Chapter 17

Integrated Systems for Managing *Bemisia tabaci* in Protected and Open Field Agriculture

Philip A. Stansly and Eric T. Natwick

Introduction

The combined efforts of disparate entities have produced notable advances in management of *Bemisia tabaci* (Gennadius) over the decades. On the one hand, entomologists and academicians have focused on specific problems, approaches and solutions, and designed experiments with replicated treatments to provide statistically valid results that hold up to scientific scrutiny. On the other hand, growers must integrate information from all disciplines into a profitable cropping and marketing system in order to survive. The gap between these extremes is often filled by crop consultants or agrochemical sales representatives who may have limited interests, focus or experience. There is clearly a need for more and better information on how management practices can be integrated to provide the desired level of pest suppression while still maintaining a balanced and profitable cropping system. The key challenge to implementing new practices will be to sustain or improve current levels of productivity while minimizing impact on the environment and biodiversity.

Integrated pest management (IPM) as conceived by Stern et al. (1959) stressed the rational combination of chemical, biological, and other control methods. These authors also introduced the key concept of the economic injury level (EIL), essentially the equivalence point between the cost and benefit of pesticide use. This approach has been widely adopted for low cost agronomic crops, but less so in high value vegetable and ornamental crops, many of which are susceptible to attack by *B. tabaci*. There are a number of reasons why this is so. On the one hand, pesticides may represent a small fraction of the total cost of production, often less than 5%. Therefore, controlling their cost has little effect on profit. On the other, it is difficult to base decisions on projected earnings because commodity prices often fluctuate unpredictably in a given season. Furthermore, these fluctuations in price do not always have the predicted effect on EIL because of the counteracting

---

P.A. Stansly (✉)
Department of Entomology and Nematology, Southwest Florida Research and Education Center, University of Florida/IFAS, 2685 SR 29N., Immokalee, FL 34142, USA
e-mail: pstansly@ufl.edu

P.A. Stansly, S.E. Naranjo (eds.), *Bemisia*: Bionomics and Management of a Global Pest,
DOI 10.1007/978-90-481-2460-2_17,

effect of price on demand. When prices go down the EIL should go up proportionately, but buyers can afford to be more exigent and therefore less tolerant of insect injury, effectively lowering the threshold. As a result, the need for insect control can increase when it can be least afforded. Product scarcity raises prices but also increases buyer tolerance for damage which augments supply. This tends to counteract the expected decrease in EIL, even though the grower will attempt to maintain production to take advantage of the good market. Therefore, the grower's strategy may be to maximize yield to take advantage of ephemeral high prices, rather than to control costs.

An "action threshold" requiring less rigorous criteria has often been employed to help rationalize management decisions when definition of an economic threshold based on EIL seems impractical. Action threshold has been defined as the level of pest populations at which control should be implemented to avoid significant damage to the crop (Dik and Albejas 1999). All that is required is demonstration of significant crop loss with no economic consideration. Even so, we are unaware of any action threshold that has been set for an insect that acts as a disease vector, including *B. tabaci*. Such a threshold would have to be based on the number of immigrating whiteflies that are viruliferous, a difficult estimate to obtain. This uncertainty leads to an attitude that any number of whiteflies is too many, especially in high value commodities and where viral transmission is a threat. Thus risk management has come to replace cost management as the goal of whitefly control in high value crops.

While the inability to define thresholds in high value crops tends toward intensified use of pesticides, the counteracting tendency is provided by legal restrictions and increased liability. Public concern for health risks associated with pesticides is evidenced by the increasing market for organic produce, valued in the USA at $10.3 billion and in the EU at $13 billion (Dimitri and Oberholtzer 2005). Clearly, reduced dependence on insecticides will require strengthening the remaining two legs of the IPM triangle, biological and cultural control. The opportunities and constraints for accomplishing this are often distinctly different for protected and open field crops. In particular, protected (greenhouse) horticulture offers the possibility of both excluding pest populations and confining natural enemies. Control over environmental conditions, to the extent that it can be achieved in protected horticulture, can also be used to favor beneficial organisms.

The many advantages of protected horticulture in terms of yield, quality, and duration of production have contributed to its increasing prominence in many high value crops on which *B. tabaci* is a significant pest. The division of this chapter into two sections recognizes the distinctive management challenges represented by protected versus open field cropping systems. The agronomic crops (cotton and alfalfa) will be considered as part of open field systems with special attention given to area-wide management. An emphasis on cropping systems rather than particular crops is in concert with the more general approach of this chapter, as it is mostly in the finer details that commodity distinctions come into play, especially with regard to augmentative biological control as it is practiced in protected vegetable production. Nevertheless, open field horticulture can benefit from experience in the greenhouse environment and efforts at adapting some of these augmentative control tactics to field grown vegetable production will also be discussed.

Biologically Based Management of *B. tabaci* in Protected Vegetable Crops

Key Pests of Greenhouse Vegetables

The objective of protected agriculture to provide an ideal environment for plant growth and development year round also provides favorable conditions for arthropod pests. These conditions favor non-diapausing pests with high reproductive rates. The diversity of crop plants found in greenhouses favors polyphagous species with efficient detoxification systems. Constant selection pressure from insecticides on confined populations, coupled with high rates of increase can result in rapid development of resistant populations common among greenhouse pests. Rapid population growth is typical of small pest species whose often cryptic habits make them difficult to detect. Many have attained global distributions in recent years thanks to the world wide trade in greenhouse grown commodities, especially ornamentals. Consequently, many greenhouse pests tend to be small, polyphagous, capable of rapid population growth, resistant to insecticides, and globally distributed (Table 17.1).

Table 17.1 Principal pests of greenhouse vegetable production in approximate order of importance

Tomato	Pepper	Beans	Cucurbits
Whiteflies	Thrips	**Whiteflies**	**Whiteflies**
Spider mites	**Whiteflies**	Spider mites	Spider mites
Russet mite	Noctuidae	Thrips	Thrips
Leafminers	Broadmite	Aphids	Leafminers
Gelechiidae	Aphids	Noctuidae	Aphids

Whiteflies: *B. tabaci* predominating in the tropical and subtropics, *T. vaporiariorum* in temperate regions

Thrips: Primarily *Frankliniella occidentalis* with *Thrips tabaci* and *T. palmi* being more localized problems

Spidermites: *Tetranichus* spp., principally *T. urticae*

Leafminers: *Liriomyza* spp. especially *L. trifolii*, followed by *L. huidobrensis* an *L. sativae*, all with world wide distributions and *L. bryoniae* still with an Old World distribution

Russet mite: *Aculops lycropersici*

Broadmite: *Polyphagotarsonemus latus*

Aphids: most often *Myzus persicae*, or *Aphis gossypii*, as well as *Macrosiphus euphorbiae* (especially Solanaceae) and *Aulacorthum solani* (especially pepper)

Noctuidae such as *Spodoptera literalis*, *S. exigua*, *Chrysodeixis* spp. and *Tricoplusia ni*, and Gelechiidae (*Tuta absoluta, Keiferia lycopersicella*)

Growers and pest control consultants cannot afford to focus on a single pest, leading to a tendency for calendar sprays with broad spectrum insecticides. Yet, it is also clear that one or the other of the whitefly species *Trialeurodes vaporariorum* (Westwood) and *B. tabaci* can be considered a key pest in many greenhouse crops. This is especially true when whiteflies are acting as virus vectors, which is often the case when tomatoes and cucurbits are grown, but also in some regions with beans, peppers and other crops (Polston and Anderson 1997). Consequently, effective whitefly control may often be the top pest management priority. This situation in most major greenhouse growing regions justifies our focus on *B. tabaci.*

