus et al. 1998, Costa and Robb 1999), row covers (Natwick and Durazo III 1985, Cohen and Berlinger 1986, Perring et al. 1989, Webb and Linda 1992, Costa et al. 1994, Orozco-Santos et al. 1994, Farias-Larios et al. 1995, Orozco-Santos et al. 1995, Farias-Larios et al. 1996, Avilla et al. 1997), barriers (Cohen et al. 1988, Smith and McSorley 2000, Hilje et al. 2001), and high planting density (Fargette and Fauquet 1988, Fargette et al. 1990, Ahohuendo and Sarkar 1995). Whitefly behavioral modifications with varying levels of control can be achieved by mulches (Cohen 1982, Cohen and Berlinger 1986, Suwwan et al. 1988, Orozco-Santos et al. 1994, Csizinszky et al. 1995, Orozco-Santos et al. 1995, Csizinszky et al. 1997, Hooks et al. 1998, Csizinszky et al. 1999, Simmons et al. 2010) and intercropping (Al-Musa 1982, Stansly et al. 1998, Smith et al. 2000, Schuster 2004). Host suitability alterations, e.g., changes in fertilization (Blua and Toscano 1994, Bentz et al. 1995b, Blackmer and Byrne 1999, Bi et al. 2001) and irrigation (Mor 1987, Leggett 1993, Flint et al. 1994, Flint et al. 1995, Flint et al. 1996), can affect whitefly reproduction and survival. Adult whitefly counts decline after a rain event (personal observation) and other authors have documented a similar decline in whitefly populations in other regions (Zalom et al. 1985, Henneberry et al. 1995). Researchers such as Castle et al. (1996)

and Castle (2001) have shown reductions in whitefly eggs and nymphs in overhead irrigated cotton and cantaloupe as compared to furrow irrigation treatments.

Cultural practices have been used and tested worldwide but widespread adoption of practices is limited due to conventional cropping systems not allowing substantial change in grower acceptance, regional scale necessary for implementation, research experimentation difficulty, and the dependence of cultural practices on other control tactics.

**Chemical control**

The use of insecticides has been the primary strategy to control *B. tabaci* in many agronomic and vegetable crops around the world (Dennehy et al. 1996, Horowitz and Ishaaya 1996, Ellsworth and Martinez-Carrillo 2001, Palumbo et al. 2001). Unfortunately, *B. tabaci* has developed resistance to all chemical classes applied for its control, as reviewed by Dittrich et al. (1990a) and Palumbo et al. (2001). Palumbo et al. (2001) reviewed the then-current literature and determined that synergized pyrethroids were the most efficacious of the neurotoxic insecticides and combining pyrethroids with other chemical classes (tank mixing) could be more efficacious (Watson 1993, Ellsworth et al. 1994, Horowitz and Ishaaya 1996, Prabhaker et al. 1998). The increased efficacy of tank mixing can be linked to the inhibition of insecticide resistance mechanisms due to increased esteratic activity and insensitive acetylcholinesterase towards inhibitors (Ishaaya et al. 1987, Prabhaker et al. 1988, Dittrich et al. 1990a, Byrne and Devonshire 1993, Denholm et al. 1998). Synergized pyrethroid sprays are more effective on adult whiteflies through contact action (Horowitz and Ishaaya 1996), but there is some efficacy against nymphs (Prabhaker et al. 1989).

Newer insecticides with novel or less-exploited modes of action are becoming more important for *B. tabaci* control around the world (Horowitz and Ishaaya 1994, Denholm et al. 1996). The chloronicotinyls or neonicotinoids (imidacloprid, acetamiprid, nitenpyram, and thiamethoxam) have shown good efficacy in controlling whiteflies and other insects (Elbert et al. 1990, Bethke and Redak 1997, Palumbo et al. 2001, Bacci et al. 2007). These compounds most likely target the nicotinic acetylcholine receptors in the post-synaptic region of insect nerves and, because of their systemic activity, they can be used as soil applications or used as foliar sprays (Bai et al. 1991). Prabhaker et al. (1997) was able to create an imidacloprid resistant strain under laboratory conditions and Cahill et al. (1996) found resistance to imidacloprid in greenhouse conditions in Southern Europe. These new chemistries have been great tools for controlling whiteflies in recent years, but overuse and cross-resistance between compounds within the neonicotinoid class threatens the continued efficacy of these products in the future (Palumbo et al. 2001).

Though oils and soaps have been available for control of whiteflies for a hundred years, synthetic organic insecticides have been in greater use. With the reduction in use of these synthetic insecticides, other alternatives such as soaps and oils have either been discovered or rediscovered. Oils show toxicity against nymphs (Butler et al. 1993, Stansly et al. 1996, Liu and Stansly 2000) and adults (Stansly et al. 1996) but there is some risk of phytotoxicity. Certain oils have also reduced oviposition (Liu and Stansly 1995b, Fenigstein et al. 2001, Schuster et al. 2009) and landing/settling (Liu and Stansly 1995a, Fenigstein et al. 2001, Schuster et al. 2009). Soaps in the form of surfactants or household detergents have efficacy against whitefly adults and nymphs

(Butler et al. 1993). The mode of action of soaps and oils is a combination of physical action, suffocation, or repellency (Larew and Locke 1990, Stansly et al. 1996, Fenigstein et al. 2001). Soaps and oils are effective whitefly insecticides and are generally safer for non-target organisms than conventional insecticides, but good plant coverage is required and the risk of phytotoxicity is increased.

Other novel insecticides such as insect growth regulators (IGRs), diafenthiuron, and pymetrozine have expanded the list available for sweetpotato whitefly control. IGRs affect normal insect physiology and can include chitin synthesis inhibitors (buprofezin) and juvenile hormone mimics (pyriproxyfen) (Horowitz and Ishaaya 1996, Palumbo et al. 2001). These compounds require the user to know and understand basic insect biology and ecology because they have selective efficacy on certain life stages of the insect (Ellsworth and Martinez-Carrillo 2001, Palumbo et al. 2001). Diafenthiuron is a thiourea derivative and has a unique mode of action (Kadir and Knowles 1991, Ishaaya et al. 1993). Pymetrozine is in the pyridine-azomethine class of insecticides and is selectively active against sucking insects within Homoptera (Nicholson et al. 1996). The mode of action of pymetrozine has been described as neural inhibition of feeding behavior by affecting the activity of cibarial and salivary pumps (Fluckiger et al. 1992, Kayser et al. 1994, Harrawijn and Kayser 1997). These newer chemistries, along with their diverse modes of action, can fit well with current management practices in controlling whiteflies and resistance issues (Palumbo et al. 2001, Ishaaya et al. 2007).

Resistance monitoring has been conducted all over the world and will continue to be a central theme in insecticide research for *Bemisia* spp. control (Perry 1985, Ahmed

et al. 1987, Dittrich et al. 1990b, Dittrich et al. 1990a, Prabhaker et al. 1992, Perez et al. 2000, Schuster 2007). With continued resistance monitoring and implementation of resistance management techniques such as non-chemical control, limited use of chemical control tactics, rotation of chemistries, selective use of certain chemistries and the balanced use of insecticides across commodities, chemical control can be continued as a main control tactic for *B. tabaci* (Ellsworth and Martinez-Carrillo 2001).

**Biological control**

The widespread use of broad spectrum insecticides in many crops has limited the contribution of predators and parasitoids to control of *B. tabaci*. With the increased use of selective insecticides and a greater adoption of IPM practices, interest in biological control for *B. tabaci* has grown in the literature (Naranjo 2001). In a recent review by Gerling et al. (2001) 114 arthropod predators from 9 orders and 31 families were listed. There are also parasitoids (*Hymenoptera*) attacking *B. tabaci* and Gerling et al. (2001) noted 34 species of *Encarsia*, 14 species of *Eretmocerus* and several species in the genera *Amitus* and *Metaphycus* based on a review of current literature. There are also 9 described and 2 undescribed species of fungi shown to naturally occur in *B. tabaci* populations (Faria and Wraight 2001). Though biological control agents have been identified and studied for many years, only in the last 20 years have researchers attempted to apply them for control of *B. tabaci*.

Predators have a unique advantage in biological control systems because many species are generalists and exhibit behavioral plasticity. They are able to feed and change prey species as prey availability changes, thus making them important biological control agents (Gerling et al. 2001). Predators of *B. tabaci* include insects in the orders *Coleoptera*, *Diptera*, *Hemiptera*, *Hymenoptera*, *Neuroptera*, *Odonata* and

*Thysanoptera* and other orders of non-insect arthropods including *Acari* and *Araneae*. Some important predators include beetles from the *Coccinellidae* family (Gerling 1986, Obrycki and Kring 1998); true bugs from *Anthocoridae* (Gerling 1986), *Lygaeidae* (Hagler and Naranjo 1994), *Miridae* (Hagler and Naranjo 1994, Van Schelt et al. 1996, Jones and Snodgrass 1998); and *Neuroptera* from *Chrysopidae* (Gerling 1986, Dean and Schuster 1995). Predatory mites from *Acari* feed on *B. tabaci* and some are commercially available (Nomikou et al. 2001). Predators of *B. tabaci* have been shown to control damaging populations in some systems, though their potential is limited by the efficacy of insecticides against them (Gerling and Kravechenko 1996).

Knowledge of *B. tabaci* parasitoids has been hampered by taxonomic complexity of both *B. tabaci* and its parasitoids, parasitoid biology, host range of *B. tabaci* and diversity of cropping patterns for *B. tabaci* crop hosts (Hoelmer 1996). Parasitoids of *Bemisia* spp. belong to genera in the order *Hymenoptera* and include *Encarsia*, *Eretmocerus* and *Amitus* as reviewed by Gerling et al (2001). These *Hymenoptera* parasitize whitefly nymphs and complete their development on fourth instars, so they do not control adult whiteflies directly (Gerling et al. 2001). Many whitefly parasitoids are oligophagous, allowing for control of new introduced whitefly species; however, this may limit their efficacy as biological control agents (Gerling et al. 2001).

Under certain conditions entomopathogenic fungi can control *B. tabaci* populations. Rainy seasons or cool, humid conditions can lead to epizootics of fungi to control whiteflies; however, fungi usually cannot be relied on for complete control because the development of epizootics relies on environmental conditions and crop production practices (Faria and Wraight 2001). Fungi controlling populations of whitefly

usually lag behind build-up of the pest insect and usually do not control adults (Faria and Wraight 2001). Some commercially available entomopathogens are suggested for use in protected systems (Dowell 1990).

Since the expansion of *B. tabaci* as a global pest, biological control has been researched and applied in some agricultural systems. This application and research will continue but much more work will need to be done before widespread adoption of biological control tactics will become ubiquitous for control of this noxious pest. Many issues complicate biological control and in some systems the efficiency of *Bemisia* spp. to transmit plant viruses damper adoption of biological control tactics.

**Spatial Distribution**

Like most insects, *B. tabaci* is aggregated both within individual leaves and within plants at all life stages (Naranjo 1996). Dispersion is typically described with models including Taylor's power law (Taylor 1961) or Iwao's patchiness regression (Iwao 1968). Naranjo and Flint (1994) used Taylor's power law to describe aggregation of *B. tabaci* eggs and immatures in cotton on individual plants. Adult *B. tabaci* populations were shown to be aggregated on cotton plants within fields using Taylor's power law (Naranjo and Flint 1995). Using mean crowding index, a mean-variance model similar to Taylor's power law or Iwao's regression, Von Arx et al. (1984) determined aggregation of *B. tabaci* in cotton within fields. In Florida, *B. tabaci* was shown to be aggregated in commercial tomato using Morisita's index, although the population distribution fluctuated throughout the season (Polston et al. 1996). Distribution of whitefly adults changed seasonally in Texas from aggregated in the spring to more diffuse in the summer and early fall using the Taylor power law and the Morisita index (Riley and Ciomperlik 1997).

Using Taylor's power law and Iwao's patchiness methods, the sweetpotato whitefly and the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood), were shown to be aggregated between plants in all life stages on greenhouse ornamentals (Liu et al. 1993a). In another study, greenhouse whitefly adults were shown to be aggregated in cherry tomato greenhouses using both Taylor's power law and Moran's I index (Kim et al. 2001). In a study comparing B and Q biotypes of *B. tabaci*, both biotypes were reluctant to move from tomato onto other tomato in glasshouse production, though if dispersed, the whitefly adults from both biotypes moved equally over a short range (Matsuura and Hoshino 2008). Distribution of whiteflies has been shown to be altered by insecticide application as well (Liu et al. 1993b, Tonhasca et al. 1994). Liu et al. (1993b) examined distribution of *B. tabaci* on poinsettia in the greenhouse and those immatures surviving an insecticide application were less likely to be aggregated than those that were not sprayed with an insecticide. In field populations in cantaloupe, whiteflies of all stages were aggregated, although the results for individual aggregation indices differed (Tonhasca et al. 1994). Other indices used to examine dispersion of insects and plant diseases are discussed in further detail in subsequent sections. Improved methods for studying distribution of *B. tabaci* in and around crops need to be developed and incorporated into a landscape level analysis similar to those applied to other pests (Carriere et al. 2006, Reay-Jones et al. 2010).

**Migration and Dispersal**

Migration is defined as "persistent and straightened-out movement effected by the animal's own locomotory exertions on or by its active embarkation on a vehicle. It depends on some temporary inhibition of station-keeping responses, but promotes their eventual disinhibition and recurrence" (Kennedy 1985). Flight that is not migratory is

termed trivial flight and is associated with short duration flights between hosts. Dispersal is movement that increases distance between individuals and can encompass both migratory and trivial flight. Insect migration and dispersal research has been focused on long-range migrations and movement of moths and locusts. Long-range dispersal is widely understood as an important economic threat in some agricultural systems (Showers 1997). Short-range dispersal (< 5 – 10km) of insects classified as weak fliers has become important for pests such as homopterans (Aleyrodidae and Aphididae) because of their economic importance in many agricultural areas.

Fortunately, much short-range dispersal research has been conducted on *B. tabaci* in order to develop IPM programs for the insect. Long distance flight peaks during morning hours between 06.00 and 10.00 hours (Gerling and Horowitz 1984, Blackmer and Byrne 1993b). Both males and females are capable of sustaining flights longer than 2 hours and up to 7km (Byrne 1999). The distribution of whitefly adults in flight has been described as bimodal with most of the population of dispersing *B. tabaci* traveling under 2.7 km. These trivial flying insects traveling under 2km responded to vegetative clues and landed, indicating that local populations of whiteflies surrounding agricultural fields are important for managing *B. tabaci* (Byrne 1999). In some areas, whitefly hosts are found in close proximity to planted crops which could allow for very short dispersal distance and account for the majority of the immigrating population (Coudriet et al. 1985, Cohen et al. 1988, Byamukama et al. 2004). Cohen et al. (1988) captured whiteflies in a mark recapture study up to 7 km away, suggesting that the dispersal range may be much further than described by Byrne et al. (1996). Though vertical whitefly flight is strongly biased towards low altitudes (< 2 meters) regardless of

sex (Isaacs and Byrne 1998), whiteflies have been captured at heights above 36 meters (Byrne 1999). These high flying whiteflies could be influenced by prevailing winds, resulting in higher concentrations of insects leeward of windbreaks (Cohen et al. 1988, Pasek 1988).

Whitefly flight activity is influenced by endogenous factors such as age, sex and nutritional status. Age effect studies on *B. tabaci* showed that younger insects between 3-5 days of age had a greater propensity to takeoff, and exhibited phototactic orientation and increased flight duration (Blackmer and Byrne 1993b). Deterioration of indirect flight muscles and mitochondria in the thorax has been suggested as a cause of reduced flight propensity in older individuals (Blackmer et al. 1995a). Though long-duration flights (> 30 min) weren't common in the study population (≈ 10%), there were differences between the sexes in long-duration flight (Blackmer and Byrne 1993b). Long duration flights occurred only in the morning with females, whereas males flew throughout the day (Blackmer and Byrne 1993b). Blackmer and Byrne (1993b) also looked at the effect of host quality on flight and found that diet did influence flight patterns. Adult insects that were raised on poor quality hosts were more likely to take flight earlier, had a narrower window of flight age, and initiated longer phototactic flights. Insects reared on high quality hosts had a longer period for flight and flew longer but were less responsive to phototactic cues (Blackmer and Byrne 1993b).

Exogenous factors such as temperature, wind speed and solar radiation also have an effect on flight in *B. tabaci*. Temperature was the best predictor of flight activity which increased with rising temperature and peaked at 24-27ºC (Blackmer and Byrne 1993a, Riis and Nachman 2006). Higher wind speed is deleterious to whitefly flight,

although whitefly adults are able to fly against head winds up to 30 cm/s (Isaacs et al. 1999, Riis and Nachman 2006). Light is also a cue in initiating flights in *B. tabaci* and flight propensity increases with solar radiation up to 0.73 kW/m² (Riis and Nachman 2006). Blackmer and Byrne (1993b) recorded the longest flights of whiteflies in the early morning hours and other researchers have suggested that flight is retarded during night hours between 18.00 and 07.00 h (Byrne and von Bretzel 1987, Bellows et al. 1988).

*B. tabaci* has other characteristics suggesting that it could be considered a migratory species. For example, in some insects a polymorphic population emerges with migratory individuals (Palmer 1985). Byrne and Houck (1990) found wing polymorphisms in field populations of *B. tabaci* in which males that left the host plant had significantly smaller wing measurements compared to individuals that didn't take flight. Further research by Blackmer et al. (1995b), contradicted Byrne and Houck (1990) but did indicate that males with larger wings were more likely to take part in long-duration flights than males with smaller wings. There were no wing morphology differences of females in either study. Another principle of a migratory species is the presence of oogenesis-flight syndrome which is characterized by the delay of reproductive activity (usually the production of eggs) in favor of using resources for flight (Johnson 1969, Liquido and Irwin 1986). There has been no evidence of oogenesis-flight syndrome found in *B. tabaci* (Tu et al. 1997, Byrne 1999) as in other insects considered migratory (Sappington and Showers 1992). *Bemisia* adults could be considered migratory because they can: take off and ignore vegetative cues, have flights over 2 hours, and fly against the wind (Byrne 1999). *B.* adult flight distances,

however, are not as great as those of some insects (Ritchie and Pedgley 1989, Showers 1997, Westbrook et al. 1997).

### *Tomato yellow leaf curl virus*

**Biology and Distribution**

*Tomato yellow leaf curl virus* (TYLCV) has a circular, single stranded DNA (ssDNA) genome that has a single genomic component of approximately 2.8 kb and is transmitted by *B. tabaci* in a circulative and persistent manner. Symptoms appear on tomato 2-4 weeks after inoculation and can vary based on virus isolate, host genetic background, environmental conditions, the growth stage and physiological condition of the plant (Ioannou 1985, Rom et al. 1993). Symptoms in tomato include upward curling of leaflet margins, reduction of leaflet size, yellowing of younger leaves, stunting and flower abortion (Pico et al. 1996, Moriones and Navas-Castillo 2000). These symptoms can lead to reduction of yields and, if the plant obtains the virus early in the growth cycle, production is lost almost entirely due to reduction of leaf surface and flower abscission (Levy and Lapidot 2008, Mohamed 2010).

TYLCV has had a highly economic impact on tomato production around the world. Since being first observed in Israel in the early 1940s and with the destruction of the tomato crop in the Jordan Valley in the 1960s, TYLCV has been a limiting factor of tomato production across the globe (Varma and Malathi 2003). From Israel through the Middle East and Asia (Makkouk 1978, Navot et al. 1989, Czosnek et al. 1990), TYLCV spread into Africa (D'Hondt and Russo 1985, Czosnek et al. 1990), Europe (Ioannou 1985, Czosnek et al. 1990, Moriones et al. 1993) and then to the Americas (Nakhla et al. 1994, Polston et al. 1994, Ascencio-Ibanes et al. 1999). In the United States, it was first reported by Polston et al. (1999) in Florida and later was found in Georgia (Momol

et al. 1999) and Louisiana (Valverde et al. 2001). The spread of geminiviruses including TYLCV is associated with increased outbreaks of the B biotype of *B. tabaci* (Polston and Anderson 1997, Rybicki and Pietersen 1999).

**Hosts**

TYLCV has been shown to infect tomato and at least 30 other plant species in over 12 plant families (Polston and Lapidot 2007). Hosts range from cultivated crops to weeds and their importance for TYLCV management is subject to availability in tomato growing regions. Identification of hosts both in cultivated crops and weeds is important for management of TYLCV.

Tomato is the most important host of TYLCV but other cultivated crops have been shown to be hosts. Lisianthus, *Eustoma grandiflorum* (Raf.) Shim. is a host of TYLCV in Israel and TYLCV has become a limiting factor of lisianthus cultivation (Cohen and Gera 1995). Common bean, *Phaseolus vulgaris* L., has been shown to be a host of TYLCV-Is in Spain (Navas-Castillo et al. 1999). Also in Spain, tobacco, *Nicotiana tabacum* L. has been labeled as a host of TYLCV (Font et al. 2005). Tomatillo, *Physalis philadelphica* (Lam.) has been identified as a host of TYLCV in Sinaloa, Mexico (Gamez-Jimenez et al. 2009). With regard to pepper, there has been some debate in the literature concerning its host status. Morilla et al. (2005) were unable to transmit TYLCV from infected pepper (*Capsicum* spp.) plants using *B. tabaci* biotype Q. On the other hand, Polston et al. (2006) demonstrated some genotypes of pepper could serve as symptomless reservoirs for TYLCV transmission to tomato with *B. tabaci* biotype B. These latter authors suggested the differences in results between the two studies could be based on the differences in cultivars used, the number of viruliferous whiteflies used for inoculation and the ability of biotype Q and B to feed and acquire TYLCV in pepper.

Anfoka et al. (2009) showed that *B. tabaci* could transmit TYLCV-Mld from cucumber, *Cucumis sativus* L. to tomato, although transmission with TYLCV-Is was unsuccessful. It was recommended that trap crop systems using cucurbits could affect tomato yellow leaf curl disease (TYLCD) epidemics. Squash, *Curcubita pepo* (L.) was determined to be a host of TYLCV in Cuba (Martinez Zubiaur et al. 2004). In Florida, a survey was conducted to identify weed reservoirs of TYLCV and no weed samples were found to harbor the virus (Polston et al. 2009).

Weeds can also play a role in TYLCV epidemiology. In Israel, *Cynanchum acutum* L. was identified as the most important host of TYLCV and a good source of inoculum (Cohen et al. 1988). *Datura stramonium* L. has been identified as a symptomatic host of TYLCV in the Dominican Republic (Salati et al. 2002) and other tomato production areas (Cohen and Nitzany 1966, Mansour and Al-Musa 1992, Cohen and Antignus 1994). Naturally infected *M. parviflora* is an annual weed host in Israel (Cohen et al. 1988) and also in the Dominican Republic although the viral titer was very low in tested plants (Salati et al. 2002). Other weeds shown to be hosts of TYLCV around the world include: *Hyoscyamus desertorum* (Asch.) Eig, *Nicotiana benthamiana*, *N. glutinosa*, *Solanum nigrum*, *Mercurialis ambigua*, *Cleome viscosa*, *Croton lobatus*, *Physalis* spp., *Macroptilium* spp., *Bastardia* spp., *Euphorbia* spp., and *Polygonum* spp. (Mansour and Al-Musa 1992, Cohen and Antignus 1994, Sanchez-Campos et al. 2000, Gilbertson et al. 2007). Other hosts such as *Chaerogphyllum* spp., *Lens esculenta* (Moench), *M. nicaensis* (All.), *N. tabacum*, *P. vulgaris* and *S. oleraceus* are considered hosts, although these plants were not infected under natural conditions (Cohen and Antignus 1994). Weeds can serve as good sources of inoculum of TYLCV and be important

reservoirs of genetic diversity for TYLCD associated virus populations (Garcia-Andres et al. 2006).

**TYLCV - Plant Relationship**

After injection into the phloem by *B. tabaci,* TYLCV replicates in infected cell nuclei and spreads systemically through the plant. After the whitefly injects its stylets intercellularly between epidermal cells, virions are usually deposited into the sieve elements (SE), although in some cases they are deposited into companion cells or vascular parenchyma cells (Pollard 1955, Wege 2007). For replication, the genomic DNA must enter a nucleus via coat protein (CP) mediation of the TYLCV genome (Kunik et al. 1998, Rojas et al. 2001). After entering the nucleus, viral DNA replicates by a rolling circle mechanism (Laufs et al. 1995) and moves systemically through the plant via sieve tubes assisted by the capsid and movement proteins (Gronenborn 2007, Wege 2007).

TYLCV moves systemically through the plant and accumulates preferentially in the tissues containing dividing cells. Viral DNA can be detected at the inoculation site 4-5 days post infection and reaches a peak 12-15 days post inoculation (Rom et al. 1993). Maximum viral accumulation occurs in the developing leaves close to the apex and the axillary shoots, while lower viral accumulation occurs in the stems, roots and expanding leaves (Pico et al. 1996, Wege 2007). Symptoms are expressed tomato 2-3 weeks post infection (Rom et al. 1993).

**TYLCV - *B. tabaci* Relationship**

Cohen and Harpaz (1964) described the TYLCV – *B. tabaci* interaction as periodic acquisition due to the loss of inoculative potential of the insect after initial acquisition of the virus. It is now understood that age and sex of *B. tabaci* affects the efficacy of

acquisition and transmission of TYLCV. Female whiteflies transmit TYLCV with higher efficiency than males (Cohen and Nitzany 1966). Also, as the insect ages, TYLCV inoculation efficiency decreases (Cohen and Nitzany 1966, Mansour and Al-Musa 1992, Rubinstein and Czosnek 1997). Nymphs can acquire the virus and transmit TYLCV in the adult stage, thus supporting the circulative mode of transmission (Cohen and Nitzany 1966, Mehta et al. 1994). Association of *B. tabaci* with TYLCV was shown to lead to a reduction in life expectancy (Rubinstein and Czosnek 1997). Mehta et al. (1994) demonstrated that virus titers increase over time in *B. tabaci* and virus concentration is higher in the whitefly than in the plant. TYLCV could be a pathogen of *B. tabaci* because of virus replication in the insect (Moriones and Navas-Castillo 2000). The adverse effects of the virus on the insect included reduced life expectancy and fecundity (Czosnek et al. 2002).

For successful TYLCV acquisition, *B. tabaci* must be feeding in the phloem where the virus is located. Using electrical penetration graph (EPG) techniques, strong correlations were found between $E(pd)_1$ (regarded as ingestion from phloem, (Jiang et al. 1999)) and virus inoculation (Jiang et al. 2000). Transmission rate increases with numbers of viruliferous whiteflies feeding on the plant, with a minimum of ten to 20 insects needed for 100% transmission (Pico et al. 1996). Mehta et al. (1994) concluded that the efficiency of transmission increased fourfold after the number of adults were increased to five per plant. The minimum acquisition access period (AAP) for transmission of TYLVC by *B. tabaci* was 15 - 30 min (Ioannou 1985, Mansour and Al-Musa 1992, Mehta et al. 1994, Caciagli et al. 1995, Muniyappa et al. 2000, Czosnek et

al. 2002). With longer AAPs there were higher rates of transmission, peaking at 24hrs (Mehta et al. 1994).

After ingestion, TYLCV is not immediately available for transmission due to an approximately 8 h latent period (Ghanim et al. 2001). The latent period allows for translocation of the virus particles out of the digestive tract and into the salivary glands. The latent period is not solely based on the rate of movement of virus in the insect but rather defined as the time from acquisition to transmission of the virus into plant material (Czosnek 2007). Ghanim et al. (2001) stated that TYLCV DNA could be found in the insect's head, midgut and hemolymph using PCR within 10, 40, and 90 min, respectively, but transmission wasn't possible until 8 h after AAP. The latent period was reported by Cohen and Nitzany (1966) to be 21 h. As virus particles move through the body of the insect, they pass through the stylets, esophagus, filter chamber, midgut, hemolymph and finally into the salivary system. This pathway is dependent on the transition through the midgut wall and into the salivary glands. To cross into the hemolymph from the midgut it is suggested that the microvilli along the epithelial cells within the gut wall have begomovirial receptors (Ghanim and Medina 2007, Ohnishi et al. 2009). While in the hemolymph, TYLCV may be protected from degradation by an endosymbiotic bacteria or GroEL homologue (Morin et al. 1999). Transition into the salivary glands is less understood and the method of transportation from the haemolymph into the salivary glands is unclear (Ghanim and Medina 2007). Entry of virus particles into the salivary glands does not guarantee transmission (Caciagli et al. 2009).

It has been shown that the sex and age of the whitefly affect the transmission efficiency of TYLCV. Female whiteflies are more efficient at transmitting TYLCV; as females 1 to 2 weeks old infected ≈ 100% of the plants during a 48 hour inoculation access period (IAP) while males infected 20% of the plants during the same time span (Czosnek et al. 2001). Efficiency rates aren't due to the translocation times of TYLCV particles within the whiteflies but may be due to differences in viral titers in the salivary glands (Ghanim et al. 2001). Age also affected the efficiency of transmission of TYLCV, with the younger adults being better at transmitting the virus (Ioannou 1985, Mansour and Al-Musa 1992, Caciagli et al. 1995, Czosnek et al. 2001, Czosnek 2007). In females, the percentage of infection went down from ≈ 100% in 1 to 2 week old insects to 60% in 3 week old and 20% in 6 week old adults. The percentage of infection by males went from 20% for week 1 to 2 week old males to 0% in 3 week old males (Czosnek et al. 2001). Other researchers have found that *B. tabaci* retains the ability to transmit TYLCV until around 8 – 12 days after AAP (Ioannou 1985, Mansour and Al-Musa 1992, Caciagli et al. 1995). Rubinstein and Czosnek (1997) measured the amount of virus acquired by different aged individuals and found that, as the whitefly aged (10 to 17 days), the amount of virus accumulated by feeding was reduced by half.

TYLCV likely remains associated with *B. tabaci* during the entire life of the vector (Rubinstein and Czosnek 1997). The association of TYLCV with *B. tabaci* is ultimately harmful to *B. tabaci* and resulted in a reduction of 17 – 23% in life expectancy and a 40 – 50% reduction in fecundity (Rubinstein and Czosnek 1997). Whether or not TYLCV actually replicates within the whitefly is subject to debate. Harrison (1985) suggested that geminiviruses do not replicate in their insect vectors. Other researchers have

shown that TYLCV DNA is detectable in the adult body longer than the whitefly might actually be infected (Caciagli et al. 1995, Rubinstein and Czosnek 1997, Sinisterra et al. 2005). Mehta et al. (1994) concluded TYLCV accumulated and replicated in *B. tabaci*. Czosnek et al. (2001) noticed an increase in TYLCV DNA up to 16 h and Czosnek (2007) suggested that the increase of TYLCV DNA was due to the ingestion of viral replicative complexes. TYLCV can also be transmitted transovarially for at least two generations (Ghanim et al. 1998), although other authors have suggested that transovarial transmission is more complicated than previously thought (Goldman and Czosnek 2002, Bosco et al. 2004). Also, TYLCV can be transmitted horizontally between individuals of the same biotype through contamination of the hemolymph without passing through the midgut barrier (Ghanim et al. 1998, Ghanim et al. 2007).

**Management**

In most tomato growing areas, TYLCV management is highly dependent on chemical control targeting the adult *B. tabaci* (Polston and Lapidot 2007). Conventional insecticides such as organochlorines, organophosphates, carbamates, pyrethroids, formamidines and cyclodienes have been used historically for whitefly control (Sharaf 1986, Palumbo et al. 2001). Most insecticides used for control of *B. tabaci* don't reduce feeding quickly enough to stop transmission of TYLCV. The number of insects necessary for field epidemics is usually very low and the efficiency of TYLCV transmission is high (Pico et al. 1996). Development of newer chemistries with novel modes of action like the neonicotinoids, and pymetrozine have given growers more choices for managing *B. tabaci* adults (Palumbo et al. 2001). The neonicotinoid, imidacloprid, is an effective chemical for early season control of TYLCV due to its long-lasting systemic activity (Ahmed et al. 2001, Attard 2002, Polston and Lapidot 2007).

Another neonicotinoid, thiamethoxam, has been shown to reduce TYLCV incidence by preventing virus transmission by *B. tabaci* (Mason et al. 2000). Unfortunately, *B. tabaci* adults have developed tolerance to both of these neonicotinoids in Florida (Schuster and Caballero 2010) and elsewhere (Byrne et al. 2003, Horowitz et al. 2004). Pymetrozine, a pyridine-azomethine, has the ability to interfere with whitefly feeding behavior and can reduce TYLCV infection by up to 7 days (Polston and Sherwood 2003). Unfortunately, with the judicious use of insecticides long-term control of *B. tabaci* has been difficult to maintain with certain chemistries and resistance issues have hampered TYLCV pesticide control tactics (Horowitz and Ishaaya 1996, Horowitz et al. 2007).

Use of resistant or tolerant tomato varieties is one of the best approaches to reduce losses due to infection of TYLCV (Pico et al. 1996, Moriones and Navas-Castillo 2000, Lapidot and Friedmann 2002). Since searching for resistance in the cultivated tomato (*S. lycopersicum*) failed, breeding programs have been based on the introgression of resistance from wild *Solanum* species including; *L. peruvianum* (Rom et al. 1993, Friedmann et al. 1998), *L. chilense* (Michelson et al. 1994, Zamir et al. 1994, Scott et al. 1996, Pico et al. 1999), *L. pimpinellifolium* (Vidavsky et al. 1998) and *L. hirsutum* (Vidavsky and Czosnek 1998). Vidavsky et al. (2008) pyramided genes from wild tomato species in order to have more than one source of resistance. Data suggests that under high inoculum pressure, some resistance can be overcome (Michelson et al. 1994, Pico et al. 1996). Resistant cultivars must be carefully managed in order to reduce the selection of TYLCV variants that could possibly overcome current resistant cultivars and alter the virus population structure (Seal et al. 2006).

Unfortunately, in most tomato production areas including Florida, growers are reluctant to use currently available resistant cultivars due to lack of bacterial and fungal resistance, lack of horticultural properties and lower than expected yields (Polston and Lapidot 2007). Also, current resistant cultivars are tolerant, don't deteriorate as badly as highly susceptible cultivars, and harbor the virus. Thus, the extent of virus inoculum in the field may be underestimated and the cultivars could serve as virus reservoirs (Lapidot et al. 2001). Genetic engineering approaches show good promise for the future and research is being conducted in order to better understand the mechanisms and approaches for incorporating genetically engineered resistance into tomato. These genetic techniques confer resistance through expression of viral capsid protein (Kunik et al. 1994), altered viral Rep protein (Brunetti et al. 1997, Brunetti et al. 2001, Antignus et al. 2004, Yang et al. 2004, Praveen et al. 2005), GroEL gene (Akad et al. 2007) and post transcriptional gene silencing (Abhary et al. 2006).

Cultural control tactics are useful in managing TYLCV and have been used in tomato production areas in both greenhouse and open field production. The use of virus-free planting material along with avoidance of adjacent TYLCV reservoirs through time and space can limit the amount of initial virus inoculum (Ioannou 1987, Cohen et al. 1988, Lapidot et al. 2001, Polston and Lapidot 2007). To avoid TYLCV inoculum sources, mandatory crop and host free periods were established in the arid Arava region in Israel (Ucko et al. 1998) and the Dominican Republic (Polston and Anderson 1997, Salati et al. 2002). Physical barriers have been used for tomato protection in the Mediterranean since 1990 (Berlinger and Lebiush-Mordechi 1996, Berlinger et al. 2002) and other areas (Bethke et al. 1994, Arsenio et al. 2002). Screening greenhouses with

whitefly exclusion material in Israel was very cost effective (Taylor et al. 2001). Ultraviolet absorbing plastic films have been used in protected culture and have shown good results (Antignus et al. 1998, Antignus et al. 2001). Unfortunately, these protective covers can cause problems in tomatoes in hot temperatures and can increase the spread of foliar diseases. Proper ventilation and cooling systems are needed to avoid overheating (Weintraub and Berlinger 2004).

In open field production areas, which currently includes Florida, UV-reflective soil mulches have been widely adopted as a control tactic for reducing TYLCV settling of *B. tabaci* adults on tomato plants (Csizinszky et al. 1997, Csizinszky et al. 1999). In Israel, yellow plastic mulch reduced the number of *B. tabaci* adults on tomato plants because adults were attracted to the yellow color and were then rapidly dehydrated by the high temperature of the mulch (Cohen 1982, Cohen and Berlinger 1986). The effectiveness of yellow mulch was not corroborated in Florida tomatoes, however (Csizinszky et al. 1997).

Weeds can also serve as a host of TYLCV and good in-field and field edge weed management is suggested though beneficial insects and pathogens of *B. tabaci* can inhabit these areas and can provide control in certain situations. Roguing is also recommended and plants with early symptoms can be removed to reduce the inoculation source within the field and reduce secondary spread (Polston and Lapidot 2007). Bait (trap) crops have also been used as control tactics and alternating rows of cucumbers and tomatoes delayed the spread of TYLCV for 2 months (Al-Musa 1982). In Florida, similar results were found when squash was used as a bait crop (Schuster 2004). Cucurbit crops can serve as reservoirs of *Tomato yellow leaf curl Sardinia virus*

(TYLCSV) and TYLCV-Mld, and in areas of the world where these viruses exist, it is suggested that growers do not use trap crop systems (Anfoka et al. 2009).

## Geographic Information Systems and Spatial Statistics

### GIS

Geographic information systems (GIS) are tools for studying and mapping the spatial relationship of unknown variables. Data are stored in a GIS using both vector and raster based models and combined with defined locations in a geographic coordinate system (Kennedy 2000). GIS can also be used to create maps that show a picture of pest populations and visually express point data (Nelson et al. 1999). Area-wide pest management has become important in today's agriculture and, with the influence of GIS and geostatistics, ecological, pathological and entomological questions on larger scales will be easier to identify and research. GIS and geostatistics have been used to monitor and predict pest populations and amend pest management strategies in medical, entomological and plant disease systems. This review will focus on the use of GIS in the entomology and plant disease management context. For review of GIS uses in medical and veterinary entomology see Thomson and Connor (2000), Noonan (2003) and Patz and Confalonieri (2005).

To be considered a GIS, the system must be able to input, store, retrieve, manipulate and report spatial data (Bolstad 2005). Spatial data can be collected in many forms and may include paper maps, remotely sensed data, digital line graphs or field-acquired point data (Liebhold et al. 1993). Spatial data input is essential to a GIS and most systems can import from a variety of data formats. Once in a GIS, data are stored and retrieved in two main models, vector and raster. Raster data use a grid-cell data structure where each cell has a value and groups of adjacent cells with identical

values define a spatial object. The raster data format is good for mathematical modeling and representing continuous variables. Unfortunately, the size of the grid cells determine the resolution at which data are represented and the boundaries can tend to look blocky rather than smooth like vector data representations. Vector data represents geographic features with points, lines, curves or areas. Vector data use less storage space and are good at representing linear features such as roads, data points and boundaries between objects. Image data can also be imported into a GIS and can include background information for spatial maps.

A GIS defines locations with a geographic coordinate system or *x, y* coordinates for a given map layer. Coordinates are usually acquired by a global positioning system (GPS) device. GPS units are usually handheld and connect to satellites to calculate location. Latitude and longitude is the most commonly used geographic coordinate system along with Universal Transverse Mercator (UTM), which is an adaptation of the Mercator projection and is based on distance in meters (Noonan 2003). These coordinates must be expressed on a 2-D flat surface such as a computer monitor or map so they need to be projected, which distorts the map to some degree.

Pest density maps can be created in a GIS using interpolation methods to mathematically estimate values at unsampled locations (Fleischer et al. 1999). Some commonly used interpolation methods are inverse-distance weighted (IDW) and kriging. The ability of maps to show pest densities and, thus, to better measure and understand spatial variation is valuable to researchers and crop managers. They can be used to indicate hot spots or drive pest management tactics to control local populations.

**Geostatistics**

Geostatistics quantifies and models spatial and temporal data and predicts the value of a variable at unsampled locations. Geostatistics can also model the uncertainty about those unknown values. Isaaks and Srivastava (1989) provide an introduction to applied geostatistics. The central theme of geostatistics rests on the expectation that closer objects are more related than objects farther apart. Dispersion patterns can provide useful information about population structure but ignore spatial location of samples and assume independently distributed data (Rossi et al. 1992). One can also characterize dispersion patterns by quantifying spatial dependence with semivariograms. Semivariograms use distance between data points to create a graph of the spatial dependence of attribute values and serve as a tool to find the range of spatial autocorrelation. Spatial autocorrelation is a correlation of a variable with itself through space and thus helps describe patterns of variables.

Interpolation methods estimate predicted values at unsampled locations based on values at sampled locations. IDW interpolated values are determined using a linear weighted combination of observed values and those weights are functions of the distance between locations. Unlike other interpolation methods, IDW does not require a variogram model and is appropriate for small data sets (Kravchenko 2003). IDW values are estimated by:

$$Z_j = \frac{\sum_i \frac{Z_i}{d^n_{ij}}}{\sum_i \frac{1}{d^n_{ij}}} \quad (2\text{-}1)$$

where $Z_j$ is the estimated value for the unknown point at location I, $d_{ij}$ is the distance from known point *i* to unknown point *j*, $Z_i$ is the value for the known point *i*, and *n* is a user defined exponent (Equation 2-1). The farther away the point the smaller the

weight, so the less influence it has on the estimate of the unknown point. Care must be taken when *n* (number of samples) is selected because when a larger *n* is used, the closer points become more influential. Cross validation has been used to estimate the fit of the IDW model. Cross validation removes one sample point at a time and compares observed and predicted values for that point (Isaaks and Srivastava 1989). The root mean square prediction error (RMSE) produced by cross validation has been presented as the summary statistic to check the accuracy of the model produced in IDW (Bonsignore et al. 2008, Tillman et al. 2009, Reay-Jones et al. 2010). IDW is a good tool for initial analysis and because of its simplicity it has been used extensively in the literature to create interpolation maps (Bonsignore et al. 2008, Tillman et al. 2009, Reay-Jones et al. 2010).

Geostatistical theory was first developed for geology and mining to estimate ore and mineral quantities (Vieira et al. 1983, Goovaerts 1997). Entomologists have focused on describing spatial patterns of insects due to their spatially heterogeneous populations. Some commonly used dispersion indices ignore valuable information such as the spatial location of samples (Rossi et al. 1992). Geostatistics allows for the description of spatial patterns using spatial locations. To display the spatial dependence of an organism, a semivariogram or variogram is produced. A variogram is a graph that expresses the variance of sample pairs against the distance between sample points and is defined as:

$$\hat{y}(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{i=1}^{N(\mathbf{h})} [z(x_i) - z(x_i + \mathbf{h})]^2 \qquad (2\text{-}2)$$

where $\hat{y}$ (**h**) is the estimated semivariance value for lag **h,** N (**h**) is the number of pairs of points separated by **h**, z($x_i$) is the variable as a function of spatial location and z ($x_i$ – **h**)

is the lagged version of the variable (Equation 2-1). The variograms can be evaluated as an average over all directions or in a specific direction. A general variogram is presented in Figure 2-1.

The central theorem of geostatistics states that objects closer are more related than those far away; therefore, as semivariance increases with distance, it eventually levels off and becomes constant (Figure 2-1). At the y-intercept there should be no variability between a sample and itself, though, when extrapolated to lag zero, the y-intercept is commonly greater than zero. This value of the y-intercept is termed the nugget and was established by gold mining engineers who found gold nuggets not spatially associated with ore deposits (Liebhold et al. 1993). This nugget represents two sources of variability: spatial variability at a scale smaller than the minimum lag distance and experimental error or the human nugget. Sometimes variograms appear horizontal, which indicates a complete lack of spatial structure. These variograms are termed pure nugget variograms. The sill is the point at which the curve levels off and is usually equivalent to the sample variance. The distance at which the sill levels off is called the range and is commonly used to express the distance at which spatial dependency is lost. The general rule of thumb is that there are at least 30-50 pairs of points needed to create variograms although the more points, the greater the statistical reliability. Also, only half the total distance measured in any direction over the sampling area may be represented legitimately in a variogram. Variograms may be omnidirectional or calculated for specific directions. Similar spatial continuity with direction is known as isotropy. Variograms can be greatly affected by outliers, as

variograms assume local means and variances are stationary across the study area (Rossi et al. 1992, Fleischer et al. 1999).

The modeled variogram can be used for many purposes, including spatial prediction. Spatial prediction tools such as kriging can estimate values by taking a weighted linear average of available samples. Values are determined using a linear weighted combination of observed values and those weights are functions of the distance between locations. Unlike IDW, kriging prediction maps use geostatistical methods and are based on statistical models that include autocorrelation. Kriging can provide a certainty and accuracy of the predictions, even though it is more complicated to produce and requires data exploration before a map can be produced. One criticism of the utility of geostatistics in applied agriculture is the high level of understanding of mathematical concepts.

**GIS Uses in Entomology**

Historically, applications of GIS in entomology have been limited to forest and rangeland entomology (Kemp et al. 1989, Schotzko and O'Keeffe 1989). Recently, GIS has been applied to manage insect pests in agricultural systems (Barnes et al. 1999, Park and Obrycki 2004, Carriere et al. 2006, Garcia 2006). Using GIS, entomologists have able been to relate insect populations to biological and physiographic features of the landscape (Shepherd et al. 1988, Van Sickle 1989, Bryceson 1991). Spatial dependence in insects shows that interpolating counts at un-sampled locations can be valuable (Borth and Huber 1987, Schotzko and O'Keeffe 1989, Liebhold et al. 1993, Setzer 1995).

GIS technology relates questions of insect ecology with their spatial components. In rangeland entomology, locust populations and their subsequent outbreaks can be

modeled and pest density maps can be created (Cigliano et al. 1995, Schell and Lockwood 1997). Locust populations have been studied on an area-wide scale and locust counts have been predicted at these scales using kriging and geostatistics (Kemp et al. 1989). GIS have correlated grasshopper populations with their distribution through different landscapes (Kemp et al. 2002). Locust population outbreaks have also been evaluated for dependency on ecological variables (Schell and Lockwood 1997). Forest pests have been subjected to analysis with GIS including gypsy moths, *Lymantria dispar* (L.). Data acquired from a GIS by Sharav et al. (1996) quantified spatial variation of the gypsy moth, which could be used to develop IPM strategies aimed at monitoring and trapping. The efficacy of aerial applications of insecticides against gypsy moth was evaluated using a GIS (Liebhold et al. 1996). Liebhold et al. (1991) used semivariograms to model gypsy moth egg masses in forest landscapes and created kriged prediction and threshold maps. Similar geostatistical tools including semivariogram production and cokriging were used to estimate gypsy moth egg mass abundance in Sardinia (Cocco et al. 2010). Similar egg mass prediction studies were used for developing regional gypsy moth defoliations maps (Gribko et al. 1995). GIS and geostatistics have also contributed to studies in other forest pests, including the southern pine beetle, *Dendroctonus frontalis* (Zimmermann) (Fitzgerald et al. 1994) and spruce budworm, *Choristoneura fumiferana* (Clemons) (Candau et al. 1998, Lyons et al. 2002).

GIS technologies and other geostatistical tools have been used to examine insect populations in agricultural systems as well. Studies have shown that most arthropod species are spatially aggregated (Taylor et al. 1978, Wilson and Room 1983). GIS and

geostatistical programs can help determine the spatial distribution of insects, which can help with management and prediction of insects at unsampled locations. Insect distributions have been mapped for statewide monitoring of European corn borer, *Ostrinia nubilalis* (Hübner) and corn earworm, *Helicoverpa zea* (Boddie) in New Jersey (Holmstrom et al. 2001). Using kriging analysis the bollworm, *H. armigera* (Hübner), exhibited an edge effect in a tomato field in Spain (Garcia 2006). Other researchers showed clustering of *H. armigera* in cotton, though patterns changed with the population density (Ge et al. 2005). The pink bollworm, *Pectinophora gossypiella* (Saunders) and its spatial dynamics were examined visually by kriged maps (Borth and Huber 1987). The spatial dynamics of the potato tuberworm, *Phthorimaea operculella* (Zeller) were described by Debano et al. (2010). In corn, aggregation of the fall armyworm, *Spodoptera frugiperda* (Smith) diffuses throughout the season (Farias et al. 2008). The western tarnished plant bug, *Lygus hesperus* (Knight) was shown in lentils to be aggregated in the early season and to be uniformly distributed in mid-season (Schotzko and O'Keeffe 1989). Geostatistical tools were also used to determine sample placement for *L. hesperus* to assist with management (Schotzko and O'Keeffe 1990). Stinkbugs species including; the green stinkbug, *Acrosternum hilare* (Say); brown stinkbug, *Euschistus servus* (Say); and the southern green stinkbug, *Nezara viridula* (L.) demonstrated aggregated spatial patterns (Reay-Jones et al. 2010). IDW maps were created to visually express stinkbug populations along edges of cotton associated with peanuts (Tillman et al. 2009). Populations of the sharpshooters *Dilobopterus costalimai* (Young), *Acrogonia* sp. and *Oncometopia facialis* (Signoret), which vector *Xylella fastidiosa,* were found to be aggregated during the summer, winter and spring (Farias et

al. 2004). Aggregated patterns and anisotropy in the direction of rows in vineyards were found for *Lobesia botrana* (Denis and Schiffermüller) in Northern Greece (Ifoulis and Savopoulou-Soultani 2006). Byrne et al. (1996) used geostatistics to describe patchy distribution of migrating whiteflies.