Damage to Vegetable Crops Caused by **Bemisia tabaci**

In ascending order by damage potential, plants may experience direct injury from sap removal, buildup of honeydew and sooty mold, physiological disorders, and transmission of plant viruses (see Section III of this volume). Honeydew can be washed off during packing, but sooty mold blackens the leaves, interfering with transmission of light to the chloroplasts, and also causes cosmetic damage that may downgrade product acceptability and value (Howard et al. 1994). Physiological disorders caused by nymphal feeding include tomato irregular ripening and squash silverleaf that may affect fruit color as well as foliage (Schuster et al. 1996). Like sooty mold, both disorders can significantly downgrade fruit quality and value in ways that cannot be corrected in the packing house. The worst consequence of whitefly infestation is often the early and devastating appearance plant viruses such as *Tomato yellow leaf curl virus* (TYLCV), *Tomato chlorosis virus* (ToCV), *Cucurbit yellow stunting disorder virus* (CYSDV), *Cucumber vein yellowing virus* (CVYV), *Squash vein yellowing virus* (SqVYV), and *Bean golden mosaic virus* (BGMV) (see Moriones and Navas-Castillo Chapter 8; Morales Chapter 9; Wintermantel Chapter 10). In fact, more than 150 plant viruses are known to be transmitted by whiteflies and the number continues to grow (Polston and Anderson 1997; Jones 2003). Therefore, protection from whitefly attack early in the crop cycle may be the most important pest management task facing the grower or consultant.

Greenhouse Exclusion Technology

Greenhouse construction runs the gamut from simple polyethylene tunnels to elaborate structures of plastic or glass fitted with computerized controls for climate control, irrigation and fertilization. Even more germane to pest management in greenhouses is the capacity to exclude insect pests with fine netting and/or UV absorbing films (Antignus Chapter 13). However, there is a tradeoff between exclusion and ventilation as finer netting means less air exchange with the outside and consequent rise of temperature during the heat of the day (Harmanto and Tantau 2006; Teitel 2006). High rates of evaporation from the substrate and evapotranspiration from the crop maintain high humidity that can reach 100%. Poor ventilation may be especially acute in greenhouses with screened ventilation retrofitted rather than included in the original design. The result is often replacement of a pest problem with a fungal disease problem.

It may be necessary to entirely screen sides and ends of the greenhouse and ventilate large portions of the roof to create an insect barrier in tropical or subtropical areas and still maintain reasonable growing conditions. However, even with screened surface areas as large as the floor space, mesh sizes small enough to exclude whiteflies may not allow for sufficient ventilation rate (Alvarez et al. 2006; Harmanto and Tantau 2006). In such cases, forced ventilation with fans may be necessary to improve air exchange. However, the insect excluding ability of a particular netting is inversely proportional to air approach velocity. Therefore, air must be drawn into the greenhouse as uniformly as possible over the entire screened surface to minimize pest penetration. Netting can also become plugged with dust and debris, requiring periodic cleaning and/or replacement. Additional cooling can be provided in dry climates by evaporation using fogging or fan and pad evaporation systems. However, the latter must also be housed in screen enclosures sufficiently large to allow for the required air flow. Increasing gutter height is another way of improving air circulation and homogeneity of physical conditions in the greenhouse (Raya et al. 2006).

Thoracic width is generally the criterion used to determine mesh size for pest exclusion. The commonly accepted value for *B. tabaci* is 239 μm (Bethke and Paine 1991). Although increasing exclusion capability generally results in increased air resistance (static pressure), these two characteristics of screens are not always well correlated (Bell and Baker 2000). Rectangular interstices are increasingly used to minimize air resistance while maintaining exclusion ability (Cabrera et al. 2006). Commonly used netting to exclude *B. tabaci* is constructed of woven, UV stabilized (and often UV absorbing) polyethylene with 10 threads per cm in the vertical plane and 22 in the horizontal plane, providing openings of approximately 200 by 700 μm (Table 17.2). This mesh size has been shown to provide reliable exclusion of *B. tabaci* while allowing free entry of the parasitoid *E. mundus* (Hanafi et al. 2007).

Table 17.2 Thorax width of greenhouse pests (Bethke and Paine 1991) and corresponding mesh sizes of insect nettings in microns that could be used to exclude them

Insect	Thorax (μ)	Screen	Hole size (μm)	Static pressure
Flower thrips	192	Bugbed®	135×135	High
B. tabaci	240	Projar 22×10	230×900	Moderate
Melon aphid	340	Green-tek antivirus	266×818	Moderate
Leafminer	640	Lumite 32×32	530×530	Low

Host Plant Resistance

Effective mechanisms of plant resistance to TYLCV in tomato were first demonstrated in Israel over 40 years ago. However, the process of incorporating resistant characteristics from tomato relatives such as *Solanum habrochaites* and *S. pennellii* into the many varieties preferred by growers using classical breeding techniques has been understandably slow (Ji et al. 2007; see Nombela and Muñiz Chapter 14 for a review of plant resistance to the vector). The technology exists to speed this process markedly (Beachy 1997), but unfortunately, widespread prejudice against genetically engineered crops has impeded development (Baker and Burnham 2001). Thus, the grower must often content himself with what he considers to be horticulturally inferior cultivars if he is to incorporate TYLCV resistance into his program. Nevertheless, the risk of loss from TYLCV is so great that considerable adoption of these cultivars has occurred (Stansly et al. 2004a, b; Polston and Lapidot 2007; Ozores-Hampton et al. 2008). Rejection of genetically modified crops in the marketplace may also explain why no horticulturally acceptable cultivars have been developed that resist or tolerate other whitefly-borne viruses of tomato such as ToCV or *Tomato infectious chlorosis virus* (TICV).

Effective mechanisms for plant resistance to CYSDV have not been incorporated into commercial melon varieties, although resistant cucurtbit germ plasm is known. CYSDV incidence has been partially managed in the desert southwest USA. through reduction of the *B. tabaci* vector with a summer host free period between the spring and fall melon cropping seasons (Gilbertson 2007) and more recently in Arizona, 2008, with a grower-imposed host free period (D. Byrne, personal communication).

Biological Control of Bemisia tabaci

Entomopathogenic Fungi

Three species of entomopathogenic fungi active against *B. tabaci* are available commercially, *Paecilomyces fumosoroseus* = *Isaria fumorosea*, *Verticillium lecanii* and *Beauveria bassiana* (Table 17.3). The first two are naturally found infecting whiteflies whereas *B. bassiana* is only seen infecting whiteflies when applied as part of a formulation.

Entomopathogenic fungi are easy to apply although good coverage is required on the abaxial foliar surfaces where whiteflies reside. These fungi present essentially no risk to human health and most studies show that they are relatively innocuous to other natural enemies (Goettel et al. 2001; Vestergaard et al. 2003; Zimmerman 2008). Registration is often expedited in the USA, although not in Europe, where, unlike the USA, efficacy is a required criterion. Use of fungal products is compatible with many insecticides and resistance to mycopesticides has not yet been reported. However, fungi are slow acting compared to chemical insecticides, exhibit poor adulticidal activity, and are incompatible with many commonly used fungicides. In addition, they are relatively expensive, have limited shelf life, and are dependent on favorable environmental conditions (Inglis et al. 2001; Faria and Wraight 2001; Vidal et al. 2003).

Table 17.3 Commercial formulations of entomopathogenic fungi for whitefly control. Modified from Faria and Wraight (2001)

Fungus	Product	Company	Country
Beauveria bassiana	BotaniGard	Laverlam International/Bioworks	USA
	Ago Biocontrol Beauveria	Ago Biocontrol	Columbia
	Bea-Sin	Agrobiologicos de Noroeste S.A. de C. V.	Mexico
Isaria fumorosea = *(Paecilomyces fumosoroseus)*	PFR-97	Certis	USA
	PreFerRal	Biobest N.V.	Belgium
	Pae-Sin	Agrobiologicos de Noroeste S.A. de C. V.	Mexico
Verticillium lecanii	Ago Biocontrol Verticillium	Ago Biocontrol	Columbia
	Mycotal	Koppert Biological Systems	Holland

Hymenoptera: Aphelinidae

The pioneering work with *Encarsia formosa* Gahan on the greenhouse whitefly, *T. vaporariorum* (Van Lenteren and Woets 1988; Hu et al. 2002) ushered in the augmentative biological control strategy for whiteflies. While *En. formosa* will also attack *B. tabaci* (Enkegaard 1993; Hu et al. 2003), it is not as effective against this host as are many *Eretmocerus* spp. (Bosclair et al. 1990; Szabo et al. 1993; Gerling et al. 2001; Hoddle 2004). This may in part be due to the high temperature sensitivity of *En. formosa* which is at a disadvantage above 20°C (Qui et al. 2004). Furthermore, the more proovigenic *Eretmocerus* spp. have higher reproductive rates than the synovogenic *En. formosa* (Jervis et al. 2001; Qui et al. 2004; Urbaneja et al. 2007, Arnó et al. Chapter 15) and also are able to locate patches of *B. tabaci* more quickly (Hoddle et al. 1998). Therefore, interest has turned to *Eretmocerus*, in particular *Er. eremicus* and *Er. mundus* for control of *B. tabaci* (Stansly 2004a, b, 2005a, b).

Eretmocerus eremicus is a New World species that attacks both *B. tabaci* and *T. vaporariorum* with apparently equal facility (Greenberg et al. 2002; Soler-Gamborena and van Lenteren 2004). Therefore, it is especially useful for controlling mixed infestations of the two whiteflies. It has also been used to control pure infestations of *B. tabaci*, albeit with limited success (van Driesche et al. 2001, 2002). *Er. eremicus* was displaced by *Er. mundus* in greenhouses in Spain where both species were released (Stansly et al. 2004a, b, 2005a, b). Although immigration from outside the greenhouse explained this displacement in part, behavioral traits such as willingness to multi-parasitize hosts parasitized by the other species (Ardeh et al. 2005) may have assisted *Er. mundus* in competition with *Er. eremicus*. Coincidentally, native *Eretmocerus* spp. have been largely displaced by introduced old world species in open agriculture in the American Southwest, Florida and elsewhere in the USA and in Australia (Stansly unpublished data; Naranjo 2008; De Barro and Coombs 2008).

Successful management of *B. tabaci* using *Er. mundus* was demonstrated in large-scale commercial trials in protected pepper production facilities near Cartagena in southern Spain (Stansly et al. 2004b, 2005a). The primary pest, western flower thrips, *Frankliniella occidentalis*, was being controlled biologically in many of these greenhouses which facilitated acceptance of whitefly biological control. Control in tomato was also shown to be possible, although higher release rates were required to obtain the same level of control as in pepper (Stansly et al. 2005b). Large scale field trials in commercial greenhouses supported this conclusion, although results were somewhat compromised in tomato by pesticide use (see Table 17.4), presumably in response to the greater threat posed by the pest in its role as a virus vector in that crop (Stansly et al. 2004a, b).

Heteroptera: Miridae

The availability and use of predators alone and in combination with other control agents is discussed in detail by Arnó et al. (Chapter 15) and is summarized here. Three species of Miridae are widely used for augmentative biological control of *B. tabaci*: two European species *Macrolophus caliginosus* and *Nesidiocoris tenuis* and the American species, *Dicyphus hesperus*. All are naturally found on hirsute hosts and adapt best to tomato and to a lesser extent eggplant, but not at all to pepper. Effective control of *B. tabaci* by *N. tenuis* was demonstrated in large cage studies (Calvo et al. 2008a, b). However, trials in experimental and commercial greenhouses were less successful (Nannini 2001) and high release rates were required for satisfactory control. Best results were obtained when releases were made early during the warm season and/or reinforced with releases of *En. formosa*.

Establishment of mirid predators is generally slow and all feed on plants when prey is scarce (Alomar and Albajes 1996; Urbaneja et al. 2005; Sanchez 2008; Calvo et al. 2008a, b). Nevertheless, *D. hesperus* has been shown to prefer tomato leaves to fruit, so potential for damage is relatively low (McGregor et al. 2000). Shipp and Wang (2006) observed that damage to tomato by *D. hesperus* increased exponentially when a ratio of 1:10 (predator: prey) was exceeded. Calvo et al. (2008a, b) showed that the ratio of *B. tabaci* nymphs and *N. tenuis* individuals was the best predictor of incidence of damage in the form of necrotic rings on the peduncle. Alomar and Albajes (1996) provided a decision chart indicating that insecticidal control against *Dicyphus tamanini* was required when it exceeded 4 per plant and adult whitefly were less than 20 per plant.

Acari: Phytoseiidae

The most recent breakthrough in whitefly biological control has been development and commercialization of the predatory mite, *Amblyseius swirskii* (Nomikou et al. 2001a; Calvo et al. 2008a, b). In contrast to the mirids, *A. swirskii* seems to be well-adapted to every vegetable crop host except tomato, including pepper, cucumber, and eggplant (Nomikou et al. 2001b; Calvo et al. 2008a, b: Stansly and Castillo

2009). The ability to feed on alternate hosts is a distinct advantage and significant suppression of broadmite and western flower thrips has also been observed (Messelink et al. 2005; Tal et al. 2007). The mites also feed on pollen and therefore could be released preventively before pests are present Nomikou et al. 2003; Hoogerbrugge et al. 2007).

Nomikou, et al. (2001b) showed that populations of *B. tabaci* were reduced 16- to 21-fold on plants receiving the mites compared to those that did not, 9 weeks after *A. swirskii* had been released on cucumber plants provided with *Typhus* sp. pollen. Similar results were reported by Belda and Calvo (2006) and Calvo et al. (2008a, b). Whiteflies were virtually eliminated from pepper plants having received eight whitefly adults per week over a 3-week period followed by a single release of either 25 or 50 mites per plant. Messelink et al. (2008) found better suppression of *T. vaporariorum* was achieved following release of *A. swirskii* on cucumber when western flower thrips was also present, presumbably because the additional food source allowed higher populations of the mite to be maintained. Belda and Calvo (2006) and Calvo et al. (2008a, b) reported that the best biological control strategy for *B. tabaci* in eggplant was the combination of *A. swirskii* and *E. mundus*. Effectiveness, host range and compatibility of *A. swirskii* with other natural enemies has lead to widespread adoption of biological control in greenhouse pepper and other protected vegetable crops in Spain and elsewhere, and greatly furthered acceptance of biological control as a viable strategy for management of greenhouse pests (van der Blom 2007).

Compatibility of Various Pest Control Practices

While the threat of whitefly-transmitted viruses motivates reliance on insecticidal control, consumer demand for produce grown with little or no pesticides provides incentive for alternative management. Additional impetus comes from the example of successful biological control in vegetable greenhouse industries of northern Europe, especially the Netherlands (Bolckmans 1999). However, biological control may not seem like a viable alternative in the face of insect-borne virus were it not for compatible technologies that can provide protection early in the crop cycle. These include insect excluding structures alluded to above and in a previous chapter, spunbonded or embossed floating row covers (Natwick and Laemmlen 1993; Orozco-Santos et al. 1995), crop free periods, and the availability of disease resistant or tolerant cultivars.