Much work has been conducted on spatial variation of beetle populations in corn and other crops. Aggregation of the sugarbeet wireworm, *Limonius californicus* (Mannerheim) using geostatistical tools was shown by Williams et al. (1992). Aggregated spatial distributions of northern corn rootworm, *Diabrotica barberi* (Smith and Lawrence) and western corn rootworm, *D. virgifera virgifera* (Leconte) were found in South Dakota corn (Beckler et al. 2005). Other researchers found similar aggregated spatial structures in *D. barberi and D. virgifera virgifera* and found the range of spatial dependence to be lower in *D. barberi* (Ellsbury et al. 1998). Aggregated populations of *D. virgifera virgifera* were also presented by Midgarden et al. (1993) and Park and Tollefson (2005). Site-specific IPM for Colorado potato beetle, *Leptinotarsa decemlineata* (Say), was designed using kriging and IDW maps (Weisz et al. 1995). Predaceous lady beetles, *Harmonia axyridis* (Pallas), *Coleomegilla maculata* (DeGeer) and *Coccinella septempunctatata* (L.) and their prey, the corn leaf aphid, *Rhopalosiphum maidis* (Fitch), are aggregated during peak populations and randomly distributed in the early and late season (Park and Obrycki 2004). The cereal leaf beetle, *Oulema melanopus* (L.), has an edge effect and is spatially aggregated (Reay-Jones 2010). The Mexican bean beetle egg mass distribution indicated an edge effect, but there were no aggregated patterns of egg masses as indicated by the researchers' semivariogram (Barrigossi et al. 2001). The buprestid, *Capnodis tenebrionis* (L.) was

spatially and temporally modeled using IDW in an apricot orchard in Sicily and pest populations were found to be higher in crowns associated with sun exposure (Bonsignore et al. 2008).

Environmental factors such as temperature and elevation can affect population dynamics as well. Using nonparametric multiplicative regression along with a GIS, increased trap counts of the potato tuberworm corresponded with increased temperature (DeBano et al. 2010). Decreased trap counts of potato tuberworm corresponded with increased elevations and latitudes (DeBano et al. 2010). Crop phenology can affect *D. virgifera virgifera* spatial patterns in corn (Darnell et al. 1999). *L. hesperus* populations are affected by habitat types and distance to available habitats (Carriere et al. 2006). The authors used a GIS to evaluate the spatial arrangement of fields to help design and improve area wide management of *L. hesperus* (Carriere et al. 2006). Vegetation types and their interactions with grasshopper species composition and distribution were evaluated using GIS (Kemp et al. 2002). Stinkbugs demonstrate an edge effect and adjacent crops and landscapes can affect populations within a target crop (Tillman et al. 2009, Reay-Jones et al. 2010, Reeves et al. 2010). Cereal leaf beetles are found aggregated on field edges in wheat fields, particularly on edges bordering corn (Reay-Jones 2010).

Strong spatial dependence in insect data indicates that estimating populations at unsampled locations is a possibility (Liebhold et al. 1993). Agroecosystem heterogeneity has a direct effect on pest population dynamics, dispersal and habitat selection and pest problems commonly extend beyond the boundaries of individual growers, thus illustrating the importance for developing regional or areawide pest

management. Spatial distribution of insects is important for developing crop management tactics, and spatial models can help researchers and growers target pest insects for a successful integrated pest management system (Legaspi Jr. et al. 1998). However, geostatistical analysis is complicated and specialized expertise cannot be expected from every researcher or farm manager; nevertheless, proper applications of spatial distribution of pest insects could lead to better sampling, detection and management.

**GIS Uses in Plant Disease Management**

GIS can be used in conjunction with geostatistics to better understand insect-vectored plant diseases and the factors that influence their epidemics. Spatial patterns of disease can provide information such as direction and distance of spread and importance and proximity of the sources of inoculum and vectors (Thresh 1976). Research is commonly undertaken on the small scale plot, but GIS allows for regional scale studies and extrapolation of knowledge of small scale variation to a larger geographic area. Disease problems and their associated vectors commonly extend beyond an individual grower's fields, so management of some pests could or should be addressed regionally. Area-wide management of plant disease is valuable and, with the development of GIS systems, new research efforts can focus on spatial relationships of landscape features and management tactics on a much larger scale.

Within-field studies focus on fine scale variation and results acquired should set the basis for future work on larger regional studies. Understanding this field scale variability allows for extrapolation of knowledge into larger management areas. African cassava mosaic disease (ACMD) is caused by a whitefly-vectored geminivirus and early work with geostatistics indicated a spatially dependent structure that was influenced

heavily by wind (Lecoustre et al. 1989). The influence of wind on the distribution of ACMD was further suggested by Fargette et al. (1985) and corroborated by Colvin et al. (1998). Lack of aggregation of *Citrus tristeza virus*, which is vectored by the aphids *Aphis gossypii* (Glover), *A. spiraecola* (Patch), *Toxoptera aurantii* (Fons.) and *T. citricida*, was confirmed by geostatistical analysis (Gottwald et al. 1996). Almond leaf scorch disease (ALS), caused by *Xylella fastidiosa*, which is vectored by sharpshooter leafhoppers and spittlebugs, had spatial aggregation patterns in certain almond cultivars (Groves et al. 2005). Pierce's disease, a limiting disease in grapes in California and other areas of the country is caused by the same causal agent of ALS. In grapes in California, Pierce's disease displayed highly aggregated patterns and showed anisotropy consistent with vine to vine spread related to the movement of its vector, a glassy-wing sharpshooter, *Homalodisca coagulata* (Germar) (Tubajika et al. 2004). If plant diseases exhibit spatial autocorrelation beyond the boundary of a single field, then regional management would be useful.

There have been successful regional management programs for plant pathogens that were aided by the use of GIS and geostatistics. Cotton leaf curl disease, caused by *Cotton leaf curl virus,* vectored by a whitefly is under evaluation in Punjab, Pakistan and includes risk analysis of spatial landscape characteristics (Nelson et al. 1999). Similar work in Arizona with *Cotton crumple virus*, vectored by *B. tabaci*, could help with understanding the distribution of whiteflies and their associated vectored plant viruses (Nelson et al. 1999). There are some pitfalls with creating area-wide pest density or risk maps. If adjacent fields are highly dissimilar with abrupt differences, surface maps over larger regional areas can be misleading (Nelson et al. 1999). The level of knowledge

and cost associated with area-wide management programs based on a GIS can be large (Nelson et al. 1999). A regional plant virus management program based on risk assessment and virus disease-incidence data was developed for the multivirus, multivector, disease complex of tomatoes in the Del Fuerte Valley, Sinaloa, Mexico (Nelson et al. 1994). Risk maps created by a GIS were correlated to disease incidence and were used as a decision tool for adapting disease management tactics (Nelson et al. 1994). Although GIS analysis was not required for implementation of management tactics for control of plant viruses and their insect vectors in the Del Fuerte Valley, Sinaloa, Mexico, the output from the GIS was instrumental in providing a regional perspective of the problems (Barnes et al. 1999). In Florida, a decision support system for management of *B. tabaci* and TYLCV is being developed from regional surveys using a GIS (Turechek 2010). The use of GIS coupled with integration of agroecosystem data at the regional level could improve management of pest problems at a much larger scale.

**Spatial Analysis by Distance IndicEs (SADIE)**

Most arthropods are spatially aggregated in nature and many have been mapped with GIS technologies, which use geostatistics to determine spatial structure. Entomological data sets are often patchy and can include a majority of zero values and be highly dynamic, which limits the use of geostatistical methods and these limitations led to the development of SADIE (Perry 1995). SADIE measures the degree of clustering in georeferenced data. Unlike geostatistics, SADIE is based on discrete count data and results are conditional to the observed heterogeneity of the data (Xu and Madden 2004). The basis of SADIE is to quantify the degree of clustering by calculating the distance to regularity (*D*). Distance to regularity is defined as the minimum distance

individuals in a sample would have to move to result in a uniform distribution. The overall aggregation index $I_a$, is defined as $D/E_a$, where $E_a$ is the mean expected distance to regularity for the randomized samples. Values of $I_a > 1$ suggest aggregation, $I_a < 1$ suggest a regular pattern and $I_a = 1$ indicates a random pattern (Perry 1998). SADIE was designed to detect clusters in patch or gap form, which makes it sensitive to patterns when disease incidence is low (Dallot et al. 2003). SADIE also provides overall clustering indices $\upsilon_j$, indicating negative gap cluster and $\upsilon_i$, indicating positive patch cluster to quantify the degree to which the count for each sample unit contributes towards the overall degree of clustering (Perry et al. 1999).

SADIE has been used to describe spatial patterns in insects and plant diseases. It can also be combined with GIS produced maps to visualize the aggregation or uniformity of populations. Spatial and temporal dynamics of *H. coagulata* and *H. liturata* were examined using SADIE and trap counts were aggregated overall where *H. coagulata* and *H. liturata* were associated with their respective hosts, citrus and desert saltbush scrub (Park et al. 2006). SADIE was used to determine that carabid beetles were spatially aggregated in winter oats in relation to food availability or microclimate (Korie et al. 2000). The stink bugs *A. hilare*, *E. servus* and *N. viridula*, and their associated damage to cotton bolls, indicated an aggregated pattern in South Carolina and Georgia (Reay-Jones et al. 2010). Other studies with *N. viridula* and *E. servus* indicated similar aggregation patterns using SADIE analysis (Tillman et al. 2009). In winter oilseed rape, the cabbage seed weevil, *Ceutorhynchus assimilis* (Payk.) was distributed in an aggregated pattern during colonization as the insect moved from the edges toward the center of the crop (Ferguson et al. 2000). Another pest of winter oil

seed rape, the cabbage stem flea beetle, *Psylliodes chrysocephala* (L.), showed aggregation after immigration from the edges of the crop (Warner et al. 2003). SADIE was also used to evaluate the spatio-temporal distribution of carabid beetles [*Trechus quadristriatus* (Schrank), *Pterostichus madidus* (Fabricius) and *Nebria brevicollis* (Fabricius)] related to their control of *P. chrysocephala* in winter oil seed rape (Warner et al. 2003). Carabid beetles were also found to be spatially and temporally aggregated in field and hedgerow areas in the United Kingdom (Thomas et al. 2001). SADIE was used as a dispersion indices for development of sampling plans for corn rootworm, *Diabrotica* spp. adults, which were shown to be aggregated (Park and Tollefson 2006). The western flower thrips, *Frankliniella occidentalis* (Pergande), demonstrated aggregated spatial patterns in both the adult and immature stage in greenhouse cucumbers (Park et al. 2009).

SADIE analysis was used to describe aggregated distribution of strawberries infected with Strawberry leaf blight in fields in Ohio (Turechek and Madden 1999). In France, peach trees infected with the aphid transmitted, *Plum pox virus* Strain M, varied in aggregation throughout orchards, suggesting transmission of the virus was frequent though not systematic and ecological conditions had a major influence on spread of the virus (Dallot et al. 2003). *Bean yellow mosaic virus*, vectored by the lupin aphid, *Macrosiphum albifrons* (Essig) and the peach aphid, *Myzus persicae* (Sulzer) was shown to have an aggregated spatial distribution in lupins (Korie et al. 2000). A foliar and glume disease of wheat caused by *Stagonospora nodorum* (E. Mūll.) Hedjar., was shown to be aggregated in at least one wheat field using SADIE analysis thus

demonstrating that SADIE successfully evaluates discrete data which contain many zero counts (Shah et al. 2001).

**Classification and Regression Tree Analysis**

Ecological data are often complex and unbalanced and may be strongly nonlinear. Classification and regression tree (CART) analysis are statistical techniques designed to explore and model such data and can deal with nonlinear, complex and missing data values (Breiman et al. 1984). Classical regression methods rely on assumptions of the distribution and variance of data that are usually invalidated with ecological data sets. CART based models are non-parametric and can use either categorical or continuous data types, or both. The goal of CART models is that each partition is as homogenous as possible and each split is defined by a simple rule based on a single explanatory variable (De'ath and Fabricius 2000).

Landscape elements and other factors influencing insect populations and plant pathogens have been identified using CART. CART has been to used to identify mortality factors in larvae of a sawfly, *Profenusa thomsoni* (Konow) (MacQuarrie et al. 2010). Using CART analysis, outbreaks of the southern pine beetle in the southeastern United States were described to be associated with average climatic conditions (temperature and precipitation) instead of extreme conditions (Duehl et al. 2011). Climatic factors were also used to predict historic outbreaks of the spruce beetle, *Dendroctonus rufipennis* (Kirby), in Utah and Colorado (Hebertson and Jenkins 2008). CART analysis was used to identify several factors influencing colony collapse disorder (CCD) of honey bees *Apis mellifera* (L.) (vanEngelsdorp et al. 2010). Although CART analysis is a relatively new technique for insect data analysis, it is ideally suited for complex ecological data. It can handle nonlinear relationships, high-order interactions

and missing values and is not constrained by the restrictions placed on widely used multi-regression analysis tools.

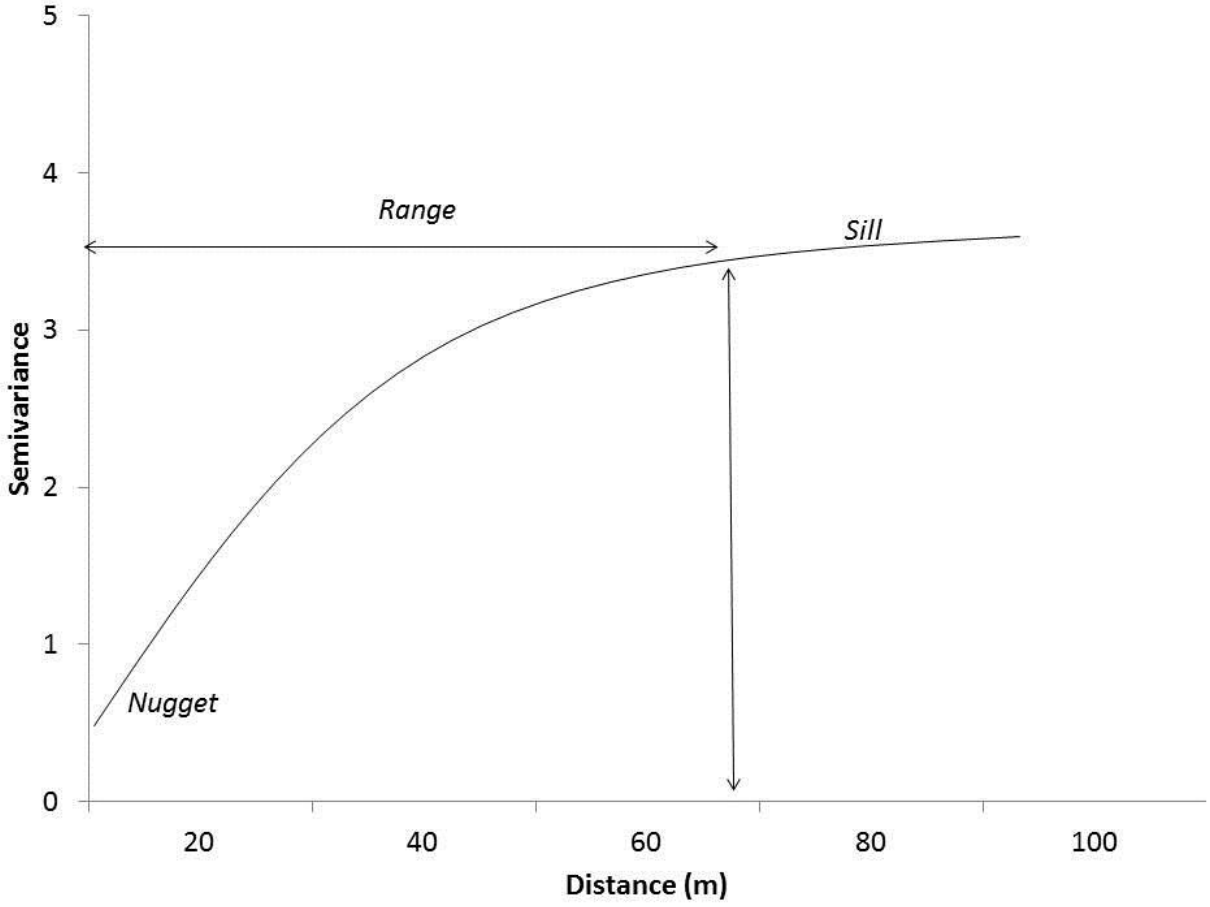


Figure 2-1. An example of a variogram used in geostatistical analysis

# CHAPTER 3
# SPATIAL AND TEMPORAL DISTRIBUTION OF *BEMISIA TABACI* AND TYLCV IN TOMATO

## Purpose

Biotype B of the sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), also known as the silverleaf whitefly, *B. argentifolii* (Bellows and Perring), is a serious pest of many agricultural crops around the world (Perring et al. 1993). Biotype B has become the key insect pest of tomatoes, *Solanum lycopersicum* (L.), in south Florida (Schuster et al. 1996a), displacing the native non-B biotypes (McKenzie et al. 2004). Biotype B of *B. tabaci* can cause direct damage to tomatoes including an irregular ripening disorder of fruit, inhibition of fruit softening and general reduction of plant vigor (Schuster et al. 1996b, Schuster 2001, McCollum et al. 2004). In Florida, *B. tabaci* has become a limiting pest species due to its ability to vector plant viruses such as *Tomato yellow leaf curl virus* (TYLCV) (family *Geminiviridae,* genus *Begomovirus*) (Polston et al. 1999). TYLCV causes one of the most devastating diseases of cultivated tomato world-wide. Infection by TYLCV can result in losses of up to 100% in tropical and subtropical regions and can be the limiting factor in commercial tomato production (Czosnek and Laterrot 1997). TYLCV is transmitted in a persistent, circulative manner by *B. tabaci* and symptoms of infection in tomato include upward curling of leaflet margins, reduction of leaflet area, yellowing of young leaves, stunting of plants and abscission of flowers (Polston et al. 1999). With these symptoms there is considerable loss in plant vigor and significant yield loss if infection occurs during early growth. Symptoms are expressed in tomato approximately 2-3 weeks post infection (Rom et al. 1993).

Like most insects, *B. tabaci* is aggregated both within individual leaves and within-plants at all life stages (Naranjo 1996). *B. tabaci* populations are aggregated on cotton and tomato plants within fields, although a better understanding of the spatial and temporal dynamics at the field scale and larger is needed (Naranjo and Flint 1995, Naranjo 1996, Polston et al. 1996, Naranjo et al. 2010). Spatial and temporal structure of pest populations can be very important and studies on spatial patterns could provide a better understanding of pest dynamics and refine sampling plans (Naranjo and Flint 1995, Byrne et al. 1996, Naranjo 1996). With the increased significance of *B. tabaci* and TYLCV as limiting factors on world-wide commercial tomato production, there is a need for a better understanding of their population dynamics; therefore, spatio-temporal dynamics of *B. tabaci* and TYLCV were evaluated in tomato using Geographical Information Systems (GIS) and Spatial Analyses by Distance IndicEs (SADIE).

GIS are tools for studying and mapping the spatial relationship of unknown variables. Interpolation can provide population densities at points not sampled. One interpolation method that is simple to use and can be used with limited sampling points is inverse distance weighted (IDW) (Kravchenko 2003). IDW interpolates values using a linearly weighted combination of a set of sampled points and assumes the variable being mapped decreases in influence with distance from its sampled location. IDW has been used to interpolate insect populations including stinkbugs, buprestids, cereal beetles and corn rootworms (Beckler et al. 2005, Bonsignore et al. 2008, Tillman et al. 2009, Reay-Jones 2010).

SADIE was developed to quantify spatial patterns of organisms and can be used for insect count data. SADIE measures the degree of clustering in geo-referenced data

and, unlike most geostatistical methods, SADIE is based on discrete count data and its results are conditional to the observed heterogeneity of the data (Xu and Madden 2004). SADIE has been used to describe spatial patterns in insects and plant diseases (Turechek and Madden 1999, Dallot et al. 2003, Park et al. 2006, Reay-Jones et al. 2010).

## Methods and Materials

### Study Sites

Populations of *B. tabaci* and TYLCV incidence were monitored on commercial tomato farms for four seasons in central Florida. Farm sizes ranged from 23.6 to 273.0 ha and were located in a study area of ≈ 53.8 $km^2$ in Manatee Co., Florida. The farms were selected because they were spatially isolated by distances over 10 km from other commercial tomato production. *B. tabaci* is capable of traveling ≈ 7 km, with most migration under ≈ 2.7 km (Cohen et al. 1988, Byrne 1999). Farms were managed by commercial growers so pesticide sprays and cultural practices were based on standard grower practices. There were cultivar differences between and within farms and all samples were taken on plastic-cultured, staked and tied tomatoes.

Twice weekly sampling by scouts was initiated as each field was transplanted and included adult whitefly counts (total number of adults on 6 contiguous plants) and incidence of TYLCV infection (visual inspection of 50 contiguous plants). Before first tie (≈ 3-4 weeks after transplanting), whitefly counts were taken on whole plant samples and after first tie, counts were taken on the abaxial surface from two leaves at the third node from the top of two branches on each of the six plants, using a leaf turn technique (Naranjo et al. 1995, Palumbo et al. 1995). The incidence of TYLCV-infected plants was based on the presence of characteristic foliar symptoms and was considered

cumulative throughout the growing season. Scouts were trained to only record tomato plants with unequivocal symptoms of TYLCV infection, which included upward curling of leaves, reduction of leaflet area and yellowing of young leaves (Polston et al. 1999). The growers' farms were divided into blocks and sampling points remained constant throughout the season (i.e. the same 6 plants were used for *B. tabaci* counts and the same 50 plants were evaluated for incidence of TYLCV infection). Along with scouting methodology, the total number of sample sites was determined by previous work by Schuster et al. (2007b) and the number of sample points was determined by block size within farms. The area of tomatoes sampled, the number of sample points, the sample density (ha/sample) and the duration of sampling varied by season (Table 3-1). Sampling varied throughout the season because certain fields were planted at different times, pesticide applications kept scouts from entering fields, or rain events postponed scouting efforts. At the beginning of each season, geographical positioning system (GPS) coordinates were collected using a GeoExplorer 3000 Series (Trimble©). Data coordinates were converted from decimal degrees to Universal Transverse Mercator (UTM) coordinate system using ArcGIS 9.2 (ESRI 2006). UTM is an adaptation of the Mercator projection and is based on distance in meters.

**Data Analyses**

Spatial and temporal distribution of *B. tabaci* and TYLCV incidence was interpolated using IDW, a statistical method in GIS software ArcView 9.2 (ESRI 2006). IDW is based on the assumption that points close by are more closely related than points farther apart, and estimated predictions are based on values at sampled locations. Values are determined using a linear weighted combination of observed values and those weights are functions of the distance between locations. The most

commonly used weighed power of two was used. Unlike other interpolation methods, IDW does not require a variogram model and is appropriate for small data sets (Kravchenko 2003). Cross validation was used to estimate the fit of the IDW model. Cross validation removes one sample point at a time and compares observed and predicted values for that point (Isaaks and Srivastava 1989). The root mean square prediction error (RMSE) produced by cross validation is presented as the summary statistic to check the accuracy of the model. IDW maps were created using seasonal means of *B. tabaci* adults and totals of final TYLCV incidence. Underlying digital images in the form of digital orthographic photos were downloaded from the Land Boundary Information System (LABINS 2011).

SADIE (version 1.22) analyses of adult *B. tabaci* were conducted on year end means over the entire season (Perry et al. 1999). TYLCV incidence, expressed as a percentage of 50 plants, was subjected to SADIE analysis using the final cumulative seasonal virus incidence per sampling point. Spatial scales were evaluated at the level of the entire sampling area and within farms. Additionally, weekly adult *B. tabaci* and TYLCV incidence was subjected to SADIE analyses over the entire tomato growing season to analyze the spatio-temporal distribution.

The purpose of SADIE is to quantify the spatial pattern by calculating the distance to regularity ($D$), defined as the minimum distance to which individuals in a sample would have to move to result in a uniform distribution. The overall aggregation index $I_a$ is defined as $D/E_a$, where $E_a$ is the arithmetic mean distance to regularity for the randomized samples. Values of $I_a > 1$ suggest aggregation, $I_a < 1$ suggest a regular pattern and $I_a = 1$ indicates a random pattern (Perry 1998). The probability ($P$) is

derived after randomizations as a formal test of randomness: the null hypothesis of spatial randomness is rejected at $\alpha = 0.1$ ($P < 0.05$, aggregation or $P > 0.95$, uniformity). Similar levels of significance are presented in other spatio-temporal insect studies (Kim et al. 2007, Park et al. 2009, Reay-Jones et al. 2010). SADIE also provides overall clustering indices $\bar{v}_j$, indicating negative gap cluster and $\bar{v}_i$, indicating positive patch cluster to quantify the degree to which the count for each sample unit contributes to the overall degree of clustering. Random spatial pattern has clustering indices around 1. In the convenience of time and effort a total of 3900 randomizations were used for each test.

## Results

### Fall 2007

In the fall of 2007, 5351 data points were recorded for *B. tabaci* adults over the entire study area and season from 231 geo-referenced sample sites (Table 3-1). There was a maximum number of whiteflies of 121 per six plants, per sample, per day and a mean of 1.354 over all sample sites and sampling dates (Table 3-2). Farms had varying levels of adult whiteflies ranging from a daily maximum of 10 to 121 per sample site per day and seasonal means from 0.842 to 2.861 over entire farms and sampling dates (Table 3-2). The 232 geo-referenced sample sites were used to record the final virus per farm and the progression of virus over weeks. Final virus incidence maximums per farm ranged from 30% to 100%. Mean virus incidence averaged from final virus incidence levels per site ranged from 7.58% to 68.21% from individual farms (Table 3-2).

**Spring 2008**

In the spring of 2008, 7515 data points were recorded for *B. tabaci* adults from 334 sample sites (Table 3-1). The overall season high adult *B. tabaci* count was 45 per sample site, per day and the overall seasonal mean was 0.377 over all sampling sites (Table 3-3). Individual farms varied in whitefly pressure and had daily maximums of 8 to 45 and farm means from 0.076 to 0.569 over all sample dates (Table 3-3). In the spring of 2008, 334 sites were used for virus incidence measurement. Virus incidence was much lower than the previous season and farms had final virus incidence per sample site ranging from 2% to 14% incidence. Final mean virus incidence per farm varied from 0.17% to 3.49% (Table 3-3).

**Fall 2008**

In the fall of 2008, 4103 data points were recorded for *B. tabaci* adults from 226 sample sites (Table 3-1). *B. tabaci* counts were similar to spring of 2008 with an overall season high of 45 whiteflies per sample site and a seasonal mean of 0.47 (Table 3-4). Adult whitefly maximum counts on individual farms ranged from 3 to 45 and means from 0.218 to 1.591 (Table 3-4). The maximum virus incidence was 32% at one sample site over the entire sampling area. Levels of final overall virus incidence ranged from 0% to 32% and final mean virus incidence per farms varied from 0% to 6.55% (Table 3-4).

**Spring 2009**

During the spring of 2009, 4121 data points were recorded for *B. tabaci* adults from 372 geo-referenced samples (Table 3-1). During this season the lowest *B. tabaci* counts were taken over the entire study (Table 3-5). The maximum number of whiteflies over all sample sites, over the entire season was 4 and the overall mean was 0.1 (Table 3-5). *B. tabaci* adult maximum counts per farm ranged from 2 to 4 and means from

0.081 to 0.149 (Table 3-5). Like *B. tabaci* counts, TYLCV incidence was much lower, with a maximum virus incidence per sample site over the entire study area of 2%. Final mean virus incidence per farm varied from 0% to 0.211% (Table 3-5).

**IDW Interpolation**

For interpolation methods such as IDW, mean error and root mean square error (RMSE) from cross validation tests can be used to evaluate how precise the method is producing interpolation maps. The value of the root mean square error depends on the scale of the data, so overall adult whitefly RMSE were lower than TYLCV incidence RMSE (Table 3-6). Smaller RMSE indicate a better fit of the model to the observed data. Overall, mean errors were low, indicating good estimates of *B. tabaci* populations and TYLCV incidence (Table 3-6) (Figures 3-1 to 3-11). Similar RMSE were presented for other IDW interpolation maps of insect counts (Tillman et al. 2009, Reay-Jones et al. 2010).

**SADIE Analysis**

Significant aggregation (positive $I_a$ values) over all sample sites from seasonal means of *B. tabaci* and seasonal incidence of TYLCV was found in fall 2007, spring 2008, and fall 2008 (Table 3-2, 3-3, and 3-4). Within those three seasons, populations also showed a strong presence of gap (negative $\bar{v}_j$) and patchiness (positive $\bar{v}_i$). Individual farms had varying levels of overall aggregation and in fall 2007, using seasonal means, *B. tabaci* was significantly aggregated in 16.7% of the farms and TYLCV incidence was aggregated in 50% of the farms (Table 3-2). There was also significant clustering into gaps in the fall 2007. In the spring of 2008, only Farm J had significantly aggregated populations of *B. tabaci* and incidence of TYLCV (Table 3-3). In the fall of 2008, 40% of the farms had seasonal mean aggregation of *B. tabaci* and

none showed significant aggregation of TYLCV incidence. Significant patch and gap clusters varied (Table 3-4). In the spring of 2009, there were no significantly aggregated populations of *B. tabaci* or incidence of TYLCV (Table 3-5).

Weekly adult *B. tabaci* means and TYLCV incidence at the last virus incidence per week were subjected to SADIE analysis. In the interest of space, only aggregation indices and their associated probabilities are presented. Weekly populations varied in distribution throughout each season. In the fall of 2007, *B. tabaci* populations were significantly aggregated in 14.7% and significantly uniform in 2.1% of farms per weeks sampled (Table 3-7). TYLCV incidence was significantly aggregated in 30% and significantly uniform in 2.5% of farms per weeks sampled (Table 3-8). In the spring of 2008, *B. tabaci* were significantly aggregated in 37.0% of farms per weeks sampled (Table 3-9). TYLCV was significantly aggregated in 36.4% and significantly uniform in 4.6% of farms per weeks sampled (Table 3-10). In the fall of 2008, *B. tabaci* were significantly aggregated 23.1% and significantly uniform in 1.9% of farms per weeks sampled (Table 3-11). TYLCV was significantly aggregated in 14.8% and significantly uniform in 3.7% of farms per weeks sampled (Table 3-12). In the spring of 2009, *B. tabaci* were significantly aggregated in 7.3% and significantly uniform in 7.4% of farms per weeks sampled (Table 3-13). TYLCV was not significantly aggregated or uniform on any farm at any week sampled (Table 3-14).

## Discussion

The sampling of adult *B. tabaci* and TYLCV across commercial Florida tomato farms combined with mapping of their distribution and analyses by SADIE has produced a much more detailed explanation of distribution than previously reported. SADIE confirmed the dynamic distribution of *B. tabaci* populations and showed *B. tabaci*

tended to be aggregated within the study area and within individual farms. Results showed that TYLCV distribution tended to follow spatio-temporal patterns associated with its vector. Strong spatial dependence in insect data indicates that estimating populations at unsampled locations is possible (Liebhold et al. 1993).

With the use of IDW, a map allows for visual expression of pest populations, which is valuable to researchers and farm managers. From IDW maps created by seasonal means, visual expression of seasonal populations of whiteflies and TYLCV can be evaluated. In some farms, including Farms A, C, and D from fall 2007, seasonal mean IDW maps indicated little to no evidence of adult whiteflies distributing uniformly throughout the farms. Rather, populations appeared to be aggregated along field edges (Figures 3-1 and 3-2). This edge effect was also apparent in other farms regardless of the scale of whitefly density as was observed in Farms E and F from fall 2007; Farms I and J from spring 2008; and Farms C, L, E, and F from fall 2008 (Figures 3-3, 3-5, 3-6, 3-7, 3-8, and 3-9). Even in years with very low *B. tabaci* pressure, such as in spring 2009, IDW maps faintly indicated edge effects as in Farms H and J (Figures 3-10 and 3-11). Some farms, such as Farms B and G in fall 2007 and Farm B in spring 2009, indicated populations of whiteflies scattered across the farm with no indication of edge effects (Figure 3-1, 3-4, and 3-10). Other observations suggested that some adult *B. tabaci* populations were located on the northwest and southeast corners of farms, as indicated by the following IDW maps: Farms A, D, and E fall 2007; Farm J Spring 2008; and Farm L Fall 2008 (Figures 3-1, 3-2, 3-3, 3-6, and 3-8). Seasonal means do not take into consideration daily fluctuations of *B. tabaci* within the farm ecosystem which could be influenced by surrounding crops or habitats or by events including weather (wind,

rain, etc.), pesticide applications or grower cultural manipulations (pruning, staking, tying, etc.). However, maps of seasonal means of *B. tabaci* describe the overall trends among and across sampled farms.

SADIE analysis provided tools to evaluate population distributions within the study area at multiple spatial scales. Over the entire study area, distributions of whiteflies were significantly aggregated in every season except spring 2009. This corroborates previous research about the aggregated distribution of *B. tabaci* in tomato and other crops (Naranjo and Flint 1995, Polston et al. 1996). Significant $I_a$ and clustering into gaps and patches indicated that populations were highly spatially aggregated and there were large areas with few or no whiteflies (Tables 3-2, 3-3 and 3-4). Xu and Madden (2004) suggested that the $I_a$ index was more influenced by the number and position of clusters rather than the cluster size. A limitation of SADIE is that the geographic position of aggregated clusters is not taken into account. However, where the aggregation occurs in geographic space (e.g. edge of tomato field) plays a role in determining causes for abundance of *B. tabaci* and plant expressing symptoms of TYLCV. Recent work (Taylor, unpublished) points to populations of *B. tabaci* and plants expressing symptoms of TYLCV influenced by unknown reservoir sources surrounding tomato fields with populations of both *B. tabaci* and TYLCV being influenced greatly by distance to field edge.

Weekly fluctuations in aggregation indicate either a highly mobile pest species or one that has many dynamic variables influencing distribution. Although aggregation varied throughout each season within farms, some interesting conclusions can be drawn from individual farms. In Farms A, D, and G from fall 2007; Farms H and J from

spring 2008; Farms C, L, and E from fall 2008; and Farms I and J from spring 2009; significant aggregation of *B. tabaci* adults was shown in some of the earliest sampling dates but showed more random trends in later weeks (Tables 3-7, 3-9, 3-11 and 3-13). Some of those farms that had earlier significant *B. tabaci* aggregated populations had brief periods of significant re-aggregation 6 to 10 weeks later. In contrast to this observation, the corn leaf aphid, *Rhopalosiphum maidis* (Fitch), a dynamic pest of field corn, was aggregated during the peak populations in the middle of the crop and randomly distributed early and late in the crop (Park and Obrycki 2004). Though it is unclear biologically what was influencing the periods of re-aggregation in this study, it is possible that re-introduction of adult *B. tabaci*, in-farm reproduction, or management tactics were influencing population distribution. Pesticides, which are a central tactic for controlling *B. tabaci* and the TYLCV it vectors, have been shown to alter the dispersion patterns of whiteflies (Liu et al. 1993b, Tonhasca et al. 1994).

As expected, the distribution of plants with symptoms of TYLCV was more static than the distribution of *B. tabaci*. TYLCV symptom expression lags behind *B. tabaci* populations by 2-3 weeks; therefore, significant aggregation indices of TYLCV were delayed. In the fall of 2007, every farm except Farm F had at least one week of significant aggregation of TYLCV incidence (Table 3-8). Farms B, C, and E had significant aggregation indices through almost the entire season, suggesting re-introduction of whiteflies in the same areas or secondary spread after the initial introduction (Table 3-8). Similar results were suggested from Farm J in spring 2008 and Farm F in fall 2008 (Tables 3-10 and 3-12). Other farms such as Farms A and D from fall 2007 and Farm H from spring 2008 had brief significantly aggregated distributions in

the early to middle of the season before returning to a random distribution (Tables 3-8 and 3-10). Farm G in fall 2007, Farm I in spring 2008 and Farm C in fall 2008 had significant weekly uniform distributions of TYLCV and tended towards uniformity over the entire season (Tables 3-8, 3-10, and 3-12).

Traditional indices for determining non-randomness, such as variance-mean ratios, do not include the spatial patterns of sample points. SADIE analysis, which uses spatial patterns, was developed for highly dynamic populations and takes into account extremely patchy counts, many counts of zeros and dynamic populations over space and time. SADIE analysis demonstrated aggregated populations of *B. tabaci* in tomato which confirmed earlier work with other indices (Polston et al. 1996). Spatial patterns of *B. tabaci* and TYLCV demonstrated different patterns within some farms while patterns were very similar in other farms. This could be explained by the movement of *B. tabaci* populations that were able to transmit TYLCV.

Analysis with IDW indicated edge effects and aggregated populations in certain areas of many farms. Future work could encompass more area or increase the level of sampling. Future work could also include geostatistical analysis of this data set and use of semivariograms and kriging rather than deterministic methods such as IDW. Semivariograms express the variance of sample pairs against the distance between sample points and provide important ecological information on the spatial patterns of organisms. These spatial patterns could be used to indicate the distance between sampling locations to derive sampling plans which require independent samples. Unlike IDW, kriging prediction maps use geostatistical methods and are based on statistical models that include autocorrelation or the correlation of a variable with itself through

space. Kriging can provide a certainty and accuracy of the predictions, even though it is more complicated to produce and requires data exploration before a map can be produced. Highly dynamic populations such as those seen in insect count data increase the level of uncertainty in geostatistical analysis and much work will have to be conducted to create validated results. One criticism of the utility of geostatistics in applied agriculture is the high level of understanding of mathematical concepts.

*B. tabaci* is a mobile pest and has been shown in the present study to have varying aggregation in both space and time. The dynamic distribution patterns are more likely driven by hosts outside tomato because IDW maps and SADIE analyses suggest that most populations arose from outside of the sampled farms. Cultivated crop hosts of *B. tabaci* grown relatively close to tomato and old tomato fields have been indicated as hosts of *B. tabaci* and TYLCV (Polston and Lapidot 2007). Weeds can be important hosts for *B. tabaci* and TYLCV, and in a heterogeneous landscape weeds could be heavily influencing populations in tomato. *B. tabaci* has a host range of over 600 plant species (Mound and Halsey 1978, Greathead 1986, Secker et al. 1998). Future work will need to be conducted to evaluate which weed hosts are the most important reservoirs of both *B. tabaci* and TYLCV.

Table 3-1. Total scouting area and sample sites, 2007-2009

| Season | Total ha Scouted | Sample Sites | Mean ha per sample | Samples Taken | Mean Number of Samples per site | Scouting Initiated | Scouting Ended |
|---|---|---|---|---|---|---|---|
| Fall 2007 | 318.9 | 231 | 1.4 | 5351 | 23.2 | 8/17/07 | 12/11/07 |
| Spring 2008 | 489.2 | 334 | 1.5 | 7515 | 22.5 | 1/15/08 | 5/1/08 |
| Fall 2008 | 268.0 | 226 | 1.2 | 4103 | 18.2 | 8/28/08 | 12/4/08 |
| Spring 2009 | 641.7 | 372 | 1.7 | 4121 | 11.1 | 2/19/09 | 5/22/09 |

Table 3-2. Summary data for distribution of *B. tabaci* adults and TYLCV incidence including SADIE analysis, Fall 2007

| Farm | Variable[a] | Mean | Min | Max | Std. Dev. | N | $I_a$[b] | $P$[c] | Mean $ō_j$ | $P_j$[c] | Mean $ō_i$ | $P_i$[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Overall | AW | 1.354 | 0 | 121 | 4.459 | 5351 | 2.87* | < 0.001 | -3.108* | < 0.001 | 3.03* | < 0.001 |
| | TYLCV | 29.672 | 0 | 100 | 26.650 | 232 | 2.59* | < 0.001 | -3.132* | < 0.001 | 2.18* | 0.045 |
| A | AW | 1.051 | 0 | 45 | 3.235 | 877 | 2.27* | 0.004 | -2.270* | 0.002 | 1.38 | 0.110 |
| | TYLCV | 38.821 | 4 | 82 | 22.774 | 39 | 1.148 | 0.251 | -1.134 | 0.261 | 0.117 | 0.272 |
| B | AW | 0.468 | 0 | 16 | 1.430 | 1278 | 0.865 | 0.791 | -0.834 | 0.847 | 0.864 | 0.779 |
| | TYLCV | 20.536 | 0 | 96 | 21.947 | 56 | 1.718* | 0.002 | -1.807* | 0.001 | 1.229 | 0.116 |
| C | AW | 0.842 | 0 | 10 | 1.758 | 317 | 0.821 | 0.763 | -0.9 | 0.618 | 0.948 | 0.537 |
| | TYLCV | 11.067 | 0 | 30 | 7.554 | 15 | 1.164 | 0.177 | -1.075 | 0.290 | 1.253 | 0.107 |
| D | AW | 1.628 | 0 | 116 | 6.469 | 749 | 1.311 | 0.069 | -1.392* | 0.041 | 1.125 | 0.192 |
| | TYLCV | 30.063 | 4 | 66 | 18.854 | 32 | 1.486* | 0.024 | -1.882* | 0.002 | 1.368 | 0.053 |
| E | AW | 2.861 | 0 | 60 | 6.001 | 792 | 1.124 | 0.238 | -1.072 | 0.327 | 0.961 | 0.511 |
| | TYLCV | 68.214 | 10 | 100 | 24.162 | 28 | 1.486* | 0.024 | -1.882* | 0.002 | 1.368 | 0.053 |
| F | AW | 1.928 | 0 | 121 | 6.188 | 751 | 0.771 | 0.446 | -0.334 | 0.527 | 0.69 | 0.365 |
| | TYLCV | 32.138 | 2 | 96 | 24.802 | 29 | 0.458 | 0.692 | -0.399 | 0.449 | 1.045 | 0.198 |
| G | AW | 0.894 | 0 | 16 | 1.701 | 587 | 0.915 | 0.572 | -1 | 0.419 | 0.817 | 0.820 |
| | TYLCV | 7.576 | 0 | 36 | 7.981 | 33 | 0.936 | 0.531 | -0.928 | 0.536 | 0.963 | 0.465 |

Note: [a] Variable AW equals adult *B. tabaci* and TYLCV equals cumulative TYLCV incidence. [b] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern (< 1). [c] P value for null hypothesis of spatial randomness. * values indicate significant indices for $\alpha = 0.1$ ($P < 0.05$).

Table 3-3. Summary data for distribution of *B. tabaci* adults and TYLCV incidence including SADIE analysis, Spring 2008

| Farm | Variable[a] | Mean | Min | Max | Std. Dev. | N | $I_a$[b] | $P$[c] | Mean $\bar{v}_j$ | $P_j$[c] | Mean $\bar{v}_i$ | $P_i$[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Overall | AW | 0.377 | 0 | 45 | 1.732 | 7515 | 6.276* | < 0.001 | -8.244* | < 0.001 | 7.567* | < 0.001 |
| | TYLCV | 0.743 | 0 | 14 | 1.967 | 334 | 3.52* | < 0.001 | -4.312* | < 0.001 | 2.413* | 0.005 |
| H | AW | 0.076 | 0 | 14 | 0.405 | 4315 | NA | NA | NA | NA | NA | NA |
| | TYLCV | 0.172 | 0 | 6 | 0.764 | 151 | 0.977 | 0.443 | -0.993 | 0.431 | 1.032 | 0.363 |
| I | AW | 0.569 | 0 | 30 | 1.920 | 2027 | 1.094 | 0.261 | -1.075 | 0.288 | 1.156 | 0.181 |
| | TYLCV | 0.207 | 0 | 6 | 0.763 | 116 | 0.974 | 0.465 | -0.949 | 0.522 | 1.078 | 0.276 |
| J | AW | 1.225 | 0 | 45 | 3.516 | 1051 | 2.69* | < 0.001 | -3.118* | < 0.001 | 1.64* | 0.046 |
| | TYLCV | 3.491 | 0 | 14 | 3.378 | 55 | 3.447* | < 0.001 | -4.097* | < 0.001 | 2.723* | < 0.001 |
| K | AW | 0.770 | 0 | 8 | 1.589 | 122 | 1.409 | 0.076 | -1.611* | 0.043 | 1.410 | 0.102 |
| | TYLCV | 0.833 | 0 | 2 | 1.030 | 12 | 0.852 | 0.679 | -0.835 | 0.652 | 0.770 | 0.817 |

Note: [a] Variable AW equals adult *B. tabaci* and TYLCV equals cumulative TYLCV incidence. [b] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern (< 1). [c] P value for null hypothesis of spatial randomness. * values indicate significant indices for $\alpha = 0.1$ ($P < 0.05$).

Table 3-4. Summary data for distribution of B. tabaci adults and TYLCV incidence including SADIE analysis, Fall 2008

| Farm | Variable[a] | Mean | Min | Max | Std. Dev. | N | $I_a$[b] | $P$[c] | Mean $\bar{v}_j$ | $P_j$[c] | Mean $\bar{v}_i$ | $P_i$[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Overall | AW | 0.470 | 0 | 45 | 2.105 | 4103 | 2.977* | < 0.001 | -3.595* | < 0.001 | 3.218* | < 0.001 |
| | TYLCV | 2.352 | 0 | 32 | 4.414 | 226 | 1.92* | 0.005 | -1.756* | 0.037 | 1.305 | 0.151 |
| A | AW | 0.293 | 0 | 3 | 0.219 | 307 | NA | NA | NA | NA | NA | NA |
| | TYLCV | 0.000 | 0 | 0 | 0 | 22 | NA | NA | NA | NA | NA | NA |
| C | AW | 0.267 | 0 | 6 | 0.670 | 719 | 0.995 | 0.434 | -0.99 | 0.458 | 0.982 | 0.500 |
| | TYLCV | 2.100 | 0 | 14 | 3.536 | 40 | 0.864 | 0.800 | -0.931 | 0.583 | 0.817 | 0.864 |
| E | AW | 1.591 | 0 | 45 | 4.247 | 492 | 1.518* | 0.015 | -1.476* | 0.021 | 1.307 | 0.076 |
| | TYLCV | 6.552 | 0 | 32 | 8.798 | 29 | 1.329 | 0.057 | -1.287 | 0.070 | 1.594* | 0.011 |
| F | AW | 0.218 | 0 | 15 | 0.752 | 898 | 1.512* | 0.045 | -1.4 | 0.080 | 1.605* | 0.046 |
| | TYLCV | 1.509 | 0 | 10 | 2.599 | 53 | 1.380 | 0.091 | -1.268 | 0.143 | 1.467 | 0.069 |
| L | AW | 0.225 | 0 | 4 | 0.564 | 1687 | 1.564 | 0.061 | -1.646* | 0.047 | 1.646 | 0.449 |
| | TYLCV | 1.927 | 0 | 14 | 2.905 | 82 | 0.777 | 0.722 | -0.794 | 0.719 | 0.935 | 0.468 |

Note: [a] Variable AW equals adult *B. tabaci* and TYLCV equals cumulative TYLCV incidence. [b] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern (< 1). [c] P value for null hypothesis of spatial randomness. * values indicate significant indices for $\alpha = 0.1$ ($P < 0.05$).

Table 3-5. Summary data for distribution of *B. tabaci* adults TYLCV incidence including SADIE analysis, Spring 2009

| Farm | Variable[a] | Mean | Min | Max | Std. Dev. | N | $I_a$[b] | $P$[c] | Mean $\bar{v}_j$ | $P_j$[c] | Mean $\bar{v}_i$ | $P_i$[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Overall | AW | 0.100 | 0 | 4 | 0.370 | 4121 | 0.758 | 0.679 | -0.778 | 0.647 | 0.820 | 0.591 |
| | TYLCV | 0.070 | 0 | 2 | 0.368 | 372 | 1.488 | 0.107 | -1.600 | 0.074 | 1.802* | 0.047 |
| B | AW | 0.105 | 0 | 4 | 0.367 | 840 | NA | NA | NA | NA | NA | NA |
| | TYLCV | 0.070 | 0 | 2 | 0.371 | 57 | 1.107 | 0.256 | -1.100 | 0.264 | 1.137 | 0.209 |
| H | AW | 0.101 | 0 | 3 | 0.363 | 2073 | 0.976 | 0.441 | -0.964 | 0.460 | 1.039 | 0.376 |
| | TYLCV | 0.034 | 0 | 2 | 0.260 | 176 | 1.048 | 0.335 | -1.014 | 0.386 | 1.078 | 0.304 |
| I | AW | 0.081 | 0 | 4 | 0.336 | 1047 | 1.074 | 0.284 | -1.080 | 0.278 | 1.167 | 0.175 |
| | TYLCV | 0.000 | 0 | 0 | 0 | 120 | NA | NA | NA | NA | NA | NA |
| J | AW | 0.149 | 0 | 4 | 0.550 | 161 | 1.306 | 0.108 | -1.353 | 0.079 | 0.993 | 0.948 |
| | TYLCV | 0.211 | 0 | 2 | 0.631 | 19 | 1.063 | 0.293 | -1.031 | 0.346 | 1.164 | 0.174 |

Note: [a] Variable AW equals adult *B. tabaci* and TYLCV equals cumulative TYLCV incidence. [b] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern (< 1). [c] P value for null hypothesis of spatial randomness. * values indicate significant indices for $\alpha = 0.1$ ($P < 0.05$).