Excluding structures and crop free periods were classified under cultural control practices designed to provide refuge from the pest in space or time, respectively, by Hilje et al. (2001). However, there is an important difference between the two practices in that excluding structures can be implemented at the level of the individual farm whereas crop free periods must be implemented area-wide. A single farm out of phase with the rest can provide sufficient inoculum and vectors to infect nearby growing areas. Nevertheless, well implemented crop free periods have succeeded in reducing levels of whitefly and TYLCV and CYSDV to tolerable levels in open field systems such as southwest Florida, the Arava Valley in Israel and the Dominican Republic (Hilje et al. 2001), but not to our knowledge in an area dominated by protected horticulture.

Compatibility of Pesticides with Biological Control

Development of a totally pesticide-free cropping system for vegetable production is a daunting task, given market demands for blemish-free produce. Even organic crops are frequently sprayed, often more than conventional crops, due to the reduced efficacy of permitted products such as soaps, oils, plant extracts, mineral and fermentation products. It can also be said that no pesticide, regardless of how apparently benign, is totally without some negative impact on biological control agents (http://www.koppert.nl/Side_effects.html). Nevertheless, there is a wide spectrum of selectivity among active ingredients, with considerable variation among natural enemies and their life stages in susceptibility to any particular pesticide. Given the large number of products, natural enemies of interest, possible effects of life stage, environmental conditions, host plants, and time of exposure, the possible combinations are essentially unlimited and preclude certainty that any single pest management decision is the best one. Defining these effects for all life stages of natural enemies of interest and the myriad of products on the market has occupied the energies of many investigators. Much of this information has been summarized by the biological control industry in indices available on-line such as the one cited above. For example, the Koppert database gives two numbers, the first representing relative impact on a scale of 1–4 and the second the interval of residual effect in weeks.

Stansly et al. (2004a) used this guide to evaluate the impact of pesticide applications on *Eretmocerus* spp. in Spanish greenhouses characterized as either IPM or conventional based on whether or not they employed biological control or relied totally on insecticides for pest management. *Eretmocerus mundus* and *E. eremicus* were released in separate sections of 10 IPM greenhouses to control *B. tabaci*, Each application was valued as the sum of ratings (1–4) for pupae and for adults of *E. eremicus* or closest related species given – usually *En. formosa* – and the mean number of weeks of residual effect. The sum of these three numbers was termed an impact rating and varied between 2 (most selective) and 18 (least selective). Impact ratings for all applications made while the crop was being monitored were summed for each greenhouse and then divided by the number of weeks to give an index of incompatibility during the period of study. The index ranged 1.1–8.7 in IPM greenhouses and 1.1–35.7 in conventional greenhouses (Table 17.4). A low incompatibility index usually corresponded to successful biological control in the IPM greenhouses as judged by parasitism rates and pest populations. The index also proved useful for rating the pest management program on a broad spectrum vs. selective continuum.

Table 17.4 Mean (±SE) number of pesticide applications, the number broad spectrum insecticides, selective insecticides/acaracides or fungicides used in those applications, the sum of side effect ratings for all pesticides used, and index of incompatibility of pesticide regime by management system on tomato crops in 19 Spanish greenhouses, 2001–2002. The management system designation of conventional or IPM was based on whether or not biological control was employed (Stansly et al. 2004a)

	Management designation			
	Conventional ($N = 9$)		IPM ($N = 10$)	
Applications (No.)	40.3	±6.9	16.2	±2.1
Broad spectrum (No.)	9.2	±4.1	0.4	±0.4
Selective (No.)	15.0	±4.1	7.0	±1.6
Fungicides (No.)	16.1	±2.6	8.8	±1.4
Side effects (Sum)	276.4	±59.1	60.0	±9.7
Incompatibility index	11.4	±3.2	3.0	±0.5

Area-Wide Management of Whitefly in Open Field Crops

The advances described above leading to the acceptance of biologically-based management of *B. tabaci* and other pests in protected vegetable production provide a stark contrast to the realities of most open field cropping systems. Nevertheless, some commonalities exist. Both production systems may occur in a mosaic of different crop types and phenologies within which polyphagous pests like *B. tabaci* move freely (see Naranjo et al. Chapter 6). Therefore, prevention or avoidance of severe whitefly infestations through cultural manipulation of crops or area-wide management is often required. These techniques have been used successfully in conjunction with an integrated control system featuring both biological and chemical control in the desert southwest of the USA and adjoining Mexico (Ellsworth and Martinez-Carrillo 2001; Naranjo and Ellsworth 2009a). These authors proposed a model of whitefly management that organizes all *B. tabaci* control tactics into a multi-level, multi-component pyramid and defines three major keys as “sampling”, “effective chemical use”, and “avoidance” (Fig. 17.1). Insect growth regulators ([IGRs] buprofezin and pyriproxyfen) in cotton and imidacloprid in vegetables and melons were key chemical tactics, integrated with sampling plans, action thresholds, and resistance management guidelines.

An area-wide or community-based management approach for *B. tabaci* can be successful in reducing the risk of damage to cotton and other crops (cucurbits, *Brassica*, lettuce and alfalfa). However, this approach relies on cooperation of growers within a defined geographic area or community to reduce intercrop movement and buildup of *B. tabaci* populations and to manage insecticide-resistance. Therefore, organized and sustained grower education was the key to the area-wide adoption and deployment of this IPM plan (Ellsworth and Martinez-Carrillo 2001).

Adjusting planting and harvest dates to avoid the heaviest migration periods and crop overlap has been a successful strategy. In the Rio Grande Valley of Texas, short

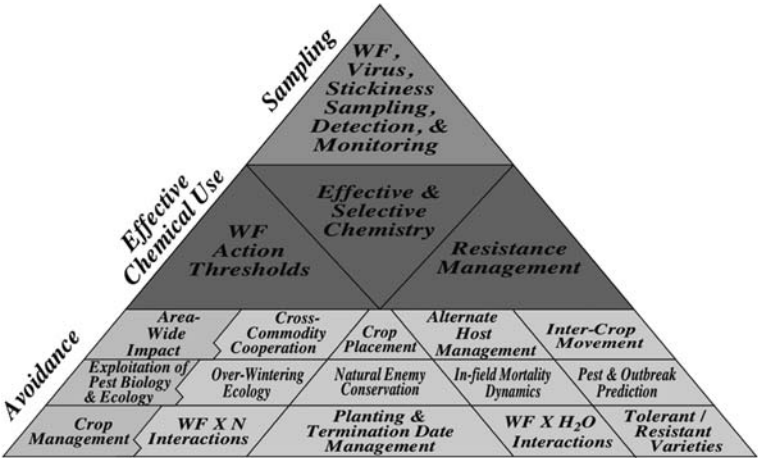

Fig. 17.1 Interaction of key aspects of whitefly management employed in the North American desert agroecosystem based on sampling, appropriate thresholds, effective chemistry and resistance management, and avoidance strategies that include exploitation of pest biology and ecology, biological control, crop management and area-wide impact (Ellsworth and Martinez-Carrillo 2001; with permission from Elsevier)

season, highly determinate cotton varieties were used to shorten the production season and successfully avoid late season *B. tabaci* infestations that lead to sticky cotton (Cook and Scott 1995). Early or delayed plantings may also be used, depending on the crop and migration patterns. Geographic manipulation of crops has been used to avoid heavy periods of *B. tabaci* migrations. Susceptible crops such as lettuce and *Brassica* spp. should not be sown near infestation sources such as cotton or melon, which themselves should not be sown in close proximity to each other nor near urban landscape plants that are heavily infested with *B. tabaci*. The urban landscape can also be a source of whitefly-transmitted viruses, such as TYLCV, as documented in California (Rojas et al. 2007).