Table 3-6. Cross validation results of IDW interpolation analysis for *B. tabaci* means and final TYLCV incidence, 2007-2009

| Season | Farm | Adult *B. tabaci* Mean Error | Adult *B. tabaci* RSME[a] | TYLCV Incidence Mean Error | TYLCV Incidence RMSE[a] |
|---|---|---|---|---|---|
| Fall 2007 | A | -0.013 | 0.559 | -0.249 | 22.670 |
| | B | 0.008 | 0.265 | 0.054 | 22.090 |
| | C | -0.029 | 0.361 | 0.717 | 8.496 |
| | D | -0.092 | 0.555 | -1.210 | 15.310 |
| | E | -0.227 | 2.812 | -1.205 | 19.510 |
| | F | -0.061 | 1.704 | 0.566 | 25.680 |
| | G | -0.069 | 0.564 | -0.140 | 8.940 |
| Spring 2008 | H | 0.001 | 0.079 | -0.007 | 0.801 |
| | I | 0.020 | 0.549 | 0.031 | 0.776 |
| | J | -0.064 | 1.015 | -0.117 | 2.904 |
| | K | -0.050 | 0.408 | 0.016 | 1.390 |
| Fall 2008 | A | 0.000 | 0.043 | NA | NA |
| | C | -0.016 | 0.235 | -0.297 | 3.938 |
| | E | -0.051 | 0.820 | -0.622 | 8.271 |
| | F | -0.012 | 0.242 | 0.101 | 3.203 |
| | L | -0.015 | 0.165 | -0.096 | 3.320 |
| Spring 2009 | B | -0.012 | 0.112 | -0.011 | 0.387 |
| | H | -0.008 | 0.138 | 0.000 | 0.295 |
| | I | 0.004 | 0.139 | NA | NA |
| | J | -0.005 | 0.206 | 0.019 | 0.697 |

Note: Adult *B. tabaci* counts were summarized by averages of whiteflies taken over all dates and sampling points from farms. TYLCV Incidence was taken from the last scouting date of the season and presented as the cumulative virus incidence over the entire season per farm. [a] Smaller root mean square error (RMSE) indicates a better fit of the model.

Table 3-7. Weekly SADIE aggregation indices of adult *B. tabaci* counts, Fall 2007

| Date | Farm A | | Farm B | | Farm C | | Farm D | | Farm E | | Farm F | | Farm G | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] |
| 8/13 | 0.941 | 0.552 | NA | NA | NA | NA | NA | NA | 1.070 | 0.308 | 0.771 | 0.446 | NA | NA |
| 8/20 | 2.487* | 0.001 | 0.837 | 0.772 | 1.011 | 0.401 | 1.409* | 0.037 | 1.261 | 0.110 | 1.072 | 0.324 | NA | NA |
| 8/27 | 2.88* | <0.001 | 1.088 | 0.258 | 0.895 | 0.676 | 1.379* | 0.041 | 1.073 | 0.301 | 0.771 | 0.446 | NA | NA |
| 9/3 | 1.076 | 0.313 | 1.062 | 0.299 | 1.151 | 0.179 | 0.768* | 0.956 | 1.243 | 0.123 | 1.210 | 0.306 | NA | NA |
| 9/10 | 2.392* | 0.001 | 1.635* | 0.005 | 1.126 | 0.243 | 1.365 | 0.059 | 1.516* | 0.019 | 0.864 | 0.253 | 1.857* | 0.003 |
| 9/17 | 0.873 | 0.607 | 1.117 | 0.214 | 0.774 | 0.933 | 1.126 | 0.240 | 1.228 | 0.120 | 0.299 | 0.865 | 1.862* | 0.003 |
| 9/24 | 1.380 | 0.107 | 1.219 | 0.109 | 0.936 | 0.586 | 0.815 | 0.892 | 1.113 | 0.235 | 0.502 | 0.804 | 1.262 | 0.132 |
| 10/1 | 1.121 | 0.274 | 0.789 | 0.938 | 0.947 | 0.577 | 1.023 | 0.377 | 1.076 | 0.314 | 0.353 | 0.570 | 1.497* | 0.040 |
| 10/8 | 0.914 | 0.545 | 1.336* | 0.048 | 1.045 | 0.295 | 0.825 | 0.849 | 1.169 | 0.200 | 0.453 | 0.687 | 0.861 | 0.682 |
| 10/15 | 1.135 | 0.257 | 0.952 | 0.549 | 0.947 | 0.577 | 1.180 | 0.142 | 1.082 | 0.309 | 0.971 | 0.146 | 1.364 | 0.084 |
| 10/22 | 2.604* | <0.001 | 0.917 | 0.637 | 0.895 | 0.702 | 1.290 | 0.063 | 1.439* | 0.027 | 1.464 | 0.167 | 0.801 | 0.820 |
| 10/29 | 1.263 | 0.158 | 0.977 | 0.484 | 0.985 | 0.439 | 1.023 | 0.367 | 1.132 | 0.232 | 0.548 | 0.758 | 1.215 | 0.146 |
| 11/5 | 1.494 | 0.106 | 1.035 | 0.350 | NA | NA | 0.771* | 0.954 | 1.357 | 0.062 | 1.012 | 0.328 | 1.204 | 0.163 |
| 11/12 | 1.518 | 0.095 | 1.107 | 0.261 | NA | NA | 0.824 | 0.853 | 1.187 | 0.163 | 0.795 | 0.235 | 1.129 | 0.250 |
| 11/19 | NA | NA | NA | NA | NA | NA | 1.108 | 0.259 | 0.976 | 0.484 | 0.631 | 0.809 | 1.452* | 0.049 |
| 11/26 | NA | NA | NA | NA | NA | NA | NA | NA | 0.892 | 0.668 | 0.880 | 0.492 | NA | NA |

Note: [a] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern (< 1). [b] $P$ value for null hypothesis of spatial randomness. * values indicate significant aggregation indices ($P < 0.05$) or significant uniform indices at ($P > 0.95$).

Table 3-8. Weekly SADIE aggregation indices of TYLCV incidence, Fall 2007

| Date | Farm A | | Farm B | | Farm C | | Farm D | | Farm E | | Farm F | | Farm G | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] |
| 8/13 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 8/20 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 8/27 | NA | NA | NA | NA | NA | NA | 1.218 | 0.114 | 0.984 | 0.470 | NA | NA | NA | NA |
| 9/3 | 0.865 | 0.643 | 1.064 | 0.433 | NA | NA | 1.304 | 0.068 | 0.866 | 0.744 | NA | NA | NA | NA |
| 9/10 | 0.871 | 0.611 | 0.857 | 0.779 | 1.004 | 0.466 | 1.389* | 0.039 | 1.098 | 0.260 | 0.518 | 0.282 | NA | NA |
| 9/17 | 0.854 | 0.625 | 0.896 | 0.689 | 0.814* | 0.950 | 1.320 | 0.063 | 1.418* | 0.040 | 0.646 | 0.762 | NA | NA |
| 9/24 | 0.864 | 0.620 | 1.035 | 0.353 | 0.936 | 0.586 | 1.175 | 0.163 | 1.659* | 0.007 | 1.223 | 0.373 | 1.263 | 0.132 |
| 10/1 | 0.798 | 0.728 | 1.487* | 0.016 | 1.511* | 0.012 | 1.175 | 0.163 | 1.676* | 0.004 | 0.994 | 0.467 | 0.664* | 0.986 |
| 10/8 | 1.337 | 0.128 | 1.499* | 0.016 | 1.646* | 0.005 | 1.186 | 0.152 | 1.559* | 0.014 | 1.049 | 0.349 | 1.296 | 0.102 |
| 10/15 | 1.454 | 0.086 | 1.527* | 0.014 | 1.553* | 0.009 | 1.235 | 0.104 | 1.455* | 0.028 | 1.161 | 0.228 | 0.876 | 0.660 |
| 10/22 | 1.657* | 0.040 | 1.254 | 0.092 | 1.602* | 0.008 | 1.308 | 0.061 | 1.58* | 0.012 | 0.840 | 0.489 | 0.914 | 0.574 |
| 10/29 | 1.157 | 0.240 | 1.458* | 0.017 | 1.403* | 0.036 | 1.240 | 0.101 | 1.488* | 0.027 | 0.648 | 0.522 | 0.876 | 0.676 |
| 11/5 | 1.005 | 0.404 | 1.443* | 0.022 | 1.307 | 0.070 | 1.285 | 0.070 | 1.574* | 0.016 | 0.314 | 0.772 | 1.012 | 0.390 |
| 11/12 | 1.148 | 0.251 | 1.779* | 0.001 | 1.164 | 0.177 | 1.271 | 0.086 | 1.515* | 0.023 | 0.586 | 0.534 | 1.022 | 0.367 |
| 11/19 | NA | NA | 1.718* | 0.002 | NA | NA | 1.284 | 0.083 | 1.486* | 0.024 | 0.458 | 0.692 | 0.936 | 0.531 |
| 11/26 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.640 | 0.566 | NA | NA |

Note: [a] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern (< 1). [b] $P$ value for null hypothesis of spatial randomness. * values indicate significant aggregation indices ($P < 0.05$) or significant uniform indices at ($P > 0.95$).

Table 3-9. Weekly SADIE aggregation indices of adult *B. tabaci* counts, Spring 2008

| Date | Farm H | | Farm I | | Farm J | | Farm K | |
|---|---|---|---|---|---|---|---|---|
| | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] |
| 1/21 | 0.749 | 0.925 | NA | NA | NA | NA | NA | NA |
| 1/28 | 1.627* | 0.027 | NA | NA | NA | NA | NA | NA |
| 2/4 | 1.883* | 0.010 | NA | NA | NA | NA | NA | NA |
| 2/11 | 1.532* | 0.045 | NA | NA | NA | NA | NA | NA |
| 2/18 | 1.883* | 0.010 | 1.120 | 0.233 | 2.243* | < 0.001 | NA | NA |
| 2/25 | 0.855 | 0.702 | 1.036 | 0.353 | 2.642* | < 0.001 | NA | NA |
| 3/3 | 0.962 | 0.458 | 0.840 | 0.786 | 1.858* | 0.014 | 0.987 | 0.506 |
| 3/10 | 0.931 | 0.521 | NA | NA | 1.807* | 0.012 | NA | NA |
| 3/17 | 0.837 | 0.711 | 0.943 | 0.524 | 0.951 | 0.502 | 1.093 | 0.272 |
| 3/24 | 1.531* | 0.044 | 1.444* | 0.050 | 0.782 | 0.797 | NA | NA |
| 3/31 | 0.967 | 0.454 | 1.299 | 0.102 | 1.73* | 0.026 | 1.66* | 0.017 |
| 4/7 | 1.283 | 0.114 | 0.851 | 0.747 | 1.375 | 0.094 | 0.762 | 0.952 |
| 4/14 | 1.006 | 0.405 | 2.044* | 0.001 | 1.049 | 0.345 | 1.359 | 0.081 |
| 4/21 | 1.309 | 0.104 | 1.769* | 0.004 | 1.093 | 0.288 | 1.025 | 0.373 |
| 4/28 | 2.48* | < 0.001 | 1.017 | 0.385 | 2.174* | 0.002 | 1.130 | 0.220 |
| 5/5 | 1.019 | 0.376 | 1.448* | 0.033 | 2.317* | 0.001 | NA | NA |
| 5/12 | 1.196 | 0.178 | 1.482* | 0.030 | 1.946* | 0.010 | 1.470 | 0.065 |
| 5/19 | NA | NA | 1.284 | 0.090 | 1.043 | 0.354 | 0.992 | 0.434 |
| 5/26 | NA | NA | 1.319 | 0.067 | NA | NA | NA | NA |

Note: [a] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern ( < 1). [b] $P$ value for null hypothesis of spatial randomness. * values indicate significant aggregation indices ($P < 0.05$) or significant uniform indices at ($P > 0.95$).

Table 3-10. Weekly SADIE aggregation indices of TYLCV incidence, Spring 2008

| Date | Farm H | | Farm I | | Farm J | | Farm K | |
|---|---|---|---|---|---|---|---|---|
| | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] |
| 1/21 | NA | NA | NA | NA | NA | NA | NA | NA |
| 1/28 | NA | NA | NA | NA | NA | NA | NA | NA |
| 2/4 | NA | NA | NA | NA | NA | NA | NA | NA |
| 2/11 | NA | NA | NA | NA | NA | NA | NA | NA |
| 2/18 | 0.994 | 0.418 | NA | NA | 1.783* | 0.019 | NA | NA |
| 2/25 | 1.136 | 0.232 | NA | NA | 2.202* | 0.002 | NA | NA |
| 3/3 | 1.136 | 0.232 | NA | NA | 2.067* | 0.006 | NA | NA |
| 3/10 | 1.136 | 0.232 | NA | NA | 1.672* | 0.032 | NA | NA |
| 3/17 | 1.403 | 0.075 | 0.728* | > 0.999 | 1.407 | 0.052 | NA | NA |
| 3/24 | 1.7* | 0.017 | 0.728* | > 0.999 | 2.341* | 0.001 | NA | NA |
| 3/31 | 1.986* | 0.004 | NA | NA | 3.014* | < 0.001 | NA | NA |
| 4/7 | 1.658* | 0.022 | 0.953 | 0.517 | 2.418* | 0.001 | 0.835 | 0.921 |
| 4/14 | 1.091 | 0.272 | 1.312 | 0.083 | 3.309* | < 0.001 | 0.835 | 0.921 |
| 4/21 | 1.288 | 0.118 | 0.985 | 0.449 | 2.385* | 0.001 | 0.835 | 0.921 |
| 4/28 | 1.327 | 0.096 | 0.854 | 0.738 | 3.393* | < 0.001 | 0.835 | 0.921 |
| 5/5 | 0.903 | 0.584 | 0.856 | 0.757 | 3.687* | < 0.001 | 0.835 | 0.921 |
| 5/12 | 0.977 | 0.443 | 0.974 | 0.473 | 3.206* | < 0.001 | 1.155 | 0.230 |
| 5/19 | NA | NA | 1.212 | 0.148 | 3.447* | < 0.001 | 0.852 | 0.679 |
| 5/26 | NA | NA | 0.974 | 0.465 | NA | NA | NA | NA |

Note: [a] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern ( < 1). [b] P value for null hypothesis of spatial randomness. * values indicate significant aggregation indices (P < 0.05) or significant uniform indices at (P > 0.95).

Table 3-11. Weekly SADIE aggregation indices of adult *B. tabaci* counts, Fall 2008

| Date | Farm A | | Farm C | | Farm E | | Farm F | | Farm L | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] |
| 8/25 | NA | NA | 1.096 | 0.233 | NA | NA | NA | NA | 1.297 | 0.066 |
| 9/1 | NA | NA | 1.539* | 0.006 | 1.279 | 0.093 | 1.033 | 0.339 | 1.664* | 0.003 |
| 9/8 | NA | NA | 1.248 | 0.088 | NA | NA | 0.902 | 0.581 | 2.974* | < 0.001 |
| 9/15 | 1.8* | 0.031 | 1.118 | 0.200 | 1.748* | 0.001 | 1.176 | 0.216 | 1.015 | 0.411 |
| 9/22 | 0.955 | 0.665 | 1.154 | 0.153 | 1.035 | 0.352 | 0.964 | 0.450 | 0.710 | 0.836 |
| 9/29 | NA | NA | 0.977 | 0.484 | 0.928 | 0.584 | 1.105 | 0.266 | 0.928 | 0.563 |
| 10/6 | NA | NA | 1.151 | 0.163 | NA | NA | 0.831 | 0.710 | 1.006 | 0.414 |
| 10/13 | NA | NA | 1.132 | 0.302 | 1.331 | 0.054 | 1.345 | 0.098 | 1.211 | 0.224 |
| 10/20 | NA | NA | 1.040 | 0.334 | 1.094 | 0.258 | 0.850 | 0.663 | 1.311 | 0.160 |
| 10/27 | NA | NA | 1.235 | 0.086 | 1.405* | 0.024 | 0.608* | 0.999 | 0.886 | 0.546 |
| 11/3 | NA | NA | 0.992 | 0.449 | 1.356* | 0.049 | 1.139 | 0.246 | 0.832 | 0.648 |
| 11/10 | 0.719 | 0.674 | 1.187 | 0.121 | 1.200 | 0.136 | NA | NA | 0.893 | 0.533 |
| 11/17 | NA | NA | 1.080 | 0.264 | 1.567* | 0.010 | 0.949 | 0.557 | NA | NA |
| 11/24 | NA | NA | NA | NA | 1.433* | 0.015 | 0.812 | 0.757 | 2.222* | 0.005 |

Note: [a] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern (< 1). [b] $P$ value for null hypothesis of spatial randomness. * values indicate significant aggregation indices ($P < 0.05$) or significant uniform indices at ($P > 0.95$).

Table 3-12. Weekly SADIE aggregation indices of TYLCV incidence, Fall 2008

| Date | Farm A | | Farm C | | Farm E | | Farm F | | Farm L | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] |
| 8/25 | NA | NA | 1.043 | 0.451 | NA | NA | NA | NA | NA | NA |
| 9/1 | NA | NA | 0.827 | 0.885 | NA | NA | NA | NA | 1.003 | 0.390 |
| 9/8 | NA | NA | 0.958 | 0.535 | NA | NA | NA | NA | 0.931 | 0.429 |
| 9/15 | NA | NA | 0.790 | 0.949 | 1.182 | 0.139 | NA | NA | 1.453 | 0.094 |
| 9/22 | NA | NA | 0.993 | 0.443 | 1.403* | 0.038 | 0.65* | 0.987 | 1.119 | 0.291 |
| 9/29 | NA | NA | 0.841 | 0.897 | 1.4* | 0.038 | 0.723 | 0.919 | 1.086 | 0.328 |
| 10/6 | NA | NA | 1.039 | 0.356 | 1.4* | 0.038 | 0.711 | 0.935 | 1.043 | 0.374 |
| 10/13 | NA | NA | 0.76* | 0.969 | 1.105 | 0.249 | 0.884 | 0.591 | 1.046 | 0.360 |
| 10/20 | NA | NA | 0.831 | 0.859 | 1.108 | 0.279 | 1.166 | 0.213 | 0.918 | 0.516 |
| 10/27 | NA | NA | 0.814 | 0.897 | 1.244 | 0.101 | 1.137 | 0.239 | 0.877 | 0.579 |
| 11/3 | NA | NA | 0.846 | 0.836 | 1.330 | 0.058 | 1.597* | 0.041 | 0.695 | 0.850 |
| 11/10 | NA | NA | 0.814 | 0.899 | 1.253 | 0.090 | 1.597* | 0.041 | 0.647 | 0.916 |
| 11/17 | NA | NA | 0.851 | 0.823 | 1.253 | 0.090 | 1.706* | 0.017 | 0.647 | 0.916 |
| 11/24 | NA | NA | 0.851 | 0.823 | 1.315 | 0.063 | 1.826* | 0.012 | 0.773 | 0.727 |
| 12/1 | NA | NA | 0.864 | 0.800 | 1.292 | 0.067 | 1.71* | 0.024 | 0.777 | 0.722 |
| 12/8 | NA | NA | NA | NA | 1.329 | 0.057 | 1.380 | 0.091 | NA | NA |

Note: [a] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern (< 1). [b] P value for null hypothesis of spatial randomness. * values indicate significant aggregation indices (P < 0.05) or significant uniform indices at (P > 0.95).

Table 3-13. Weekly SADIE aggregation indices of adult *B. tabaci* counts, Spring 2009

| Date | Farm B | | Farm H | | Farm I | | Farm J | |
|---|---|---|---|---|---|---|---|---|
| | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] |
| 2/16 | 1.095 | 0.287 | NA | NA | NA | NA | NA | NA |
| 2/23 | 1.000 | 0.412 | NA | NA | NA | NA | NA | NA |
| 3/2 | 1.269 | 0.111 | 1.077 | 0.366 | NA | NA | NA | NA |
| 3/9 | 0.819 | 0.818 | 0.879 | 0.775 | 1.507* | 0.016 | NA | NA |
| 3/16 | 0.777 | 0.856 | 1.002 | 0.429 | 1.342 | 0.057 | NA | NA |
| 3/23 | 1.239 | 0.129 | 1.269 | 0.074 | NA | NA | 1.706* | 0.009 |
| 3/30 | 1.006 | 0.368 | 1.102 | 0.233 | 0.834 | 0.775 | 1.132 | 0.217 |
| 4/6 | 1.270 | 0.122 | 0.766 | 0.947 | 1.057 | 0.314 | 0.752* | 0.953 |
| 4/13 | 0.924 | 0.563 | 1.166 | 0.166 | 1.044 | 0.334 | 0.791 | 0.892 |
| 4/20 | 1.187 | 0.158 | 1.000 | 0.431 | 0.942 | 0.551 | NA | NA |
| 4/27 | 1.081 | 0.283 | 0.928 | 0.610 | NA | NA | NA | NA |
| 5/4 | 1.258 | 0.130 | 0.942 | 0.576 | 1.060 | 0.326 | 0.809 | 0.847 |
| 5/11 | 1.346 | 0.055 | 1.307* | 0.046 | 0.556* | 0.990 | NA | NA |
| 5/18 | 1.099 | 0.250 | 1.120 | 0.192 | 0.723* | > 0.999 | NA | NA |

Note: [a] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern ( < 1). [b] $P$ value for null hypothesis of spatial randomness. * values indicate significant aggregation indices ($P < 0.05$) or significant uniform indices at ($P > 0.95$).

Table 3-14. Weekly SADIE aggregation indices of TYLCV incidence, Spring 2009

| Date | Farm B | | Farm H | | Farm I | | Farm J | |
|---|---|---|---|---|---|---|---|---|
| | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] | $I_a$[a] | $P$[b] |
| 2/16 | NA | NA | NA | NA | NA | NA | NA | NA |
| 2/23 | NA | NA | NA | NA | NA | NA | NA | NA |
| 3/2 | NA | NA | NA | NA | NA | NA | NA | NA |
| 3/9 | NA | NA | NA | NA | NA | NA | NA | NA |
| 3/16 | NA | NA | NA | NA | NA | NA | 1.087 | 0.285 |
| 3/23 | NA | NA | NA | NA | NA | NA | 1.087 | 0.285 |
| 3/30 | NA | NA | 0.911 | 0.681 | NA | NA | 1.087 | 0.285 |
| 4/6 | 0.918 | 0.558 | 1.107 | 0.256 | NA | NA | 1.087 | 0.285 |
| 4/13 | 1.110 | 0.242 | 1.107 | 0.256 | NA | NA | 1.087 | 0.285 |
| 4/20 | 1.081 | 0.283 | 1.107 | 0.256 | NA | NA | 1.063 | 0.293 |
| 4/27 | 1.081 | 0.283 | 1.107 | 0.256 | NA | NA | 1.063 | 0.293 |
| 5/4 | 1.065 | 0.303 | 1.107 | 0.256 | NA | NA | 1.063 | 0.293 |
| 5/11 | 1.048 | 0.335 | 1.107 | 0.256 | NA | NA | 1.063 | 0.293 |
| 5/18 | 1.048 | 0.335 | 1.107 | 0.256 | NA | NA | 1.063 | 0.293 |

Note: [a] Overall index of dispersion ($I_a$) indicates either an aggregated (> 1), random (= 1), or uniform pattern ( < 1). [b] P value for null hypothesis of spatial randomness. * values indicate significant aggregation indices (P < 0.05) or significant uniform indices at (P > 0.95).

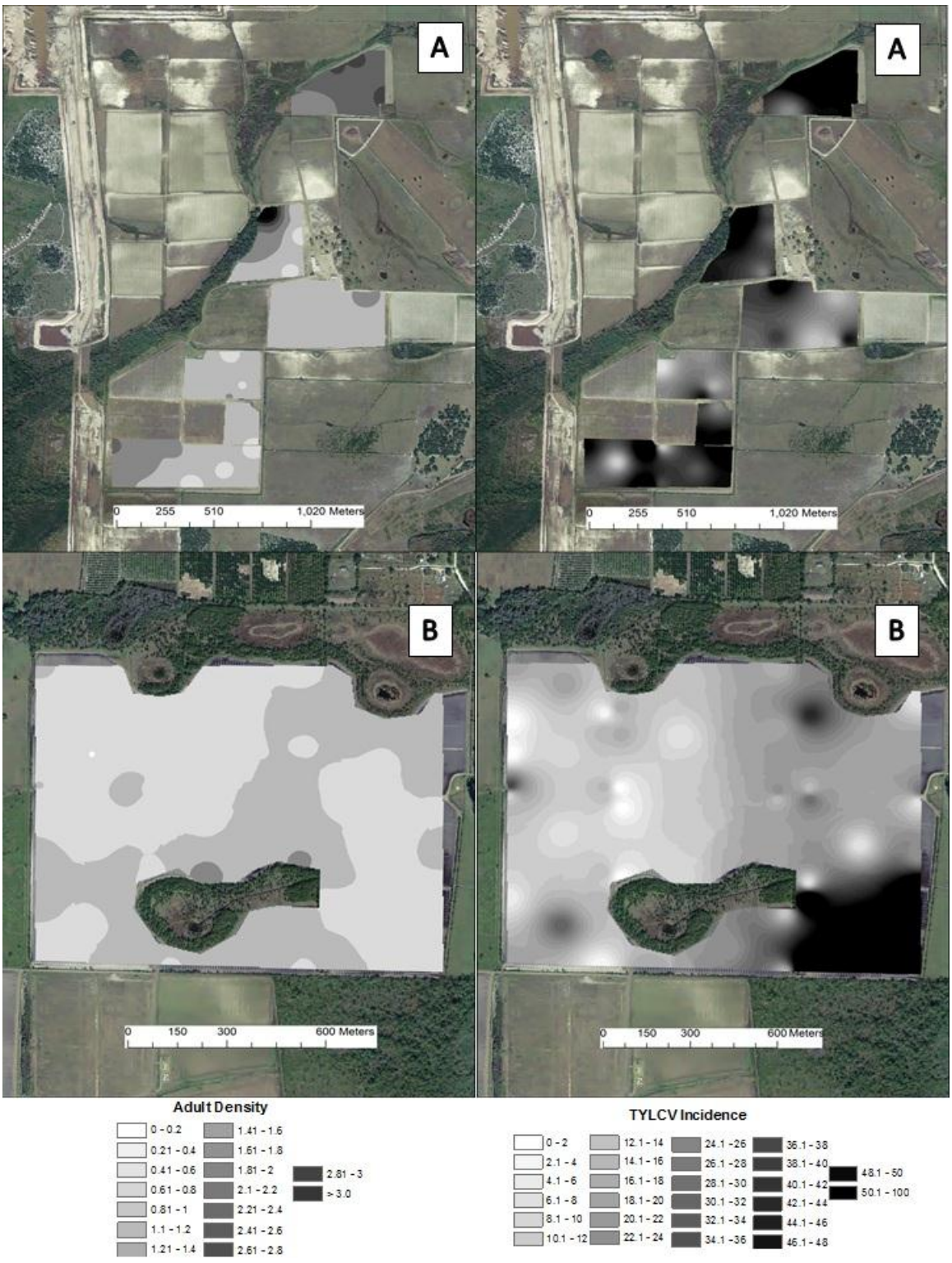


Figure 3-1. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm A and Farm B, Fall 2007.

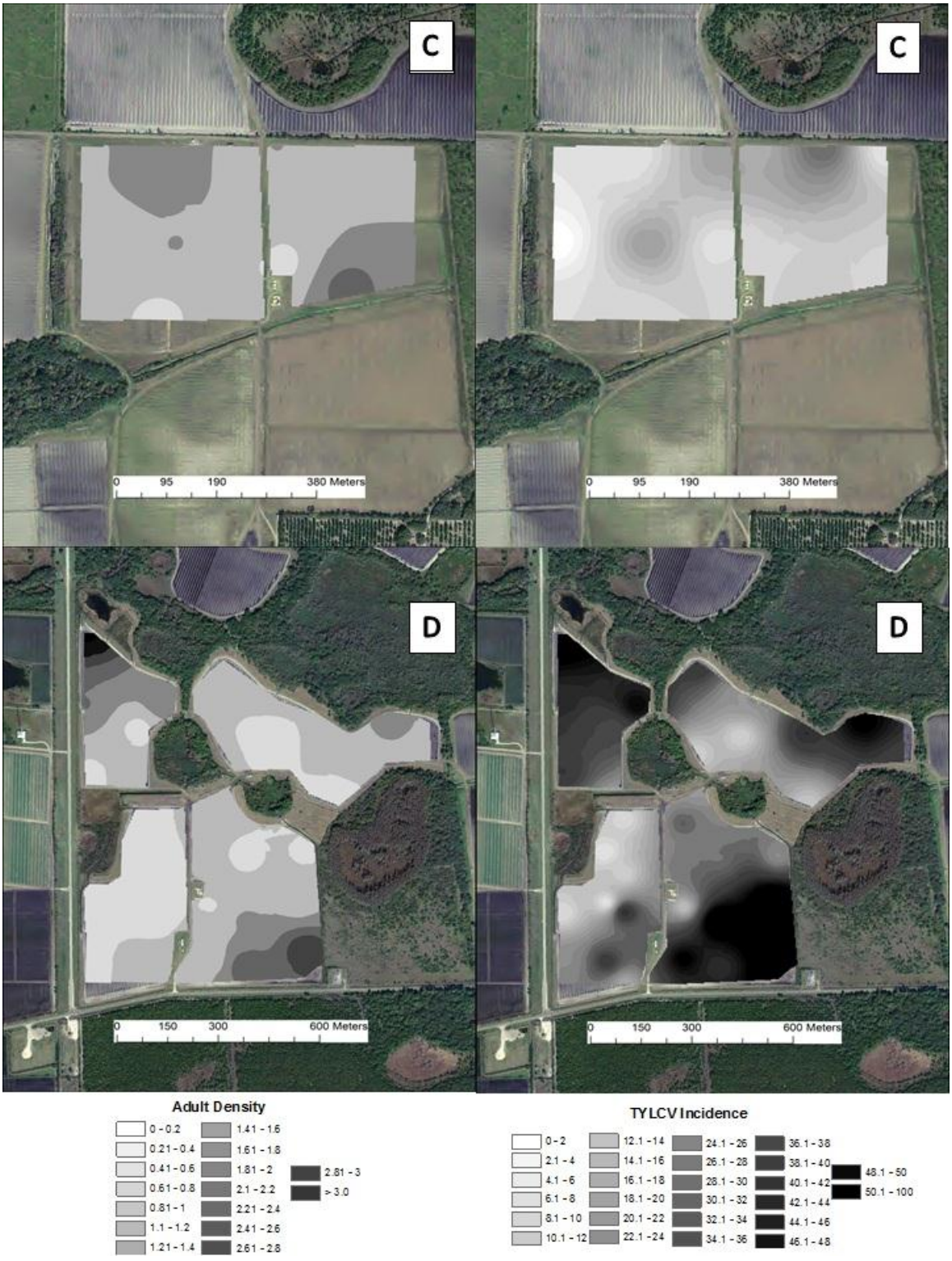


Figure 3-2. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm C and Farm D, Fall 2007.

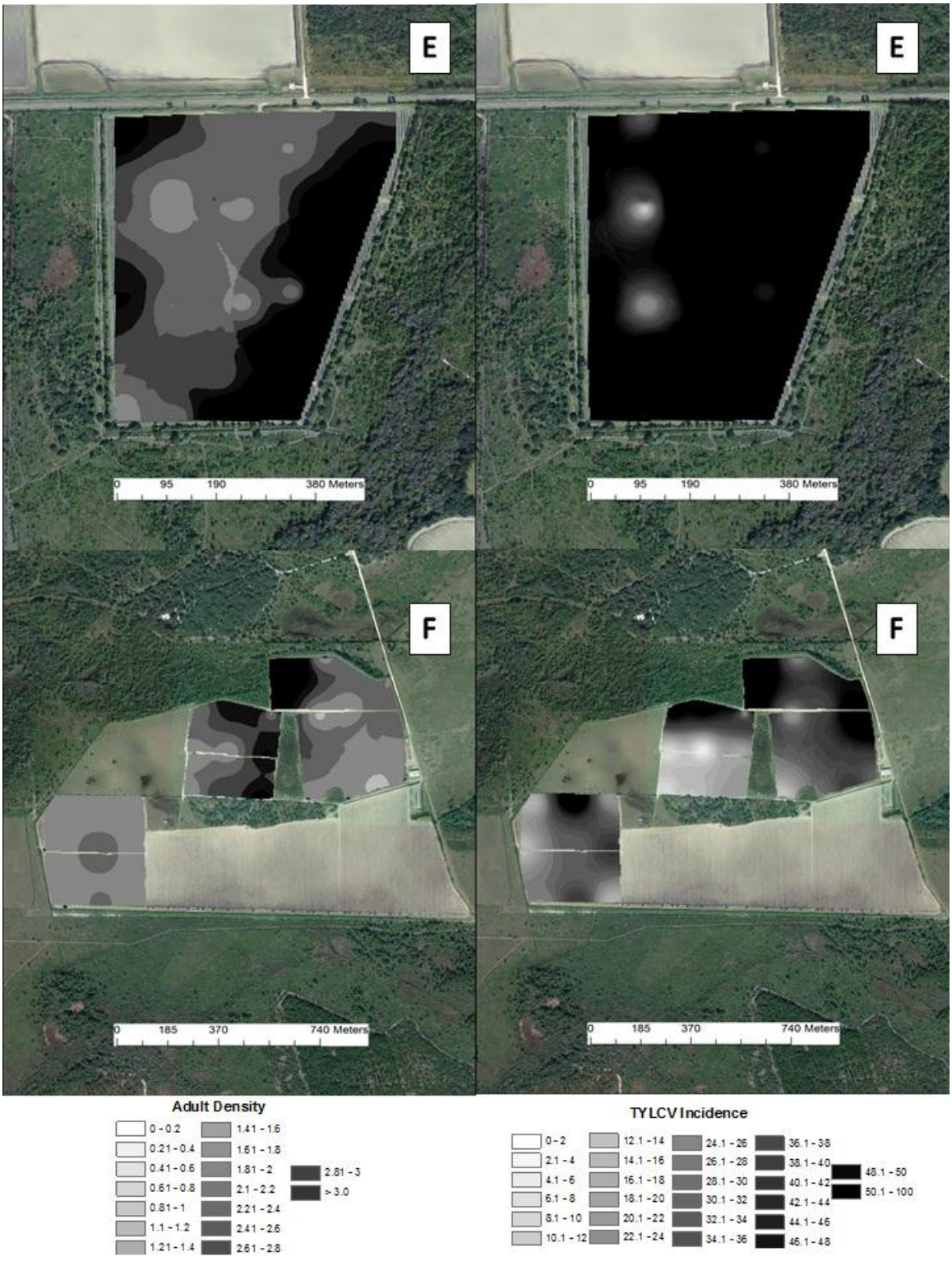


Figure 3-3. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm E and Farm F, Fall 2007.


Figure 3-4. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm G, Fall 2007.


Figure 3-5. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm H and Farm I, Spring 2008.


Figure 3-6. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm J and Farm K, Spring 2008.

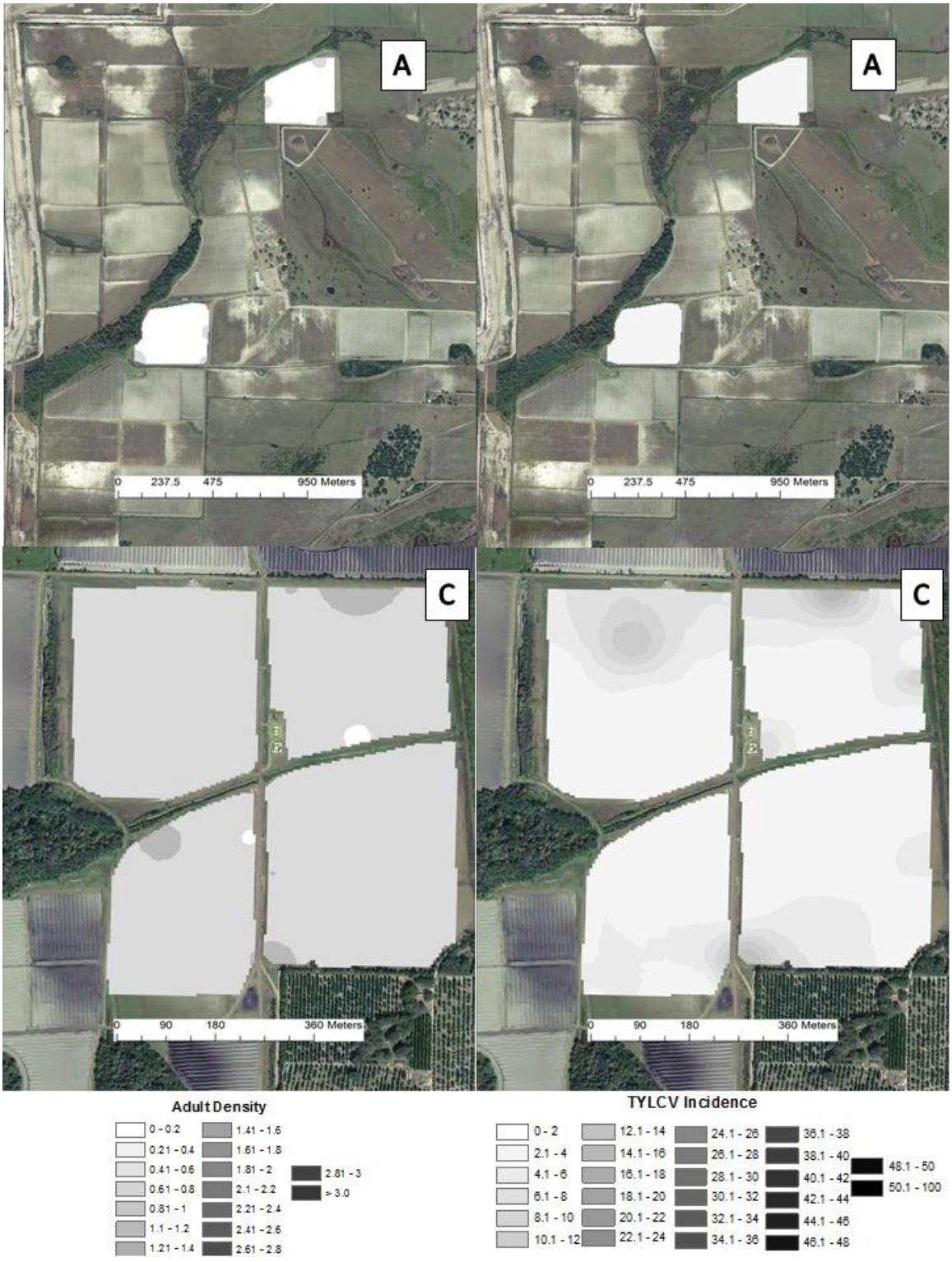


Figure 3-7. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm A and Farm C, Fall 2008.

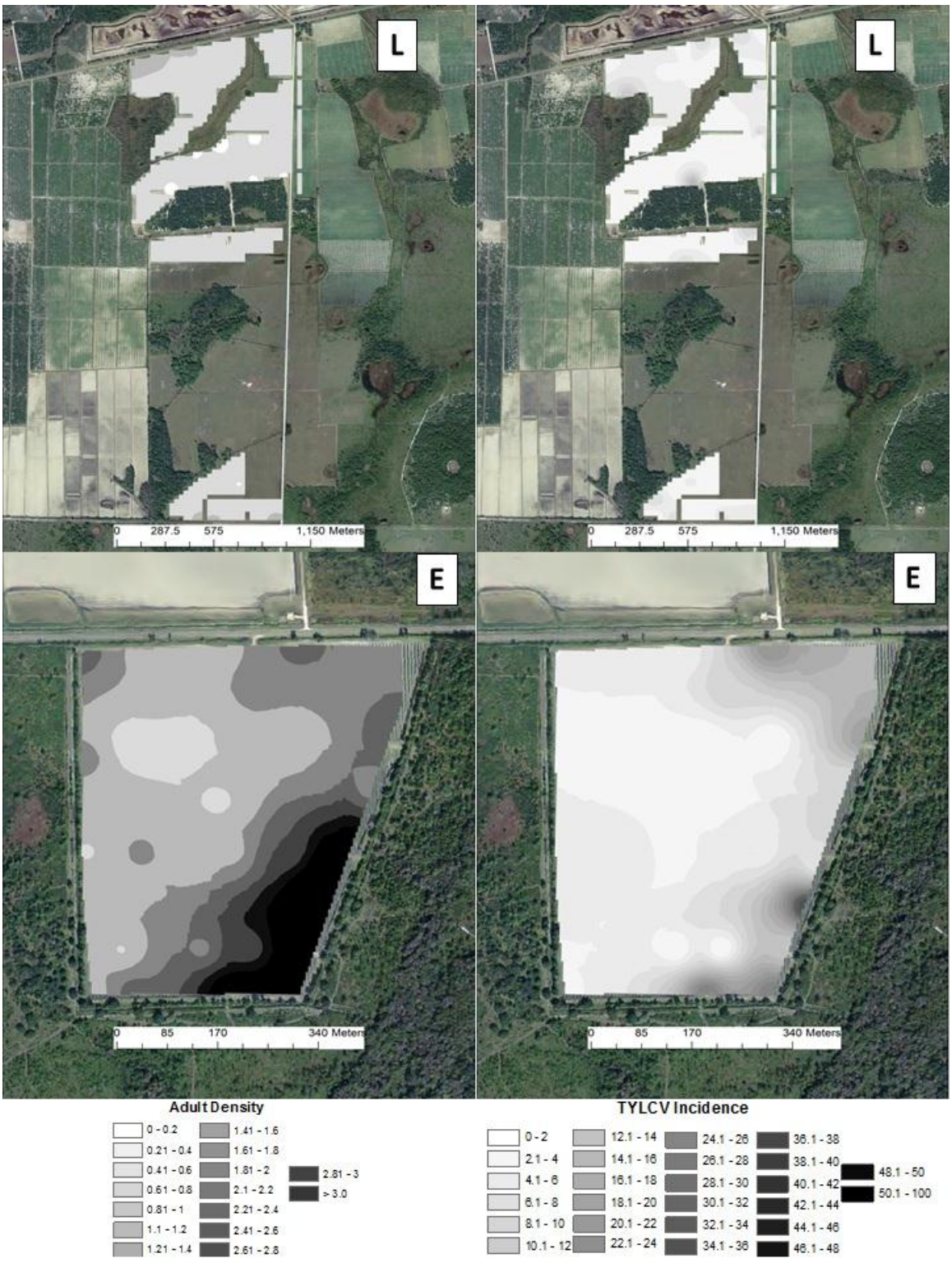


Figure 3-8. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm L and Farm E, Fall 2008.


Figure 3-9. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm F, Fall 2008.

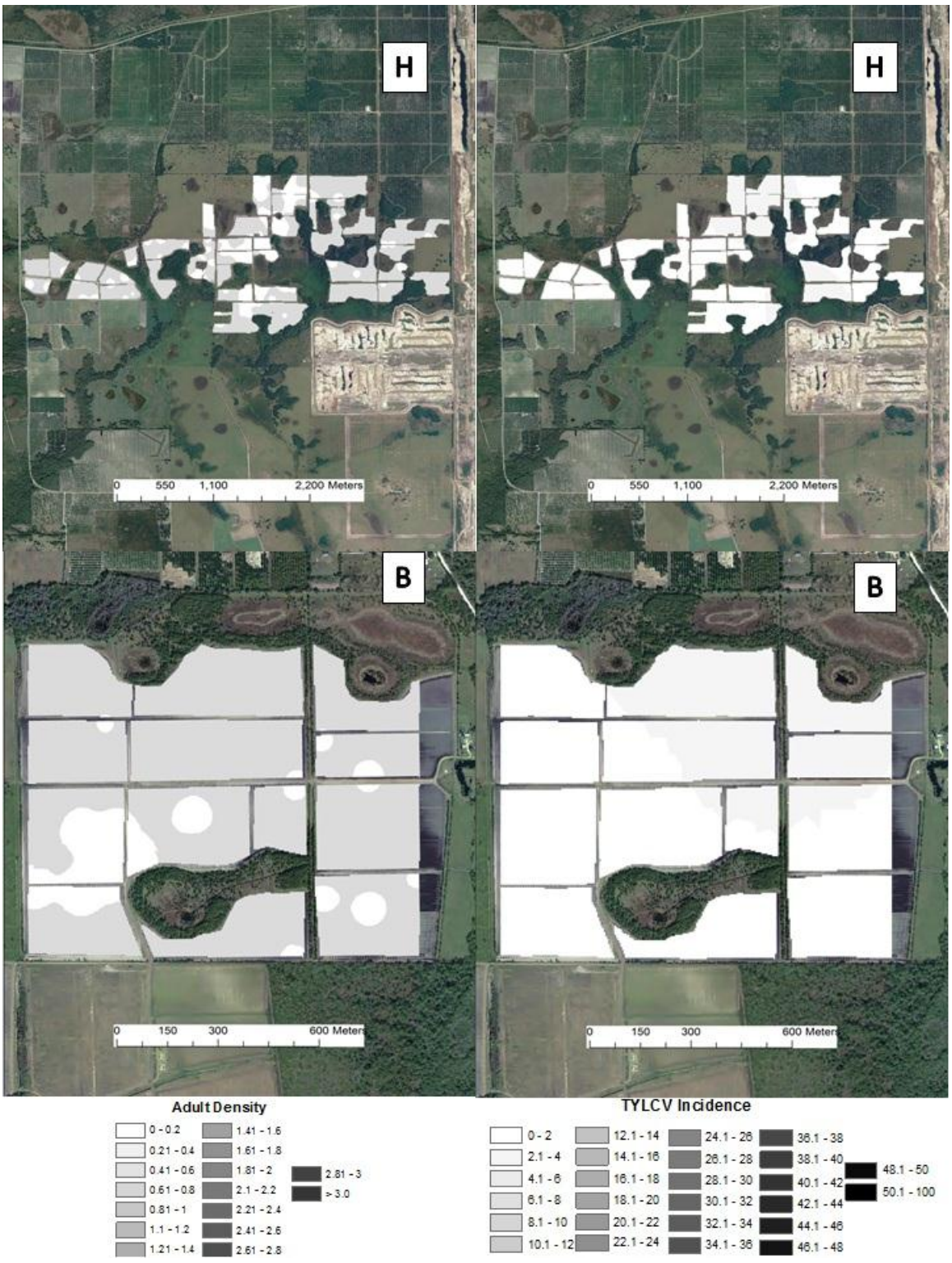


Figure 3-10. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm H and Farm B, Spring 2009.

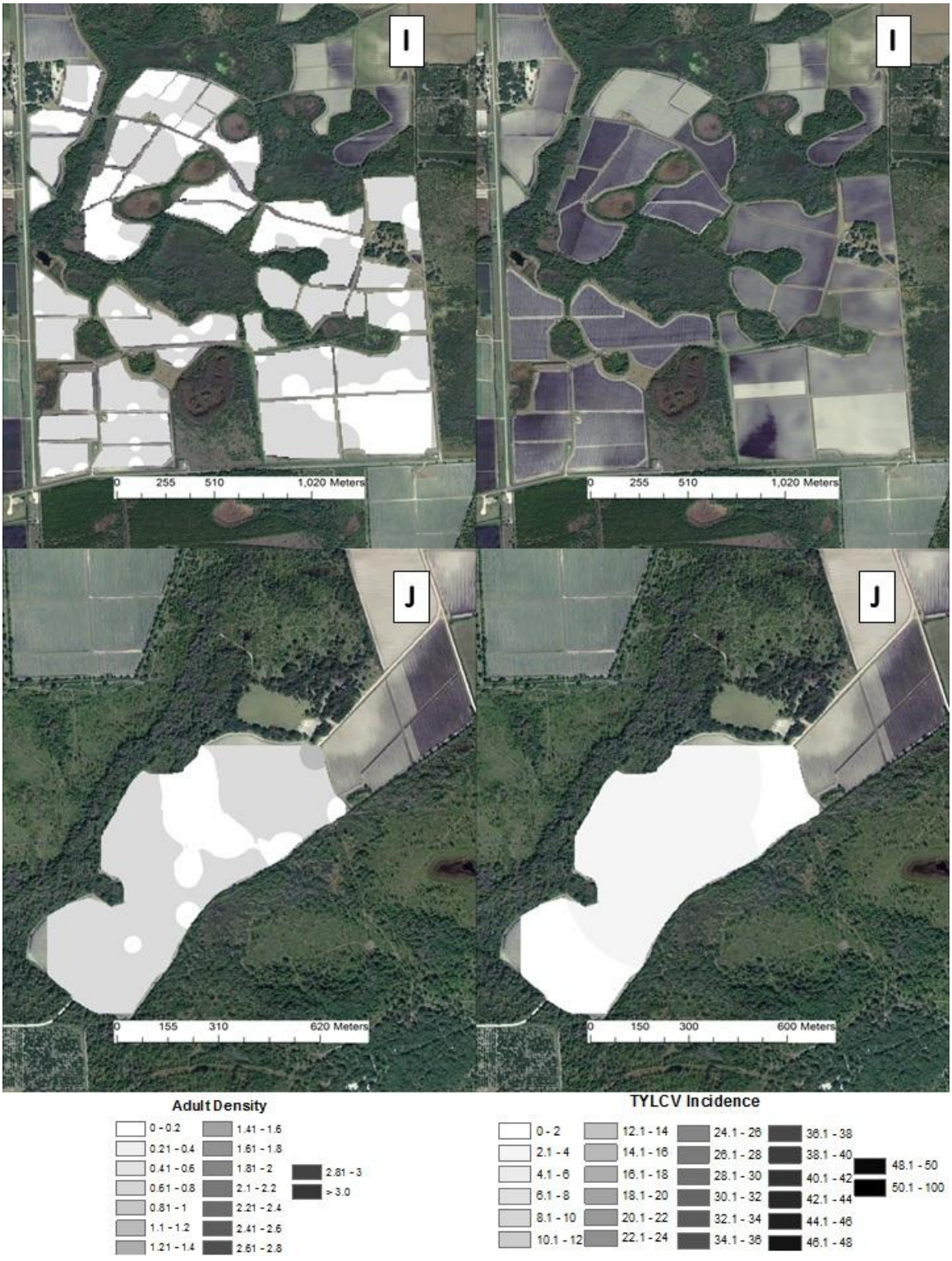


Figure 3-11. Spatial interpolation of adult populations of *B. tabaci* and TYLCV from Farm I and Farm J, Spring 2009.