Selection of crop varieties for each area is a key component in making this approach successful. Crops resistant to whitefly infestation or nymphal development help to limit insect population growth, reduce damage to the resistant crop and reduce mass migrations to other crops. An example is the development of the whitefly-resistant alfalfa variety UC-Impalo-WF (Teuber et al. 1997), which provides high levels of resistance to whiteflies (Jaing et al. 2003; Jaing and Walker 2007). Adjusted planting and harvest dates are also key components in establishment of a host-free period for management of *B. tabaci* and its vectored virus pathogens. These practices are being used to manage whitefly-transmitted virus diseases such as CYSDV (Natwick et al. 2008). Good sanitation practices are also key components critical for establishment of host-free periods and for reducing whitefly adult intercrop migration. Crop residues from winter vegetable crops (primarily *Brassica* sp. and *Lactuca* sp.) and melons crops should be shredded and turned into the soil immediately following harvest. Control of weed species that harbor *B. tabaci* in non-crop areas including head rows and fallow fields may also be helpful. However, weeds may also serve as sources of whitefly predators and parasitoids that play an important role in whitefly suppression and should be conserved (Godfrey et al. 2008). The Arizona area-wide management plan promotes the shortest possible growing season for cotton, winter vegetable crops (cole crops and lettuce), melon crops (spring and fall), the shortest acceptable alfalfa cutting cycles, encourages geographic separation between susceptible crops, and the maximum time between whitefly host crops and cotton planting (Palumbo et al. 1999).

Management System for Cotton in the Desert Southwest USA

Worldwide, whiteflies cause serious economic damage to cotton via direct feeding that removes phytosynthates and nutrients, by the deposition of sugary excrement "honeydew" on lint (sticky and stained cotton), and by transmission of viral pathogens. Several biotypes of *B. tabaci* are major pest problems in cotton worldwide, mostly in warm desert regions (Munro 1987). Cotton grown in the desert Southwest of the United States is infested by the B biotype of *B. tabaci*, but cotton grown in Mediterranean countries and in China may also be infested with the Q biotype and other indigenous biotypes (Liu et al. 2007). More temperate cotton growing regions and those with higher rainfall do not receive as much direct feeding damage and lint contamination from *B. tabaci*, but may be susceptible to virus pathogens it transmits such as *Cotton leaf curl virus* (CLCuV) (Mansor et al. 1993). Several other whitefly species may infest cotton, especially greenhouse whitefly, *T. vaporariorum* and bandedwinged whitefly, *T. abutiloneus* (Haldeman). These usually do not cause economic damage in cotton, so correct identification is important. *B. tabaci* adults are approximately 0.8 to 1.5 mm long, yellowish, with white wings that are held somewhat vertically tilted, or roof-like, over the body, generally not meeting over the back. *T. vaporariorum* adults are similar in size and color, but hold their wings flatter over the back with no space separating the two pairs of wings when at rest. *T. abutiloneus* adults are easily distinguished from the aforementioned species, having brownish bands across the wings. Greenhouse and bandedwinged whitefly nymphs and pupae have a marginal fringe of wax filaments or long waxy rods on the dorsum of their scale-like body that is lacking in *B. tabaci*. Also the oval body of the *B. tabaci* pupa tapers down to the leaf surface rather than being ridged like the other two species. *B. tabaci* biotypes can only be reliably distinguished by molecular techniques (Gill 2007).

Integrated management of whiteflies in cotton needs to begin before planting, relying as much as possible on cultural and biological controls and later use of insecticides only when needed. Overuse of insecticides for whitefly control in cotton, and using a single class of pesticide or another class with the same mode of action, has lead to development of insecticide-resistance in *B. tabaci*, in the desert southwest of the United States and in other countries (Dennehy and Williams 1997; Castle et al. Chapter 16).

Cultural Control

Crop rotation patterns, special considerations for type and spatial arrangement of crops planted, and other cultural treatments can be used to increase host-free periods or reduce inter-crop migrations as a means to control whitefly populations (Hilje et al. 2001; Ellsworth and Martinez-Carrillo 2001). Choosing where to plant cotton is important for whitefly management. Cotton should be planted at least one-half mile upwind from other key host crops (e.g., melons, cole crops, and tomatoes), from key ornamental plants, and from key weed species that harbor populations of *B. tabaci* (Godfrey et al. 2008). Cotton should not be grown as a perennial crop which would provide overwintering sites for *B. tabaci* and for whitefly-transmitted virus pathogens such as the new world *Cotton leaf crumple virus* (CLCrV) (Dickson et al. 1954; Seo et al. 2006) and the old world CLCuV (Mansor et al. 1993). Because cotton worldwide is generally grown as an annual, *B. tabaci* must migrate to other crops, ornamental plants and weeds to overwinter. In the desert southwest of the USA, populations of *B. tabaci* that overwinter in vegetable crops, ornamental plants and weeds migrate to spring melon crops where populations begin to increase rapidly with warmer weather (Watson et al. 1992). Problems in cotton develop as populations of migratory *B. tabaci* move into the crop in late spring and early summer (Chu et al. 2005a, 2007; Ellsworth and Martinez-Carrillo 2001). Once temperatures warm up in summer, populations can build rapidly with the highest populations occurring in mid- to late-summer (Chu et al. 2001, 2007; Naranjo and Ellsworth 2009a). Naranjo et al. (Chapter 6) provide further discussion of the seasonal cycle of *B. tabaci.*

Water and fertility management play important roles as cultural tactics in whitefly management. Over use of both water and nitrogen fertilizer can greatly exacerbate damage from *B. tabaci* infestations by increasing whitefly numbers and honeydew production (Bi et al. 2001, 2005). Although *B. tabaci* developed higher populations on water-stressed cotton compared with well-watered cotton (Flint et al. 1996), individuals feeding on well-watered plants produced more honeydew and sugars per gram of honeydew (Henneberry et al. 2002).

Crop termination through cessation of irrigation and chemical defoliation are cultural tools for whitefly management. Nuessly et al. (1994) found that *B. tabaci* can continue to increase up to 6 weeks after the final cotton irrigation even following defoliation because red eye nymphs were able to continue development to the adult stage on cotton leaves that abscised and fell from the plants. In the low desert production areas of California, a final cotton irrigation on July 21 followed by defoliation on August 20, followed by sugarbeets and vegetable crops planted after September 15, provided only a one to 2 week host crop-free period. However, early cotton crop termination and defoliation, including an herbicide to prevent regrowth, helped limit additional whitefly buildup and reduced whitefly migration from cotton to other crops.

Whitefly population levels as monitored by year-round trapping decreased following the implementation of a mandatory short season cotton production program in the Imperial Valley for pink bollworm management that included cotton defoliation by September 1 (Chu et al. 2001, 2007). It was not possible to attribute yearly declines entirely to the short season cotton program, but the program was almost certainly a contributing factor. Defoliation in mid-September when approximately 95% of the crop matured and early harvest is important to avoid sticky lint in upland cotton, *Gossypium hirsutum* (Henneberry et al. 1998). Early defoliation and harvest to avoid sticky lint at harvest may not be as practical for Pima cotton, *G. barbadense*, due to its later fruiting and lack of a distinct termination of the first cotton fruiting cycle.

Host Plant Resistance

Hirsute cotton varieties are generally more susceptible than glabrous varieties (Pollard and Saunders 1956; Mound 1965; Butler and Henneberry 1984; Flint and Parks 1990; Norman and Sparks 1997; Chu et al. 1999). It has also been well documented that cotton genotypes with okra-leaf shape are generally less susceptible to *B. tabaci* colonization than genotypes with normal palmate leaf shape (Berlinger 1986; Chu et al. 2005b). The wild cotton, *G. thurberi* Todaro, has resistance to *B. tabaci* (Walker and Natwick 2006) and can be bred and manipulated to cross with *G. hirsutum* to produce more resistant cotton (Beasley 1940). Slow maturing Pima cotton is generally more susceptible than faster maturing upland cotton, although Natwick et al. (1995) also found whitefly susceptibility differences among Pima cotton varieties. Therefore, a glabrous or okra-leaf upland cotton that is determinate in its fruiting cycle provides a better fit for an area management scheme. Whitefly populations will build up more slowly, and early termination helps to avoid potentially higher *B. tabaci* infestation levels in the fall. These factors allow for a host-free period between cotton and winter vegetable crops in the Southwestern USA.

Biological Control

B. tabaci is indigenous to many cotton systems where a full suite of natural enemies would be expected to occur. Where *B. tabaci* is an introduced pest, indigenous natural enemies have adopted it as prey, and numerous exotic parasitoids and a few coccinellid predator species have often been introduced. Although biological control alone has yet to solve the whitefly problem in cotton, natural enemies can still play an important role in cotton IPM systems (Naranjo and Ellsworth 2005, 2009a). The initially depauperate parasitoid complex attacking *B. tabaci i*n the USA desert Southwest was later enriched through release of exotic species of *Eretmocerous* and *Encarsia* (Gould et al. 2008; Roltsch et al. 2008) a few of which became established. Using multiple ELISAs, Hagler and Naranjo (1994) determined that several predator species in Arizona cotton also prey on *B. tabaci* eggs and adult females, but the most common in the southwestern United States are *Geocoris* spp. and *Orius tristicolor* (Say). Other whitefly predators found in cotton include several species of lady beetles such as the convergent lady beetle, *Hippodamia convergens*, the seven-spotted lady beetle, *Coccinella septempunctata*, *Collops* spp. (Coleoptera: Melyridae), several lacewing species, and an empidid fly, *Drapetis* nr. *divergens*, which is a voracious predator of adult whiteflies (Hagler 2002; Hagler and Naranjo 2005). Use of insecticides is a limiting factor in establishment of effective biological control in cotton (Gerling and Naranjo 1998); however, use of selective insecticides such as the IGRs early in the cotton season can minimize the risk of destroying whitefly natural enemies (Naranjo et al. 2004) and allowing them to contribute significantly to pest control (Naranjo and Ellsworth 2009b). IGRs allow increased benefit to cotton growers and the environment while also reducing the risk of insecticide-resistance by decreasing the number of insecticide treatments needed for whitefly control.

Monitoring and Treatment Decisions

Whitefly control with foliar insecticides in cotton and other crops is complicated by two factors: (1) adults and nymphs are found mostly on the abaxial leaf surface, often escaping contact with spray droplets, and (2) *B. tabaci* has developed resistance to many insecticides. Whiteflies need to be monitored on abaxial surfaces of leaves from early squaring to harvest. Prior to registration of IGRs for whitefly control, only adults were monitored for treatment decisions in cotton. Later, nymphal action thresholds were also established (Naranjo and Flint 1994; Ellsworth and Martinez-Carrillo 2001; Naranjo and Ellsworth 2009a). When whiteflies are first found in sweep samples, sampling via leaf-turn method (Naranjo and Flint 1995; Ellsworth et al. 1995) should begin and continue through crop termination. All parts of the cotton field should be checked; however, field margins should be checked for whitefly adults as often as twice weekly during critical periods, especially early in the season when populations can build up as nearby host crops are being harvested or are senescing. Action thresholds as high as ten and as low as three adults per cotton leaf, sampling the fifth main stem leaf from the top, have been published (Naranjo et al. 1996; Naranjo et al. 1998). Chu and Henneberry (1999) found that initiating chemical control at four adults per leaf-turn produced higher lint yields and less sticky lint compared to initiating chemical control at 15 adults per leaf-turn. The relationship between pest density and yield for cotton is fairly straight forward. However, the relationship between stickiness and treatment thresholds is not consistent due to the onset and duration of the whitefly infestation, relative humidity, and possible occurrence of rainfall during the period cotton bolls are open; all factors that contribute to the level of stickiness (Naranjo et al. 1998).

Nymphs must be present to justify treatment with IGRs. Whitefly nymphs can be monitored on the abaxial leaf surface by placing a ca. 2.5 cm ring between the central and left-side main veins and checking for presence or absence of large nymphs. A leaf is scored as infested if any third and fourth instar nymphs are present within the ring, and the action threshold is 40% infested leaves (Ellsworth and Martinez-Carrillo 2001). Although five adults per cotton leaf is the generally accepted action threshold for conventional insecticidal control of *B. tabaci* in Arizona and Southern California, Naranjo et al. (2002) suggested that predator conservation may be enhanced by raising the initial threshold to delay the first application or initially using more selective materials such as IGRs (Naranjo et al. 2004).

Early season treatment for *B. tabaci* nymphs with selective insecticides such as IGRs (buprofezin and pyriproxyfen), and lipid synthesis inhibitors such as spiromesifen, minimizes impact of insecticidal control on whitefly parasitoids and predators (Naranjo et al. 2004; Ellsworth et al. 2006). Long-term pest suppression afforded by use of selective insecticides such as the IGRs is a combination of several weeks of chemical residual control and many additional weeks of control from conserved natural enemies. This effect has been coined the bioresidual and it is the mechanism allowing long-term pest control (Naranjo and Ellsworth 2009a, b). Limiting IGRs with the same mode of action to no more than one application per season is the strategy being employed to reduce the rate of selection for resistance to these materials. Classification of insecticides by mode of action is available from the Insect Resistance Action Committee (IRAC) http://www.irac-online.org/. This strategy was adopted from the Israeli system originally suggested by Horowitz et al. (1994). Foliar applied neonicotinoid insecticides such as acetamiprid are also effective against *B. tabaci*, but are more disruptive to predators and parasitoids of whiteflies and other cotton pests (Naranjo and Akey 2005). Furthermore, neonicotinoids in general might better be saved for use as drenches in vegetable crops where they are most effective. A cross-commodity insecticide resistance plan has been developed for the low desert production areas of the southwestern USA which takes into account differing crop mixtures and classes of chemistry to try and preserve insecticidal efficacy in cotton and many other crops grown in the area (Palumbo et al. 2001, 2003). Deferring broad spectrum insecticides until later in the season is a way to preserve and build populations of natural enemies of whitefly and secondary pests that might otherwise be released from their natural enemies.

A quick knockdown of adults obtained with tank mixes of pyrethroids such as bifenthrin or fenpropathrin in combination with endosulfan or an organophosphate is sometimes required to protect open bolls from contamination with honeydew caused by a massive influx of whitefly adults from other cotton fields (Natwick 1993; Chu et al. 1998). Henneberry et al. (1998) found that timing of defoliation in relation to the last insecticide application or detectable increase in population of *B. tabaci* can be an important tool to manage the cotton crop to avoid sticky lint. Extending the cotton season may increase yield, but lower profit to the grower due to sticky lint.