# CHAPTER 4
# RELATIONSHIP OF ABUNDANCE OF *BEMISIA TABACI* TO INCIDENCE OF TYLCV IN THE FIELD AND ITS IMPLICATIONS TO MANAGEMENT AND EPIDEMIOLOGY

## Purpose

The sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) biotype B also known as the silverleaf whitefly, *B. argentifolii* Bellows and Perring is the key insect pest of tomatoes, *Solanum lycopersicum* (L.) in south Florida (Schuster et al. 1996a). In tomatoes, Biotype B can cause direct damage including irregular ripening disorder of fruit, inhibition of fruit softening and general reduction of plant vigor (Schuster 2001, McCollum et al. 2004). In Florida, *B. tabaci* has become a limiting pest species due to its ability to vector plant viruses such as *Tomato yellow leaf curl virus* (TYLCV) (family *Geminiviridae,* genus *Begomovirus*) (Polston et al. 1999). TYLCV causes one of the most devastating diseases of cultivated tomato world-wide and is transmitted in a persistent circulative manner by *B. tabaci*. Symptoms of TYLCV in tomato are usually expressed 2-3 weeks after infection (Rom et al. 1993) and include leaf curling, chlorosis of leaf margins, reduction of leaf size, mottling, abscission of flowers, plant stunting and yield reduction (Polston et al. 1999, Mohamed 2010).

First observations of a disease with TYLCV-like symptoms was reported in Israel in 1939-1940 and was associated with outbreaks of *B. tabaci* (Pico et al. 1996). Later work indicated this disease was caused by a virus transmitted by *B. tabaci* (Cohen and Harpaz 1964). TYLCV can cause losses of 100% in tropical and subtropical regions and can be the limiting factor in commercial tomato production (Czosnek and Laterrot 1997). The effect of field populations of *B. tabaci* on incidence of TYLCV is of great importance to researchers and crop managers. Some south Florida tomato growers and IPM scouts have indicated confusion of the relationship between *B. tabaci* and

TYLCV, i.e., some populations of *B. tabaci* appear to result in a higher incidence of TYLCV in tomato than others. For TYLCV management, early season adult *B. tabaci* populations are more important than late season populations. Plants infected early can have a greater negative impact on yield (Saikia and Muniyappa 1989) and serve as inoculum for future epidemics. Previous observations in the present study area concluded from area-wide maps created from bi-weekly monitoring of *B. tabaci* in tomato that populations appeared to originate close (< 2 km) to tomato fields (Taylor, unpublished). There were no indications of mass migrations of *B. tabaci* as seen in other drier areas of the world (Cohen et al. 1988, Byrne 1999). Because there was no indication of area wide migration of *B. tabaci*, areas surrounding tomato farms were indicated as important to *B. tabaci* populations and TYLCV epidemiology. These populations of *B. tabaci* were evaluated for their effect on subsequent TYLCV incidence in southern Florida tomato. Implications for management of both *B. tabaci* and TYLCV are discussed.

## Methods and Materials

### Study Sites

Populations of *B. tabaci* and TYLCV incidence were monitored on commercial tomato farms for four seasons in central Florida. Farm sizes ranged from 23.6 to 273.0 ha and were located in Manatee Co., Florida. The farms were selected because they were spatially isolated by distances over 10 km from other commercial tomato production. *B. tabaci* is capable of traveling ≈ 7 km, with most migration considered trivial and under ≈ 2.7 km (Cohen et al. 1988, Byrne 1999). Farms were managed by commercial growers so pesticide sprays and cultural practices were based on standard grower practices. There were cultivar differences between and within farms and all

samples were taken on plastic-culture staked tomatoes. After transplanting, sampling included adult whitefly counts (total number of adults on 6 contiguous plants) and TYLCV incidence (visual inspection of 50 contiguous plants). Before first tie (≈ 3-4 weeks after transplant), adult whitefly counts were taken by scouts on whole plant samples. After first tie, counts were taken on the abaxial surface from two leaves of the third node from the top of two stems per plant, using a leaf turn technique (Naranjo et al. 1995, Palumbo et al. 1995). Scouts were advised to only record tomato plants with obvious symptoms of TYLCV infection, which included upward curling of leaves, reduction of leaflet area and yellowing of young leaves (Polston et al. 1999). The growers' farms were divided into blocks and sampling points remained constant throughout the season (i.e. the same 6 plants were used for *B. tabaci* counts and the same 50 plants were evaluated for TYLCV incidence). There was approximately one sample point for ≈ 1.4 ha within each block. Scouting methodology, sample distribution and sample size were based on results collected from previous work by Schuster et al. (2007b). Sampling varied throughout the season as certain blocks were planted at different times, pesticide applications kept scouts from entering blocks, or rain events postponed scouting efforts. At the beginning of each season, geographical positioning system (GPS) coordinates were collected using a GeoExplorer 3000 Series (Trimble©). Data coordinates were converted from decimal degrees to Universal Transverse Mercator (UTM) coordinate system using ArcGIS 9.2 (ESRI 2006). UTM is an adaptation of the Mercator projection and is based on distance in meters.

**Data Analyses**

Bi-weekly counts of *B. tabaci* adults were averaged by week over all four seasons. Incidence of plants with symptoms of TYLCV infection was collected bi-weekly and

weekly virus percentages of infection were taken from the last recording per week. To estimate the effect of *B. tabaci* populations on incidence of TYLCV, the percentage of incidence of TYLCV infection from the observed week of *B. tabaci* counts were subtracted from the percentage of TYLCV infection three weeks after counts of *B. tabaci*. This lag is based on the length of time to symptom expression at a conservative 3 week period (Rom et al. 1993). Other authors have used a lag period to express relationships of field populations of insect vectors and their viruses (Korie et al. 2000). *B. tabaci* weekly means and their subsequent lag virus were analyzed using Pearson's correlation (PROC CORR) (SAS Institute 2002). Further analysis of the relationship between *B. tabaci* and TYLCV was examined by linear regression analysis using the PROC REG function of SAS (SAS Institute 2002). The slopes and intercepts of regression equations of individual farms were compared within the same week using the PROC GLM: Generalized Linear Model function of SAS (SAS Institute 2002). From this analysis, populations of *B. tabaci* on farms could be compared against other populations from the same week and inferences to their origin could be discussed.

Using *B. tabaci* counts and lag incidence of TYLCV, Spatial Analyses by Distance IndicEs (SADIE) (version 1.22) was used to establish spatial associations between two data sets that share the same spatial locations (Perry and Dixon 2002). SADIE uses spatial patterns to assess correlation and differs from correlation analysis because of the inclusion of the spatial relationship between *B. tabaci* counts and subsequent TYLCV symptom expression. This spatial association is expressed as the correlation coefficient, $X$, with a positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.975$). The significance of $X$ was tested against values $X_{rand}$

from a randomization test that included a Dutilleul (1993) adjustment procedure to provide a probability value. Positive values arise when two data sets have either patches or gaps coinciding spatially. Negative values indicate that gaps or patches between two data sets are spatially disassociated with each other. Other authors have determined spatial associations of different species taken at different times, two different species sampled together, and the same species sampled at different times (Ferguson et al. 2000, Thomas et al. 2001, Holland et al. 2005, Tillman et al. 2009, Reay-Jones et al. 2010).

Weekly maps of adult *B. tabaci* and incidence of TYLCV were interpolated using inverse distance weighted (IDW), a statistical method in GIS software ArcView 9.2 (ESRI 2006). IDW is based on the assumption that points nearby are more closely related than points farther apart and estimated predictions are based on values at sampled locations. Values are determined using a linear weighted combination of observed values and those weights are functions of the distance between locations. The most commonly used weighed power of two was used. Unlike other interpolation methods, IDW does not require a variogram model and is appropriate for small data sets (Kravchenko 2003). Cross validation was used to estimate the fit of the IDW model. Cross validation removes one sample point at a time and compares observed and predicted values for that point (Isaaks and Srivastava 1989). The root mean square prediction error (RMSE) produced by cross validation is presented as the summary statistic to check the accuracy of the model. IDW maps were created using weekly means of *B. tabaci* adults and final weekly lag of TYLCV incidence. Underlying digital

images in the form of digital orthographic photos were downloaded from the Land Boundary Information System (LABINS 2011).

## Results

### Fall 2007

In the fall of 2007, significant positive correlations ($P < 0.05$) between the numbers of *B. tabaci* and incidence of TYLCV were found in 17.3% of comparisons of sampled farms per weeks sampled (Table 4-1). On some weeks (weeks starting on 8 August 2007, 3 September 2007, 10 September 2007, 17 September 2007, and 22 October 2007) there were multiple farms with significant correlations between the numbers of adult whiteflies and later TYLCV incidence (Table 4-1). Of those weeks with significant correlations, some farms had significant linear regressions of *B. tabaci* to TYLCV (Table 4-2). On week 20 August 2007, Farms A, B and D had significant regressions, although the slopes and intercepts were not significantly different from each other [($F = 3.03$; df = 2, 101; $P = 0.0529$) ($F = 1.2$; df = 2, 103; $P = 0.304$), respectively] (Figure 4-1). On week 3 September 2007, Farms C and E had significant regressions; however, the slopes were not significantly different but the intercepts were [($F = 0.66$; df = 1, 39; $P = 0.422$) ($F = 11.13$; df = 1, 40; $P = 0.0018$), respectively] (Figure 4-2). On week 10 September 2007, Farms E and F had significant regressions and the slopes and intercepts were significantly different [($F = 23.78$; df = 1, 53; $P < 0.0001$) ($F = 21.56$; df = 1, 54; $P < 0.0001$), respectively] (Figure 4-3). On week 17 September 2007, Farms E and F had significant regressions; however, the slopes were not significantly different but the intercepts were [($F = 2.86$; df = 1, 53; $P = 0.0965$) ($F = 24.71$; df = 1, 54; $P < 0.0001$), respectively (Figure 4-4)]. On week 22 October 2007, Farms D and F had significant regressions and the slopes were not significantly different but the intercepts

were [(F = 2.16; df = 1, 57; *P* = 0.147) (F = 7.09; df = 1, 58; *P* = 0.0023), respectively] (Figure 4-5). Significant positive spatial associations from SADIE analysis were shown in 11.1% of available comparisons between *B. tabaci* numbers and TYLCV incidence (Table 4-3).

**Spring 2008**

In the spring of 2008, significant positive correlations of *B. tabaci* numbers and incidence of TYLCV were found in 10.5% and negative correlations were found in 2.6% in comparisons of sampled farms per weeks sampled (Table 4-4). On some weeks and some farms there were significant regressions of adult *B. tabaci* to TYLCV; however, none of the analyses were for the same week of sampling (Table 4-2). Significant positive spatial associations from SADIE analysis were shown in 2.6% and negative spatial associations were shown in 2.6% of available comparisons of *B. tabaci* numbers and TYLCV incidence (Table 4-5).

**Fall 2008**

In the fall of 2008, significant positive correlations of the numbers of *B. tabaci* and incidence of TYLCV were found in 15.2% of sampled farms per weeks sampled (Table 4-6). On some weeks there were significant regressions of adult whiteflies to TYLCV (Table 4-2). On week 1 September 2007, Farms C and E had significant regressions, but the slopes and intercepts were not significantly different from each other [(F = 0.06; df = 1, 66; *P* = 0.80) (F = 1.83; df = 1, 67; *P* = 0.180), respectively] (Figure 4-6). Significant positive spatial associations from SADIE analysis were shown in 6.5% of available pairs of *B. tabaci* and TYLCV (Table 4-7).

**Spring 2009**

In the spring of 2009, significant positive correlations between numbers of *B. tabaci* and incidence of TYLCV were found in 8.3% of sampled farms per weeks sampled (Table 4-8). On one week there was one farm with significant regression of adult whiteflies to TYLCV (Table 4-2). Significant negative spatial associations from SADIE analysis were shown in 8.3% of available pairs of *B. tabaci* and TYLCV (Table 4-9).

**IDW Interpolation**

IDW maps were created to visually express populations of *B. tabaci* and TYLCV for each week in which there was more than one farm with significant regression coefficients (Figures 4-7 to 4-12). IDW interpolation was conducted on individual farms to create IDW maps of multiple farms on weekly summary maps. For interpolation methods such as IDW, mean error and root mean square error (RMSE) from cross validation tests can be used to evaluate how precisely the method is producing interpolation maps. The value of the mean square error depends on the scale of the data so overall, adult whitefly RMSE were similar to TYLCV incidence RMSE (Table 4-10). Smaller RMSE indicate a better fit of the model to the observed data. Similar RMSE were presented for other IDW interpolation maps of insect counts (Tillman et al. 2009, Reay-Jones et al. 2010).

## Discussion

Tomato growers, scouts, and consultants in southern Florida report inconsistent relationships between field populations of *B. tabaci* and subsequent incidence of plants with symptoms of TYLCV infection. Some populations of *B. tabaci* appear more viruliferous than others, which causes crop managers to treat every whitefly as

viruliferous. We can conclude in our study area that not all populations of *B. tabaci* were equally viruliferous; however, determining the underlying reasons behind these differences is much more difficult. In this study, there were instances of *B. tabaci* populations being highly correlated with symptomatic TYLCV infected plants and other instances of *B. tabaci* populations having no relationship to symptomatic TYLCV-infected plants. Depending upon the origin of the whiteflies, populations of *B. tabaci* could vary in their ability to cause TYLCV epidemics. Low correlations of *B. tabaci* to TYLCV-infected plants could have been due to our sampling method, because not all plants examined for symptoms of TYLCV infection were examined for adult *B. tabaci*. Insecticide applications were also not recorded due to privacy issues with commercial growers. Due to the dynamic population fluctuations of *B. tabaci* it is possible that bi-weekly sampling was not precise enough to account for all populations.

Since early infection of TYLCV in tomato can cause significant losses, early season immigrating adult *B. tabaci* populations are more important than late season populations. Early fall season populations of adult *B. tabaci* had stronger and more frequent correlations to incidence of TYLCV-infected than late season populations in fall 2007 and fall 2008 (Tables 4-1 and 4-6). In the spring seasons, populations later in the season had stronger correlations to symptomatic TYLCV infected plants than earlier populations (Tables 4-4 and 4-8). This suggests that temperature or other variables had an effect on adult *B. tabaci* and incidence of TYLCV between these seasons. Also, our method of determining new symptomatic TYLCV infected plants was a destructive sample; that is, once a plant was indicated as symptomatic it would remain that way throughout the season, thus removing it from future new virus counts. Using fixed, geo-

referenced sites for evaluating incidence of TYLCV-infected plants was based upon preliminary research which used geo-referenced sites that changed weekly and gave no indication of the degree of virus progression. Also, linear regression models can be a concern for this type of analysis. The underlying principle assumes that the relationship is linear and that the distribution is normal. These analysis tools were chosen to give a better understanding and evaluate *B. tabaci* populations based on the severity of subsequent virus at each farm. Because samples were taken at fixed geo-referenced points, data collected was not considered random as the data suggested aggregated spatial patterns associated with both abundance of *B. tabaci* and symptomatic TYLCV-infected plants. A suggested Markov Chain model could be used to model random processes between time steps as indicated by our disease development and fluctuations in *B. tabaci* counts.

SADIE analyses suggested similar findings to correlations but gave an indication of the spatial association of *B. tabaci* and subsequent incidence of plants with symptoms of TYLCV infection. Early season populations of *B. tabaci* in the fall of 2007 and 2008 were more likely to be positively spatially associated with symptomatic TYLCV-infected plants than dates later in the season (Tables 4-3 and 4-7). In the spring seasons of 2008 and 2009, two of the three weeks with significant spatial associations between *B. tabaci* and symptomatic TYLCV infected plants were negative (Table 4-5 and 4-9). These data highlight the difficulties in analyzing such a dynamic pest. Positive spatial associations of populations of *B. tabaci* to symptomatic TYLCV infected plants are the most critical because they reveal the origin of those immigrating populations. Because of the two-tailed nature of the spatial association test,

significance is lowered to $P < 0.025$ and $P > 0.975$, reducing the number of significant associations relative to the number of significant associations indicated in the correlation analyses. Farms with positive spatial associations in the early season (weeks of 20 August 2007, 3 September 2007, 10 September 2007 and 17 September 2007) and late season (week of 22 October 2007) of fall 2007 provide similar results to correlation analyses but give some indication to the positive spatial relationships between numbers of *B. tabaci* and symptomatic TYLCV-infected plants (Table 4-3). Another week, 1 September 2008, had significantly associated populations of *B. tabaci* to TYLCV on multiple farms (Table 4-7).

Early season populations of whiteflies would not be originating from within the newly planted tomato because of the short time available for whitefly reproduction. Therefore, these populations can be assumed to have originated outside tomato fields. On the week of 20 August 2007, the slopes of the regression lines of the numbers of *B. tabaci* adults and symptomatic TYLCV-infected plants from Farms A, B and D were not significantly different from each other at $P < 0.05$ but the slopes were significantly different at $P < 0.1$ (Figure 4-1). After a visual inspection of IDW maps, Farms A and D have very different densities and in-farm distributions of *B. tabaci* populations as compared to Farm B (Figure 4-7), although the incidence of symptomatic TYLCV-infected plants was very low on all three farms. There is no indication as to the origin of these populations other than mining operations along the northwest corner of Farm A and a cultural manipulation of a field (field discing) to the east of Farm D. On the weeks of 3 September 2007, 17 September 2007, and 22 October 2007, only the intercepts of the regression lines between farms were significantly different (Figures 4-2, 4-4 and 4-

5). IDW maps of week 3 September 2007 (notice scale change), indicated different pest pressure and TYLCV incidence between Farms C and E (Figures 4-8); however, the regression analysis indicated similar rates of TYLCV-infected plants (Figure 4-2). Similar findings occurred on 17 September 2007 and 22 October 2007 (Figures 4-10 and 4-11). These data suggest that *B. tabaci* counts were much higher on some farms, but the rate of newly infected tomato did not change significantly. On the week of 10 September 2007, Farms E and F had significantly different slopes, indicating *B. tabaci* populations arose from different sources (Figure 4-3). These populations were also much higher than counts at other farms, which prompted a more thorough investigation. Previous to the 10 September 2007 scouting date, weeds were removed from a water ditch along the north side of Farm F adjacent to those sample sites with high *B. tabaci* populations (Figure 4-9). Although the *B. tabaci* populations of Farm E were located in the southeast corner closest to the ditch clean-up along Farm F's northern border, the *B. tabaci* populations of Farm E and F were significantly different in terms of the amount of new incidence of TYLCV-infected plants three weeks later. Other weeks throughout the study had individual farms with significant regressions of *B. tabaci* counts to subsequent TYLCV-infected plants, but no comparisons to their *B. tabaci* populations could be made between weeks (Table 4-2).

The present study area was separated from other tomato production by a distance greater than the suggested migratory patterns of *B. tabaci* (Cohen et al. 1988). This site was selected to reduce the amount of tomato area that needed to be scouted and to reduce the influence of non-sampled tomato farms influencing populations. Cultivated tomato has been indicated as a main influence of *B. tabaci* and TYLCV outbreaks, but

as shown in some areas of the world, weeds can influence the system as well (Cohen et al. 1988, Polston and Lapidot 2007). Studies in south Florida indicated that weeds, especially in the over-summering period, are poor intermediate hosts of *B. tabaci* (Stansly 1995), but populations within weeds paralleled those found in neighboring tomato fields, suggesting that weeds can bridge the gap between crops (Schuster et al. 1992).

In India, populations of immature lifestages of *B. tabaci* found on weeds outnumbered those found on tomato, suggesting the importance of weeds (Ramappa et al. 1998). As indicated by an epidemiological model, a *B. tabaci* vectored Indian tomato leaf curl geminivirus (TLCV), was primarily influenced by the immigration of vectors from alternative hosts (Holt et al. 1997). The authors demonstrated that disease incidence was sensitive to vector mortality only when vector numbers were low. Viruliferous vectors may migrate into tomato in numbers greater than those needed for disease "saturation" (Holt et al. 1997). Similar results were presented in this study. Seasons had varying levels of pest pressure and, in those seasons which had very low *B. tabaci* counts, subsequent virus incidence was also low. In the seasons where *B. tabaci* counts were high, incidence of TYLCV was also high, even though management tactics were similar across all seasons. These results indicate that the system is much more complex than previously thought and confirms the theory that areas closely surrounding tomato fields are very important to *B. tabaci* populations and TYLCV epidemiology (Turechek 2010).

These results indicate the need for further research into the influence of weeds and other hosts including cultivated crops. Area-wide management is important, as *B.*

*tabaci* has over 600 hosts and could be considered a mobile pest (Mound and Halsey 1978, Greathead 1986, Secker et al. 1998, Byrne 1999). The origins of viruliferous populations in the present study are unclear. There were indications that *B. tabaci* may have migrated from areas in which possible whitefly hosts were destroyed or disturbed, including a mining operation, a fallow field and a large drainage ditch. Some cucurbit species have been shown to host TYLCV-Mld (Anfoka et al. 2009) and some cultivars of pepper can host TYLCV (Polston et al. 2006). Cucurbits were in production within the study area but unfortunately limited resources precluded scouting them. Also, no weeds were indicated as hosts of TYLCV in a recent survey in west-central Florida (Polston et al. 2009). Fallow fields can harbor hosts of both *B. tabaci* and TYLCV and it has been suggested that fallow fields be planted with a known non-host of both *B. tabaci* and TYLCV. Sorghum sudangrass, *Sorghum bicolor* (L.) has been suggested as one such option because, not only is it a non-host of either pest, it also suppresses growth of broadleaf plants through allelopathy (Putnam et al. 1983 ). To manage *B. tabaci* and TYLCV, it is recommended that field preparation for future plantings should be spatially and temporally separated from the early season plantings when tomato is most vulnerable to *B. tabaci* and TYLCV.

Table 4-1. Correlations of adult *B. tabaci* weekly means to tomato plants with new incidence of TYLCV infection three weeks later, Fall 2007

| Date | Farm A | | Farm B | | Farm C | | Farm D | | Farm E | | Farm F | | Farm G | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] |
| 8/13 | -0.06 | 0.740 | NA | NA | NA | NA | NA | NA | -0.03 | 0.902 | NA | NA | NA | NA |
| 8/20 | 0.43* | 0.007 | 0.57* | 0.001 | -0.13 | 0.635 | 0.51* | 0.003 | 0.10 | 0.617 | -0.16 | 0.523 | NA | NA |
| 8/27 | 0.07 | 0.688 | 0.26 | 0.057 | 0.35 | 0.206 | 0.61* | 0.001 | 0.10 | 0.618 | -0.09 | 0.651 | NA | NA |
| 9/3 | 0.22 | 0.181 | 0.11 | 0.428 | 0.56* | 0.031 | -0.04 | 0.825 | 0.58* | 0.001 | -0.13 | 0.514 | NA | NA |
| 9/10 | 0.12 | 0.460 | -0.22 | 0.096 | -0.32 | 0.244 | 0.15 | 0.496 | 0.63* | 0.001 | 0.37* | 0.049 | -0.03 | 0.881 |
| 9/17 | 0.05 | 0.747 | -0.11 | 0.427 | 0.01 | 0.979 | 0.12 | 0.567 | 0.38* | 0.047 | 0.40* | 0.033 | -0.12 | 0.517 |
| 9/24 | 0.27 | 0.096 | -0.07 | 0.608 | 0.01 | 0.973 | 0.21 | 0.257 | -0.19 | 0.343 | -0.02 | 0.918 | 0.01 | 0.950 |
| 10/1 | -0.01 | 0.938 | -0.09 | 0.519 | -0.16 | 0.562 | -0.13 | 0.466 | 0.00 | 0.999 | 0.17 | 0.388 | -0.25 | 0.166 |
| 10/8 | -0.25 | 0.137 | -0.12 | 0.386 | -0.02 | 0.938 | -0.08 | 0.648 | 0.00 | 0.994 | 0.50* | 0.006 | 0.26 | 0.162 |
| 10/15 | -0.15 | 0.371 | -0.08 | 0.546 | 0.21 | 0.459 | -0.15 | 0.408 | -0.15 | 0.447 | 0.50* | 0.007 | 0.07 | 0.693 |
| 10/22 | 0.09 | 0.590 | -0.18 | 0.196 | 0.34 | 0.217 | 0.36* | 0.046 | -0.19 | 0.344 | 0.54* | 0.003 | 0.24 | 0.170 |
| 10/29 | -0.10 | 0.545 | 0.03 | 0.829 | -0.31 | 0.261 | -0.08 | 0.653 | -0.32 | 0.102 | 0.07 | 0.724 | -0.23 | 0.195 |
| 11/5 | NA | NA | 0.05 | 0.691 | NA | NA | -0.08 | 0.681 | -0.20 | 0.297 | 0.24 | 0.240 | NA | NA |

Note: [a] Correlation of adult *B. tabaci* to new TYLCV three weeks later. [b] P value of < 0.05 indicates significant values for $\alpha = 0.1$. * values indicate significance. NA indicates one or more variables with no value.

Table 4-2. Regression of *B. tabaci* adults to incidence of tomato plants with symptoms of TYLCV infection three weeks later, 2007-2009

| Season | Date | Farm | Slope | Intercept | $R^2$ | P-value |
|---|---|---|---|---|---|---|
| Fall 2007 | 8/20 | A | 0.178 | 0.612 | 0.19 | 0.007 |
| | | B | 1.202 | 0.0859 | 0.33 | 0.0002 |
| | | D | 0.346 | 0.631 | 0.26 | 0.0027 |
| | 8/27 | D | 0.147 | 0.917 | 0.38 | 0.0002 |
| | 9/3 | C | 0.336 | -0.0531 | 0.31 | 0.0307 |
| | | E | 0.86 | 4.311 | 0.34 | 0.0012 |
| | 9/10 | E | 2.122 | 7.49 | 0.4 | 0.0003 |
| | | F | 0.143 | 4.015 | 0.14 | 0.0489 |
| | 9/17 | E | 4.937 | 18.067 | 0.14 | 0.0472 |
| | | F | 1.181 | 4.251 | 0.16 | 0.0325 |
| | 10/8 | F | 6.155 | 8.789 | 0.25 | 0.006 |
| | 10/15 | F | 6.249 | 10.553 | 0.24 | 0.0069 |
| | 10/22 | D | 7.691 | 9.909 | 0.13 | 0.0458 |
| | | F | 2.291 | 4.51 | 0.29 | 0.0028 |
| Spring 2008 | 3/3 | I | 1 | 0 | 0.49 | 0.0001 |
| | 3/31 | J | -0.551 | 0.984 | 0.09 | 0.0357 |
| | 4/7 | H | 0.332 | 0.113 | 0.03 | 0.0269 |
| | 4/14 | H | 0.609 | 0.058 | 0.11 | 0.0001 |
| Fall 2008 | 9/1 | C | 0.608 | 0.52 | 0.15 | 0.0138 |
| | | E | 0.521 | 0.0034 | 0.14 | 0.0383 |
| | 9/8 | C | 1.25 | 0.475 | 0.21 | 0.003 |
| | 9/22 | E | 2.925 | -0.165 | 0.29 | 0.0026 |
| | 10/13 | E | 2.26 | 0.0179 | 0.38 | 0.0003 |
| | 10/20 | L | 0.552 | 0.0154 | 0.06 | 0.0285 |
| | 11/17 | F | 1.028 | 0.287 | 0.22 | 0.003 |
| Spring 2009 | 3/30 | B | 0.4 | 0.0001 | 0.18 | 0.0093 |

Table 4-3. Indices of spatial association (*X*) for adult *B. tabaci* and tomato plants with new symptoms of TYLCV infection three weeks later, Fall 2007

| Date | Farm A | | Farm B | | Farm C | | Farm D | | Farm E | | Farm F | | Farm G | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ |
| 8/13 | 0.210 | 0.080 | NA | NA | NA | NA | NA | NA | -0.030 | 0.445 | NA | NA | NA | NA |
| 8/20 | 0.433 | 0.028 | 0.57* | 0.005 | -0.134 | 0.197 | 0.51* | 0.007 | 0.099 | 0.310 | -0.161 | 0.618 | NA | NA |
| 8/27 | 0.043 | 0.378 | 0.256 | 0.040 | 0.347 | 0.104 | 0.61* | 0.003 | 0.099 | 0.293 | -0.088 | 0.591 | NA | NA |
| 9/3 | 0.222 | 0.090 | 0.108 | 0.222 | 0.558 | 0.045 | -0.041 | 0.597 | 0.58* | 0.002 | -0.126 | 0.739 | NA | NA |
| 9/10 | 0.123 | 0.221 | -0.222 | 0.956 | -0.321 | 0.835 | 0.146 | 0.254 | 0.63* | 0.001 | 0.369 | 0.053 | -0.033 | 0.420 |
| 9/17 | 0.054 | 0.340 | -0.108 | 0.792 | 0.007 | 0.504 | 0.123 | 0.285 | 0.378 | 0.029 | 0.398 | 0.035 | -0.117 | 0.706 |
| 9/24 | 0.271 | 0.061 | -0.070 | 0.652 | 0.010 | 0.456 | 0.206 | 0.135 | 0.51* | 0.007 | -0.035 | 0.557 | 0.113 | 0.458 |
| 10/1 | -0.013 | 0.490 | -0.091 | 0.710 | -0.163 | 0.602 | -0.134 | 0.730 | 0.000 | 0.435 | 0.117 | 0.192 | -0.247 | 0.910 |
| 10/8 | -0.246 | 0.948 | -0.122 | 0.787 | -0.022 | 0.392 | -0.084 | 0.624 | -0.011 | 0.452 | 0.50* | 0.007 | 0.266 | 0.080 |
| 10/15 | -0.149 | 0.819 | -0.089 | 0.704 | 0.207 | 0.278 | -0.152 | 0.783 | -0.150 | 0.699 | 0.49* | 0.009 | 0.073 | 0.344 |
| 10/22 | 0.090 | 0.260 | -0.175 | 0.937 | 0.339 | 0.099 | 0.356 | 0.033 | -0.188 | 0.788 | 0.54* | 0.015 | 0.245 | 0.102 |
| 10/29 | -0.101 | 0.699 | 0.029 | 0.393 | -0.310 | 0.732 | -0.083 | 0.641 | -0.316 | 0.974 | 0.069 | 0.291 | 0.245 | 0.102 |
| 11/5 | NA | NA | 0.058 | 0.339 | NA | NA | -0.076 | 0.435 | -0.204 | 0.841 | 0.285 | 0.115 | NA | NA |

Note: [a] Overall index of association (*X*) between adult *B. tabaci* and incidence of TYLCV three weeks later. [b] *P* value for positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.0975$). * values indicate significant values. NA indicates one or more variables with no value.

Table 4-4. Correlations of adult *B. tabaci* weekly means to tomato plants with new incidence of TYLCV infection three weeks later, Spring 2008

| Date | Farm H | | Farm I | | Farm J | | Farm K | |
|---|---|---|---|---|---|---|---|---|
| | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] |
| 1/21 | NA | NA | NA | NA | NA | NA | NA | NA |
| 1/28 | NA | NA | NA | NA | NA | NA | NA | NA |
| 2/4 | 0.136 | 0.095 | NA | NA | -0.301 | 0.240 | NA | NA |
| 2/11 | -0.032 | 0.701 | NA | NA | -0.106 | 0.498 | NA | NA |
| 2/18 | -0.030 | 0.744 | NA | NA | -0.113 | 0.454 | NA | NA |
| 2/25 | 0.079 | 0.337 | -0.032 | 0.792 | 0.200 | 0.143 | NA | NA |
| 3/3 | NA | NA | 0.703* | 0.001 | 0.137 | 0.318 | NA | NA |
| 3/10 | -0.046 | 0.641 | NA | NA | 0.088 | 0.059 | NA | NA |
| 3/17 | 0.033 | 0.690 | NA | NA | 0.045 | 0.748 | NA | NA |
| 3/24 | -0.049 | 0.557 | NA | NA | -0.202 | 0.138 | -0.091 | 0.779 |
| 3/31 | -0.059 | 0.472 | -0.099 | 0.358 | -0.303* | 0.027 | -0.041 | 0.898 |
| 4/7 | 0.180* | 0.027 | -0.042 | 0.655 | 0.127 | 0.356 | -0.135 | 0.676 |
| 4/14 | 0.327* | 0.001 | 0.067 | 0.474 | 0.058 | 0.674 | 0.104 | 0.747 |
| 4/21 | -0.041 | 0.613 | 0.064 | 0.494 | 0.181* | 0.027 | 0.155 | 0.630 |
| 4/28 | NA | NA | 0.007 | 0.944 | 0.245 | 0.072 | 0.404 | 0.193 |
| 5/5 | NA | NA | -0.111 | 0.235 | NA | NA | NA | NA |

Note: [a] Correlation of adult *B. tabaci* to new TYLCV three weeks later. [b] P value of < 0.05 indicates significant values for α = 0.1. * values indicate significance. NA indicates one or more variables with no value.

Table 4-5. Indices of spatial association (*X*) for adult *B. tabaci* and tomato plants with new symptoms of TYLCV infection three weeks later, Spring 2008

| Date | Farm H | | Farm I | | Farm J | | Farm K | |
|---|---|---|---|---|---|---|---|---|
| | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ |
| 1/21 | NA | NA | NA | NA | NA | NA | NA | NA |
| 1/28 | NA | NA | NA | NA | NA | NA | NA | NA |
| 2/4 | 0.136 | 0.044 | NA | NA | -0.301 | 0.798 | NA | NA |
| 2/11 | -0.032 | 0.148 | NA | NA | -0.125 | 0.499 | NA | NA |
| 2/18 | -0.030 | 0.101 | NA | NA | -0.113 | 0.539 | NA | NA |
| 2/25 | 0.079 | 0.373 | -0.032 | 0.082 | 0.200 | 0.105 | NA | NA |
| 3/3 | NA | NA | 0.703 | 0.027 | 0.137 | 0.181 | NA | NA |
| 3/10 | -0.046 | 0.571 | NA | NA | 0.088 | 0.233 | NA | NA |
| 3/17 | 0.033 | 0.491 | NA | NA | 0.045 | 0.255 | NA | NA |
| 3/24 | -0.049 | 0.331 | NA | NA | -0.203 | 0.969 | -0.091 | 0.083 |
| 3/31 | -0.059 | 0.886 | -0.099 | 0.547 | -0.300* | 0.989 | -0.041 | 0.249 |
| 4/7 | 0.192 | 0.048 | -0.043 | 0.173 | 0.127 | 0.218 | -0.135 | 0.173 |
| 4/14 | 0.327* | 0.006 | 0.067 | 0.312 | 0.058 | 0.378 | 0.104 | 0.253 |
| 4/21 | -0.041 | 0.970 | -0.013 | 0.410 | 0.181 | 0.160 | 0.155 | 0.445 |
| 4/28 | NA | NA | -0.016 | 0.617 | 0.245 | 0.070 | 0.404 | 0.250 |
| 5/5 | NA | NA | -0.111 | 0.745 | NA | NA | NA | NA |

Note: [a] Overall index of association (*X*) between adult *B. tabaci* and incidence of TYLCV three weeks later. [b] *P* value for positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.0975$). * values indicate significant values. NA indicates one or more variables with no value.

Table 4-6. Correlations of adult *B. tabaci* weekly means to tomato plants with new incidence of TYLCV infection three weeks later, Fall 2008

| Date | Farm A | | Farm C | | Farm E | | Farm F | | Farm L | |
|---|---|---|---|---|---|---|---|---|---|---|
| | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] |
| 8/25 | NA | NA | -0.087 | 0.596 | NA | NA | NA | NA | -0.131 | 0.294 |
| 9/1 | NA | NA | 0.386* | 0.014 | 0.380* | 0.038 | -0.091 | 0.694 | 0.142 | 0.255 |
| 9/8 | NA | NA | 0.457* | 0.003 | NA | NA | 0.033 | 0.813 | -0.069 | 0.537 |
| 9/15 | NA | NA | 0.258 | 0.109 | 0.000 | 1.000 | -0.003 | 0.986 | -0.013 | 0.909 |
| 9/22 | NA | NA | -0.095 | 0.594 | 0.538* | 0.003 | -0.063 | 0.654 | -0.045 | 0.687 |
| 9/29 | NA | NA | -0.009 | 0.955 | 0.000 | 1.000 | 0.065 | 0.642 | -0.072 | 0.496 |
| 10/6 | NA | NA | 0.065 | 0.690 | NA | NA | -0.024 | 0.865 | 0.188 | 0.131 |
| 10/13 | NA | NA | 0.103 | 0.563 | 0.617* | 0.001 | 0.235 | 0.091 | -0.016 | 0.888 |
| 10/20 | NA | NA | -0.026 | 0.873 | 0.251 | 0.180 | -0.025 | 0.860 | 0.242* | 0.029 |
| 10/27 | NA | NA | 0.060 | 0.714 | -0.040 | 0.836 | -0.109 | 0.436 | 0.057 | 0.656 |
| 11/3 | NA | NA | -0.002 | 0.989 | -0.219 | 0.245 | -0.098 | 0.486 | 0.135 | 0.228 |
| 11/10 | NA | NA | -0.081 | 0.620 | 0.258 | 0.169 | NA | NA | -0.004 | 0.975 |
| 11/17 | NA | NA | -0.090 | 0.583 | 0.146 | 0.451 | 0.469* | 0.003 | NA | NA |

Note: [a] Correlation of adult *B. tabaci* to new TYLCV three weeks later. [b] P value of < 0.05 indicates significant values for $\alpha = 0.1$. * values indicate significance. NA indicates one or more variables with no value.

Table 4-7. Indices of spatial association (*X*) for adult *B. tabaci* and tomato plants with new symptoms of TYLCV infection three weeks later, Fall 2008

| Date | Farm A | | Farm C | | Farm E | | Farm F | | Farm L | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ |
| 8/25 | NA | NA | -0.061 | 0.126 | NA | NA | NA | NA | -0.131 | 0.816 |
| 9/1 | NA | NA | 0.219 | 0.123 | 0.380* | 0.023 | -0.091 | 0.145 | 0.142 | 0.127 |
| 9/8 | NA | NA | 0.000 | 0.483 | NA | NA | 0.033 | 0.264 | -0.069 | 0.703 |
| 9/15 | NA | NA | 0.273 | 0.050 | 0.000 | 0.377 | -0.003 | 0.391 | -0.013 | 0.448 |
| 9/22 | NA | NA | 0.360 | 0.030 | 0.538* | 0.002 | -0.063 | 0.605 | -0.045 | 0.494 |
| 9/29 | NA | NA | -0.151 | 0.746 | 0.000 | 0.370 | 0.065 | 0.386 | -0.076 | 0.368 |
| 10/6 | NA | NA | 0.014 | 0.427 | NA | NA | -0.024 | 0.352 | 0.188 | 0.105 |
| 10/13 | NA | NA | 0.059 | 0.323 | 0.617* | 0.001 | 0.235 | 0.082 | -0.016 | 0.355 |
| 10/20 | NA | NA | -0.067 | 0.465 | 0.251 | 0.120 | -0.025 | 0.552 | 0.242 | 0.040 |
| 10/27 | NA | NA | 0.145 | 0.253 | -0.040 | 0.396 | -0.109 | 0.464 | 0.057 | 0.382 |
| 11/3 | NA | NA | 0.181 | 0.151 | -0.219 | 0.887 | -0.098 | 0.808 | 0.135 | 0.084 |
| 11/10 | NA | NA | 0.075 | 0.321 | 0.258 | 0.137 | NA | NA | -0.004 | 0.534 |
| 11/17 | NA | NA | 0.191 | 0.116 | 0.146 | 0.220 | 0.469 | 0.030 | NA | NA |

Note: [a] Overall index of association (*X*) between adult *B. tabaci* and incidence of TYLCV three weeks later. [b] *P* value for positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.0975$). * values indicate significant values. NA indicates one or more variables with no value.

Table 4-8. Correlations of adult *B. tabaci* weekly means to tomato plants with new infection of TYLCV incidence three weeks later, Spring 2009

| Date | Farm B | | Farm H | | Farm I | | Farm J | |
|---|---|---|---|---|---|---|---|---|
| | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] | R[a] | *P*[b] |
| 2/16 | NA | NA | NA | NA | NA | NA | NA | NA |
| 2/23 | NA | NA | NA | NA | NA | NA | NA | NA |
| 3/2 | NA | NA | NA | NA | NA | NA | NA | NA |
| 3/9 | 0.107 | 0.429 | NA | NA | NA | NA | NA | NA |
| 3/16 | 0.066 | 0.626 | 0.126 | 0.137 | NA | NA | NA | NA |
| 3/23 | -0.025 | 0.085 | -0.046 | 0.546 | NA | NA | -0.102 | 0.678 |
| 3/30 | 0.422* | 0.009 | NA | NA | NA | NA | -0.165 | 0.500 |
| 4/6 | NA | NA | -0.028 | 0.725 | NA | NA | NA | NA |
| 4/13 | NA | NA | -0.040 | 0.605 | NA | NA | NA | NA |
| 4/20 | NA | NA | 0.172 | 0.057 | NA | NA | NA | NA |
| 4/27 | NA | NA | -0.032 | 0.790 | NA | NA | NA | NA |

Note: [a] Correlation of adult *B. tabaci* to new TYLCV three weeks later. [b] P value of < 0.05 indicates significant values for α = 0.1. * values indicate significance. NA indicates one or more variables with no value.

Table 4-9. Indices of spatial association (*X*) for adult *B. tabaci* and tomato plants with new symptoms of TYLCV infection three weeks later, Spring 2009

| Date | Farm B | | Farm H | | Farm I | | Farm J | |
|---|---|---|---|---|---|---|---|---|
| | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ | $X^a$ | $P^b$ |
| 2/16 | NA | NA | NA | NA | NA | NA | NA | NA |
| 2/23 | NA | NA | NA | NA | NA | NA | NA | NA |
| 3/2 | NA | NA | NA | NA | NA | NA | NA | NA |
| 3/9 | 0.182 | 0.296 | NA | NA | NA | NA | NA | NA |
| 3/16 | 0.059 | 0.466 | 0.127 | 0.163 | NA | NA | NA | NA |
| 3/23 | -0.026 | 0.034 | -0.047 | 0.331 | NA | NA | -0.102 | 0.160 |
| 3/30 | 0.422 | 0.138 | NA | NA | NA | NA | -0.165 | 0.393 |
| 4/6 | NA | NA | -0.029 | 0.128 | NA | NA | NA | NA |
| 4/13 | NA | NA | -0.041 | 0.239 | NA | NA | NA | NA |
| 4/20 | NA | NA | 0.171 | 0.186 | NA | NA | NA | NA |
| 4/27 | NA | NA | -0.032* | >.999 | NA | NA | NA | NA |

Note: [a] Overall index of association (*X*) between adult *B. tabaci* and incidence of TYLCV three weeks later. [b] *P* value for positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.0975$). * values indicate significant values. NA indicates one or more variables with no value.

Table 4-10. Cross validation results of IDW interpolation analysis for *B. tabaci* weekly means and tomato plants with new symptoms of TYLCV incidence three weeks later, Fall 2007-2008

| Season | Date | Farm | Adult *B. tabaci* Mean Error | Adult *B. tabaci* RMSE | TYLCV Incidence Mean Error | TYLCV Incidence RMSE |
|---|---|---|---|---|---|---|
| Fall 2007 | 8/20 | A | -0.0441 | 4.165 | -0.021 | 1.849 |
| | | B | 0.00958 | 0.573 | 0.036 | 1.259 |
| | | D | -0.348 | 3.312 | -0.103 | 2.105 |
| | 9/3 | C | -0.185 | 2.239 | 0.1 | 1.672 |
| | | E | -0.369 | 5.497 | -0.774 | 6.331 |
| | 9/10 | E | -0.458 | 4.51 | -3.477 | 12.57 |
| | | F | 0.0136 | 13.15 | -0.172 | 6.106 |
| | 9/17 | E | -0.141 | 1.401 | -3.923 | 16.2 |
| | | F | -0.0337 | 2.195 | 0.225 | 6.489 |
| | 10/22 | D | -0.00734 | 0.465 | -0.535 | 8.924 |
| | | F | -0.23 | 2.64 | -0.231 | 12 |
| Fall 2008 | 9/1 | C | -0.0449 | 0.822 | 0.0224 | 1.54 |
| | | E | -0.0602 | 1.542 | -0.15 | 1.886 |

Note: Adult *B. tabaci* counts were summarized by weekly averages and incidence of TYLCV was taken from the new virus three weeks after the *B. tabaci* counts. Smaller root mean square error (RSME) indicates a better fit of the model.

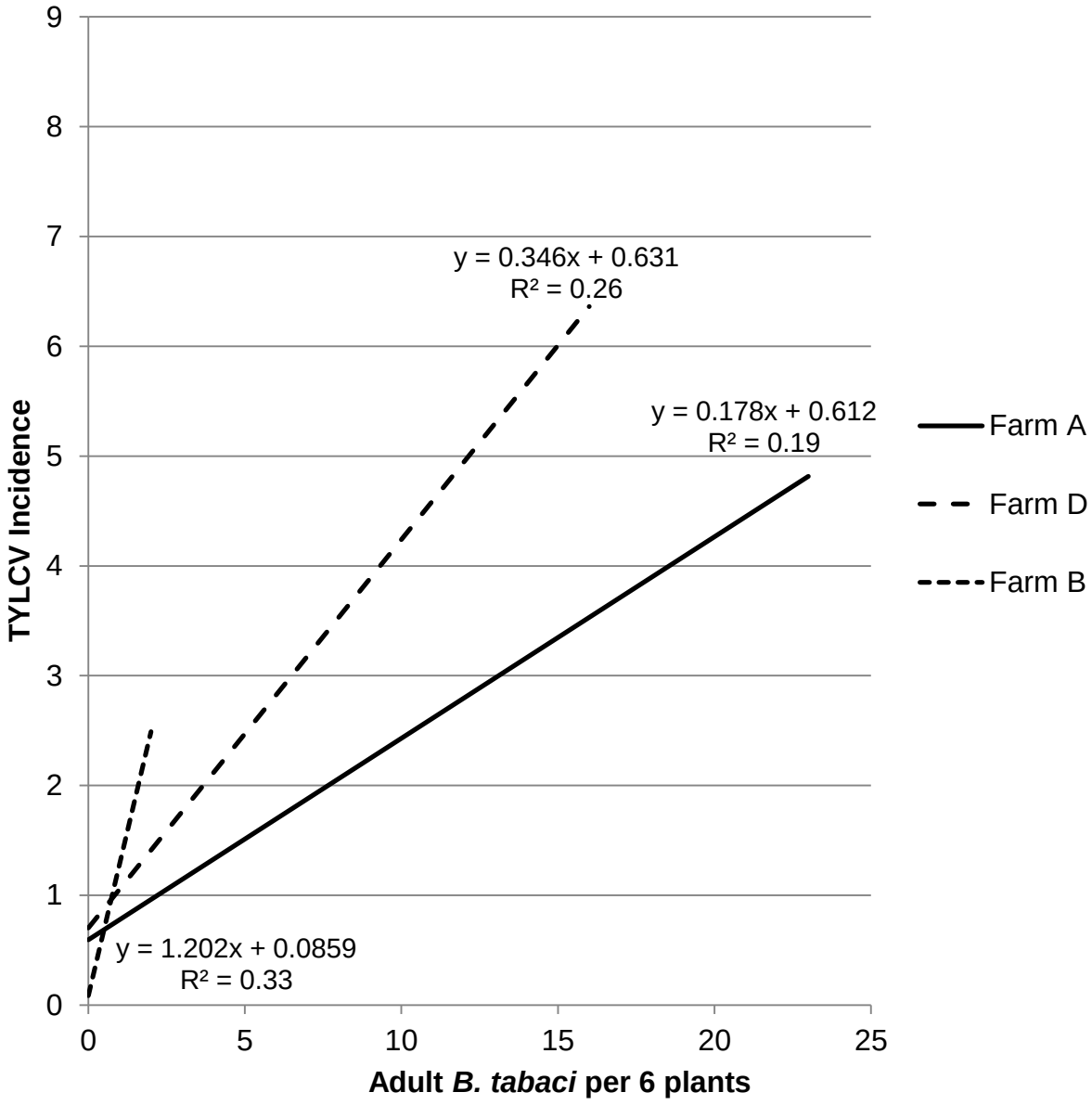


Figure 4-1. Regression of adult *B. tabaci* counts on tomato plants with new symptoms of TYLCV three weeks later, Week of 20 August 2007

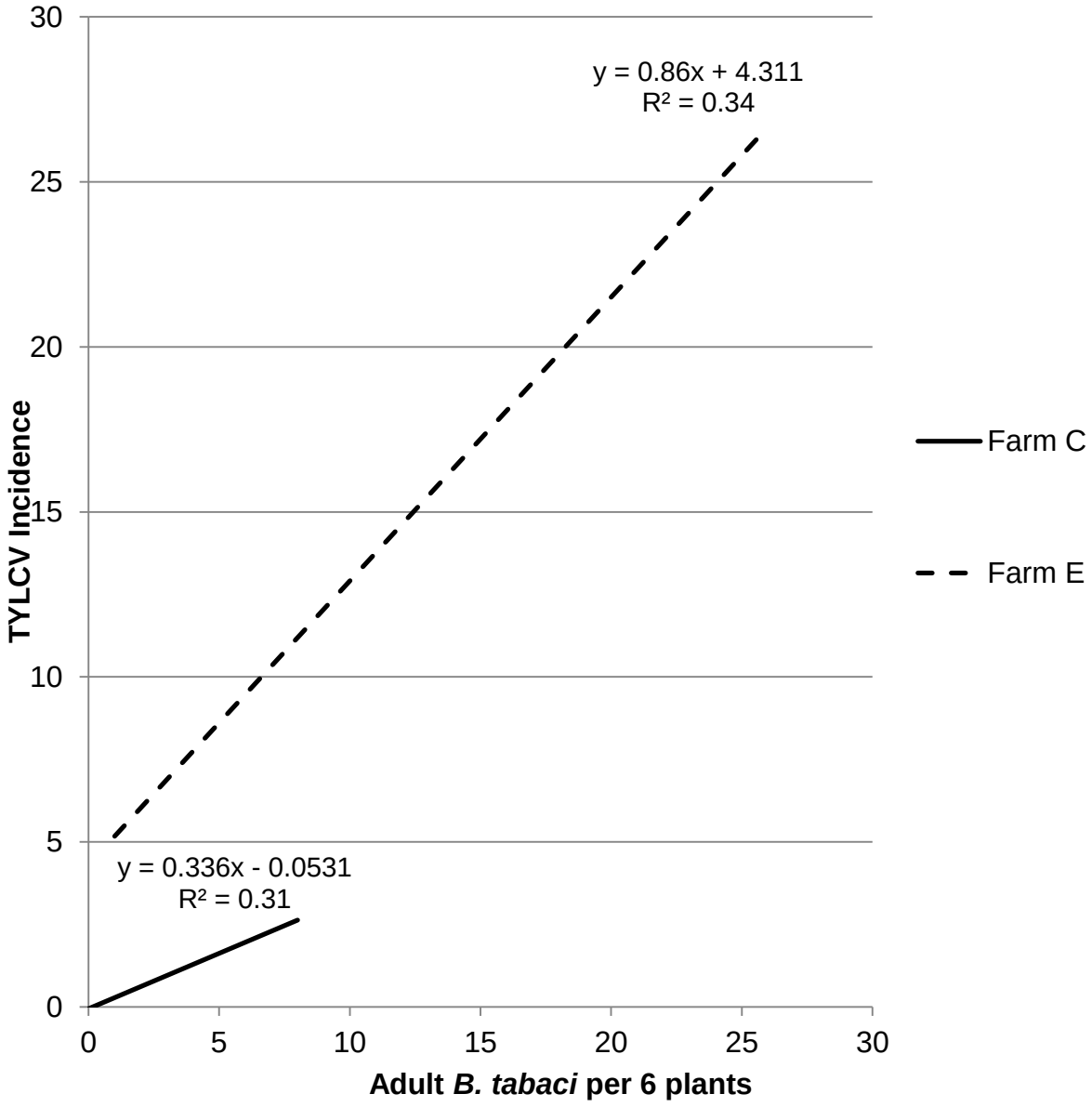


Figure 4-2. Regression of adult *B. tabaci* counts on tomato plants with new symptoms of TYLCV three weeks later, Week of 3 September 2007

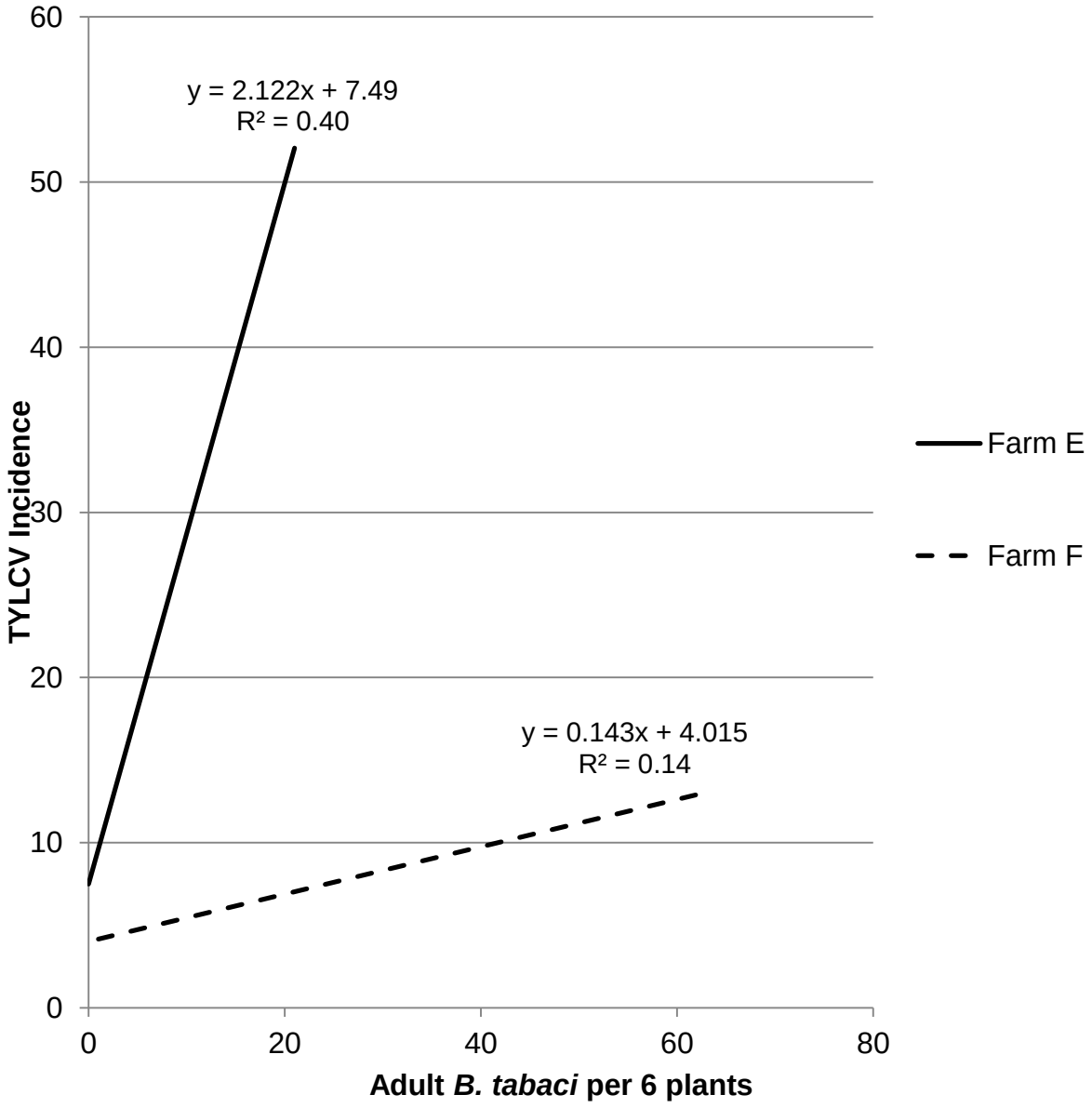


Figure 4-3. Regression of adult *B. tabaci* counts on tomato plants with new symptoms of TYLCV three weeks later, Week of 10 September 2007

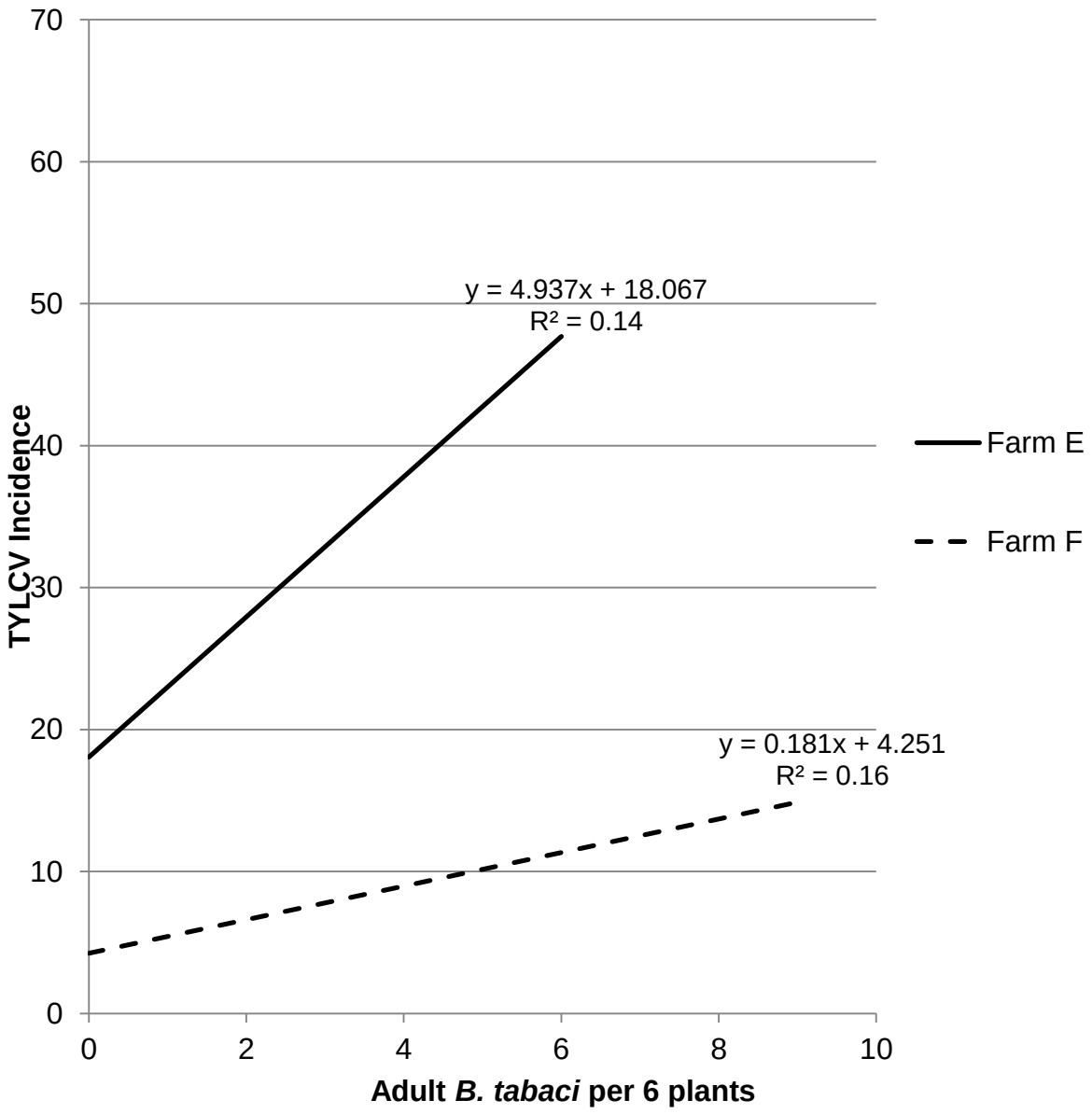


Figure 4-4. Regression of adult *B. tabaci* counts on tomato plants with new symptoms of TYLCV three weeks later, Week of 17 September 2007

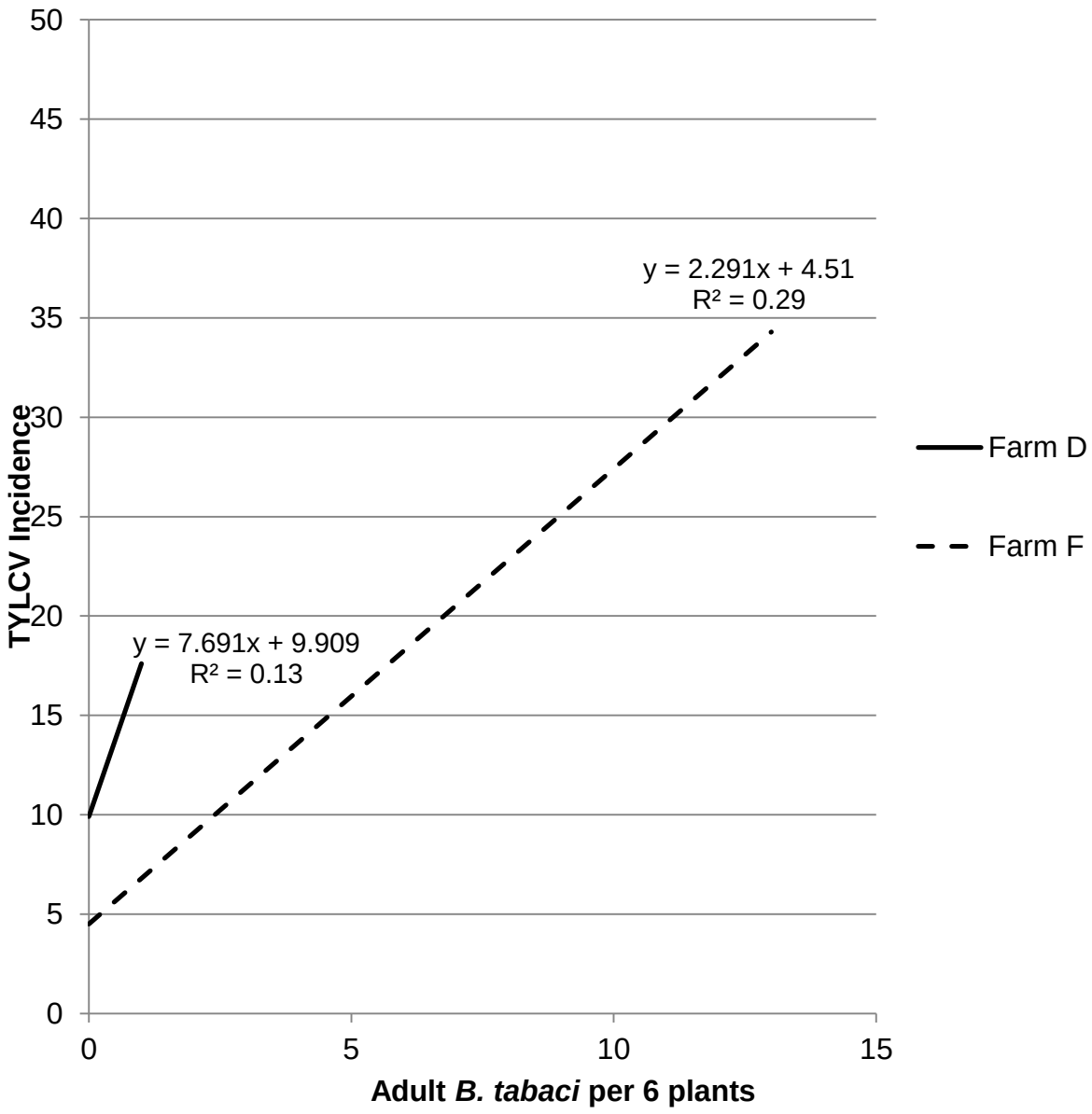


Figure 4-5. Regression of adult *B. tabaci* counts on tomato plants with new symptoms of TYLCV three weeks later, Week of 22 October 2007

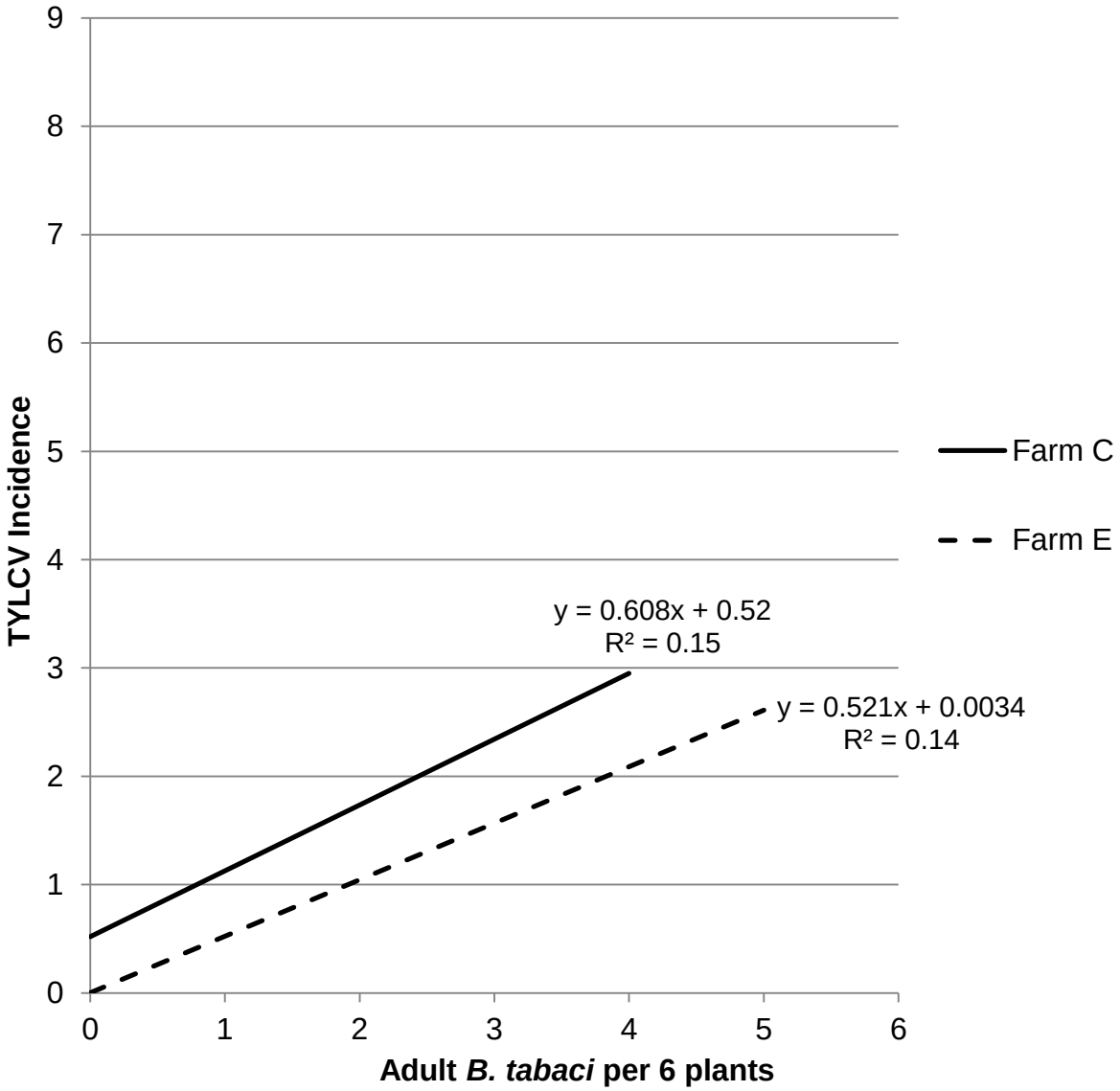


Figure 4-6. Regression of adult *B. tabaci* counts on tomato plants with new symptoms of TYLCV three weeks later, Week of 1 September 2008.

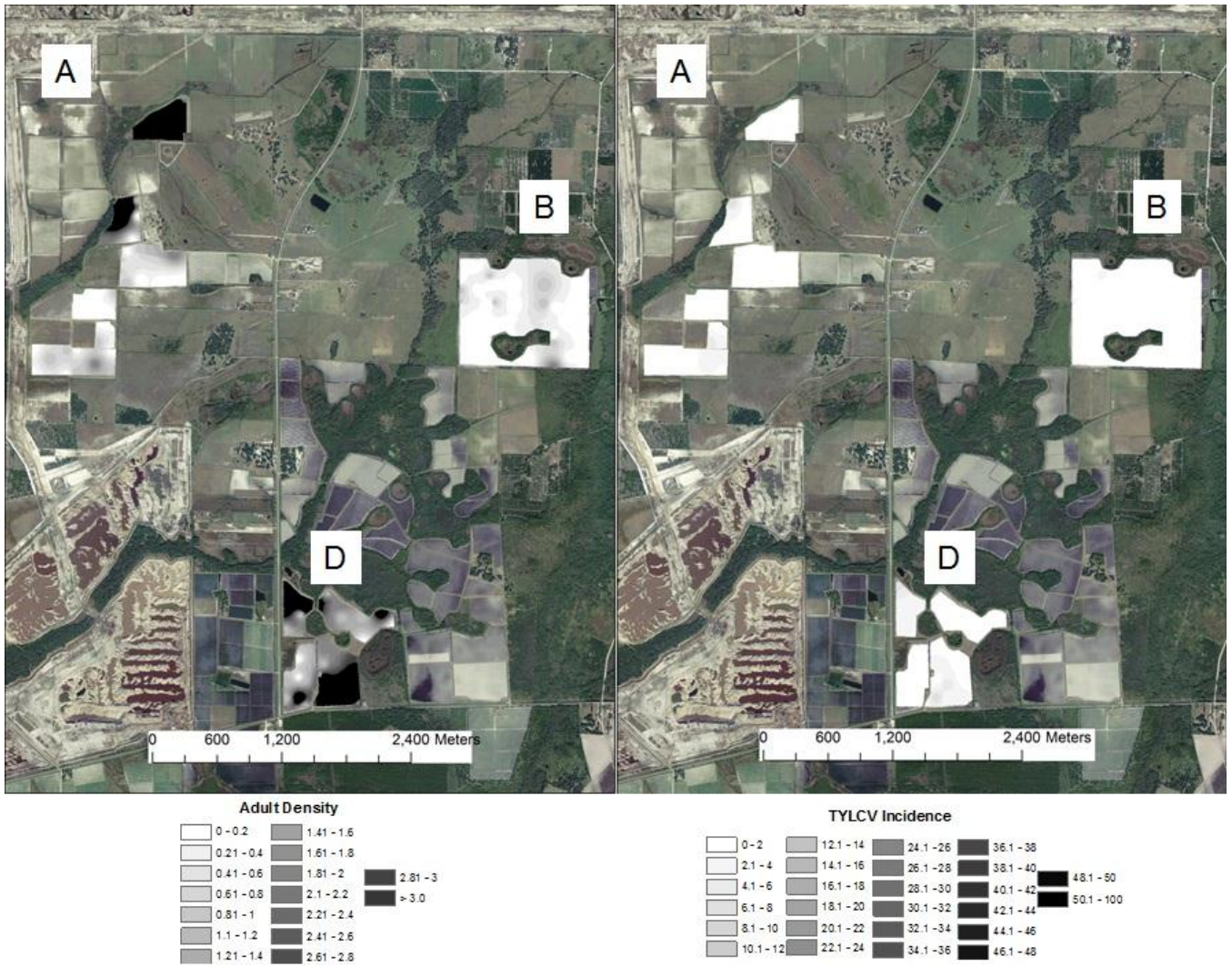


Figure 4-7. Spatial interpolation of adult populations of *B. tabaci* and incidence of tomato plants with new symptoms of TYLCV infection three weeks later from Farms A, B, and D from the week of 20 August 2007.

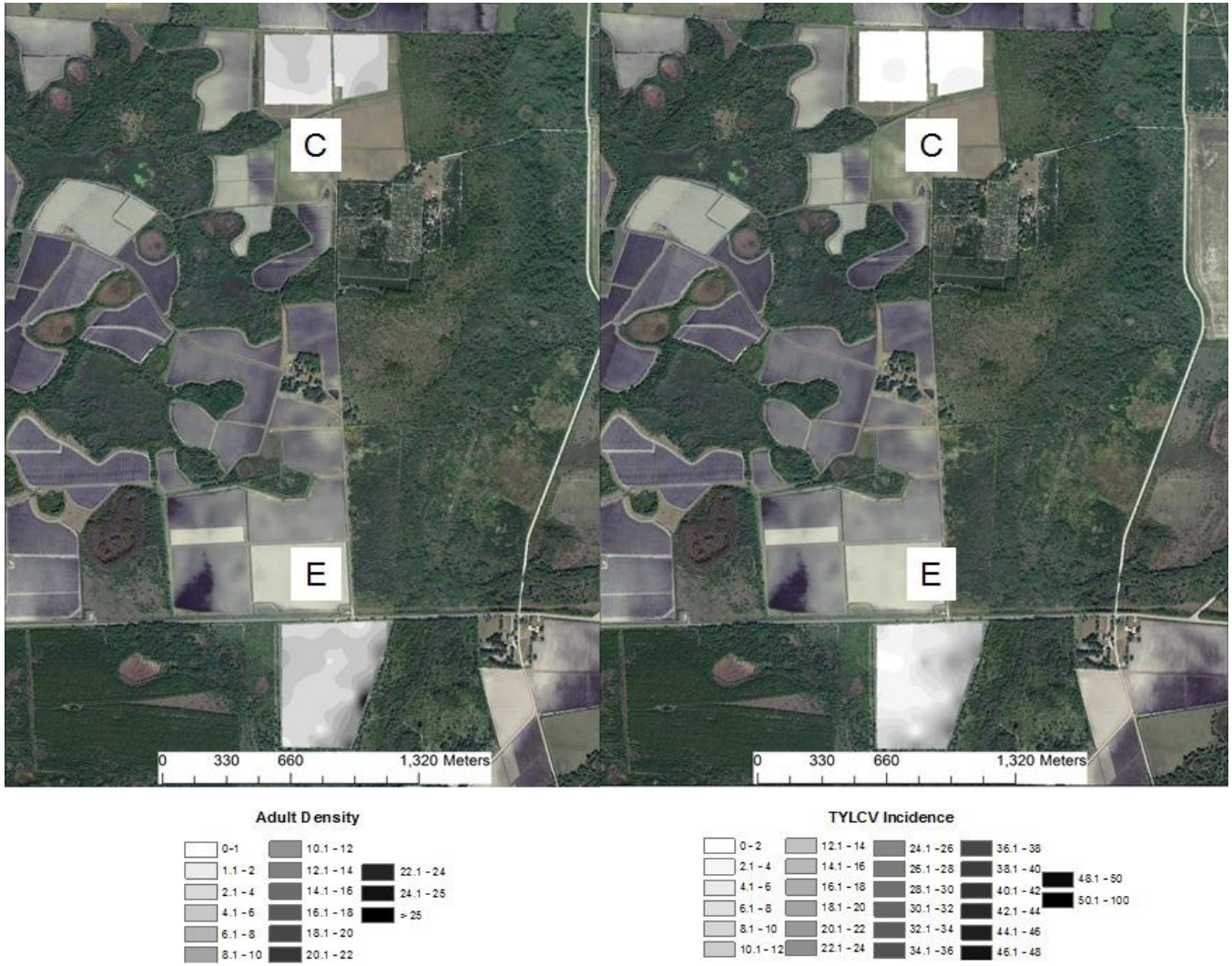


Figure 4-8. Spatial interpolation of adult populations of *B. tabaci* and incidence of tomato plants with new symptoms of TYLCV infection three weeks later from Farms C and E from the week of 3 September 2007.

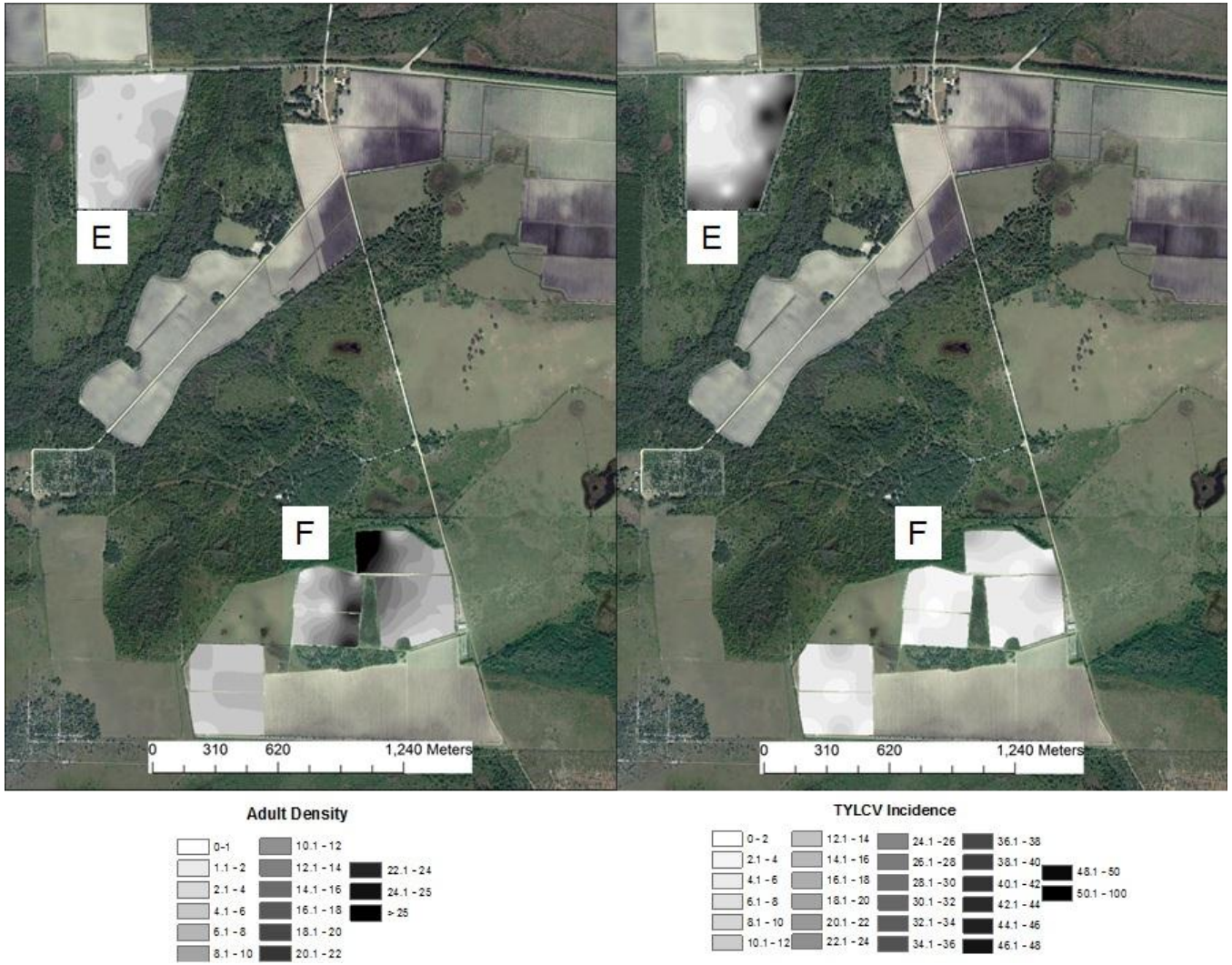


Figure 4-9. Spatial interpolation of adult populations of B. tabaci and incidence of tomato plants with new symptoms of TYLCV infection three weeks later from Farms E and F from the week of 10 September 2007.

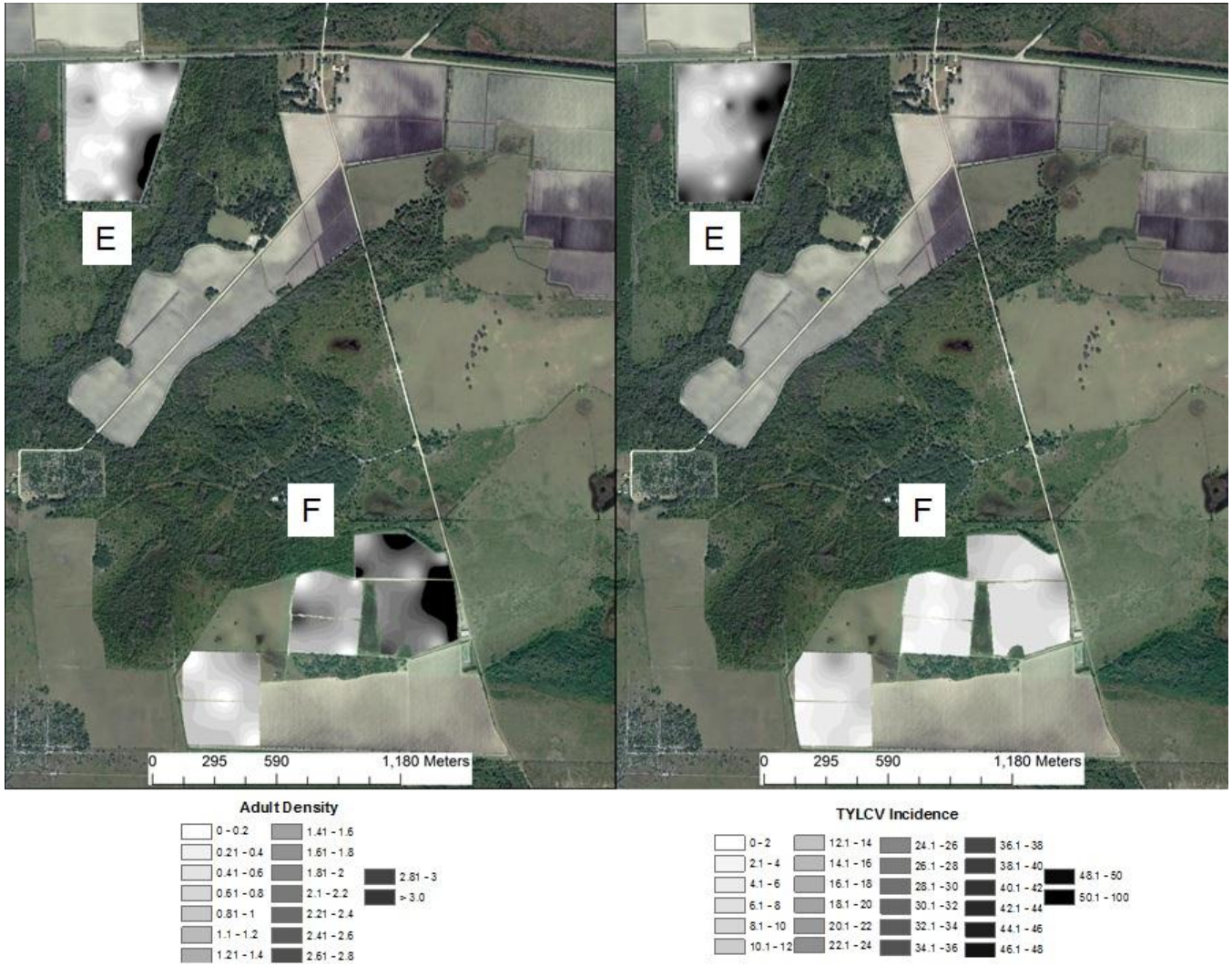


Figure 4-10. Spatial interpolation of adult populations of *B. tabaci* and incidence of tomato plants with new symptoms of TYLCV infection three weeks later from Farms E and F from the week of 17 September 2007.

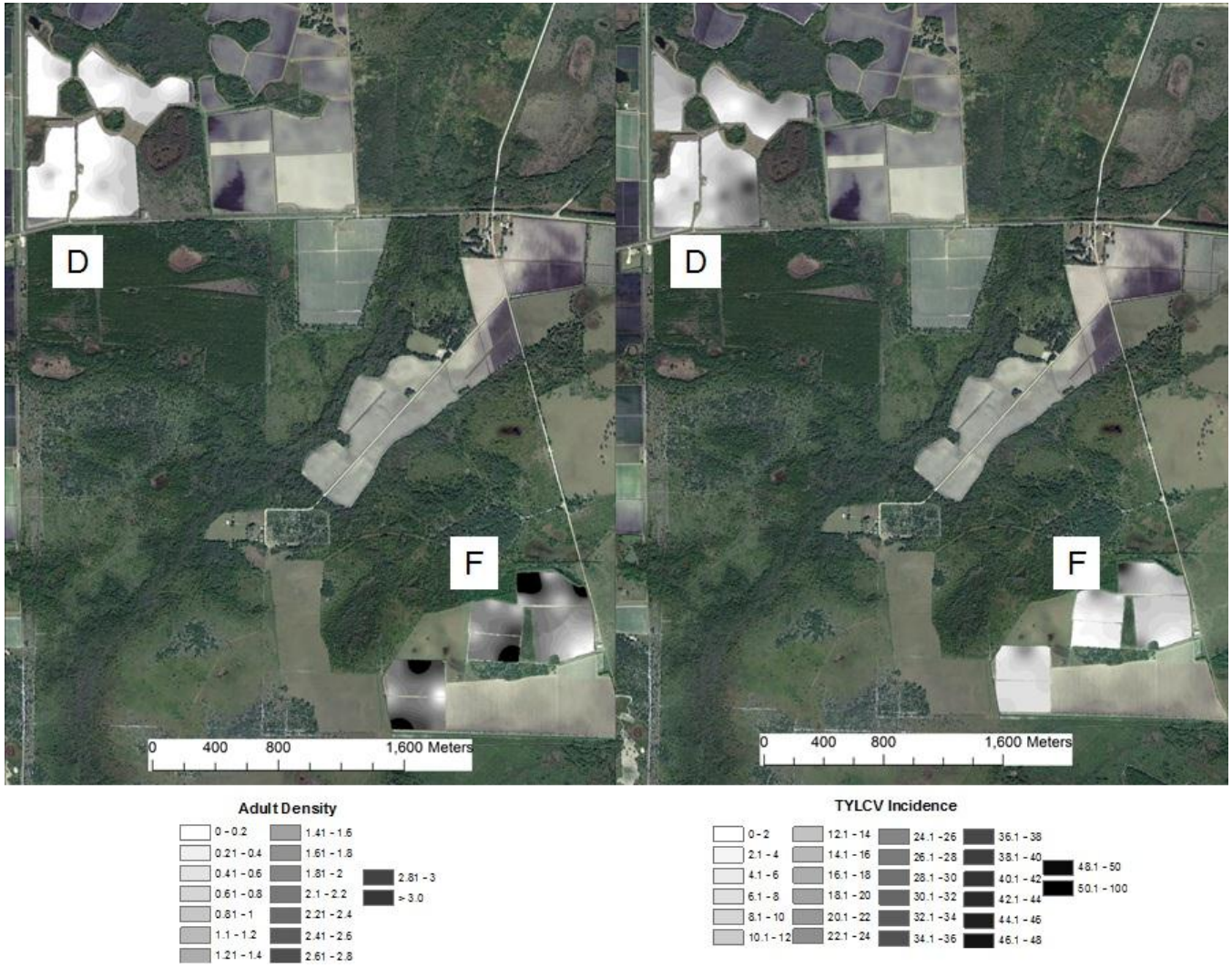


Figure 4-11. Spatial interpolation of adult populations of *B. tabaci* and incidence of tomato plants with new symptoms of TYLCV infection three weeks later from Farms D and F from the week of 22 October 2007.

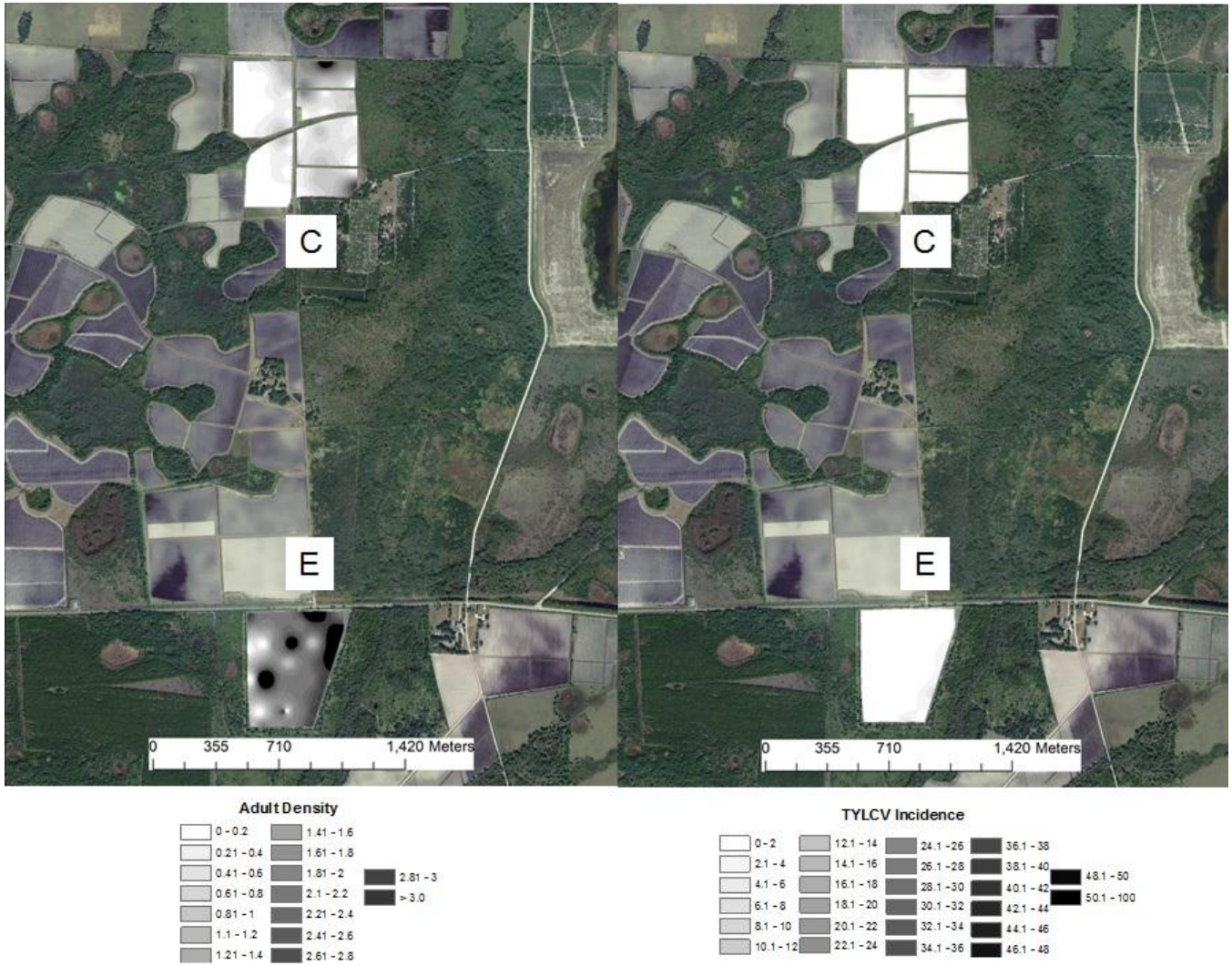


Figure 4-12. Spatial interpolation of adult populations of *B. tabaci* and incidence of tomato plants with new symptoms of TYLCV infection three weeks later from Farms C and E from the week of 1 September 2008.

# CHAPTER 5
# FACTORS INFLUENCING ABUNDANCE AND SEVERITY OF *BEMISIA TABACI* AND TYLCV IN TOMATO

## Purpose

Biotype B of the sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), also known as the silverleaf whitefly, *B. argentifolii* Bellows and Perring, is a serious pest of many agricultural crops around the world (Perring et al. 1993). Biotype B has become the key insect pest of tomatoes, *Solanum lycopersicum* (L.), in southern Florida (Schuster et al. 1996a), displacing the native non-B biotypes (McKenzie et al. 2004). Biotype B of *B. tabaci* can cause direct damage to tomatoes including an irregular ripening disorder of fruit, inhibition of fruit softening and general reduction of plant vigor (Schuster et al. 1996b, Schuster 2001, McCollum et al. 2004). In southern Florida, *B. tabaci* has become a limiting pest species due to its ability to vector plant viruses such as *Tomato yellow leaf curl virus* (TYLCV) (family *Geminiviridae,* genus *Begomovirus*) (Polston et al. 1999). TYLCV causes one of the most devastating diseases of cultivated tomato world-wide. Infection by TYLCV can result in losses of up to 100% in tropical and subtropical regions and can be the limiting factor in commercial tomato production (Czosnek and Laterrot 1997).

Many environmental and geographical factors can influence distribution of *B. tabaci* and TYLCV. One of the most important environmental variables for all insects is temperature, which can affect both life history and flight of *B. tabaci* (Butler et al. 1983, Blackmer and Byrne 1993b). Relative humidity affects *B. tabaci* development with extreme humidity being unfavorable for development (Gerling et al. 1986). *B. tabaci* also exhibited a greater phototactic orientation between relative humidity of 40-60% in glasshouse studies (Blackmer and Byrne 1993a). Because *B. tabaci* are capable of

sustaining flights longer than 2 hours and into head winds up to 30 cm/s, wind speed and direction could influence long-distance and trivial migrations (Byrne 1999, Isaacs et al. 1999). Adult populations of *B. tabaci* decline after a rain event (Zalom et al. 1985, Henneberry et al. 1995) and in cotton and cantaloupe, overhead watering has been shown to reduce numbers of whitefly eggs and nymphs (Castle et al. 1996, Castle 2001). *B. tabaci* also shows preference for landing, feeding and oviposition on its host range of over 600 plant species (Mound and Halsey 1978, Greathead 1986, Secker et al. 1998). Along with other insects, *B. tabaci* has exhibited edge effects in tomato (Garcia 2006, Turechek 2010, Taylor unpublished). Cultural controls which include UV-reflective soil mulches, have been shown to reduce settling of *B. tabaci* adults on tomato plants (Csizinszky et al. 1997, Csizinszky et al. 1999). TYLCV distribution is directly related to the movement of *B. tabaci* but environmental factors can influence symptom expression in the plant (Lapidot et al. 2000, Lapidot et al. 2006). Individual cultivars within species can vary in their expression of TYLCV symptoms and some hosts can be symptomless (Lapidot et al. 2006, Polston et al. 2006). Date of infection can have a great impact on the severity of TYLCV epidemics and early infection of TYLCV in tomato causes the greatest yield loss (Polston and Lapidot 2007).

Classification and regression trees (CART) are useful for analyzing complex ecological data, including evaluating the relationships between biotic and/or abiotic factors in the system (Grunwald et al. 2009). CART is suited to analyze datasets that are nonlinear, have missing data values and are complex (Breiman et al. 1984). Classical regression methods rely on assumptions of the distribution and variance of data, whereas CART-based models do not require the data to be linear and can handle

categorical and continuous data. CART analysis uses “trees” to explain variation of target variables by repeatedly splitting the data. Each split is defined by a simple rule based on a single explanatory variable to which the overall goal of the split is to make each partition as homogeneous as possible (De'ath and Fabricius 2000). Parent nodes are always split into exactly two child nodes, which may then be further split leading to a tree. Optimized splitting rules are identified at each level of the tree. CART has been used to identify factors influencing insect populations including southern pine beetles, sawflies, and honey bees (MacQuarrie et al. 2010, vanEngelsdorp et al. 2010, Duehl et al. 2011). In this study, CART analysis was used to evaluate the environmental, geographical and cropping variables that influenced the distribution of *B. tabaci* adult populations and plants with symptoms of TYLCV infection in southern Florida tomato.

## Methods and Materials

### Study Sites

Populations of *B. tabaci* and incidence of TYLCV-infected plants were monitored on commercial tomato farms for four seasons in west-central Florida. Farm sizes ranged from 23.6 to 273.0 ha and were located in a study area of ≈ 53.8 $km^2$ in Manatee Co., Florida. The farms were selected because they were spatially isolated by distances over 10 km from other commercial tomato production. Farms were managed by commercial growers so pesticide sprays and cultural practices were based on standard grower practices. There were cultivar differences between and within farms and all samples were taken on plastic-cultured, staked and tied tomatoes.

Twice weekly sampling by scouts was initiated as each field was transplanted and included adult whitefly counts (total number of adults on 6 contiguous plants) and incidence of TYLCV infection (visual inspection of 50 contiguous plants). Before first tie

(≈ 3-4 weeks after transplanting), whitefly counts were taken on whole plant samples. After first tie, counts were taken on the abaxial surface from two leaves at the third node from the top of two branches on each of the six plants, using a leaf turn technique (Naranjo et al. 1995, Palumbo et al. 1995). Incidence of TYLCV-infected plants was based on a conservative estimate of visual symptom expression and was considered cumulative throughout the growing season. Scouts were trained to only record tomato plants with obvious symptoms of TYLCV infection, which included upward curling of leaves, reduction of leaflet area and yellowing of young leaves (Polston et al. 1999). The growers' farms were divided into blocks, and sampling points remained constant throughout the season (i.e. the same 6 plants were used for *B. tabaci* counts and the same 50 plants were evaluated for incidence of TYLCV infection). Scouting methodology was determined by previous work by Schuster et al. (2007b).