Management in Alfalfa in the Desert Southwest USA

The B biotype of *B. tabaci* first became an economically important pest of alfalfa in California and Arizona during the summer of 1991 (Natwick and Robinson 1993). *B. tabaci* can cause economic damage to alfalfa in the low desert regions of Southern California and Arizona from July through September. This perennial crop serves as a transitional host between crop harvests of melons, cole crops, lettuce and cotton (Yee et al. 1997). Palumbo et al. (2000) demonstrated the nature of the damage to alfalfa: reduced growth rate, diminished forage yield, and contamination of hay with honeydew causing harvest and bailing problems. *B. tabaci* also reduces hay quality by removal of plant assimilates and contamination of hay with sooty molds that grow on honeydew. Most of the damage, however, is restricted to two forage harvest periods during the summer coinciding with peak adult populations and dispersal from alternate hosts (Yee et al. 1997). Definitive monitoring and treatment guidelines have not been developed for whitefly control in alfalfa, and no insecticides are registered for whitefly control in this crop, nor would they be cost-effective due to relatively low profit margins for alfalfa hay. Large acreages of alfalfa grown for forage in Arizona and California preclude an area-wide management approach that incorporates cultural practices such as strip-cutting, summer fallowing or shortened harvest cycles. The economic infeasibility of treating with insecticides coupled with the impracticality of cultural practices over such large areas has focused attention on host plant resistance to *B. tabaci* (Palumbo et al. 2000). Breeding efforts by Teuber et al. (1997) lead to the release of a whitefly-resistant alfalfa cultivar (UC-Impalo-WF), and continuing research by Jaing et al. (2003) may lead to the release of improved whitefly-resistant alfalfa cultivars.

Vegetables in the USA Desert Southwest and Elsewhere

Fall vegetable and melon plantings as well as sugar beets were decimated during the 1980s in the Southwest USA by *Lettuce infectious yellows virus* (LIYV) transmitted by *B. tabaci*, later designated “biotype A” (Duffus et al. 1986). Biotype B, first detected in Florida in 1986, eventually displaced biotype A, bringing even greater infestation levels of *B. tabaci*, but an abatement of LIYV due to lower vector efficiency in transmitting the virus (Cohen et al. 1992). When cotton crops were terminated, huge cloud of whiteflies were observed moving directly into newly planted vegetable and melon crops (Blua et al. 1994; Nuessly et al. 1994). To break this cycle, a combination of early termination of cotton and delayed planting of vegetable and melon crops was recommended to reduce the overall impact of whitefly populations and virus incidence on fall plantings of vegetables.

Whiteflies first appeared as a problem in Florida fruiting vegetables in 1987 with the advent of *B. tabaci* biotype B. Appearing first in poinsettia and termed the poinsettia strain, biotype B attacked plants never before seen as whitefly hosts in Florida, including tomato, eggplant, potato, and various cucurbits, causing the silverleaf symptom in squash, a disorder not previously attributed to whiteflies (Maynard and Cantliffe 1990; Yokomi et al. 1990; Schuster et al. 1996). Irregular ripening soon followed and millions of dollars worth of tomatoes were dumped, often at their market destination. The begomovirus *Tomato mottle virus* (ToMoV) appeared in 1989 and TYLCV in 1994. However, use of imidacloprid drenches began the same year and whitefly related problems abated for several years (Stansly 1996).

Soil applied imidacloprid and other neonicotinoids are still key insecticides for protecting open field vegetables and other crops in the USA and elsewhere. Soil drenches are often followed by regular foliar applications of various insecticides, including IGRs. Use of neonicotinoids is increasing due to several factors: (1) patent expiration on imidacloprid and the ensuing decrease in cost, (2) availability of additional neonicotinoids that further depress prices or are more effective as foliar sprays, and (3) appearance of new virus diseases such as SqVYV in watermelon and *Cucurbit leaf crumple virus* (CuLCV) that motivate use on these crops.

Increased use of neonicotinoids has placed the burden on users to adopt science-based plans for sustaining their efficacy and sharing their use among different agricultural interests. Through identification of crop communities (i.e., "multi-crop", "cotton-intensive", and "cotton/melon") common to agriculture to the southwest desert region, plans for use of neonicotinoids and other chemistries have been developed that should allow more effective use, while helping to avoid resistance (Palumbo et al. 2001, 2003). Therefore, whitefly management on cole crops and lettuce in the desert agricultural valleys of Arizona and southeastern California depends on avoidance of *B. tabaci* sources such as cotton and melon crops in addition to use of neonicotinoid insecticides at planting.

To this same end, neonicotinoid insecticides are recommended for use only during the first 6 weeks of the crop cycle in the Florida fruiting vegetable system, regardless of whether the application is foliar or soil drench at planting (Schuster et al. 2007). The objective is to relax selection for resistance against neonicotinoids during the latter part of the crop cycle. Selective versus broad-spectrum insecticides are recommended for the next third of the crop cycle to conserve natural enemies. Cultural recommendations that apply anywhere whitefly-borne viruses are an issue include rapid crop destruction and establishment of a minimum 2 month crop-free period during the summer, practices to assure production of virus and whitefly free transplants, and use of TYLCV resistant tomato and pepper cultivars. Pepper is included because some cultivars have been shown to be non-symptomatic hosts of TYLCV (Polston et al. 2006). Also recommended are ultraviolet light reflective ("aluminized") mulches and living mulches that have been shown to protect crops from whiteflies and other visually orienting pests early in the crop cycle (Csizinszky et al. 1999; Hilje et al. 2001; Stapleton and Summers 2002; Hilje and Stansly 2008; Nyoike et al. 2008; see Antignus Chapter 13). All these practices are aimed at reducing the whitefly population and therefore the need for insecticidal control in the crop.

Action Thresholds for Whiteflies in Open-Field Vegetables

Economic thresholds are difficult to establish in high value crops for the reasons mentioned above. Economic injury levels of four nymphs per leaf and one adult per 3 × 45 cm beat tray were obtained in a study of open field tomato in Brazil (Gusmao et al. 2006). However, the study was conducted in processing tomatoes valued at only $US181.78 per ton. This economic injury level would scale down in proportion to the increased value of tomato crops destined for the fresh market.

An economic injury level of 18 adult *B. tabaci* per cucumber plant in the four-leaf stage was determined for China (Chen et al. 2005). This threshold would relate to market and environmental conditions in China when study was done, and also would have to be revised if CYSDV were to appear as it has in American desert southwest cucurbit production areas. Such a threshold would have to take into account the damage potential of the virus disease which typically is greatest when the crop is young and decreases subsequently (Schuster et al. 1996). Moreover, the threshold would have to be based, not only on number whiteflies per sample unit, but also the proportion carrying virus and capable of transmitting the disease. No such thresholds have been proposed to our knowledge.

By resorting to an "action" rather than economic threshold, consideration of unstable or difficult to estimate parameters inherent in the economic injury level, such as crop value and cost of control can be avoided. It may be sufficient to show a minimum level infestation associated with significant loss of crop yield or quality. Action thresholds also depend on efficacy of the control tactic. Therefore, the action threshold of one whitefly nymph per two leaflets to prevent irregular ripening of tomato with IGRs was established by comparison with an imidacloprid-treated standard (Schuster 2002).

Action thresholds can vary greatly, presumably due to different experimental conditions. Action thresholds for melon of one large nymph per 15 cm^2 of leaf area or one adult per leaf in Texas and three adults per leaf in Arizona have also been established (Riley and Palumbo 1995). Later, Nava-Camberos et al. (2001) revised these based on number of insecticide treatments to range from 0.02 to 3.92 adults/leaf, or from 0.2 to 54.4 nymphs/6.5 cm^2 leaf surface! We were unable to find any other action or economic thresholds for *B. tabaci* on vegetables in the literature. Clearly this basic IPM concept is still underutilized in vegetable IPM for the many reasons mentioned.