**Explanatory Variables**

Predictor variables were environmental, geographical, or cropping variables (Table 5-1). Environmental data were taken from the nearest Florida Automated Weather Network (FAWN) located in Balm, Florida, which was approximately 10 miles from the study area. Environmental data from the previous day was chosen as the most important for whitefly movement because sampling occurred from early morning until mid-afternoon of each sample day. Along with daily averages, the hours between 6:00 and 10:00 AM were included because those times have been indicated as peak hours for *B. tabaci* flight (Blackmer and Byrne 1993b). Relative humidity and rainfall have been indicated as factors in both life history and flight propensity in *B. tabaci*. For predicting TYLCV incidence, both wind speed and direction were excluded because

wind speed from the day of virus counts would not have any effect on TYLCV incidence due to lag of symptom expression.

Geographical variables such as proximity to a buffer area and area of block were included in this analysis. Buffer was indicated as the distance (m) to nearest non-tomato. Non-tomato buffer includes non-tomato crops, old tomato fields, woods, weed banks, ditches and other similar areas. This excludes roads between fields and any non-tomato area under 5 m in width. Area of block was indicated by the area (ha) of contiguous tomato surrounding a sample site. Tomato blocks were considered contiguous if separation between tomato fields was less than 100 m. Mulch types (white, UV-reflective, black), row orientation (north/south, northeast/southwest, east/west, northwest/southeast) and grass along in-field, shallow drainage ditches (grass planted for wind protection of newly set tomato transplants), varied throughout seasons and within farms. Tomato type (round, roma, grape and cherry) has been indicated as an important variable in management of both *B. tabaci* and TYLCV in southern Florida (Polston and Lapidot 2007).

**CART Analysis**

The data analysis used CART methodology developed by Breiman et al. (1984) implemented in CART 6.0 software (Salford Systems, San Diego, CA). In the single regression tree analysis, adult *B. tabaci* and TYLCV incidence were target variables (dependent) and other environmental, geographical and cropping factors were predictor variables (independent) (Table 5-1). The CART analysis repetitively splits the data into homogeneous subsets. Splitting is conducted until all splits are pure as compared to their parental node and the least squares splitting rule was used.

CART can test the predictive capacity of the obtained trees and a 10-fold cross-validation method was used. Cross-validation allows CART to build trees based on data subsets then calculates the error rate based on the unused portions of the data set. The data set is first broken into 10 randomly selected partitions. At each step, nine parts of the data are used to construct the largest possible tree and the remaining part is used to obtain estimates of the error rate of the selected sub-tree. This procedure is repeated for each partition and the error rate is averaged over all ten partitions to generate the cross-validated relative error. The resubstitution relative error (RRE) is a measure of the goodness of the fit of the model for the regression tree predictions and 1-REE is an approximation of the $R^2$ statistic (Breiman et al. 1984, Steinberg and Colla 1995). The "best tree" was identified using the minimum cost tree, although there is a limit on the number of nodes one can express. CART also allows for the calculation of the relative importance of each explanatory variable. In this study, multiple trees are presented as possible tree sequences for adult *B. tabaci* and TYLCV incidence (Table 5-2). Our study consisted of four seasons, so data from fall of 2007 and fall 2008 were combined and data from spring of 2008 and spring 2009 were combined for analysis (Table 5-2).

## Results

### *B. tabaci*

CART analysis of *B. tabaci* in the combined fall seasons indicated average temperature (100) was the most important predictor variable, followed by wind direction (79.66), wind speed 6:00-10:00 AM (73.52), wind speed average (65.97), buffer (62.07), wind direction 6:00-10:00 AM (60.26), relative humidity (55.47), area of block (42.29), farm (19.34),…, mulch (1.21) (Table 5-3). To express the importance of these predictor

variables, a regression tree of 18 terminal nodes is presented in Figure 5-1. In the first split, farm is indicated as the most important variable, with farms A, B, C, F, G and L having fewer whiteflies [Average (Avg) = 0.543, standard deviation (STD) = 2.42] than farms D and E (Avg = 2.179, STD = 5.945). In the fall seasons, environmental variables such as temperature and wind speed/direction play a large role in predicting adult *B. tabaci* populations (Table 5-3 and Figure 5-1). The split leading to terminal node 1 (TNode), node 3, node 7 and node 14 was determined by average temperature, the most important predictor variable. Cooler temperatures (< 26.13°C in the left branch and < 28.22ºC in the right branch) indicated lower adult *B. tabaci* populations (Figure 5-1). Average temperature continued to split the left branch until temperature was < 26.20°C at node 5. At higher temperatures, buffer distance < 18.5 m resulted in higher whitefly counts. On the right tree branch, when temperature was lower, farms D and E also had lower counts of *B. tabaci*. Buffer distance was important in multiple splits within the right tree, with shorter distances to non-tomato increasing counts of *B. tabaci.* Tomato type, tomato age and mulch type had relatively low importance to whitefly counts in the fall seasons.

In contrast, CART analysis of *B. tabaci* in the combined spring seasons indicated buffer distance (99.99) was the most important predictor variable, followed by relative humidity (87.21), row orientation (62.6), age (57.01), average temperature (56.75), tomato type (44.44), rainfall (34.85), wind direction 6:00-10:00 AM (25.55),…, area of block (3.97) (Table 5-4). From the regression tree of 19 terminal nodes, environmental variables are important in the higher parts of the tree but later splits indicate the importance of buffer distance, row orientation and age (Figure 5-2). Wind direction from

the southeast to south (< 328.67 deg) caused a small first split followed by more influential second splits on the left and right branches of average temperature and tomato type. Of those data with south-west to south winds, roma tomatoes had higher whitefly counts. On the left branch, warmer average temperature (> 23.52°C) increased whitefly counts. Farms B, H and I had lower *B. tabaci* populations than farms J and K. Higher relative humidity favored an increase in whitefly counts. Buffer distances that influenced *B. tabaci* counts in the spring season were not as short as those found in the fall season. Like the fall seasons, spring adult *B. tabaci* populations were less influenced by mulch type but were more influenced by age of tomato and tomato type (Figure 5-2).

**TYLCV**

CART analysis of the incidence of TYLCV-infected plants in the combined fall seasons indicated buffer distance (100) was the most important predictor variable, followed by average temperature (99.99), area of block (76.14), farm (73.16), age (46.5), tomato type (44.96), row orientation (32.11), rainfall (21.62) and mulch (19.35) (Table 5-3). In the TYLCV analysis, wind data was not included, but geographical variables such as buffer distance and area of block were very important along with the environmental variable, average temperature. From the regression tree of 12 terminal nodes, the variable farm was the first split and farms B, C, F, G and L had less TYLCV incidence (Avg = 3.556, STD = 8.541) compared to farms A, D and E (Avg = 12.683, STD = 19.413). The first split was followed by average temperature and further down the tree there were splits by geographical and cropping factor predictor variables (Figure 5-3). In the fall seasons, both grape and cherry tomato types had more incidence of TYLCV than round and roma type tomatoes (Figure 5-3).

In the combined spring seasons, CART analysis of incidence of TYLCV-infected plants indicated buffer distance (100) was the most important predictor variable, followed by row orientation (80.12), farm (72.46), mulch (67.84), average temperature (34.96), relative humidity (22.71), area of block (22.66), age (20.1), tomato type (9.51) and rainfall (0.68) (Table 5-4). From the regression tree of 13 terminal nodes, farm was the first split followed by average temperature. On the first split, farms B, H, I and K had very low incidence of TYLCV (Avg = 0.058, STD = 0.378) where farm J had higher incidence of TYLCV (Avg = 2.457, STD = 1.33). Similarly to the fall seasons, geographical and cropping factor variables were important further down the tree but average temperature played a major role in determining splits (Figure 5-4). Although buffer distance was considered very influential, differences in distance were very subtle during the spring seasons because virus incidence was very low.

## Discussion

Overall, results from CART analysis suggest that temperature was very influential in predicting *B. tabaci* abundance and the incidence of TYLCV-infected plants. *B. tabaci* populations were highest during warmer conditions in the early fall seasons and the end of the spring seasons. The increase of TYLCV incidence, regardless of temperature change, suggests that average temperature is only an indicator of the length of season. This analysis suggests that, towards the end of the growing season, there were greater incidences of TYLCV-infected plants. This result was to be expected. Widespread and substantial freeze events before both the spring 2008 and spring 2009 crops were not included in the environmental data set because they occurred before scouting commenced (Turechek 2010). These events had the potential to cause widespread destruction of hosts of whiteflies, including crops and weeds.

Temperature was also low enough to cause mortality of whiteflies in unprotected areas. Relative humidity was influential for predicting *B. tabaci* in the fall and spring seasons and marginally influential for predicting TYLCV incidence in the spring season. Relative humidity > 83 % increased whitefly counts and lower humidity < 76 % increased TYLCV incidence. Environmental variables such as wind speed and direction were more influential in the fall season's adult whitefly counts. Higher wind speed was shown to increase whitefly numbers in at least one terminal node split in fall 2007 (Figure 5-1). Wind speed has been positively correlated with whitefly density in similar work by Turechek (2010). Rainfall has been observed to reduce adult whitefly counts but was only marginally influential in the spring seasons. This indicated winter and spring rains influenced whitefly populations greater than in the fall.

Buffer distance was important in predicting both adult *B. tabaci* and symptomatic TYLCV infected plants. In most cases, smaller buffer distances resulted in increased *B. tabaci* abundance and TYLCV incidence. The average buffer distance over all data sets most influential to adult whitefly counts was 38 m and for the incidence of TYLCV-infected plants was 72 m. The area of block was marginally influential in predicting *B. tabaci* abundance and TYLCV incidence. Larger contiguous areas have been indicated as having fewer whiteflies and TYLCV incidence (Turechek, personal communication). In the present study, area of block was influential in the prediction of *B. tabaci* in two farms at the end of the fall seasons, with the larger blocks (> 33 ha) having more whiteflies. This split of farm size was associated with a difference between farms as this split indicated the differences in populations associated with farms D and E. Both block sizes were under 35 ha though the larger block of farm D (35 ha) was indicated to

have higher populations of *B. tabaci* than farm E (31 ha). Similarly, smaller blocks of tomato (< 33 ha) had a higher TYLCV incidence indicating the interior of smaller blocks were closer to buffers and to sources of viruliferous hosts. In the spring season, the regression tree indicated larger field size had more TYLCV incidence. After reviewing the data set, it was determined that in reality the split was caused by the differences in incidence of TYLCV-infected plants between the 2008 and 2009 seasons. Farm J was smaller in size in 2008 than in 2009 seasons, thus, influencing the split between TNode 12 and TNode 13 (Figure 5-4).

Rows in farm F oriented east/west or northwest/southeast had higher incidences of TYLCV infection compared to rows oriented north/south or northeast/southwest. The influence of tomato type varied between seasons and was greater in the fall seasons. Age of tomato was only a predictor in one split in any tree. Middle aged tomatoes at the end of the spring seasons had more whiteflies than the earliest and latest plantings. Mulch types were more influential in predicting TYLCV incidence than predicting *B. tabaci* populations.

Environmental, geographical, and cropping factor variables can impact both adult populations of *B. tabaci* and the incidence of TYLCV-infected plants. CART analysis confirmed assumptions that environmental variables such as temperature, wind speed and wind direction influence populations of *B. tabaci*. Geographical variables such as buffer distance are important to both *B. tabaci* populations and TYLCV incidence. As indicated in a previous study, smaller block size resulted in higher *B. tabaci* abundance and incidence of TYLCV-infected plants (Turechek, personal communication). Other factors such as rainfall, mulch type and tomato type were thought to have more

influence on *B. tabaci* counts and/or incidence of TYLCV-infected plants, but this analysis suggests that on a large scale those factors do not have as much influence as previously thought. Future work could be designed to evaluate on a smaller scale some of those factors that were indicated as important in the present study. Other variables could only be assessed on a large scale study which, as the present study points out, is very dynamic with many factors influencing *B. tabaci* and TYLCV.

Table 5-1. Description of variables in the CART analysis used to study the influence of environmental, geographical and cropping variables on the abundance of *B. tabaci* adults and the incidence of tomato plants with symptoms of TYLCV infection

| Variable | Character[a] | Type[b] | Values |
|---|---|---|---|
| Farm | farms | C | Farms A-K |
| Buffer | buffer | N | distance to nearest non-tomato (m) |
| Tomato type | tomtype | C | 1 (round), 2 (roma), 3 (grape), 4 (cherry) |
| Row orientation | row | C | 1 (north/south), 2 (northeast/southwest), 3 (east/west), 4 (northwest/southeast) |
| Plastic mulch | mulch | C | 1 (white), 2 (UV-reflective), 3 (black) |
| Area of Block | areaofblock | N | area of contiguous tomato (ha) |
| Age of tomato | age | C | age of tomato based on planting date by months, 1 (1st), 2 (2nd), 3 (3rd) |
| Grass row middles | rowmid | C | 1 (grass), 2 (no grass) |
| Average daily temperature | tempavdb | N | temperature (°C) from day before sample |
| Relative humidity | rhdb | N | % relative humidity from day before sample |
| Wind speed average | windspavdb | N | wind speed average from 2 meters above ground (mph) from day before sample |
| Wind direction average | winddiravgdb | N | wind direction average from 2 meters above ground from day before sample |
| Wind speed average 6:00-10:00 AM | wind sp 6-10 db | N | wind speed average from 2 meters above ground (mph) 6:00-11:00 AM from day before sample |
| Wind direction average 6:00-10:00 AM | wind dir 6-10 db | N | wind direction average from 2 meters above ground 6:00-11:00 AM from day before sample |
| Sum of rainfall | rainfalldb | N | sum of rainfall (inches) from day before sample |

Note: [a] Character corresponds to variable in CART analysis. [b] C = categorical variable and N = numeric variable.

Table 5-2. Summary of 10-fold cross-validation results to predict adult *B. tabaci* and TYLCV incidence

| Season | Dependent variable | Terminal Nodes | Cross-validated relative error | Resubstitution relative error | $R^2$ |
|---|---|---|---|---|---|
| Fall Seasons | *B. tabaci* | 139 | 0.72 | 0.36 | 0.64 |
| | | 18 | 0.80 | 0.56 | 0.44 |
| | TYLCV | 673 | 0.22 | 0.09 | 0.91 |
| | | 12 | 0.55 | 0.53 | 0.47 |
| Spring Seasons | *B. tabaci* | 24 | 0.81 | 0.46 | 0.54 |
| | | 19 | 0.83 | 0.50 | 0.50 |
| | TYLCV | 42 | 0.51 | 0.41 | 0.59 |
| | | 13 | 0.66 | 0.61 | 0.39 |

Table 5-3. Ranking of predictor variables on *B. tabaci* abundance and TYLCV incidence in Fall 2007/2008

| Target variables | Predictor variables | Relative Importance |
|---|---|---|
| *B. tabaci* | tempavdb | 100 |
| | winddiravdb | 79.66 |
| | wind sp 6-10 db | 73.52 |
| | windspavdb | 65.97 |
| | buffer | 62.07 |
| | wind dir 6-10 db | 60.26 |
| | rhdb | 55.47 |
| | areaofblock | 42.29 |
| | farm | 19.34 |
| | rainfalldb | 6.23 |
| | tomtype | 5.53 |
| | age | 1.89 |
| | row | 1.55 |
| | mulch | 1.21 |
| TYLCV | buffer | 100 |
| | tempavdb | 99.99 |
| | areaofblock | 76.14 |
| | farm | 73.16 |
| | age | 46.5 |
| | tomtype | 44.96 |
| | row | 32.11 |
| | rainfalldb | 21.62 |
| | mulch | 19.35 |

Table 5-4. Ranking of predictor variables on *B. tabaci* abundance and TYLCV incidence in Spring 2008/2009

| Target variables | Predictor variables | Relative Importance |
|---|---|---|
| *B. tabaci* | buffer | 99.99 |
| | rhdb | 87.21 |
| | row | 62.6 |
| | age | 57.01 |
| | tempavdb | 56.75 |
| | tomtype | 44.44 |
| | rainfalldb | 34.85 |
| | winddir 6-10 db | 25.55 |
| | windsp 6-10 db | 8.57 |
| | farm | 7.85 |
| | mulch | 7.55 |
| | winddiravdb | 7.07 |
| | windspavdb | 6.73 |
| | areaofblock | 3.97 |
| TYLCV | buffer | 100 |
| | row | 80.12 |
| | farm | 72.46 |
| | mulch | 67.84 |
| | tempavdb | 34.96 |
| | rhdb | 22.71 |
| | areaofblock | 22.66 |
| | age | 20.1 |
| | tomtype | 9.51 |
| | rainfalldb | 0.68 |
| | rowmid | 0 |

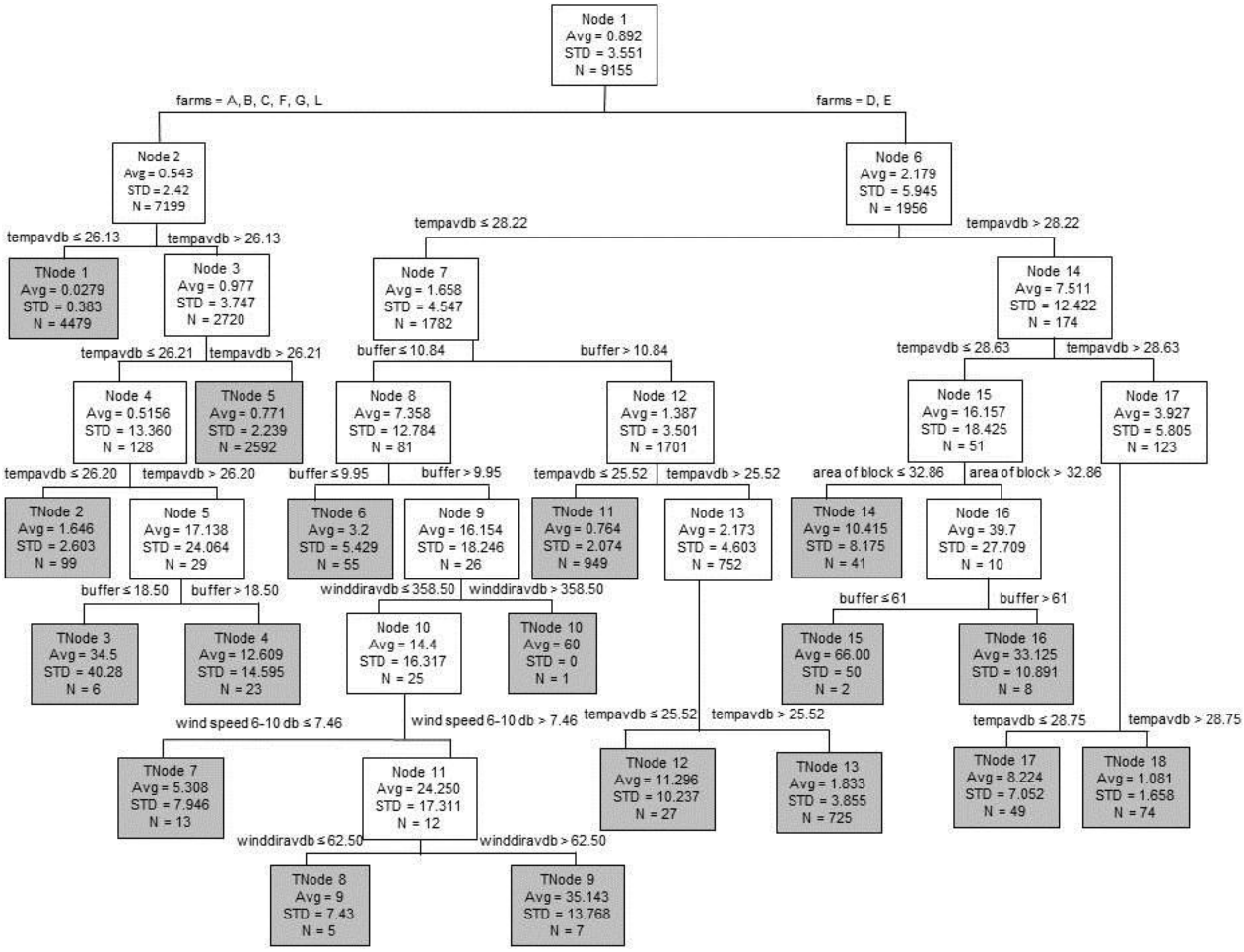


Figure 5-1. Regression tree of the variables influencing populations of *B. tabaci* in Fall 2007/2008.

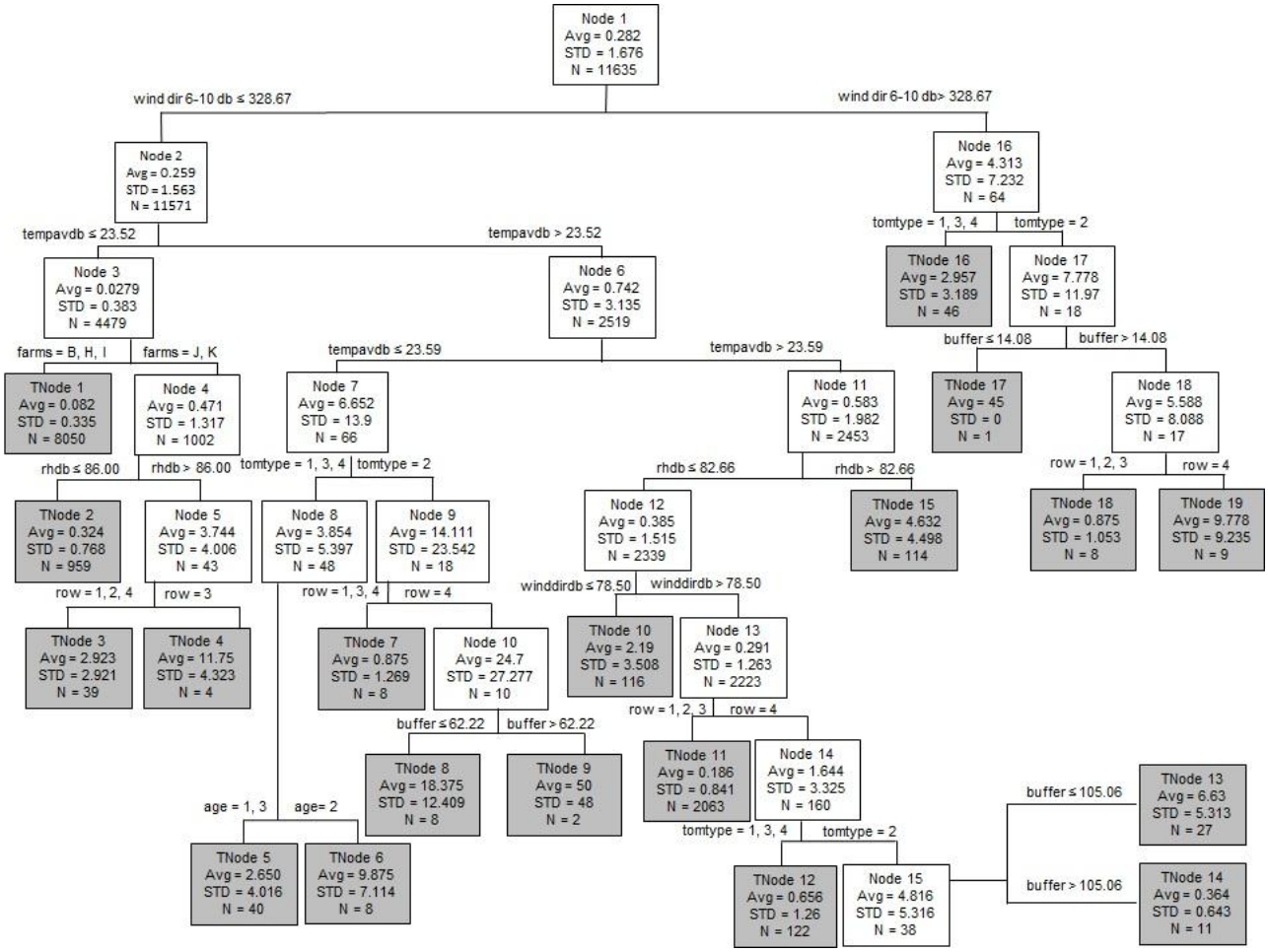


Figure 5-2. Regression tree of the variables influencing populations of *B. tabaci* in Spring 2008/2009.

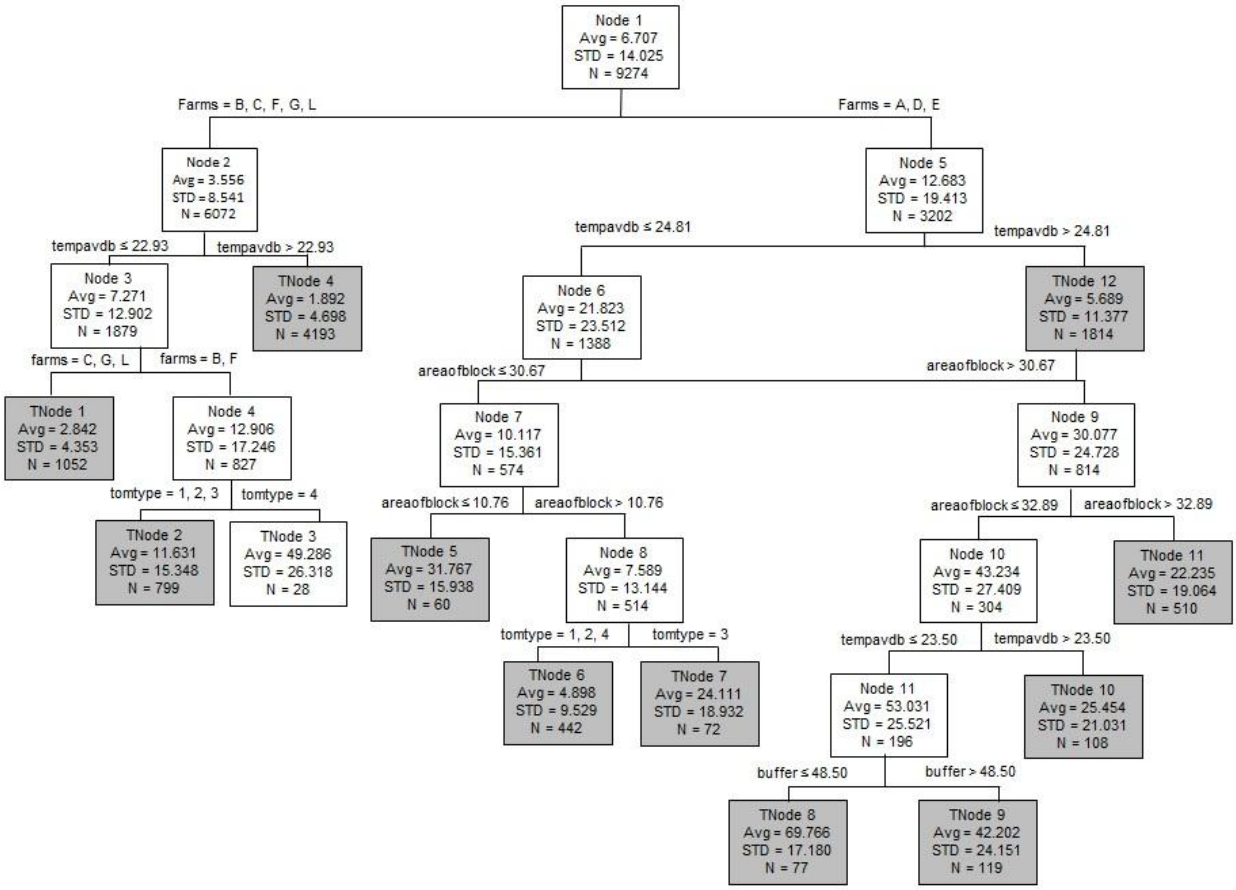


Figure 5-3. Regression tree of the variables influencing TYLCV incidence in Fall 2007/2008.

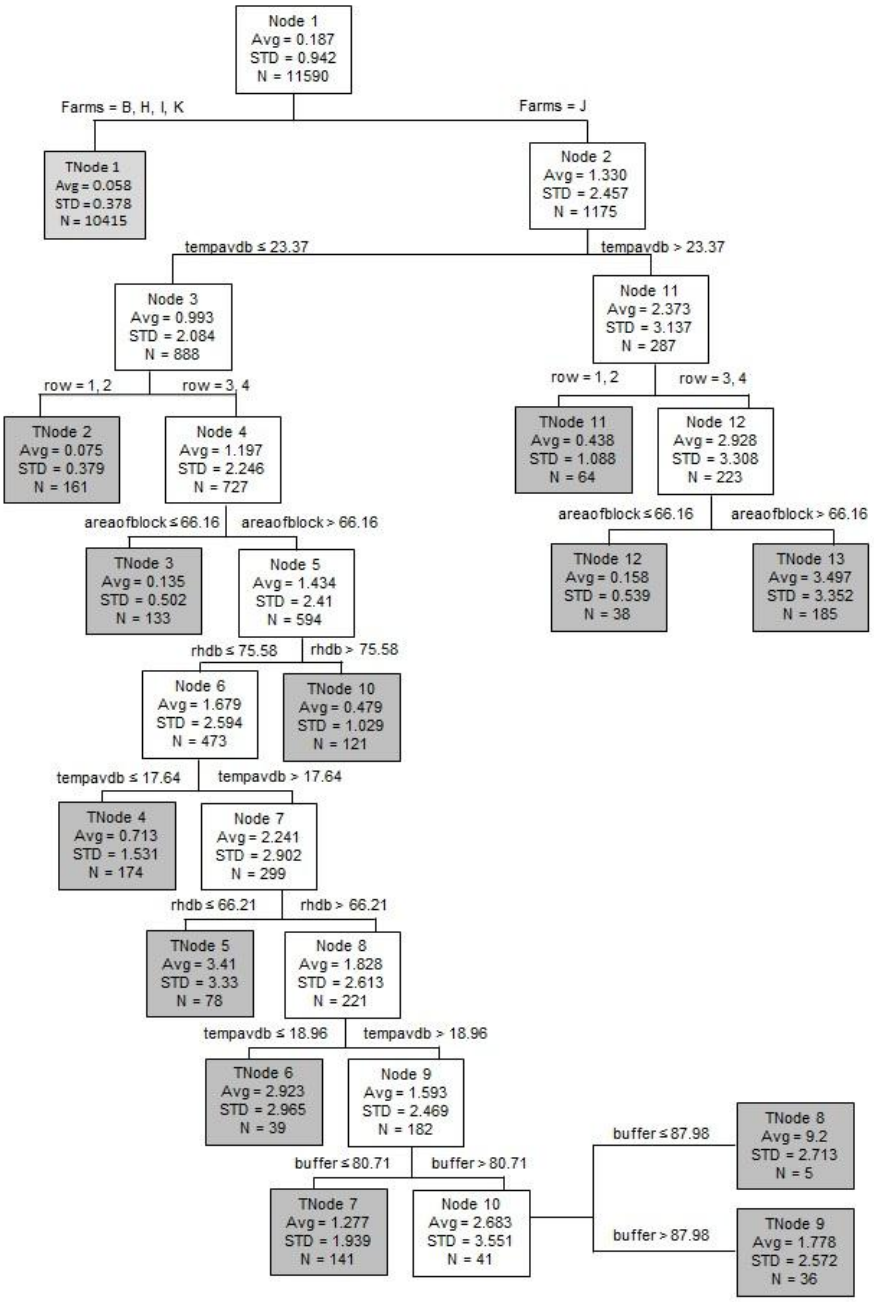


Figure 5-4. Regression tree of the variables influencing TYLCV incidence in Spring 2008/2009.

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# CHAPTER 6
# CONCLUSIONS

Biotype B of the sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), also known as the silverleaf whitefly, *B. argentifolii* Bellows and Perring, is a serious pest of many agricultural crops around the world (Perring et al. 1993). The nomenclature of *Bemisia* spp. has been widely discussed and current research suggest there are multiple unique species worldwide (Dinsdale et al. 2010). The polyphagous nature of the sweetpotato whitefly leads to management problems and could be associated with its high value pest status in many commodities (Naranjo and Ellsworth 2001). Biotype B has become the key insect pest of tomatoes, *Solanum lycopersicum* (L.), in southern Florida (Schuster et al. 1996a), displacing the native non-B biotypes (McKenzie et al. 2004). In tomatoes, Biotype B can cause direct damage including irregular ripening disorder of fruit, inhibition of fruit softening and general reduction of plant vigor (Schuster 2001, McCollum et al. 2004).

In southern Florida, *B. tabaci* has become a limiting pest species in tomato due to its ability to vector *Tomato yellow leaf curl virus* (TYLCV) (family *Geminiviridae*, genus *Begomovirus*) (Polston et al. 1999). TYLCV is vectored in a persistent circulative manner by *B. tabaci* and symptoms of infection in tomato include upward curling of leaflet margins, reduction of leaflet area, yellowing of young leaves, stunting of plants and abscission of flowers (Polston et al. 1999). With these symptoms there is considerable loss in plant vigor and significant yield loss, particularly if infection occurs during early growth. Unfortunately, growers often rely heavily on the use of insecticides targeting the whitefly vector to control TYLCV. As a result, insecticide resistance is

widespread, including many different insecticide classes (Palumbo et al. 2001, Horowitz et al. 2007).

A greater understanding of the distribution of *B. tabaci* and TYLCV-infected plants, the relationship between them, and the variables influencing populations may lead to the development of new management recommendations. The specific objectives for research were: to evaluate seasonal abundance of *B. tabaci* and incidence of TYLCV in Florida tomatoes, to investigate the spatial and temporal distribution of *B. tabaci* adults and TYLCV-infected plants in Florida tomatoes, to investigate the relationship between the abundance of *B. tabaci* and incidence of TYLCV in Florida tomatoes, and to investigate the environmental, geographical, and cropping factor variables influencing the abundance of *B. tabaci* and incidence of TYLCV-infected tomatoes in Florida.

To accomplish these objectives, the abundance of *B. tabaci* and incidence of plants with symptoms of TYLCV infection were monitored twice weekly on commercial tomato farms from the fall 2007 season through the spring 2009 season in central Florida. Farm sizes ranged from 23.63 to 272.99 ha and were located in a study area of ≈ 53.8 $km^2$ in Manatee Co., Florida. The analyses of the data using Geographical Information Systems (GIS), Spatial Analysis by Distance IndicEs (SADIE) and classification and regression tree (CART) analysis have produced much more detailed explanations of in-field distribution, vector/disease relationship and influencing factors than previously reported.

*B. tabaci* is a mobile pest and has been shown in the present study to have varying aggregation in both space and time. Over the entire study area, distributions of whiteflies were significantly aggregated in every season but spring 2009, when the

population of the whitefly was very low. Weekly fluctuations throughout the study area suggest that, within the earlier sampling dates of each season, whiteflies were more likely to be aggregated. In some seasons and on some farms, brief periods of significant re-aggregation 6-10 weeks later were indicated. Aggregation of adult *B. tabaci* could have been influenced by migration, in-farm reproduction and management tactics such as pesticide applications. TYLCV distribution was more static than *B. tabaci* counts and TYLCV was shown to follow similar spatio-temporal patterns associated with its vector.

Strong spatial dependence in insect data indicates that estimating populations at non-sampled locations is possible (Liebhold et al. 1993). With the use of inverse distance weighted (IDW) maps created by a GIS program, populations of both *B. tabaci* and TYLCV were indicated to be associated more closely with the edges of tomato fields. This edge effect was apparent in farms regardless of scale and continued throughout the study area.

Tomato growers, scouts, and consultants in southern Florida report inconsistent relationships between field populations of *B. tabaci* and subsequent incidence of plants with symptoms of TYLCV infection. In this study, there were instances of *B. tabaci* populations being highly correlated with subsequent incidence of plants with symptoms of TYLCV infection and other instances of *B. tabaci* populations having no relationship to later incidence of plants with symptoms of TYLCV infection. Early fall season populations of adult *B. tabaci* had stronger and more frequent correlations to incidence of TYLCV than late season populations. In the spring seasons, populations later in the season had stronger correlations to symptomatic TYLCV-infected plants than earlier

populations. Using SADIE spatial association tests, early season populations of *B. tabaci* in the fall of 2007 and 2008 were more likely to be positively spatially associated with symptomatic TYLCV-infected plants than dates later in the season. Early season populations of whiteflies would not be originating from within the newly planted tomato because of the short time available for whitefly reproduction. Therefore, these populations can be assumed to have originated outside tomato. The origins of viruliferous populations in the present study are unclear. There were indications that *B. tabaci* may have migrated from areas in which possible whitefly hosts were destroyed or disturbed, including a mining operation, a fallow field and a large drainage ditch.

Environmental, geographical, and cropping factor variables can impact both adult populations of *B. tabaci* and TYLCV incidence. CART analysis confirmed assumptions that environmental variables such as temperature, wind speed and wind direction influence populations of *B. tabaci*. Results from CART analysis suggest temperature was very influential in predicting *B. tabaci* abundance and TYLCV incidence. *B. tabaci* populations were highest during warmer conditions in the early fall seasons and the end of the spring seasons. The increase of TYLCV incidence throughout the season regardless of temperature change, suggests that average temperature is only an indicator of the length of season. Geographical variables such as buffer distance are important to both *B. tabaci* abundance and TYLCV incidence. In most cases, smaller buffer distances increased *B. tabaci* abundance and TYLCV incidence. The average buffer distance most influential to adult whitefly counts was about 38 m and for TYLCV incidence was 72 m. In the present study, area of block was influential in the prediction of *B. tabaci* in two farms at the end of the fall season, with the smaller block (< 33 ha)

having more whiteflies. This split of block size was associated with a difference between farms, though, as both block sizes were less than 35 ha. Smaller block size (< 33 ha) increased counts TYLCV incidence indicating the interiors of smaller blocks had less buffer distance to sources of viruliferous hosts. Other factors such as rainfall, mulch type and tomato type were thought to have more influence on *B. tabaci* counts and TYLCV incidence, but this analysis suggests that on a large scale those factors don't have as much influence as previously thought.

Future work could encompass a larger study area or increase the intensity of sampling. Future work could also include geostatistical analysis of this data set and use semivariograms along with kriging. Semivariograms express the variance of sample pairs against the distance between sample points and provide important ecological information on the spatial patterns of organisms. These spatial patterns could be used to indicate the distance between sampling locations to develop sampling plans which require independent samples. Highly dynamic populations such as those seen in insect count data increase the level of uncertainty in geostatistical analysis and much work will have to be conducted to create validated results. These results also indicate the need for further research into the influence of weeds and other hosts including cultivated crops. Area-wide management is important, as *B. tabaci* has over 600 hosts and could be considered a mobile pest (Mound and Halsey 1978, Greathead 1986, Secker et al. 1998, Byrne 1999). Future work could also be designed to address some of the factors that were indicated as important to the distribution of *B. tabaci* and TYLCV on a smaller plot scale. Due to the dynamic nature of insect movement some variables would only be able to be assessed on a larger scale study.

The distributions of *B. tabaci* adults and TYLCV infected plants were aggregated on commercial tomato throughout the study area. Populations were shown to have not migrated from distant areas and were located along field edges. Non-tomato hosts and environmental and geographical variables were shown to influence populations of *B. tabaci* and incidence of TYLCV-infected plants.

LIST OF REFERENCES

**Abhary, M. K., G. H. Anfoka, M. K. Nakhla, and D. P. Maxwell. 2006.** Post-transcriptional gene silencing in controlling viruses of the Tomato yellow leaf curl virus complex. Arch. Virol. 151: 2349-2363.

**Ahmed, A. H. M., E. A. Elhag, and N. H. H. Bashir. 1987.** Insecticide resistance in the cotton whitefly (*Bemisia tabaci* Genn.) in the Sudan Gezira. Tro. Pest. Manag. 33: 67-72.

**Ahmed, N. E., H. O. Kanan, Y. Sugimoto, Y. Q. Ma, and S. Inanaga. 2001.** Effect of imidacloprid on incidence of tomato yellow leaf curl virus. Plant Dis. 85: 84-87.

**Ahohuendo, B. C. and S. Sarkar. 1995.** Partial control of the spread of African cassava mosaic virus in Benin by intercropping. J. Plant Dis. Protec. 102: 249-256.

**Akad, F., A. Eybishtz, D. Edelbaum, R. Gorovits, O. Dar-Issa, N. Iraki, and H. Czosnek. 2007.** Making a friend from foe: expressing a GroEL gene from the whitefly *Bemisia tabaci* in the phloem of tomato plants confers resistance to tomato yellow leaf curl virus. Arch. Virol. 152: 1323-1339.

**Al-Musa, A. 1982.** Incidence, economic importance, and control of tomato yellow leaf curl in Jordan. Plant Dis. 66: 561-563.

**Alvarez, P. A. and A. J. Abud-Antun. 1995.** Reporte de Republica Dominicana. CEIBA. 36: 39-47.

**Anfoka, G., F. Haj Ahmad, M. Abhary, and A. Hussein. 2009.** Detection and molecular characterization of viruses associated with tomato yellow leaf curl disease in cucurbit crops in Jordan. Plant Pathol. 58: 754-762.

**Antignus, Y., N. Mor, R. Ben-Joseph, M. Lapidot, and S. Cohen. 1996.** Ultraviolet-absorbing plastic sheets protect crops from insect pests and from virus diseases vectored by insects. Environ. Entomol. 25: 919-924.

**Antignus, Y., M. Lapidot, D. Hadar, Y. Messika, and S. Cohen. 1998.** Ultraviolet-adsorbing screens serve as optical barriers to protect crops from virus and insect pests. J. Econ. Entomol. 91: 1401-1405.

**Antignus, Y., D. Nestel, S. Cohen, and M. Lapidot. 2001.** Ultraviolet-deficient greenhouse environment affects whitefly attraction and flight-behavior. Environ. Entomol. 30: 394-399.

**Antignus, Y., R. Vunsh, O. Lachman, M. Pearlsman, L. Maslenin, U. Hananya, and A. Rosner. 2004.** Truncated Rep gene originated from *Tomato yellow leaf curl virus-Israel* [Mild] confers strain-specific resistance in transgenic tomato. Ann. Appl. Biol. 144: 39-44.

**Arsenio, A. F., E. Neto, N. Ramos, S. Mangerico, E. Fortunato, L. Stigter, J. E. Fernandes, A. M. P. Lavadinho, and D. Jouro. 2002.** Control of the *Bemisia tabaci* / *Tomato yellow leaf curl virus* complex on protected tomato crops in Algarve (Portugal). EPPO Bulletin. 32: 31-35.

**Arx, R. V. von, J. Baumgartner, and V. Delucchi. 1984.** Sampling of *Bemisia tabaci* (Genn.) (Sternorrhyncha: Aleyrodidae) in Sudanese cotton fields. J. Econ. Entomol. 77: 1130-1136.

**Ascencio-Ibanes, J. T., R. Diaz-Plaza, J. Mendez-Lozano, Z. Monslave-Fonnerga, G. R. Arguello Astroga, and R. F. Rivera-Bustamante. 1999.** First report of tomato yellow leaf curl geminivirus in Yucatan Mexico. Plant Dis. 83: 1178.

**Attard, D. 2002.** Methods of controlling *Tomato yellow leaf curl virus* (TYLCV) and its vector *Bemisia tabaci* in the Maltese Islands. EPPO Bulletin. 32: 39-40.

**Ausher, R. 1997.** Implementation of integrated pest management in Israel. Phytoparasitica. 25: 119-141.

**Avidov, Z. 1956.** Bionomics of the tobacco whitefly (*Bemisia tabaci* Gennad.) in Israel. Ktavim. 7: 25-41.

**Avilla, C. , J. L. Collar, M. Duque, P. Perez, and A. Fereres. 1997.** Impact of floating rowcovers on bell pepper yield and virus incidence. HortScience. 32: 882-883.

**Azeb, A. K., M. M. Megahed, and H. D. El-Mirsawi. 1971.** On the range of host-plants of *Bemisia tabaci* (Genn.) (Homoptera: Aleyrodidae). Bulletin de la Societe Entomologique d'Egypte. 54.

**Azeb, A. K., M. M. Megahed, and H. D. El-Mirsawi. 1972.** On the biology of *Bemisia tabaci* (Genn.) Bulletin de la Societe Entomologique d'Egypte. 55: 305-315.

**Bacci, L., A. LB. Crespo, T. L. Galvan, E. Pereira, M. C. Picanco, G. A. Silva, and M. Chediak. 2007.** Toxicity of insecticides to the sweetpotato whitefly (Hemiptera: Aleyrodidae) and its natural enemies. Pest Manage. Sci. 63: 699-706.

**Bai, D., S. C. R. Lummis, W. Leicht, H. Breer, and D. B. Satelle. 1991.** Actions of imidacloprid and related nitromethylene on cholinergic receptors of an identified insect motor neurone. Pestic. Sci. 33: 197-204.

**Baldin, E. L. L. and R. A. Beneduzzi. 2010.** Characterization of antibiosis and antixenosis to the whitefly silverleaf *Bemisia tabaci* B biotype (Hemiptera: Aleyrodidae) in several squash varieties. J. Pest Sci. 83: 223-229.

**Barinaga, M. 1993.** Is devastating whitefly invader really a new species? Science. 259: 30.

**Barnes, J. M. , R. Trinidad-Correa, T. V. Orum, R. Felix-Gastelum, and M. R. Nelson. 1999.** Landscape ecology as the new infrastructure for improved management of plant viruses and their insect vectors in agroecosystems. Ecosystem Health. 5: 26-35.

**Barrigossi, J. A. F., L. J. Young, C. A. Gotway Crawford, G. L. Hein, and L. G. Higley. 2001.** Spatial and probability distribution of Mexican bean beetle (Coleoptera: Coccinellidae) egg mass populations in dry bean. Environ. Entomol. 30: 244-253.

**Bayhan, E., M. R. Ulusoy, and J. K. Brown. 2006.** Effects of different cucurbit species and temperature on selected life history traits of the 'B' Biotype of *Bemisia tabaci*. Phytoparasitica. 34: 235-242.

**Beckler, A. A., B. W. French, and L. D. Chandler. 2005.** Using GIS in areawide pest management: A case study in South Dakota. Transactions in GIS. 9: 109-127.

**Bedford, I. D., R. W. Briddon, J. K. Brown, R. C. Rosell, and P. G. Markham. 1994.** Geminivirus transmission and biological characterization of *Bemisia tabaci* (Gennadius) biotypes from different geographic regions. Ann. Appl. Biol. 125: 311-325.

**Bellows, T. S., T. M. Perring, K. Arakawa, and C. A. Farrar. 1988.** Patterns in diel flight activity on *Bemisia tabaci* (Homoptera: Aleyrodidae) in cropping systems in southern California. Environ. Entomol. 17: 225-228.

**Bellows, T. S. Jr., T. M. Perring, R. J. Gill, and D. H. Headrick. 1994.** Description of a species of *Bemisia* (Homoptera: Aleyrodidae). Ann. Entomol. Soc. Am. 87: 195-206.

**Bentz, J. A., J. Reeves III, P. Barbosa, and B. Francis. 1995a.** Effect of nitrogen fertilizer source and level on ovipositional choice of poinsettia by *Bemisia argentifolii* (Homoptera: Aleyrodidae). J. Econ. Entomol. 88: 1388-1392.

**Bentz, J. A., J. Reeves III, P. Barbosa, and B. Francis. 1995b.** Nitrogen fertilizer effect on selection, acceptance, and suitability of *Euphorbia pulcherrima* (Euphorbiaceae) as a host plant to *Bemisia tabaci* (Homoptera: Aleyrodidae). Environ. Entomol. 24: 40-45.

**Bentz, J. A., J. Reeves, P. Barbosa, and B. Francis. 1995c.** Within-plant variation in nitrogen and sugar content of poinsettia and its effects on the oviposition pattern, survival, and development of *Bemisia argentifolii* (Homoptera: Aleyrodidae). Environ. Entomol. 24: 271-277.

**Berlinger, M. J. 1986.** Host plant resistance to *Bemisia tabaci*. Agric. Eco. Environ. 17: 69-82.

**Berlinger, M. J. and S. Lebiush-Mordechi. 1996.** Physical methods for the control *Bemisia*, pp. 617-634. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia* 1995: Taxonomy, Biology, Damage, Control and Management. Intercept, Andover.

**Berlinger, M. J., Z. Magal, and A. Benzioni. 1983.** The importance of pH in food selection by the tobacco whitefly, *Bemisia tabaci*. Phytoparasitica. 11: 151-160.

**Berlinger, M. J., R. A. J. Taylor, S. Lebiush-Mordechi, S. Shalhevet, and I. Spharim. 2002.** Efficiency of insect exclusion screens for preventing whitefly transmission of tomato yellow leaf curl virus of tomatoes in Israel. Bull. Entomol. Res. 92: 367-373.

**Bernays, E. A. 1999.** When host choice is a problem for a generalist herbivore: experiments with the whitefly, *Bemisia tabaci*. Ecol. Entomol. 24: 260-267.

**Bethke, J. A. and R. A. Redak. 1997.** Effect of imidacloprid on the silverleaf whitefly, *Bemisia argentifolii* Bellows and Perring (Homoptera: Aleyrodidae), and whitefly parasitism. Ann. Appl. Biol. 130: 397-407.

**Bethke, J. A. , R. A. Redak, and T. D. Paine. 1994.** Screens deny specific pests entry to greenhouses. Calif. Agric. 48: 37-40.

**Bezerra, Mary-Ann S., Maria R. V. De Oliveira, and Simão D. Vasconcelos. 2004.** Does the presence of weeds affect Bemisia tabaci (Gennadius) (Hemiptera: Aleyrodidae) infestation on tomato plants in a semi-arid agro-ecosystem? Neotrop. Entomol. 33: 769-775.

**Bi, J. L. , G. R. Ballmer, D. L. Hendrix, T. J. Henneberry, and N. C. Toscano. 2001.** Effect of cotton nitrogen fertilization on *Bemisia argentifolii* populations and honeydew production. Entomol. Exp. Appl. 99: 25-36.

**Bird, T.L. and K. Kruger. 2006.** Response of the polyphagous whitefly *Bemisia tabaci* B-biotype (Hemiptera: Aleyrodidae) to crop diversification - influence of multiple sensory stimuli on activity and fecundity. Bull. Entomol. Res. 96: 15-23.

**Birdsall, S. L. , D. Ritter, and P. L. Carson. 1995.** Economic impact of the silverleaf whitefly in Imperial Valley, California, from 1991 to 1995, pp. 176. *In* T. J. Henneberry, L. C. Toscano, R. M. Faust and J. R. Coppedge [eds.], Silverleaf whitefly: 1996 supplement to the five-year national research and action plan. U. S. Department of Agriculture, Agricultural Research Server, Washington, DC.

**Blackmer, J. L. and D. N. Byrne. 1993a.** Environmental and physiological factors influencing phototactic flight of *Bemisia tabaci*. Physiol. Entomol. 18: 336-342.

**Blackmer, J. L. and D. N. Byrne. 1993b.** Flight behavior of *Bemisia tabaci* in a vertical flight chamber: effect of time of day, sex, age and host quality. Physiol. Entomol. 18: 223-232.

**Blackmer, J. L. and D. N. Byrne. 1999.** Changes in amino acid in *Cucumis melo* in relation to life-history traits and flight propensity of *Bemisia tabaci*. Entomol. Exp. Appl. 93: 29-40.

**Blackmer, J. L., V. A. Lindley, and D. N. Byrne. 1995a.** Histological examination of flight muscle development and breakdown in *Bemisia tabaci* (Homoptera: Aleyrodidae): Relationship to age and flight behavior. J. Morphol. 226: 213-221.

**Blackmer, J. L., D. N. Byrne, and Z. Tu. 1995b.** Behavioral, morphological, and physiological traits associated with migratory *Bemisia tabaci*. J. Insect Behav. 8: 251-267.

**Bleeker, P. M., P. J. Diergaarde, K. Ament, J. Guerra, M. Weidner, S. Schutz, M. T. J. de Both, M. A. Haring, and R. C. Schuurink. 2009.** The role of specific tomato volatiles in tomato-whitefly interaction. Plant Physiol. 151: 925-935.

**Blua, M. J. and N. C. Toscano. 1994.** *Bemisia argentifolii* (Homoptera: Aleyrodidae) development and honeydew production as a function of cotton nitrogen status. Environ. Entomol. 23: 316-321.

**Boica Junior, A. L. , Z. R. Campos, A. L. Lourencao, and A. L. Campos. 2007.** Adult attractiveness and oviposition preference of *Bemisia tabaci* (Genn.) (Homoptera: Aleyrodidae) B-biotype in cotton genotypes. Scientia Agricola. 64: 147-151.

**Bolstad, P. 2005.** GIS Fundamentals. Eider Press, White Bear Lake.

**Bonsignore, C. P., F. Manti, and V. Vacante. 2008.** Field and tree distribution of *Capnodis tenebrionis* (Linnaeus, 1767) (Col., Buprestidae) adults in an apricot orchard in Italy. J. Appl. Entomol. 132: 216-224.

**Borah, R. K. 1994.** Influence of planting dates on the incidence of insect pests of brinjal (*Solanum melongena* l.) in a hilly area of Assam. J. Agric. Sci. Soc. North East India. 7: 209-211.

**Borth, P.W. and R.T. Huber. 1987.** Modeling pink Bollworm establishment and dispersion in cotton with the Kriging technique, pp. 267-274, Proceedings of the Beltwide Cotton Production Research Conference. National Cotton Council of America, Memphis, TN., Dallas, TX.

**Bosco, D., G. Mason, and G. P. Accotto. 2004.** TYLCSV DNA, but not infectivity, can be transovarially inherited by the progeny of the whitefly vector *Bemisia tabaci* (Gennadius). Virology. 323: 276-283.

**Breiman, L., J. H. Friedman, R. A. Olshen, and C. J. Stone. 1984.** Classification and regression trees. Wadsworth International Group, Belmont

**Brown, J. K., D. R. Frohlich, and R. C. Rosell. 1995.** The sweetpotato or silverleaf whiteflies: biotypes of *Bemisia tabaci* or a species complex. Annu. Rev. Entomol. 40: 511-534.

**Brown, J. K., T. M. Perring, A. D. Cooper, I. D. Bedford, and P. G. Markham. 2000.** Genetic analysis of *Bemisia* (Homoptera: Aleyrodidae) populations by isoelectric focusing electrophoresis. Biochem. Genet. 38: 12-25.

**Brunetti, A., M. Tavazza, E. Noris, R. Tavazza, P. Caciagli, G. Ancora, S. Crespi, and G. P. Accotto. 1997.** High expression of truncated viral rep protein confers resistance to tomato yellow leaf curl virus in transgenic tomato plants. Mol. Plant-Microbe Inter. 10: 571-579.

**Brunetti, A., R. Tavazza, E. Noris, A. Lucioli, G. P. Accotto, and M. Tavazza. 2001.** Transgenically expressed T-Rep of tomato yellow leaf curl Sardinia virus acts as a *trans*-dominant-negative mutant, inhibiting viral transcription and replication. J. Virol. 75: 10573-10581.

**Bryceson, K. P. . 1991.** Likely locust infestation areas of western New South Wales, Australia, located by satellite. Geocarto International. 6: 21-37.

**Burban, C., L. D. C. Fishpool, C. Fauquet, D. Fargette, and J. C. Thouvenel. 1992.** Host-associated biotypes within West African populations of the whitefly *Bemisia tabaci* (Genn.), Homoptera: Aleyrodidae. J. Appl. Entomol. 113: 416-423.

**Butler, D. N., T. J. Henneberry, and T. E. Clayton. 1983.** *Bemisia tabaci* (Homoptera: Aleyrodidae): development, oviposition and longevity in relation to temperature. Ann. Entomol. Soc. Am. 76: 310-313.

**Butler, Jr., G. D. and T. J. Henneberry. 1984.** *Bemisia tabaci*: effect of cotton leaf pubescence on abundance. Southwest. Entomol. 9: 91-94.

**Butler, Jr., G. D., T. J. Henneberry, P.A. Stansly, and D. J. Schuster. 1993.** Insecticidal effects of selected soaps, oils and detergents on the sweetpotato whitefly: (Homoptera: Aleyrodidae). Flor. Ento. 76: 161-167.

**Byamukama, E., R. W. Gibson, V. Aritua, and E. Adipala. 2004.** Within-crop spread of sweet potato virus disease and the population dynamics of its whitefly and aphid vectors. Crop Protect. 2004: 109-116.

**Byrne, D. N. 1999.** Migration and dispersal by the sweet potato whitefly, *Bemisia tabaci*. Agric. Fore. Metero. 97: 309-316.

**Byrne, D. N. and T. S. Jr. Bellows. 1991.** Whitefly Biology. Annu. Rev. Entomol. 36: 431-457.

**Byrne, D. N. and M. A. Houck. 1990.** Morphometric identification of wing polymorphism in *Bemisia tabaci* (Homoptera: Aleyrodidae). Ann. Entomol. Soc. Am. 83: 487-493.

**Byrne, D. N. and P. K. von Bretzel. 1987.** Similarity in flight activity rhythms in coexisting species of Aleyrodidae, *Bemisia tabaci* and *Trialeurodes abutilonea*. Entomol. Exp. Appl. 43: 215-219.

**Byrne, D. N., R. J. Rathman, T. V. Orum, and J. C. Palumbo. 1996.** Localized migration and dispersal by the sweet potato whitefly, *Bemisia tabaci*. Oecologia. 105: 320-328.

**Byrne, F. J. and A. L. Devonshire. 1993.** Insensitive acetylcholinesterase and esterase polymorphism insusceptible and resistance populations of the tobacco whitefly, *Bemisia tabaci*. Pestic. Biochem. Physiol. 45: 34-42.

**Byrne, F. J., S. J. Castle, N. Prabhaker, and L. C. Toscano. 2003.** Biochemical study of resistance to imidacloprid in B biotype *Bemisia tabaci* from Guatemala. Pest Manage. Sci. 59: 347-352.

**Caciagli, P., D. Bosco, and L. Al-Bitar. 1995.** Relationships of the Sardinian isolate of tomato yellow leaf curl geminivirus with its whitefly vector *Bemisia tabaci* Gennadius. Eur. J. Plant Pathol. 101: 163-170.

**Caciagli, P., V. M. 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 the salivary glands does not guarantee transmissibility. J. Virol. 83: 5784-5795.

**Cahill, M. , K. Gorman, S. Day, I. Denholm, A. Elbert, and R. Nauen. 1996.** Baseline determination and detection of resistance to imidacloprid in *Bemisia tabaci* (Homoptera: Aleyrodidae). Bull. Entomol. Res. 86: 343-349.

**Calvitti, M. and P. C. Remotti. 1998.** Host preference and performance of *Bemisia argentifolii* (Homoptera: Aleyrodidae) on weeds in Central Italy. Environ. Entomol. 27: 1350-1356.

**Candau, J. , R. A. Fleming, and A. Hopkin. 1998.** Spatiotemporal patterns of large-scale defoliation caused by the spruce budworm in Ontario since 1941. Cana. J. Fores. Res. 28: 1733-1741.

**Cardoza, Y. J. , H. L. McAuslane, and S. E. Webb. 2000.** Effect of leaf age and silverleaf symptoms on oviposition site selection and development of *Bemisia argentifolii* (Homoptera: Aleyrodidae) on zucchini. Environ. Entomol. 29: 220-225.

**Carriere, Y., P.C. Ellsworth, P. Dutilleul, C. Ellers-Kirk, V. Barkley, and L. Antilla. 2006.** A GIS based approach for areawide pest management: the scales of *Lygus hesperus* movement to cotton from alfalfa, weeds, and cotton. Entomol. Exp. Appl. 118: 203-210.

**Castle, S. J. 2001.** Differences between cotton and melon in host acceptance by *Bemisia tabaci*, pp. 1056-1059, Proceedings of the Beltwide Cotton Conference. National Cotton Council, Memphis, TN.

**Castle, S. J., T. J. Henneberry, and N. C. Toscano. 1996.** Suppression of *Bemisia tabaci* (Homoptera: Aleyrodidae) infestations in cantaloupe and cotton with sprinkler irrigation Crop Protect. 15: 657-663.

**Chellemi, D. O., K. G. Rohrbach, R. S. Yost, and R. M. Sonoda. 1988.** Analysis of the spatial pattern of plant pathogens and diseased plants using geostatistics. Phytopathology. 78: 221-226.

**Chu, C. C., T. J. Henneberry, and A. Cohen. 1995.** *Bemisia argentifolii* (Homoptera: Aleyrodidae): host preference and factors affecting oviposition and feeding site preference. Environ. Entomol. 24: 354-360.

**Cigliano, M. M., W. P. Kemp, and T. M. Kalaris. 1995.** Spatiotemporal characteristics of rangeland grasshopper (Orthoptera: Acrididae) regional outbreaks in Montana. J. Orthoptera Res. 4: 111-126.

**Cocco, A., A. Q. Cossu, P. Erre, G. Nieddu, and P. Luciano. 2010.** Spatial analysis of gypsy moth populations in Sardinia using geostatistical and climate models. Agric. For. Entomol. 12: 417-426.

**Cohen, S. 1982.** Control of whitefly vectors of viruses by color mulches, pp. 45-56. *In* K. F. Harris and K. Maramorosch [eds.], Pathogens, Vectors, and Plant Diseases: Approaches to Control. Academic Press, New York.

**Cohen, S. and Y. Antignus. 1994.** Tomato yellow leaf curl virus, a whitefly-borne geminivirus of tomatoes, pp. 259-288. *In* K. F. Harris [ed.], Advances in Disease Vector Research. Springer, New York.

**Cohen, S. and M. J. Berlinger. 1986.** Transmission and cultural control of whitefly borne viruses. Agriculture, Ecosystems, & Environment. 17: 89-97.

**Cohen, J. and A. Gera. 1995.** Lisianthus leaf curl a new diseases of lisianthus caused by tomato yellow leaf curl virus. Plant Dis. 79: 416-420.

**Cohen, S. and I. Harpaz. 1964.** Periodic, rather than continual acquisition of new tomato virus by its vector, the tobacco whitefly (*Bemisia tabaci* Gennadius). Entomol. Exp. Appl. 7: 155-166.

**Cohen, S. and F. E. Nitzany. 1966.** Transmission and host range of the tomato yellow leaf curl virus. Phytopathology. 56: 1127-1131.

**Cohen, S., J. Kern, I. Harpaz, and R. Ben-Joseph. 1988.** Epidemiological studies of the tomato yellow leaf curl virus (TYLCV) in the Jordan Valley, Israel. Phytoparasitica. 16: 259-270.

**Colvin, J., L. D. C. Fishpool, D. Fargette, J. Sherington, and C. Fargette. 1998.** *Bemisia tabaci* (Hemiptera: Aleyrodidae) trap catches in a cassava field in Cote d'Ivoire in relation to environmental factors and the distribution of African cassava mosaic disease. Bull. Entomol. Res. 1998: 369-378.

**Costa, H. S. and J. K. Brown. 1991.** Variation in biological characteristics and esterase patterns among populations of *Bemisia tabaci* (Genn.) and the association of one population with silverleaf symptom induction. Entomol. Exp. Appl. 61: 211-219.

**Costa, H. S. and K. L. Robb. 1999.** Effects of ultraviolet-absorbing greenhouse plastic films on flight behavior of *Bemisia argentifolii* (Homoptera: Aleyrodidae) and *Frankliniella occidentalis* (Thysanoptera: Thripidae). J. Econ. Entomol. 92: 557-562.

**Costa, H. S., J. K. Brown, and D. N. Byrne. 1991.** Host plant selection by the whitefly, *Bemisia tabaci* (Gennadius) (Hom., Aleyrodidae) under greenhouse conditions. J. Appl. Entomol. 112: 146-152.

**Costa, H. S., D. E. Ullman, M. W. Johnson, and B. E. Tabashnik. 1994.** Row covers effect on sweetpotato whitefly (Homoptera: Aleyrodidae) densities, incidence of silverleaf, and crop yield in zucchini. J. Econ. Entomol. 87: 1616-1621.

**Coudriet, D. L., N. Prabhaker, A. N. Kishara, and D. E. Meyerdirk. 1985.** Variation in development rate on different hosts and overwintering of the sweet potato whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae). Environ. Entomol. 14: 516-519.

**Coudriet, D. L., D. E. Meyerdirk, N. Prabhaker, and A. N. Kishaba. 1986.** Bionomics of sweetpotato whitefly (Homoptera: Aleyrodidae) on weed hosts in the Imperial Valley, California. Environ. Entomol. 15: 1179-1183.

**Csizinszky, A. A., D. J. Schuster, and J. B. Kring. 1995.** Color mulches influence yield and insect pest populations in tomato. J. Amer. Soc. Hort. Sci. 120: 778-784.

**Csizinszky, A. A., D. J. Schuster, and J. B. Kring. 1997.** Evaluation of color mulches and oil sprays for yield and for the control of silverleaf whitefly, *Bemisia argentifolii* (Bellows and Perring) on tomatoes. Crop Protect. 16: 475-481.

**Csizinszky, A. A., D. J. Schuster, and J. E. Polston. 1999.** Effects of ultraviolet-reflective mulches on tomato yields and on the silverleaf whitefly. HortScience. 34: 911-914.

**Czosnek, H. 2007.** Interactions of Tomato Yellow Leaf Curl Virus with its whitefly vector, pp. 157-170. *In* H. Czosnek [ed.], Tomato Yellow Leaf Curl Virus Disease. Springer.

**Czosnek, H. and H. Laterrot. 1997.** A worldwide survey of tomato yellow leaf curl viruses. Arch. Virol. 142: 1391-1406.

**Czosnek, H., N. Navot, and H. Laterrot. 1990.** Geographical distribution of tomato yellow leaf curl virus. A first survey using a specific DNA probe. Phytophathology Mediterranean. 29: 1-6.

**Czosnek, H., M. Ghanim, G. Rubinstein, S. Morin, V. Fridman, and M. Zeidan. 2001.** Whiteflies: vectors - or victims? - of geminiviruses. Advances in Virus Research. 57: 291-322.

**Czosnek, H., M. Ghanim, and M. Ghanim. 2002.** The circulative pathway of begomoviruses in the whitefly vector *Bemisia tabaci* -- insights from studies with *Tomato yellow leaf curl virus*. Ann. Appl. Biol. 140: 215-231.

**D'Hondt, M. and M. Russo. 1985.** Tomato yellow leaf curl in Senegal. J. Phytopathol. 112: 153-160.

**Dallot, S., T. Gottwald, G. Labonne, and J.-B. Quiot. 2003.** Spatial pattern analysis of Sharka disease (*Plum pox virus* Strain M) in peach orchards in southern France. Phytopathology. 93: 1543-1552.

**Darnell, S. J., L. J. Meinke, L. J. Young, and C. Gotway. 1999.** Geostatistical investigation of the small-scale spatial variation of western corn rootworm (Coleoptera: Chrysomelidae) adults. Environ. Entomol. 28: 266-274.

**De'ath, G. and K. E. Fabricius. 2000.** Classification and regression trees: A powerful yet simple technique for ecological data analysis. Ecology. 81: 3178-3192.

**De Barro, P. J. 1995.** *Bemisia tabaci* biotype B: a review of its biology distribution and control, pp. 57. Technical Paper, Division of Entomology, SCIRO, Canberra, Australia.

**De Barro, P. J. and F. Driver. 1997.** Use of RAPD PCR to distinguish the B biotype from other biotypes of *B. tabaci* (Gennadius) (Hemiptera: Aleyrodidae). Aust. J. Entomol. 36: 149-152.

**De Barro, P. J., F. Driver, J. W. H. Trueman, and J. Curran. 2000.** Phylogenetic relationship of world populations of *Bemisia tabaci* (Gennadius) using ribosomal ITS1. Molecular Phylogeny and Evolution. 16: 29-36.

**Dean, D. E. and D. J. Schuster. 1995.** *Bemisia argentifolii* (Homoptera: Aleyrodidae) and *Macrosiphum euphorbiae* (Homoptera: Aphididae) as prey for two species of Chrysopidae. Environ. Entomol. 24: 1562-1568.

**DeBano, S. J., P. B. Hamm, A. Jensen, S. I. Rondon, and P. J. Landolt. 2010.** Spatial and temporal dynamics of potato tuberworm (Lepidoptera: Gelechiidae) in the Columbia Basin of the Pacific Northwest. Environ. Entomol. 39: 1-14.

**Denholm, I., M. Cahill, F. J. Byrne, and A. L. Devonshire. 1996.** Progress with documenting and combating insecticide resistance in *Bemisia*, pp. 577-603. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia*: 1995 Taxonomy, Biology, Damage, Control and Management. Intercept Andover.

**Denholm, I., M. Cahill, T. J. Dennehy, and A. R. Horowitz. 1998.** Challenges with managing insecticide resistance in agricultural pests, exemplified by the whitefly *Bemisia tabaci*. Philosophical Transactions of the Royal Society. 353: 1757-1767.

**Dennehy, T. J., L. Williams III, J. S. Russell, X. Li, and M. Wigert. 1996.** Monitoring and management of whitefly resistance to insecticides in Arizona, pp. 743-748. *In* P. Dugger and D. Richter [eds.], Proceedings Beltwide Cotton Conference. National Cotton Council, Memphis, TN.

**Dinsdale, A., L. Cook, C. Riginos, Y. M. Buckley, and P De Barro. 2010.** Refined global analysis of *Bemisia tabaci* (Hemiptera: Sternorrhyncha: Aleyrodoidea: Aleyrodidae) mitochondrial cytochrome oxidase 1 to identify species level genetic boundaries. Ann. Entomol. Soc. Am. 103: 196-208.

**Dittrich, V., S. Uk, and G. H. Ernst. 1990a.** Chemical control and insecticide resistance of whiteflies, pp. 263-286. *In* D. Gerling [ed.], Whiteflies: their Bionomics, Pest Status and Management. Intercept, Andover, UK.

**Dittrich, V., G. H. Ernst, O. Ruesch, and S. Uk. 1990b.** Resistance mechanisms in sweetpotato whitefly (Homoptera: Aleyrodidae) populations from Sudan, Turkey, Guatemala, and Nicaragua. J. Econ. Entomol. 83: 1665-1670.

**Dowell, R. V. . 1990.** Integrating biological control of whiteflies into crop management systems. *In* D. Gerling [ed.], Whiteflies: their Bionomics, Pest Status and Management. Intercept, Andover, UK.

**Duehl, A. J., F. H. Koch, and F. P. Hain. 2011.** Southern pine beetle regional outbreaks modeled on landscape, climate and infestation history. For. Ecol. Manage. 261: 473-479.

**Dutilleul, P. 1993.** Modifying the *t*-test for assessing the correlation between two spatial processes. Biometrics. 49: 305-314.

**Ekbom, B. S. and X. Rumei. 1990.** Sampling and spatial patterns of whiteflies., pp. 255-263. *In* D. Gerling [ed.], Whiteflies: their Bionomics, Pest Status and Management. Intercept, Andover, UK.

**El-Gendi, S. S., K. M. Adam, and M. A. Bachatly. 1997.** Effect of the planting date of tomato on the population density of *Bemisia tabaci* (Genn.) and *Heliothis armigera* (HB), viral infection and yield. Arab. J. Agric. Sci. 5: 135-144.

**Elbert, A., H. Overbeck, H. Iwaya, and S. Tsuboi. 1990.** Imidacloprid, a novel systemic nitromethylene analogue insecticide for crop protection, pp. 21-28, Proceedings of the Brighton Crop Protection Conference, Pest and Diseases. British Crop Protection Council, Farnham, UK.

**Ellsbury, M. M., W. D. Woodson, S. A. Clay, D. Malo, J. Schumacher, D. E. Clay, and C. G. Carlson. 1998.** Geostatistical characterization of the spatial distribution of adult corn rootworm (Coleoptera : Chrysomelidae) emergence. Environ. Entomol. 27: 910-917.

**Ellsworth, P. C. and J. L. Martinez-Carrillo. 2001.** IPM for *Bemisia tabaci*: a case study from North America. Crop Protect. 20: 853-869.

**Ellsworth, P. C. and D. L. Meade. 1994.** Action thresholds for whiteflies in Arizona, pp. 878-881. *In* D. J. Herber and D. A. Richter [eds.], Proceedings Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.

**Ellsworth, P. C., L. Moore, T. F. Watson, and T. J. Dennehy. 1994.** Insect pest management for cotton. The University of Arizona, Cooperative Extension. 27 pp.

**Ellsworth, P.C., R. Tronstad, J. Leser, P. B. Goodell, L. D. Godfrey, T. J. Henneberry, D. Hendrix, D. Brushwood, S.E. Naranjo, S. J. Castle, and R. L. Nichols. 1999.** Sticky Cotton Sources & Solutions. *IPM Series No. 13*.The University of Arizona Cooperative Extension.Tucson, AZ.http://ag.arizona.edu/crops/cotton/insects/wf/stickycss.pdf.4/16/2007.

**ESRI. 2006.** ArcView ArcInfo. Version 9.2. Environmental Systems Research Institute. Redlands, CA.

**Evans, G. A. 2007.** Host plant list of the whiteflies (Aleyrodidae) of the world. http://www.sel.barc.usda.gov:8080/1WF/WhiteflyHost.pdf. January 18th, 2011.

**Fargette, D. and C. Fauquet. 1988.** A preliminary study on the influence of intercropping maize and cassava on the spread of African cassava mosaic virus by whiteflies. Aspects Appl. Biol. 17: 195-202.

**Fargette, D., C. Fauquet, and J. C. Thouvenel. 1985.** Field studies on the spread of African cassava mosaic. Ann. Appl. Biol. 106: 285-294.

**Fargette, D., C. Fauquet, E. Grenier, and J. M. Thresh. 1990.** The spread of African cassava mosaic virus into the within cassava fields. J. Phytopathol. 130: 289-302.

**Faria, M. and S. P. Wraight. 2001.** Biological control of *Bemisia tabaci* with fungi. Crop Protect. 20: 767-778.

**Farias-Larios, J., M. Orozco-Santos, and S. Guzman-Gonzalez. 1995.** Yield of three cultivars of muskmelon growth on transparent mulch and floating rowcover in a tropical region. HortScience. 30: 890-891.

**Farias-Larios, J., M. Orozco-Santos, S. Guzman-Gonzalez, and J. Perez. 1996.** Effect of plastic mulch, floating rowcovers and microtunnels on insect populations and yield of muskmelon. HortScience. 31: 677.

**Farias, P. R. S., S. R. Roberto, J. R. S. Lopes, and D. Perecin. 2004.** Geostatistical characterization of the spatial distribution of Xylella fastidiosa sharpshooter vectors on citrus. Neotrop. Entomol. 33: 13-20.

**Farias, P. R. S., J. C. Barbosa, A. C. Busoli, W. L. Overal, V. S. Miranda, and S. M. Ribeiro. 2008.** Spatial analysis of the distribution of *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) and losses in maize crop productivity using geostatistics. Neotrop. Entomol. 37: 321-327.

**Fenigstein, A., M. Eliyahu, S. Gan-Mor, and D. Veierov. 2001.** Effects of five vegetable oils on the sweetpotato whitefly *Bemisia tabaci*. Phytoparasitica. 29: 197-203.

**Ferguson, A. W., Z. Klukowski, B. Walczak, J. N. Perry, M. A. Mugglestone, S. J. Clark, and I. H. Williams. 2000.** The spatio-temporal distribution of adult *Ceutorhynchus assimilis* in a crop of winter oilseed rape in relation to the distribution of their larvae and that of the parasitoid *Trichomalus perfectus*. Entomol. Exp. Appl. 95: 161-171.

**Fitzgerald, J. W., R. N. Coulson, P. E. Pulley, R. O. Flamm, F. L. Oliveria, K. M. Swain, and D. B. Drummond. 1994.** Suppression tactics for *Dendroctonus frontalis* Zimmerman (Coleoptera: Scolytidae): An examination of the occurrence of infestations adjacent to the treatment sites. J. Econ. Entomol. 87: 417-425.

**Fleischer, S. J., P. E. Blom, and R. Weisz. 1999.** Sampling in precision IPM: When the objective is a map. Phytopathology. 89: 1112-1118.

**Flint, H. M., F. D. Wilson, D. Hendrix, J. E. Leggett, S. E. Naranjo, T. J. Henneberry, and J. W. Radin. 1994.** The effect of plant water stress on beneficial and pest insects including the pink bollworm and the sweetpotato whitefly in two short-season cultivars of cotton. Southwest. Entomol. 19: 11-22.

**Flint, H. M., J. W. Radin, N. J. Parks, and L. L. Reaves. 1995.** The effects of drip or furrow irrigation of cotton on *Bemisia argentifolii* (Homoptera: Aleyrodidae). J. Agric. Ento. 12: 25-32.

**Flint, H. M., S. E. Naranjo, J. E. Leggett, and T. J. Henneberry. 1996.** Cotton water stress, arthropod dynamics, and management of *Bemisia tabaci* (Homoptera: Aleyrodidae). J. Econ. Entomol. 89: 1288-1300.

**Fluckiger, C. R., H. Kristinsson, R. Senn, A. Rindlisbacher, H. Buholzer, and G. Voss. 1992.** A novel agent to control aphids and whiteflies, Brighton Crop Protection Conference: Pests and Diseases. The British Crop Protection Council, Farnham, UK.

**Font, M. I., C. Cordoba, A. Garcia, R. Santiago, and C. Jorda. 2005.** First report of tobacco as a natural host of *Tomato yellow leaf curl virus* in Spain. Plant Dis. 89: 910.

**Friedmann, M., M. Lapidot, S. Cohen, and M. Pilowsky. 1998.** A novel source of resistance to tomato yellow leaf curl virus exhibiting a symptomless reaction to viral infection. J. Amer. Soc. Hort. Sci. 123: 1004-1007.

**Frohlich, D. R., I. Torres-Jerez, I. D. Bedford, P. G. Markham, and J. K. Brown. 1999.** A phylogeographical analysis of the *Bemisia tabaci* species complex based on mitochondrial DNA markers. Mol. Ecol. 8: 1683-1691.

**Gachoka, K. K., D. Obeng-Ofori, and E. Y. Danquah. 2005.** Host suitability of two Ghanaian biotypes of *Bemisia tabaci* (Homoptera: Aleyrodidae) on five common tropical weeds. Int. J. Trop. Insect Sci. 25: 236-244.

**Gamez-Jimenez, C., J. L. Romero-Romero, M. E. Santos-Cervantes, N. E. Leyva-Lopez, and Mendez-Lozano. 2009.** Tomatillo (*Physalis ixocarpa*) as a natural new host for Tomato yellow leaf curl virus in Sinaloa, Mexico. Plant Dis. 93: 545.

**Garcia-Andres, S., F. Monci, J. Navas-Castillo, and E. Moriones. 2006.** Begomovirus genetic diversity in the native plant reservoir *Solanum nigrum*: Evidence for the presence of a new virus species of recombinant nature. Virology. 350: 433-442.

**Garcia, F. J. 2006.** Analysis of the spatio-temporal distribution of *Heliocoverpa armigera* Hb. in a tomato field using a stochastic approach. Biosys. Eng. 93: 253-259.

**Ge, Shaw-Kui, R. I. Carruthers, Zu-Fei Ma, Guang-Xue Zhang, and Dian-Mo Li. 2005.** Spatial heterogeneity and population risk analysis of cotton bollworm, *Helicoverpa armigera*, in China. Insect Sci. 12: 255-262.

**Gennadius, P. 1889.** Disease of tobacco plantations in the Trikonia. The aleyrodid of tobacco. Ellenike Georgia. 5: 1-3.

**Gerling, D. 1967.** Bionomics of the whitefly-parasite complex associated with cotton in southern California (Homoptera: Aleyrodidae; Hymenoptera: Aphelinidae). Ann. Entomol. Soc. Am. 60: 1306-1321.

**Gerling, D. 1984.** The overwintering mode of *Bemisia tabaci* in Israel. Phytoparasitica. 12: 109-118.

**Gerling, D. 1986.** Natural enemies of *Bemisia tabaci*, biological characteristics and potential as biological control agents: a review. Agric., Ecosyst. Environ. 17: 99-110.

**Gerling, D. and A. R. Horowitz. 1984.** Yellow traps for evaluating the population levels and dispersal patterns of *Bemisia tabaci* (Gennadius) (Homoptera: Aleyrodidae). Ann. Entomol. Soc. Am. 77: 753-759.

**Gerling, D. and V. Kravechenko. 1996.** Pest Management of *Bemisia* Out of Doors. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia*: 1995 Taxonomy, Biology, Damage, Control and Management. Intercept Andover, UK.

**Gerling, D. and R. T. Mayer [eds.]. 1996.** *Bemisia*: 1995 Taxonomy, Biology, Damage, Control and Management. Intercept, Andover, UK

**Gerling, D., A. R. Horowitz, and J. Baumgaertner. 1986.** Autecology of *Bemisia tabaci*. Agric. Eco. Environ. 17: 5-19.

**Gerling, D., O. Alomar, and J. Arno. 2001.** Biological control of *Bemisia tabaci* using predators and parasitoids. Crop Protect. 20: 779-799.

**Ghanim, M. and V. Medina. 2007.** Localization of tomato yellow leaf curl virus in its whitefly vector *Bemisia tabaci* pp. 171-183. *In* H. Czosnek [ed.], Tomato Yellow Leaf Curl Virus Disease. Springer, Dordrecht.

**Ghanim, M., S. Morin, M. Zeidan, and H. Czosnek. 1998.** Evidence for transovarial transmission of tomato yellow leaf curl virus by its vector, the whitefly *Bemisia tabaci*. Virology. 240: 295-303.

**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.

**Ghanim, M., I. Sobol, M. Ghanim, and H. Czosnek. 2007.** Horizontal transmission of begomoviruses between *Bemisia tabaci* biotypes. Arthropod-Plant Interactions. 1: 195-204.

**Gilbertson, R. L., M. R. Rojas, T. Kon, and J. Jaquez. 2007.** Introduction of *Tomato yellow leaf curl virus* into the Dominican Republic: The development of a successful integrated pest management strategy, pp. 279-303. *In* H. Czosnek [ed.], Tomato Yellow Leaf Curl Virus Disease. Springer, Dordrecht.

**Gill, R. J. 1992.** A review of the sweetpotato whitefly in southern California. Pan-Pac. Entomol. 68: 144-152.

**Goldman, V. and H. Czosnek. 2002.** Whiteflies (*Bemisia tabaci*) issued from eggs bombarded with infectious DNA clones of *Tomato yellow leaf curl virus* from Israel (TYLCV) are able to infect tomato plants. Arch. Virol. 147: 787-801.

**Goovaerts, P. 1997.** Geostatistics for Natural Resource Evaluation. Oxford University Press, New York.

**Gottwald, T. R., M. Cambra, P. Moreno, E. Camarasa, and J. Piquer. 1996.** Spatial and temporal analyses of citrus tristeza virus in eastern Spain. Phytopathology. 86: 45-55.

**Greathead, A. H. 1986.** Host plants, pp. 17-26. *In* M. J. W. Cock [ed.], *Bemisia tabaci* - A Literature survey on the cotton whitefly with an annotated bibliography. CAB International Institutes, Biological Control, Silwood Park.

**Gribko, L. S., A. M. Liebhold, and M. E. Hohn. 1995.** Model to predict Gypsy moth (Lepidoptera, Lymantriidae) defoliation using Kriging and logistic regression. Environ. Entomol. 24: 529-537.

**Gronenborn, B. 2007.** The tomato yellow leaf curl virus genome and function of its proteins, pp. 67-84. *In* H. Czosnek [ed.], *Tomato Yellow Leaf Curl Virus Disease*. Springer, Dordrecht.

**Groves, R. L., J. Chen, E. L. Civerolo, M. W. Freeman, and M. A. Viveros. 2005.** Spatial analysis of almond leaf scorch disease in the San Joaquin Valley of California: Factors affecting pathogen distribution and spread. Plant Dis. 89: 581-589.

**Gruenhagen, N. M. and T. M. Perring. 2001.** Plant influences on silverleaf whitefly oviposition and development and the potential for enemy-free space. Entomol. Exp. Appl. 99: 387-391.

**Grunwald, S., S. H. Daroub, and T. A. Lang. 2009.** Tree-based modeling of complex interactions of phosphorus loadings and environmental factors. Sci. Total Environ. 407: 3772-3783.

**Hagler, J. R. and S. E. Naranjo. 1994.** Determining the frequency of heteropteran predation on sweetpotato whitefly and pink bollworm using multiple ELISAs. Entomol. Exp. Appl. 72: 59-66.

**Hanif-Khan, S., J. K. Brecht, C. A. Powell, and P. J. Stofella. 1999.** Ethylene levels and fruit quality of silverleaf whitefly-infested dwarf cherry tomatoes, pp. 134-138, Proceedings Florida State Horticulture Society.

**Harrawijn, P. and H. Kayser. 1997.** Pymetrozine, a fast acting and selective inhibitor of aphid feeding: in-situ studies with electronic feeding monitoring of feeding behavior. Pestic. Sci. 49: 130-140.

**Harrison, B. D. 1985.** Advances in geminivirus research. Annu. Rev. Phytopathol. 23: 55-82.

**Hebertson, E. G. and M. J. Jenkins. 2008.** Climate factors associated with historic spruce beetle (Coleoptera: Cuculionidae) outbreaks in Utah and Colorado. Environ. Entomol. 37: 281-292.

**Henneberry, T. J., D. H. Hendrix, H. H. Perkins, S. E. Naranjo, H. M. Flint, D. Akey, L. F. Jech, and R. A. Burke. 1995.** *Bemisia argentifolii* (Homoptera: Aleyrodidae) populations and relationships to sticky cotton and cotton yields. Southwest. Entomol. 20: 255-271.

**Hernandez, A. and J. J. Pacheco. 1998.** Chancing a planting date: a silverleaf whitely case, pp. 574-577. *In* P. Dugger and D. Richter [eds.], Proceedings Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.

**Hilje, L., H. S. Costa, and P. A. Stansly. 2001.** Cultural practices for managing *Bemisia tabaci* and associated viral diseases. Crop Protect. 20: 801-812.

**Hoelmer, K. A. 1996.** Whitefly parasitoids: Can they control field populations of *Bemisia*? *In* D. Gerling and R. T. Mayer [eds.], *Bemisia* 1995: Taxonomy, Biology, Damage, Control and Management. Intercept, Andover, UK.

**Holland, J. M., C. F. G. Thomas, T. Birkett, S. Southway, and H. Oaten. 2005.** Farm-scale spatiotemporal dynamics of predatory beetles in arable crops. J. Appl. Ecol. 42: 1140-1152.

**Holmstrom, K. E., M. G. Hughes, S. D. Walker, W. L. Kline, and J. Ingerson-Mahar. 2001.** Spatial mapping of adult corn earworm and European corn borer populations in New Jersey. HortTechnology. 11: 103-109.

**Holt, J., M. J. Jeger, J. M. Thresh, and G. W. Otim-Nape. 1997.** An epidemiological model incorporating vector population dynamic applied to African Cassava Mosaic Virus Disease. J. Appl. Ecol. 34: 793-806.

**Hooks, C. R. R. , J. R. Valenzuela, and J. Defrank. 1998.** Incidence of pests and arthropod natural enemies in zucchini grown with living mulches. Agriculture Ecosystems & Environment. 69: 217-231.

**Horowitz, A. R. and I. Ishaaya. 1994.** Managing resistance to insect growth regulators in the sweetpotato whitefly (Homoptera: Aleyrodidae). J. Econ. Entomol. 87: 866-879.

**Horowitz, A. R. and I. Ishaaya. 1996.** Chemical control of *Bemisia* - management and application, pp. 537-556. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia*: 1995 Taxonomy, Biology, Damage, Control and Management Intercept, Andover.

**Horowitz, A. R., S. Kontsedalov, and I. Ishaaya. 2004.** Dynamics of resistance to the neonicotinoids acetamiprid and thiamethoxam in *Bemisia tabaci* (Homoptera: Aleyrodidae). J. Econ. Entomol. 97: 2051-2056.

**Horowitz, A. R., I. Denholm, and S. Morin. 2007.** Resistance to insecticides in the TYLCV vector, *Bemisia tabaci*, pp. 305-325. *In* H. Czosnek [ed.], Tomato Yellow Leaf Curl Virus Disease. Springer, Dordrecht.

**Husain, M. and K. N. Trehan. 1933.** Observations on the life history, bionomics and control of the white-fly of cotton (*Bemisia gossypiperda* M. EL.). Indian J. Agric. Sci. 3: 701-753.

**Husain, M. and K. N. Trehan. 1940.** Final report on the scheme of investigations on the whitefly on cotton in the Punjab. Indian J. Agric. Sci. 10: 101-109.

**Ifoulis, A. A. and M. Savopoulou-Soultani. 2006.** Use of geostatistical analysis to characterize the spatial distribution of Lobesia botrana (Lepidoptera : Tortricidae) larvae in northern Greece. Environ. Entomol. 35: 497-506.

**Ioannou, N. 1985.** Yellow leaf curl and other diseases of tomato in Cyprus. Plant Pathol. 345: 428-434.

**Ioannou, N. 1987.** Cultural management of tomato yellow leaf curl disease in Cyprus. Plant Pathol. 36: 367-373.

**Isaacs, R. and D. N. Byrne. 1998.** Aerial distribution, flight behaviour and eggload: their inter-relationship during dispersal by the sweetpotato whitefly. J. Agric. Ento. 67: 741-750.

**Isaacs, R., M. A. Willis, and D. N. Byrne. 1999.** Modulation of whitefly take-off and flight orientation by wind speed and visual cues. Physiol. Entomol. 24: 311-318.

**Isaaks, E. H. and R. M. Srivastava. 1989.** An Introduction to Applied Geostatistics. Oxford University Press, New York.

**Ishaaya, I., Z. Mendelson, K. R. Simon Ascher, and J. E. Casida. 1987.** Cypermethrin synergism by pyrethroid esterase inhibitors in adults of the whitefly *Bemisia tabaci*. Pestic. Biochem. Physiol. 28: 155-162.

**Ishaaya, I., Z. Mendelson, and A. R. Horowitz. 1993.** Toxicity and growth suppression exerted by diafenthiuron in the sweetpotato whitefly *Bemisia tabaci*. Phytoparasitica. 21: 199-204.

**Ishaaya, I., A. Barazani, S. Kontsedalov, and A. R. Horowitz. 2007.** Insecticides with novel modes of action: Mechanism, selectivity and cross-resistance. Entomological Research. 37: 148-152.

**Iwao, S. 1968.** A new regression method for analyzing the aggregation pattern of animal populations. Res. Popul. Ecol. 10: 1-20.

**Jiang, Y. X., H. Lei, J. L. Collar, B. Martin, M. Muniz, and A. Fereres. 1999.** Probing and feeding behavior of two distinct biotypes of *Bemisia tabaci* (Homoptera: Aleyrodidae) on tomato plants. J. Econ. Entomol. 92: 357-366.

**Jiang, Y. X., C. De Blas, L. Barrios, and A. Fereres. 2000.** Correlation between whitefly (Homoptera: Aleyrodidae) feeding behavior and transmission of tomato yellow leaf curl virus. Ann. Entomol. Soc. Am. 93: 573-579.

**Jindal, V., G. S. Dhaliwal, and A. K. Dhawan. 2008.** Mechanisms of resistance in cotton to whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae): antibiosis. Int. J. Trop. Insect Sci. 27: 216-222.

**Jing, Y., J. Huang, Rui-yan Ma, and Ju-cai Han. 2003.** Host plant preferences of *Bemisia tabaci* Gennadius. Entomologia Sinica. 10: 109-114.

**Johnson, C. G. 1969.** Migration & Dispersal of Insects by Flight. Methuen & Company Limited, London.

**Jones, W. A. and G. L. Snodgrass. 1998.** Development and fecundity of *Deraeocoris nebulosus* (Heteroptera: Miridae) on *Bemisia argentifolii* (Homoptera: Aleyrodidae). Flor. Ento. 81: 345-350.

**Kadir, H. A. and C. O. Knowles. 1991.** Toxicological studies of the thiourea diafenthiuron in diamondback moth (Lepidoptera: Yponomeutidae), two-spotted spider mites (Acari: Tetranychidae) and bulb mite (Acari: Acaridae). J. Econ. Entomol. 84: 780-784.

**Kayser, H., L. Kaufmann, F. Schurmann, and P. Harrewijn. 1994.** Pymetrozine (GGA 215'944): a novel compound for aphid and whitefly control: an overview of its mode of action, pp. 737-742, Brighton Crop Protection Conference: Pests and Diseases. British Crop Protection Council, Farnham, UK.

**Kemp, W. P., T. M. Kalaris, and W. F. Quimby. 1989.** Rangeland grasshopper (Orthoptera: Acrididae) spatial variability: macroscale population assessment. J. Econ. Entomol. 82: 1270-1276.

**Kemp, W. P., K. M. O'Neill, M. M. Cigliano, and S. Torrusio. 2002.** Field-scale variations in plant and grasshopper communities: A GIS-based assessment. Transactions in GIS. 6: 115-133.

**Kennedy, J. S. 1985.** Migration, behavioral and ecological, pp. 7-26. *In* M. A. Rankin [ed.], Migration: Mechanisms and Adaptive Significance. Contributions in Marine Science Supplement.

**Kennedy, M. 2000.** Understanding Map Projections.Environmental Systems Research Institute, Inc.Redlands.http://www.duc.auburn.edu/academic/classes/fory/7470/lab08/understanding%20map%20projections.pdf.Feb. 14, 2011.

**Kim, H., S-.T. Kim, and M.-P. Jung. 2007.** Spatio-temporal dynamics of *Scotinophara lurida* (Hemiptera: Pentatomidae) in rice fields. Ecol. Res. 22: 204-213.

**Kim, J-. K., J-J. Park, H. Park, and K. Cho. 2001.** Unbiased estimation of greenhouse whitefly, *Trialeurodes vaporariorum*, mean density using yellow sticky trap in cherry tomato greenhouses. Entomol. Exp. Appl. 100: 235-243.

**Klowden, M. J. 2002.** Physiological Systems in Insects. Academic Press, San Diego, California.

**Korie, S., J. N. Perry, M. A. Mugglestone, S. J. Clark, C. F. G. Thomas, and M. N. M. Roff. 2000.** Spatiotemporal associations in beetle and virus count data. J. Agric. Biol. Envion. Stat. 5: 214-239.

**Kravchenko, A. N. 2003.** Influence of spatial structure on accuracy of interpolation methods. Soil Sci. Soc. Am. J. 67: 1564-1571.

**Kunik, T., R. Salomon, D. Zamir, N. Navot, M. Zeidan, I. Michelson, Y. Gafni, and H. Czosnek. 1994.** Transgenic tomato plants expressing the tomato yellow leaf curl capsid protein are resistant to the virus. Biotechnology. 12: 500-504.

**Kunik, T., K. Palanaichelvam, H. Czosnek, V. Citovsky, and Y. Gafni. 1998.** Nuclear import of the capsid protein of tomato yellow leaf curl virus (TYLCV) in plant and insect cells. The Plant Journal. 13: 393-399.

**LABINS. 2011.** FDEP, Bureau of Survey and Mapping. http://data.labins.org/2003/index.cfm.

**Lapidot, M. and M. Friedmann. 2002.** Breeding for resistance to whitefly-transmitted geminiviruses Ann. Appl. Biol. 140: 109-127.

**Lapidot, M., O. Goldray, R. Ben-Joseph, S. Cohen, M. Friedmann, S. Nahon, L. Chen, and M. Pilowsky. 2000.** Breeding tomatoes for resistance to tomato yellow leaf curl begomovirus. Bull. OEPP. 30: 317-321.

**Lapidot, M., M. Friedmann, M. Pilowsky, R. Ben-Joseph, and S. Cohen. 2001.** Effect of host plant resistance to *Tomato yellow leaf curl virus* (TYLCV) on virus acquisition and transmission by its whitefly vector. Phytopathology. 91: 1209-1213.

**Lapidot, M., R. Ben-Joseph, L. Cohen, Z. Machbash, and D. Levy. 2006.** Development of a scale for evaluation of *Tomato yellow leaf curl* resistance level in tomato plants. Phytopathology. 96: 1404-1408.

**Larew, H. G. and J. C. Locke. 1990.** Repellency and toxicity of a horticultural oil against whiteflies on Chrysanthemum. HortScience. 25: 1406-1407.

**Laufs, J., W. Traut, F. Heyraud, V. Matzeit, S. G. Rodgers, J. Schell, and B. Gronenborn. 1995.** *In vitro* cleavage and joining at the viral origin of replication by the replication initiator protein of tomato yellow leaf curl virus. Proceedings of the National Academy of Sciences. 92: 3879-3883.

**Lecoustre, R., D. Fargette, C. Fauquet, and P. de Reffye. 1989.** Analysis and mapping of the spatial spread of African Cassava Mosaic Virus using geostatistics and the kriging technique. Phytopathology. 79: 913-920.

**Legaspi Jr., B. C., J. C. Allen, C. C. Brewster, J. A. Morales-Ramos, and E. G. King. 1998.** Areawide management of the cotton boll weevil: use of a spatio-temporal model in augmentative biological control. Ecol. Model. 110: 151-164.

**Leggett, J. E. 1993.** Comparison of arthropods sampled from cultivars of upland and pima cotton with drip and furrow irrigation. Southwest. Entomol. 18: 37-43.

**Levy, D. and M. Lapidot. 2008.** Effect of plant age at inoculation on expression of genetic resistance to tomato yellow leaf curl virus. Arch. Virol. 153: 171-179.

**Liebhold, A. M., Z. Xu, M. E. Hohn, J. S. Elkinton, M. Ticehurst, G. L. Benzon, and R. W. Campbell. 1991.** Geostatistical analysis of Gypsy-moth (Lepidoptera, Lymantriidae) egg mass populations. Environ. Entomol. 20: 1407-1417.

**Liebhold, A. M., R. E. Rossi, and W. P. Kemp. 1993.** Geostatistics and geographic information systems in applied insect ecology. Annu. Rev. Entomol. 38: 303-327.

**Liebhold, A., E. Luzander, R. Reardon, A. Bullard, A. Roberts, W. Ravlin, S. Delost, and B. Spears. 1996.** Use of a geographic information system to evaluate regional treatment effects in a gypsy moth (Lepidoptera: Lymantriidae) management program. J. Econ. Entomol. 89: 1192-1203.

**Liquido, N. J. and M. E. Irwin. 1986.** Longevity, fecundity, change in degree of gravidity, and lipid content with adult age, and lipid utilization during tethered flight of the corn leaf aphid, *Rhopalosiphum maidis* (Fitch). Ann. Appl. Biol. 108: 449-459.

**Liu, T. X. and P.A. Stansly. 1995a.** Toxicity and repellency of some biorational insecticides to *Bemisia argentifolii* on tomato leaves. Entomol. Exp. Appl. 74: 137-143.

**Liu, T. X. and P.A. Stansly. 1995b.** Oviposition by *Bemisia argentifolii* (Homoptera: Aleyrodidae) on tomato: effects of leaf factors and insecticide residues. J. Econ. Entomol. 88: 992-997.

**Liu, T. X. and P. A. Stansly. 1998.** Life history of *Bemisia argentifolii* (Homoptera: Aleyrodidae) on *Hibiscus rosa-sinensis* (Malvaceae). Flor. Ento. 81: 437-445.

**Liu, T. X. and P.A. Stansly. 2000.** Insecticidal activity of surfactants and oils against silverleaf whitefly (*Bemisia argentifolii*) nymphs (Homoptera: Aleyrodidae) on collards and tomato. Pest Manage. Sci. 56: 861-866.

**Liu, T. X., R. D. Oetting, and G. D. Buntin. 1993a.** Distribution of *Trialeurodes vaporariorum* and *Bemisia tabaci* (Homoptera, Aleyrodidae) on some greehouse-grown ornamental plants. J. Entomol. Sci. 28: 102-112.

**Liu, T. X., R. D. Oetting, and G. D. Buntin. 1993b.** Population dynamics and distribution of *Trialeurodes vaporariorum* and *Bemisia tabaci* (Homoptera: Aleyrodidae) on Poinsettia following applications of three chemical insecticides. J. Entomol. Sci. 28: 126-135.

**Lopez-Avila, A. 1986.** Taxonomy and biology, pp. 3-11. *In* M. J. W. Cock [ed.], *Bemisia tabaci* - A Literature Survey on the cotton whitefly with an annotated bibliography. CAB International Institutes, Biological Control, Silwood Park.

**Lyons, D. B., C. J. Sanders, and G. C. Jones. 2002.** The use of geostatistics and GIS as tools for analyzing pheromone trap data at a landscape level: an update. IOBC WPRS Bulletin. 25: 1-14.

**MacQuarrie, C. J. K., J. R. Spence, and D. W. Langor. 2010.** Using classification tree analysis to reveal causes of mortality in an insect population. Agric. For. Entomol. 12: 143-149.

**Makkouk, K. M. 1978.** A study on tomato viruses in the Jordan Valley with special emphasis on Tomato yellow leaf curl. Plant Dis. 62: 259-268.

**Mansaray, A. and A. J. Sundufu. 2009.** Oviposition, development and survivorship of the sweetpotato whitefly *Bemisia tabaci* on soybean, *Glycine max*, and the garden bean, *Paseolus vulgaris*. J. Insect Sci. 9: 1-6.

**Mansour, A. and A. Al-Musa. 1992.** Tomato yellow leaf curl virus: host range and virus-vector relationships. Plant Pathol. 41: 122-125.

**Markham, P. G., I. D. Bedford, S. Liu, D. F. Frolich, R. Rosell, and J. K. Brown. 1996.** The transmission of geminiviruses by biotypes of *Bemisia tabaci* (Gennadius), pp. 69-75. *In* D. Gerling and T. Meyer [eds.], *Bemisia* 1995: Taxonomy, Biology, Damage, Control, and Management. Intercept, Andover, U.K.

**Martin, J. H., D. Mifsud, and C. Rapisarda. 2000.** The whiteflies (Hemiptera: Aleyrodidae) of Europe and the Mediterranean basin. Bull. Entomol. Res. 90: 407-448.

**Martinez Zubiaur, Y., D. Fonseca, M. Quinones, and I. Palenzuela. 2004.** Presence of *Tomato yellow leaf curl virus* infecting squash (*Curcubita pepo*) in Cuba. Plant Dis. 88: 572.

**Mason, G., M. Rancati, and D. Bosco. 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 Protect. 19: 473-479.

**Matsuura, S. and S. Hoshino. 2008.** Comparative spatial dispersal of *Tomato yellow leaf curl virus* vectored by B and Q biotypes of *Bemisia tabaci* in tomato glasshouses. Phytoparasitica. 36: 42-51.

**Maynard, D. N. and D. J. Cantliffe. 1989.** Squash silverleaf and tomato irregular ripening: new vegetable disorders in Florida VC-37: 4.

**McAuslane, H. L. 1996.** Influence of leaf pubescence on ovipositional preference of *Bemisia argentifolii* (Homoptera: Aleyrodidae) on soybean. Environ. Entomol. 25: 834-841.

**McCollum, T. G., P. J. Stofella, C. A. Powell, D. J. Cantliffe, and S. Hanif-Khan. 2004.** Effects of silverleaf whitefly feeding on tomato fruit ripening. Postharvest Biol. Technol. 31: 183-190.

**McKenzie, C. L., P. K. Anderson, and N. Villarreal. 2004.** An extensive survey of *Bemisia tabaci* (Homoptera: Aleyrodidae) in agricultural ecosystems in Florida. Fla. Entomol. 87: 403-407.

**Mehta, P. A. , J. W. Wyman, M. K. Nakhla, and D. P. Maxwell. 1994.** Transmission of tomato yellow leaf curl geminivirus by *Bemisia tabaci* (Homoptera: Aleyrodidae). J. Econ. Entomol. 87: 1291-1297.

**Mewally, S. A. G. 1999.** Effect of planting date and certain weather factors on the population fluctuations of three insect pests infesting kidney beans in Qualyobia governorate. Egyptian Journal of Agricultural Research. 77: 139-149.

**Michelson, I., D. Zamir, and H. Czosnek. 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.

**Midgarden, D. G., R. R. Youngman, and S. J. Fleischer. 1993.** Spatial analysis of counts of western corn rootworm (Coleoptera: Chrysomelidae) adults on yellow sticky traps in corn: geostatistics and dispersion indices. Environ. Entomol. 22: 1124-1133.

**Miller, G. L., S. Nakahara, R. W. Carlson, D. R. Miller, and M. B. Stoetzel. 2001.** Systematic Entomology Laboratory Whitefly Web Page. http://www.sel.barc.usda.gov/whitefly/wfframe.htm. Feb 1st, 2011.

**Mohamed, E. F. 2010.** Interaction between some viruses which attack tomato (*Lycopersicon esculentum* Mill.) plants and their effect on growth and yield of tomato plants. J. Amer. Sci. 6: 311-320.

**Momol, M. T., G. W. Simone, W. Dankers, R. K. Sprenkel, S. M. Olson, E. A. Momol, J. E. Polston, and E. Heibert. 1999.** First report of tomato yellow leaf curl virus in tomato in Georgia. Plant Dis. 83: 487.

**Momol, T., S. M. Olson, J. Funderburk, and R. K. Sprenkel. 2001.** Management of Tomato Yellow Leaf Curl Virus (TYLCV) in tomato in North Florida. http://edis.ifas.ufl.edu/NFREC1. 8/1/2007,

**Mor, U. . 1987.** *Bemisia tabaci* and cotton physiology: a 5-year summary of the influence of water-stressed plants on the pest population. Phytoparasitica. 15: 261.

**Morilla, G., D. Janssen, S. Garcia-Andres, E. Moriones, M. Cuadrado, and E. R. Bejarano. 2005.** Pepper (*Capsicum annuum*) is a dead-end host for *Tomato yellow leaf curl virus*. Phytopathology. 95: 1089-1097.

**Morin, S., M. Ghanim, M. Zeidan, H. Czosnek, M. Verbeek, and F. J. M. van den Heuvelt. 1999.** A GroEL homologue from endosymbiotic bacteria of the whitefly *Bemisia tabaci* in implicated in the circulative transmission of tomato yellow leaf curl virus. Virology. 256: 75-84.

**Moriones, E. and J. Navas-Castillo. 2000.** Tomato yellow leaf curl virus, an emerging virus complex causing epidemics worldwide. Virus Res. 71: 123-134.

**Moriones, E. J. Arno, G. P. Accotto, E. Noris, and Cavallarin. 1993.** First report of Tomato yellow leaf curl virus in Spain. Plant Dis. 77: 953.

**Mound, L. A. 1965.** Effects of leaf hair on cotton whitefly population in the Sudan Gezira. Empire Cotton Growing Review. 42: 33-40.

**Mound, L. A. and S. H. Halsey. 1978.** Whitefly of the world: A systematic catalogue of the Aleyrodidae (Homoptera) with host plant and natural enemy data. Wiley, New York.

**Muniyappa, V., H. M. Venkatesh, H. K. Ramappa, R. S. Kulkarni, M. Zeidan, C-Y Tarba, M. Ghanim, and H. Czosnek. 2000.** Tomato leaf curl virus from Bangalore (ToLCV-Ban4): sequence comparison with Indian ToLCV isolates, detection in plants and insects, and vector relationships. Arch. Virol. 145: 1583-1598.

**Muniz, M. 2000.** Host suitability of two biotypes of *Bemisia tabaci* on some common weeds. Entomol. Exp. Appl. 95: 63-70.

**Nakhla, M. K., D. P. Maxwell, R. T. Martinez, M. G. Carvalho, and R. L. Gibertson. 1994.** Widespread occurrence of the Eastern Mediterranean strains of tomato yellow leaf curl geminivirus in tomatoes in the Dominican Republic. Plant Dis. 78: 926.

**Naranjo, S. E. 1996.** Sampling *Bemisia* for research and pest management applications, pp. 209-224. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia*: 1995 Taxonomy, Biology, Damage, Control and Management. Intercept, Andover, UK.

**Naranjo, S. E. 2001.** Conservation and evaluation of natural enemies in IPM systems for *Bemisia tabaci*. Crop Protect. 20: 835-852.

**Naranjo, S.E. and P.C. Ellsworth. 2001.** Introduction Special Issue: Challenges and opportunities for pest management of *Bemisia tabaci* in the new century. Crop Protect. 20: 707.

**Naranjo, S. E. and H. M. Flint. 1994.** Spatial distribution of preimaginal *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton and development of fixed-precision, sequential sampling plans. Environ. Entomol. 23: 254-266.

**Naranjo, S. E. and H. M. Flint. 1995.** Spatial distribution of adult *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton, and development and validation of fixed-precision sampling plans for estimating population density. Environ. Entomol. 24: 261-270.

**Naranjo, S. E., H. M. Flint, and T. J. Henneberry. 1995.** Comparative analysis of selected sampling methods for adult *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton. J. Econ. Entomol. 88: 1666-1678.

**Naranjo, S. E., P. C. Ellsworth, P. C. Chu, T. J. Henneberry, D. G. Riley, T. F. Watson, and R. L. Nichols. 1998.** Action thresholds for the management of *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton J. Econ. Entomol. 91: 1415-1426.

**Naranjo, S. E., S. J. Castle, P. J. De Barro, and S.-S. Liu. 2010.** Population Dynamics, Demography, Dispersal and Spread of *Bemisia tabaci*. *In* P. A. Stansly and S. E. Naranjo [eds.], *Bemisia*: Bionomics and Management of a Global Pest. Springer, London.

**Natwick, E. T. and A. Durazo III. 1985.** Polyester covers protect vegetable from whiteflies and virus disease. Calif. Agric. 39: 21-22.

**Navas-Castillo, J., S. Sanchez-Campos, J. A. Diaz, E. Saez-Alonso, and E. Moriones. 1999.** Tomato yellow leaf curl virus-Is causes a novel disease of common bean and severe epidemics in tomato in Spain. Plant Dis. 83: 29-32.

**Naveed, M. , A Salam, and M. A. Saleem. 2007.** Contribution of cultivated crops, vegetables, weeds and ornamental plant in harboring of *Bemisia tabaci* (Homoptera: Aleyrodidae) and associated parasitoids (Hymenoptera: Aphelinidae) in cotton agroecosystems in Pakistan. J. Pest Sci. 80: 191-197.

**Navot, N., R. Ber, and H. Czosnek. 1989.** Rapid detection of tomato yellow leaf curl virus in squashes of plant and insect vectors. Phytopathology. 79: 562-568.

**Nelson, M. R., R. Felix-Gastelum, T. V. Orum, L. J. Stowell, and D. E. Myers. 1994.** Geographic information systems and geostatistics in the design and validation of regional plant virus management programs. Phytopathology. 84: 898-905.

**Nelson, M. R., T. V. Orum, R. Jaime-Garcia, and A. Nadeem. 1999.** Applications of geographic information systems and geostatistics in plant disease epidemiology and management. Plant Dis. 83: 308-319.

**Nicholson, W. F., R. Senn, C. R. Fluckiger, and D. Fuog. 1996.** Pymetrozine - a novel compound for control of whiteflies, pp. 635-639. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia*: 1995 Taxonomy, Biology, Damage, Control and Management. Intercept Andover, UK.

**Nomikou, M., A. Janssen, R. Schraag, and M. W. Sabelis. 2001.** Phytoseiid predators as potential biological control agents for *Bemisia tabaci*. Exp. Appl. Acarol. 25: 271-291.

**Noonan, G. R. 2003.** GIS Technology. A powerful tool for entomologists. *Insight. A Milwaukee Public Museum Series in Natural History*.http://www.mpm.edu/downloads/collections/pubs/insight/NoonanGISreview.pdf.Feb. 15, 2011.

**Nuessly, G. S., D. E. Meyerdirk, D. L. Coudriet, and T. J. Henneberry. 1994.** The effect of short season cotton production schedules on *Bemisia tabaci* (Gennadius). Southwest. Entomol. 19: 209-217.

**Obrycki, J. J. and T. J. Kring. 1998.** Predaceous coccinellidae in biological control. Annu. Rev. Entomol. 43: 295-321.

**Ohnishi, J., T. Kitamura, F. Terami, and K. Honda. 2009.** A selective barrier in the midgut epithelial cell membrane of the nonvector whitefly *(Trialeurodes vaporariorum*) to *Tomato yellow leaf curl virus* uptake. J. Gen. Plant Path. 75: 131-139.

**Omondi, A. B., D. Obeng-Ofori, R. A. Kyerematen, and E. Y. Danquah. 2005.** Host preference and suitability of some selected crops for two biotypes of *Bemisia tabaci* in Ghana. Entomol. Exp. Appl. 115: 393-400.

**Orozco-Santos, M., M. Lopez-Arriaga, O. Perez-Zamora, and S. F. Delgadillo. 1994.** Effect of transparent mulch, floating row covers and oil sprays on insect populations, virus diseases and yield of cantaloupe. Biol. Agric. Hort. 10: 229-234.

**Orozco-Santos, M., O. Perez-Zamora, and M. Lopez-Arriaga. 1995.** Floating row cover and transparent mulch to reduce insect population, virus diseases and increase yield in cantaloupe. Fla. Entomol. 78: 493-501.

**Palmer, J. O. 1985.** Ecological genetics of wing length, flight propensity and early fecundity in a migratory insect. *In* M. A. Rankin [ed.], Migration: Mechanisms and Adaptive Significance. Contributions in Marine Science Supplement.

**Palumbo, J. C., A. Jr. Tonhasca, and D. N. Byrne. 1995.** Evaluation of three sampling methods for estimating adult sweetpotato whitefly (Homoptera: Aleyrodidae) abundance on cantaloupes. J. Econ. Entomol. 88: 1393-1400.

**Palumbo, J. C., A. R. Horowitz, and N. Prabhaker. 2001.** Insecticidal control and resistance management for Bemisia tabaci. Crop Protect. 20: 739-765.

**Park, J-J., D. H. Lee, K-I. Shin, J-H. Lee, and K. Cho. 2009.** Analysis of spatial and temporal associations of adult and immature *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae) in cucumber greenhouses. Appl. Entomol. Zool. 44: 569-577.

**Park, Y. L. and J. J. Obrycki. 2004.** Spatio-temporal distribution of corn leaf Aphids (Homoptera: Aphididae) and lady beetles (Coleoptera: Coccinellidae) in Iowa cornfields. Biol. Control. 31: 210-217.

**Park, Y-L. and J. J. Tollefson. 2005.** Characterization of the spatial dispersion of corn root injury by corn rootworms (Coleoptera: Chrysomelidae). Field and Forage Crops. 98: 378-383.

**Park, Y-L. and J. J. Tollefson. 2006.** Development and economic evaluation of spatial sampling plans for corn rootworm *Diabrotica* spp. (Col., Chrysomelidae) adults. J. Appl. Entomol. 130: 337-342.

**Park, Y-L., T. M. Perring, C. A. Farrar, and C. Gispert. 2006.** Spatial and temporal distributions of two sympatric *Homalodisca* spp. (Hemiptera: Cicadellidae): Implications for areawide pest management. Agric., Ecosyst. Environ. 113: 168-174.

**Pasek, J. E. 1988.** Influence of wind and windbreaks on local dispersal of insects. Agric., Ecosyst. Environ. 22/23: 539-554.

**Patel, V. C. and H. K. Patel. 1966.** Inter-relationship between whitefly (*Bemisia tabaci* Genn.) population and the incidence of leaf curl in bidi tobacco (*Nicotiana tabacum* L.) in relation to different planting dates. Indian J. Entomol. 28: 339-344.

**Patz, J. A. and U. E. C. Confalonieri. 2005.** Human health: ecosystem regulation of infectious diseases, pp. 391-415, The Millenium Ecosystem Assessment Series, Findings of the Conditional and Trends Working Group. Island Press, Washington D. C.

**Perez, C. J., P. Alvarado, C. Narvaez, F. Miranda, L. Hernandez, H. Vanegas, A. Hruska, and A. M. Shelton. 2000.** Assessment of insecticide resistance in five insect pests attacking field and vegetable crops in Nicaragua. J. Econ. Entomol. 93: 1779-1787.

**Perring, T. M. 2001.** The *Bemisia tabaci* species complex. Crop Protect. 20: 725-737.

**Perring, T. M. , R. N. Royalty, and C. A. Farrar. 1989.** Floating row covers for the exclusion of virus vectors and the effect of disease incidence and yield of cantaloupe. J. Econ. Entomol. 82: 1709-1715.

**Perring, T. M., A. D. Cooper, R. J. Rodriguez, C. A. Farrar, and T. S. Bellows, Jr. 1993.** Identification of a whitefly species by genomic and behavioral studies. Science. 259: 74-77.

**Perry, A. S. 1985.** The relative susceptibility to several insecticides of adult whiteflies (Bemisia tabaci) from various cotton-growing areas in Israel. Phytoparasitica. 13: 77-78.

**Perry, J. N. 1995.** Spatial analysis by distance indices. J. Anim. Ecol. 64: 303-314.

**Perry, J. N. 1998.** Measures of spatial pattern for counts. Ecology. 79: 1008-1017.

**Perry, J. N. and P. M. Dixon. 2002.** A new method to measure spatial association for ecological count data. Ecoscience. 9: 133-141.

**Perry, J. N., L. Winder, J. M. Holland, and R. D. Alston. 1999.** Red-blue plots for detecting clusters in count data. Ecol. Lett. 2: 106-113.

**Pico, B., M. J. Diez, 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.

**Pico, B., M. Ferriol, M. J. Diez, and F. Nuez. 1999.** Developing tomato breeding lines resistant to tomato yellow leaf curl virus. Plant Breeding. 118: 537-542.

**Pollard, D. G. 1955.** Feeding habits of the cotton whitefly, *Bemisia tabaci* Genn. (Homoptera: Aleyrodidae). Ann. Appl. Biol. 43: 664-671.

**Polston, J. E. and P. K. Anderson. 1997.** The emergence of whitefly-transmitted geminiviruses in tomato in the Western Hemisphere. Plant Dis. 81: 1358-1369.

**Polston, J. E. and M. Lapidot. 2007.** Management of tomato yellow leaf curl virus: US and Israel perspectives, pp. 251-262. *In* H. Czosnek [ed.], Tomato Yellow Leaf Curl Virus Disease. Springer, Dordrecht.

**Polston, J. E. and T. Sherwood. 2003.** Pymetrozine interferes with transmission of *Tomato yellow leaf curl virus* by the whitefly *Bemisia tabaci*. Phytoparasitica. 31: 490-498.

**Polston, J. E., D. Bois, C. A. Serra, and C. Concepcion. 1994.** First report of a Tomato Yellow Leaf Curl-like Geminivirus in the Western Hemisphere. Plant Dis. 78: 831.

**Polston, J. E., D. O. Chellemi, D. J. Schuster, R. J. McGovern, and P.A. Stansly. 1996.** Spatial and temporal dynamics of tomato mottle geminivirus and *Bemisia tabaci* (Genn.) in Florida tomato fields. Plant Dis. 80: 1022-1028.

**Polston, J. E., R. J. McGovern, and L. G. Brown. 1999.** Introduction of tomato yellow leaf curl virus in Florida and implications for the spread of this and other geminiviruses of tomato. Plant Dis. 81: 1358-1369.

**Polston, J. E., A. Cohen, T. A. Sherwood, R. Ben-Joseph, and M. Lapidot. 2006.** *Capsicum* species: Symptomless hosts and reservoirs of *Tomato yellow leaf curl virus*. Phytopathology. 96: 447-452.

**Polston, J. E., D. J. Schuster, and J. E. Taylor. 2009.** Identification of weed reservoirs of *Tomato yellow leaf curl virus* in Florida, pp. 32-33. *In* E. Simonne, C. Snodgrass and M. Ozores-Hampton [eds.], Florida Tomato Institute. University of Florida, Naples, Florida.

**Powell, D. A. and T. S. Bellows. 1992.** Preimaginal development and survival of *Bemisia tabaci* on cotton and cucumber. Environ. Entomol. 21: 359-363.

**Prabhaker, N., D. L. Coudriet, and N. C. Toscano. 1988.** Effect of synergists on organophosphate and permethrin resistance in sweetpotato whitefly (Homoptera: Aleyrodidae). J. Econ. Entomol. 81: 34-39.

**Prabhaker, N., N. C. Toscano, and D. L. Coudriet. 1989.** Susceptibility of the immature and adult stages of the sweetpotato whitefly (Homoptera: Aleyrodidae) to selected insecticides. J. Econ. Entomol. 82: 983-988.

**Prabhaker, N., N. C. Toscano, T. M. Perring, G. Nuessley, K. Kido, and R. R. Youngman. 1992.** Resistance monitoring of the Sweetpotato whitefly (Homoptera: Aleyrodidae) in the Imperial Valley of California. J. Econ. Entomol. 85: 1063-1068.

**Prabhaker, N., N. C. Toscano, S. J. Castle, and T. J. Henneberry. 1997.** Selection for resistance to imidacloprid in silverleaf whiteflies from the Imperial Valley and development of a hydroponic bioassay for resistance monitoring. Pestic. Sci. 51: 419-428.

**Prabhaker, N., N. C. Toscano, and T. J. Henneberry. 1998.** Evaluation of insecticide rotations and mixtures as resistance management strategies for *Bemisia argentifolii* (Homoptera: Aleyrodidae). J. Econ. Entomol. 91: 820-826.

**Praveen, S., C. M. Kushwaha, A. K. Mishra, V. Singh, R. K. Jain, and V. Anupam. 2005.** Engineering tomato for resistance to tomato leaf curl disease using viral *rep* gene sequences. Plant Cell Tiss. Org. Cult. 83: 311-318.

**Price, J. F. 1987.** Controlling a new pest. Greenhouse Grower. 570: 72-73.

**Putnam, A. R., J. Defrank, and J. P. Barnes. 1983** Exploitation of allelopathy for weed control in annual and perennial cropping systems. J. Chem. Ecol. 9: 1001-1010.

**Ramappa, H. K., V. Muniyappa, and J. Colvin. 1998.** The contribution of tomato and alternative host plants to tomato leaf curl virus inoculum pressure in different areas of South India. Ann. Appl. Biol. 133: 187-198.

**Reay-Jones, F. P. F. 2010.** Spatial distribution of the cereal leaf beetle (Coleoptera: Chrysomelidae) in wheat. Environ. Entomol. 39: 1943-1952.

**Reay-Jones, F. P. F., M. D. Toews, J. K. Greene, and R. B. Reeves. 2010.** Spatial dynamics of stink bugs (Hemiptera: Pentatomidae) and associated boll injury in Southeastern cotton fields. Environ. Entomol. 39: 956-969.

**Reeves, R. B., J. K. Greene, F. P. F. Reay-Jones, M. D. Toews, and P. D. Gerard. 2010.** Effects of adjacent habitat on populations of stink bugs (Heteroptera: Pentatomidae) in cotton as part of a variable agricultural landscape in South Carolina. Environ. Entomol. 39: 1420-1427.

**Riis, L. and G. Nachman. 2006.** Migration, trapping and local dynamics of whiteflies (Homoptera: Aleyrodidae). Agric. For. Entomol. 8: 233-241.

**Riley, D. G. and M. A. Ciomperlik. 1997.** Regional population dynamics of whitefly (Homoptera: Aleyrodidae) and associated parasitoids (Hymenoptera: Aphelinidae). Environ. Entomol. 26: 1049-1055.

**Riley, D. G. and J. C. Palumbo. 1995.** Action thresholds for *Bemisia argentifolii* (Homoptera: Aleyrodidae) in cantaloupe. J. Econ. Entomol. 88: 1733-1738.

**Ritchie, M. and D. Pedgley. 1989.** Desert locusts cross the Atlantic. Antenna. 13: 10-12.

**Rojas, M. R., H. Jiang, R. Salati, B. Xoconostle-Cazares, M. R. Sudarshana, W. J. Lucas, and R. L. Gilbertson. 2001.** Functional analysis of proteins involved in movement of the monopartite Begomovirus, *Tomato yellow leaf curl virus*. Virology. 291: 110-125.

**Rom, M., Y. Antignus, D. Gidoni, M. Pilowsky, and S. Cohen. 1993.** Accumulation of tomato yellow leaf curl virus DNA in tolerant and susceptible tomato lines. Plant Dis. 77: 253-257.

**Rosell, R. C., I. D. Bedford, D. R. Frohlich, R. J. Gill, J. K. Brown, and P. G. Markham. 1997.** Analysis of morphological variation in distinct populations of *Bemisia tabaci* (Homoptera: Aleyrodidae). Ann. Entomol. Soc. Am. 90: 575-589.

**Rossi, R. E., D. J. Mulla, A. G. Journel, and E. H. Franz. 1992.** Geostatistical tools for modeling and interpreting ecological spatial dependence. Ecol. Monogr. 62: 277-314.

**Rubinstein, G. and H. Czosnek. 1997.** Long-term association of tomato yellow leaf curl virus with its whitefly vector *Bemisia tabaci*: effect on the insect transmission capacity, longevity and fecundity. J. Gen. Virol. 78: 2683-2689.

**Rubinstein, G., S. Morin, and H. Czosnek. 1999.** Transmission of Tomato Yellow Leaf Curl Geminivirus to imidacloprid treated tomato plants by the whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae). Horticultural Entomology. 92: 658-662.

**Russell, L. M. 1957.** Synonyms of *Bemisia tabaci* (Gennadius) (Homoptera, Aleyrodidae). Bulletin of Brooklyn Entomology 52: 122-123.

**Russell, L. M. 1975.** Collection records of *Bemisia tabaci* (Gennadius) in the United States (Hemiptera: Homoptera: Aleyrodidae). Cooperative Economic Insect Report. 25: 229-230.

**Rybicki, E. P. and G. Pietersen. 1999.** Plant virus disease problems in the developing world. Adv. Virus Res. 53: 127-175.

**Saikia, A. K. and V. Muniyappa. 1989.** Epidemiology and control of tomato leaf curl virus in India. Tropical Agriculture (Trinidad). 66: 350-354.

**Salas, J. and O. Mendoza. 1995.** Biology of the sweetpotato whitefly (Homoptera: Aleyrodidae) on tomato. Fla. Entomol. 78: 154-160.

**Salati, R., M. K. Nahkla, M. R. Rojas, P. Guzman, J. Jaquez, D. P. Maxwell, and R. L. Gilbertson. 2002.** *Tomato yellow leaf curl virus* in the Dominican Republic: Characterization of an infectious clone, virus monitoring in whiteflies, and identification of reservoir hosts. Phytopathology. 92: 487-496.

**Sanchez-Campos, S., J. Navas-Castillo, F. Monci, J. A. Diaz, and E. Moriones. 2000.** *Mercurialis ambigua* and *Solanum luteum*: two newly discovered natural hosts of tomato yellow leaf curl geminiviruses. Eur. J. Plant Pathol. 106: 391-394.

**Sappington, T. W. and W. B. Showers. 1992.** Reproductive maturity, mating status, and long-duration flight behavior of *Agrotis ipsilon* (Lepidoptera: Noctuidae) and the conceptual misuse of the oogenesis-flight syndrome by entomologists. Environ. Entomol. 21: 677-688.

**SAS. 2002.** SAS/STAT user's guide. 9.2. Cary, NC.

**Schell, S. P. and J. A. Lockwood. 1997.** Spatial analysis of ecological factors related to rangeland grasshopper (Orthoptera: Acrididae) outbreaks in Wyoming. Environ. Entomol. 26: 1343-1353.

**Schotzko, D. J. and L. E. O'Keeffe. 1989.** Geostatistical description of the spatial-distribution of *Lygus hesperus* (Heteroptera, Miridae) in lentils. J. Econ. Entomol. 82: 1277-1288.

**Schotzko, D. J. and L. E. O'Keeffe. 1990.** Effect of sample placement on the geostatistical analysis of the spatial distribution of *Lygus hesperus* (Heteroptera: Miridae) in lentils. J. Econ. Entomol. 83: 1888-1900.

**Schuster, D. J. 2001.** Relationship of the silverleaf whitefly population density to severity of irregular ripening of tomato. HortScience. 36: 1089-1090.

**Schuster, D. J. 2004.** Squash as a trap crop to protect tomato from whitefly-vectored tomato yellow leaf curl. Int. J. Pest Manage. 50: 281-284.

**Schuster, D. J. 2007.** Whitefly resistance update. *In* A. Whidden, P. Gilreath and E. Simonne [eds.], Florida Tomato Institute Proceedings. Florida Tomato Institute, Naples, FL.

**Schuster, D. J. and R. D. Caballero. 2010.** Monitoring resistance of the sweetpotato whitefly to insecticides. Gainesville, Florida.

**Schuster, D. J., T. G. Mueller, J. Kring, and J. F. Price. 1990.** Relationship of the sweetpotato whitefly to a new tomato fruit disorder in Florida. HortScience. 25: 1618-1620.

**Schuster, D. J., J. B. Kring, and J. F. Price. 1991.** Association of the sweetpotato whitefly with a silverleaf disorder of squash. HortScience. 26: 155-156.

**Schuster, D. J., J. E. Polston, and J. F. Price. 1992.** Reservoirs of the sweetpotato whitefly for tomatoes in West-Central Florida. Proceedings of the Florida State Horticulture Society. 105: 311-314.

**Schuster, D. J., J. E. Funderburk, and P. A. Stansly. 1996a.** IPM in tomatoes, pp. 387 - 411. *In* D. Rosen, J. L. Capinera and F. D. Bennet [eds.], Integrated Pest Management - A Florida Perspective. Intercept Ltd, Andover, Hants, UK.

**Schuster, D. J., P.A. Stansly, and J. E. Polston. 1996b.** 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.

**Schuster, D. J., P.A. Stansly, J. E. Polston, P. R. Gilreath, and E. McAvoy. 2007a.** Management of whiteflies, whitefly-vectored plant virus, and insecticide resistance for vegetable production in Southern Florida. *EDIS*.Entomology and Nematology Dept., Florida Cooperative Extension Service, IFAS, University of Florida.Gainesville.http://edis.ifas.ufl.edu/in695.3/10/2011.

**Schuster, D. J., J. E. Taylor, C. D. Stanley, J. E. Polston, and S. Grunwald. 2007b.** Evaluating factors affecting movement of the silverleaf whitefly and tomato yellow leaf curl virus. Tomato Research Report for 2006-2007. 56-63.

**Schuster, D. J., S. K. Thompson, L. D. Ortega, and J. E. Polston. 2009.** Laboratory evaluation of products to reduce settling of sweetpotato whitefly adults. J. Econ. Entomol. 102: 1482-1489.

**Scott, J. W., M. R. Stevens, J. H. M. Barten, C. R. Thome, J. E. Polston, D. J. Schuster, and C. A. Serra. 1996.** Introgression of resistance to whitefly-transmitted geminiviruses from *Lycopersicon chilense* to tomato. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia*: 1995 Taxonomy, Biology, Damage, Control and Management Intercept, Andover.

**Seal, S. E., F. vandenBosch, and M. J. Jeger. 2006.** Factors influencing Begomovirus evolution and their increasing global significance: Implications for sustainable control. Crit. Rev. Plant Sci. 25: 23-46.

**Secker, A. E., I. D. Bedford, P. G. Markham, and M. E. C. William. 1998.** Squash, a reliable field indicator for the presence of B biotype of tobacco whitefly, *Bemisia tabaci*, pp. 837-842, Brighton crop protection conference - pests and diseases. British Crop Protection Council, Farnham, UK.

**Setzer, R. W. . 1995.** Spatio-temporal patterns of mortality of *Pemphigus populitransversus* and *P. populicaulis* on cottonwoods. Oecologia. 67: 310-321.

**Shah, D. A., G. C. Bergstrom, and P. P. Ueng. 2001.** Foci of *Stagonospora nodorum* blotch in winter wheat before canopy development. Phytopathology. 91: 642-647.

**Sharaf, N. 1986.** Chemical control of *Bemisia tabaci* Agriculture Ecosystems & Environment. 17: 111-127.

**Sharov, A. A., A. M. Liebhold, and E. A. Roberts. 1996.** Spatial variation among counts of gypsy moths (Lepidoptera: Lymantriidae) in pheromone-baited traps at expanding population fronts. Environ. Entomol. 25: 1312-1320.

**Shepherd, R. F., G. A. Van Sickle, and D. H. L. Clarke. 1988.** Spatial relationships of douglas-fir tussock moth defoliation within habitat and climatic zones. Proceedings Lymantriidae: A comparison of features of New and Old World tussock moths. 381-400.

**Showers, W. B. 1997.** Migratory ecology of the black cutworm. Annu. Rev. Entomol. 42: 393-425.

**Simmons, A. M., H. F. Harrison, and Kai-Shu Ling. 2008.** Forty-nine new host plant species for *Bemisia tabaci* (Hemiptera: Aleyrodidae). Entomol. Sci. 11: 385-390.

**Simmons, A. M., C. S. Kousik, and A. Levi. 2010.** Combining reflective mulch and host plant resistance for sweetpotato whitefly (Hemiptera: Aleyrodidae) management in watermelon. Crop Protect. 29: 898-902.

**Sinisterra, X. H., C. L. McKenzie, W. B. Hunter, C. A. Powell, and RG Shatters, Jr. 2005.** Differential transcriptional activity of plant-pathogenic begomoviruses in their whitefly vector (*Bemisia tabaci*, Gennadius: Hemiptera Aleyrodidae). J. Gen. Virol. 86: 1525-1532.

**Smith, H. A. and R. McSorley. 2000.** Potential of field corn as a barrier crop and eggplant as a trap crop for management of *Bemisia argentifolii* (Homoptera: Aleyrodidae) on common bean in North Florida. Fla. Entomol. 83: 145-158.

**Smith, H. A., R. L. Koening, H. L. McAuslane, and R. McSorley. 2000.** Effect of silver reflective mulch and a summer squash trap crop on densities of immature *Bemisia argentifolii* (Homoptera: Aleyrodidae) on organic bean. J. Econ. Entomol. 93: 726-731.

**Sonka, S. T., M. E. Bauer, E. T. Cherry, J. W. Colburn, R. E. Heimlich, D. A. Joseph, J. B. Leboeuf, E. Lichtenberg, D. A. Mortensen, S. W. Searcy, S. L. Ustin, and S. J. Ventura. 1997.** Precision Agriculture in the 21st Century. Geospatial and Information Technologies in Crop Management. National Academy Press, Washington D.C.

**Stansly, P.A. 1995.** Seasonal abundance of silverleaf whitefly in southwest Florida vegetable fields, pp. 234-242, Proceeding of the Florida Horticultural Society. Florida State Horticultural Society.

**Stansly, P. A. and D. J. Schuster. 1990.** Whitefly Update, pp. 20-42. *In* W. M. Stall [ed.], Proceedings of the Florida Tomato Institute Vegetable Crops Special Series SS-VEC-001. IFAS, University of Florida, Gainesville.

**Stansly, P.A., T. X. Lui, D. J. Schuster, and D. E. Dean. 1996.** Role of Biorational Insecticides in Management of *Bemisia*. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia* 1995: Taxonomy, Biology, Damage, Control and Management. Intercept, Andover, UK.

**Stansly, P.A., T. X. Lui, and C. S. Vavrina. 1998.** Response of *Bemisia argentifolii* (Homoptera: Aleyrodidae) to imidacloprid under greenhouse, field and laboratory conditions. J. Econ. Entomol. 91.

**Steinberg, D. and P. Colla. 1995.** CART: Tree-Structured Non-Parametric Data Analysis. San Diego, CA.

**Suwwan, M. A., M. Akkawi, A. M. Al-Musa, and A. Mansour. 1988.** Tomato performance and incidence of tomato yellow leaf curl (TYLC) virus as affected by type of mulch. Scientific Horticulture. 37: 39-45.

**Taylor, L. R. 1961.** Aggregation, variance and the mean. Nature. 189: 732-735.

**Taylor, L. R., I. P. Woiwod, and J. N. Perry. 1978.** The density-dependence of spatial behaviour and the rarity of randomness. J. Anim. Ecol. 47: 383-406.

**Taylor, R. A. J., S. Shalhevet, I. Spharim, M. J. Berlinger, and S. Lebiush-Mordechi. 2001.** Economic evaluation of insect-proof screens for preventing tomato yellow leaf curl virus of tomatoes in Israel. Crop Protect. 20: 561-569.

**Thomas, C. F. G., L. Parkinson, G. J. K. Griffiths, A. Fernandez Garcia, and E. J. P. Marshall. 2001.** Aggregation and temporal stability of carabid beetle distributions in field and hedgerow habitats. J. Appl. Ecol. 38: 100-116.

**Thomson, M. C. and S. J. Connor. 2000.** Environmental information systems for the control of arthropod vectors of disease. Med. Vet. Entomol. 14: 227-244.

**Thresh, J. M. 1976.** Gradients of plant diseases. Ann. Appl. Biol. 82: 381-406.

**Tillman, P. G., T. D. Northfield, R. F. Mizell, and T. C. Riddle. 2009.** Spatiotemporal patterns and dispersal of stink bugs (Heteroptera: Pentatomidae) in peanut-cotton farmscapes. Environ. Entomol. 38: 1038-1052.

**Tonhasca, Jr. A., J. C. Palumbo, and D. N. Byrne. 1994.** Aggregation patterns of *Bemisia tabaci* in response to insecticide applications. Entomol. Exp. Appl. 72: 265-272.

**Toscano, L. C., A. L. Boica Junior, and W. I. Maruyama. 2002.** Nonpreference of whitefly for oviposition in tomato genotypes. Scientia Agricola. 59: 677-681.

**Tsai, J. H. and K. Wang. 1996.** Development and reproduction of *Bemisia argentifolii* (Homoptera: Aleyrodidae) on five host plants. Environ. Entomol. 25: 810-816.

**Tu, Z., D. N. Byrne, and H. H. Hagedorn. 1997.** Vitellin of the sweet potato whitefly, *Bemisia tabaci*: biochemical characterization of titer changes in the adult. Arch. Insect Biochem. Physiol. 34: 223-237.

**Tubajika, K. M., E. L. Civerolo, M. A. Ciomperlik, D. A. Luvisi, and J. M. Hashim. 2004.** Analysis of the spatial patterns of Pierce's disease incidence in the lower San Joaquin Valley in California. Phytopathology. 94: 1136-1144.

**Turechek, W. W. 2010.** Environmental and geographical variables associated with TYLCV epidemics in southwest Florida. *In* M. Ozores-Hampton and C. Snodgrass [eds.], 2010 Florida Tomato Institute Proceedings. University of Florida, Naples, Florida.

**Turechek, W. W. and L. V. Madden. 1999.** Spatial pattern analysis of strawberry leaf blight in perennial production systems. Phytopathology. 89: 421-433.

**Ucko, O., S. Cohen, and R. Ben-Joseph. 1998.** Prevention of virus epidemics by a crop-free period in the Arava Region of Israel. Phytoparasitica. 26: 313-321.

**Valverde, R. A., P. Lotrakul, and A. D. Landry. 2001.** First report of tomato yellow leaf curl virus in Louisiana. Plant Dis. 85: 230.

**Van Lenteren, J. C. and L. P. J. J. Noldus. 1990.** Whitefly-Plant Relationships: Behavioural and Ecological Aspects. *In* D. Gerling [ed.], Whiteflies: their Bionomics, Pest Status and Management. Intercept, Andover, UK.

**Van Schelt, J., J. Klapwijk, M. Letard, and C. Aucouturier. 1996.** The use of *Macrolopus caligionosus* as a whitefly predator in protected crops. *In* D. Gerling and R. T. Mayer [eds.], *Bemisia* 1995: Taxonomy, Biology, Damage, Control and Management. Intercept, Andover, UK.

**Van Sickle, G. A. 1989.** GIS - A tool in forest pest management pp. 213-219. *In* G. Wygul, J. McCoy and J. Smith [eds.], A Wider Perspective, Proceedings. GIS-89, Forestry Canada.

**vanEngelsdorp, D., N. Speybroeck, J. D. Evans, B. K. Nguyen, C. Mullin, M. Frazier, D. Cox-Foster, Y. Chen, D. R. Tarpy, E. Haubruge, J. S. Pettis, and C. Saegerman. 2010.** Weighing risk factors associated with bee colony collapse disorder by classification and regression tree analysis. J. Econ. Entomol. 103: 1517-1523.

**Varma, A. and V. G. Malathi. 2003.** Emerging geminivirus problems: A serious threat to crop production. Ann. Appl. Biol. 142: 145-164.

**Vidavsky, F. and H. Czosnek. 1998.** Tomato breeding lines resistant and tolerant to tomato yellow leaf curl virus issued from *Lycopersicon hirsutum* Phytopathology. 88: 910-914.

**Vidavsky, F., S. Leviatov, J. Milo, H. D. Rabinowitch, N. Kedar, and H. Czosnek. 1998.** Response of tolerant breeding lines of tomato, *Lycopersicon esculentum*, originating from three different sources (*L. peruvianum*, *L. pimpinellifolium* and *L. chilense*) to early controlled inoculation by tomato yellow leaf curl virus (TYLCV). Plant Breeding. 117: 165-169.

**Vidavsky, F., H. Czosnek, S. Gazit, D. Levy, and M. Lapidot. 2008.** Pyramiding of genes conferring resistance to *Tomato yellow leaf curl virus* from different wild tomato species. Plant Breeding. 127: 625-631.

**Vieira, S. R., J. L. Hatfield, D. R. Nielsen, and J. W. Biggar. 1983.** Geostatistical theory and application to variability of some agronomical properties. Hilgardia. 51: 1-75.

**Villar, A., E. Gomez, F. Morales, and P. Anderson. 1998.** Effect of legal measures to control *Bemisia tabaci* and geminiviruses in the Valley of Azua. Report from the National Integrated Pest Management Program. 16.

**Visser, J. H. 1988.** Host-plant finding by insect: orientation, sensory input and search patterns. J. Insect Physiol. 34: 259-268.

**Walker, G. P. and E. T. Natwick. 2006.** Resistance to silverleaf whitefly, *Bemisia argentifolii* (Hem., Aleyrodidae), in *Gossypium thurberi*, a wild cotton species. J. Appl. Entomol. 130: 429-436.

**Warner, D. J., L. J. Allen-Williams, S. Warrington, A. W. Ferguson, and I. H. Williams. 2003.** Mapping, characterization, and comparison of the spatio-temporal distributions of cabbage stem flea beetle (*Psylliodes chrysocephala*), carabids, and Collembola in a crop of winter oilseed rape (*Brassica napus*). Entomol. Exp. Appl. 109: 225-234.

**Watson, T. F. 1993.** Chemical control of the sweetpotato whitefly in cotton, pp. 221-239. Arizona Agricultural Experiment Station.

**Watson, T. F., J. C. Silvertooth, A. Tellez, and L. Lastra. 1992.** Seasonal dynamics of sweetpotato whitefly in Arizona. Southwest. Entomol. 17: 149-167.

**Webb, S. E. and S. B. Linda. 1992.** Evaluation of spunbonded polyethyline row covers as a method of excluding insects and viruses affecting fall-grown squash in Florida. J. Econ. Entomol. 85: 2344-2352.

**Wege, C. 2007.** Movement and localization of Tomato yellow leaf curl viruses in the infected plant, pp. 185-206. *In* H. Czosnek [ed.], Tomato yellow leaf curl disease. Springer, Dordrecht.

**Weintraub, P. G. and M. J. Berlinger. 2004.** Physical control in greenhouses and field crops. *In* A. R. Horowitz and I. Ishaaya [eds.], Insect Pest Management Field and Protected Crops. Springer, Berlin.

**Weisz, R., S. Fleischer, and Z. Smilowitz. 1995.** Map generation in high-value horticultural integrated pest management - appropriate interpolation methods for site-specific pest management of colorado potato beetle (Coleoptera: Chrysomelidae). J. Econ. Entomol. 88: 1650-1657.

**Westbrook, J. K., W. W. Wolf, P. D. Lingren, J. R. Raulston, J. D. Lopez, J. H. Matis, R. S. Eyster, J. F. Esquivel, and P. G. Schleider. 1997.** Early-season migratory flights of corn earworm (Lepidoptera: Noctuidae). Environ. Entomol. 26: 3-4.

**Williams, L., D. J. Schotzko, and J. P. McCaffrey. 1992.** Geostatistical description of the spatial distribution of *Limonis californicus* (Coleoptera, Elateridae) wireworms in the Northwestern United States, with comments on sampling. Environ. Entomol. 21: 983-995.

**Wilson, L. T. and P. M. Room. 1983.** Clumping patterns of fruit and arthropods in cotton, with implications for binomial sampling. Environ. Entomol. 12: 50-54.

**Xu, X. M. and L. V. Madden. 2004.** Use of SADIE statistics to study spatial dynamics of plant disease epidemics. Plant Pathol. 53: 38-49.

**Yang, Y., T. Sherwood, C. P. Patte, E. Hiebert, and J. E. Polston. 2004.** Use of *Tomato yellow leaf curl virus* (TYLCV) *Rep* gene sequences to engineer TYLCV resistance in tomato. Phytopathology. 94: 490-496.

**Zalom, F. G., E. T. Natwick, and N. C. Toscano. 1985.** Temperature regulation of *Bemisia tabaci* (Homoptera: Aleyrodidae) populations in imperial valley cotton. J. Econ. Entomol. 78: 61-64.

**Zamir, D., I. Ekstein-Michelson, Y. Zakay, N. Navot, M. Zeidan, M. Sarfatti, Y. Eshed, E. Harel, T. Pleban, H. van Oss, N. Kedar, H. D. Rabinowitch, and H. Czosnek. 1994.** Mapping and introgression of a tomato yellow leaf curl virus tolerance gene, TY-1. Theor. Appl. Genet. 88: 141-146.

**Zang, Lian-Sheng, Wei-Qiang Chen, and Shu-Sheng Liu. 2006.** Comparison of performance on different host plants between the B biotype and a non-B biotype of *Bemisia tabaci* from Zhejiang, China. Entomol. Exp. Appl. 121: 221-227.

**Zhang, W., H. L. McAuslane, and D. J. Schuster. 2004.** Repellency of ginger oil to *Bemisia argentifolii* (Homoptera: Aleyrodidae) on tomato. J. Econ. Entomol. 97: 1310-1318.

## BIOGRAPHICAL SKETCH

James “Shine” Taylor was born in Tifton, Ga. and graduated from Tift Co. High School in 2000. He graduated in 2004 from the University of Georgia with a B. S. in biological sciences from the College of Agriculture and Environmental Sciences. He completed a M. S. degree at the University of Georgia in 2006, working on the impact of beet armyworm in tomato. He received his Ph.D. from the University of Florida in the summer of 2011. He has worked in entomology for over 10 years in various disciplines including row crop, medical, veterinary, fruit and vegetable entomology. His current research interests include the spatial distribution of *Bemisia tabaci* and *Tomato yellow leaf curl virus* in Florida tomato. In time away from the office, he enjoys spending time with his family and enjoying the outdoors.

Glory, glory to ole Georgia!