Role of Biological Control and Adaptation of Augmentative Control Practices

The lack of usable thresholds and the reliance on broad-spectrum insecticidal control of *B. tabaci* in most vegetable crops seem to leave little room for biological control. Still, there clearly exists an important role for natural enemies in reducing populations outside the crop or in crops not treated with broad-spectrum insecticides. For example, Stansly et al. (1997) and Brewster et al. (1997) observed apparent parasitism levels of 80% or more on organically grown eggplant and tomato in southwest Florida. Combined levels of predation and parasitism on weeds around tomato fields in west-central Florida averaged from 40 to 90% (Schuster et al. 1998). As a result of this mortality, as well as the fact that crop resources are not present to support population growth, whitefly populations fall precipitously during fallow periods in southwest Florida (Stansly 1996). This is the basis for recommending the crop free period as a critical component of whitefly management (Hilje et al. 2001).

Just as in protected horticulture, the presence of whitefly-transmitted viruses in field grown crops reduces the threshold for whitefly infestation to an undetermined level, presumably below what can be reasonably achieved by conservation or augmentative biological control (Dik and Albajes 1999). Other impediments to establishing biologically based management systems in fruiting vegetable production are dependence on insecticides and negative expectations regarding effectiveness of biological control (Stansly et al. 2004a, b). Presently, vector-borne disease in south Florida is primarily a problem in tomato (TYLCV) and watermelon (SqVYV). Additionally, biological control of whiteflies in tomato is a special challenge requiring a suite of natural enemies, some of which, e.g. the mirid predators, are poorly adapted to other crops (Urbaneja et al. 2005). Nevertheless, recent success with augmentative biological control in crops not affected by whitefly-borne virus disease has demonstrated good potential for this approach (Van der Blom 2007).

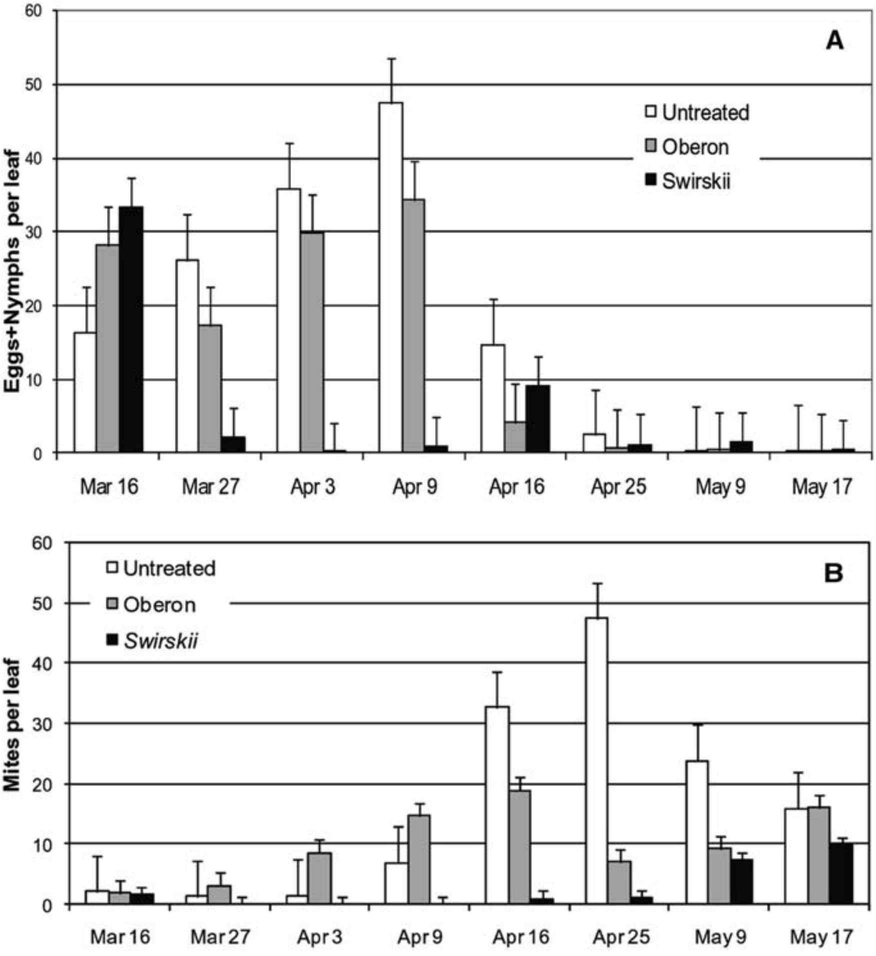

Fig. 17.2 Numbers of adult and immature whitefly per leaf (**A**) and of broad mites (**B**, all stages) on small plots of eggplant in southwest Florida in spring 2007. *A. swirskii* released 16 March and spiromesifen (Oberon 2SC) applied twice as a foliar spray at 1.3 L/ha one and 2 weeks later (Stansly and Castillo 2009)

Preliminary results in Florida have shown that, although eggplant growers spend an estimated $1,520/ha on insecticides, the principal pests of eggplant in Florida (mites, whiteflies and thrips) can all be controlled biologically with predaceous mites at comparable or even reduced cost (Stansly and Castillo 2009). We evaluated *A. swirski* on eggplant in experimental plots and on a commercial farm in southwest Florida. In one experiment, *A. swirskii* provided better control of both *B. tabaci* and *Polyphagotarsonemus latus* than the widely used insecticide/acaracide spiromesifen (Oberon®) (Fig. 17.2). Eggplant receiving *A. swirskii* yielded significantly more fruit at first harvest than untreated plants or even eggplants receiving two acaricide sprays (data not shown). However, as plants grew older, they became heavily infested with spider mites (*Tetranichus urticae*). Subsequent experiments demonstrated that all three pests could be controlled with mixtures of *A. swirskii* and *Neoseulus* = *Amblyseius californicus* (Stansly and Castillo, 2009).

Although a relatively minor crop, working systems in eggplant may set the stage for acceptance of biological control in other crops including cucumber and pepper. Pepper and eggplant share a number of pests such as broad mite and western flower thrips. Pepper is also attacked by beet armyworm, *Spodoptera exigua* (Hübner), although this pest can be controlled by selective insecticides that are relatively compatible with whitefly natural enemies. Unfortunately, broad spectrum insecticides used to control for pepper weevil, *Anthonomus eugenii* Cano, are incompatible with predaceous mites and minute pirate bugs that otherwise frequently colonize pepper. However, pepper weevil infestation can be minimized by cultural practices such as field sanitation, summer fallows, and control of back nightshade, its main alternate host. Pests of cucurbits such as whiteflies and spider mites can also be managed by predaceous mites and lepidopteron pests by compatible insecticides. Thus, the door is open to implement biological control in a number of key fruiting vegetable crops in areas such as south Florida.

Conclusions

Integrated, biologically-based management of *B. tabaci* has become a reality in some greenhouse grown vegetables not affected by whitefly vectored virus. This is particularly true in Spain and elsewhere where *A. swirskii* has played a major role in controlling *B. tabaci* in pepper. In contrast, biological control of *B. tabaci* remains a challenge in some other crops, especially tomato, to which mite predators are poorly adapted and in which whitefly-borne virus is a major threat. However, more acceptable virus resistant varieties coupled with improvements in insect exclusion technology should open the door to greater use of available natural enemies such as *Eretmocerus* spp. and the mirid predators that have demonstrated good potential to control *B. tabaci* in greenhouse grown tomato.

In contrast, augmentative biological control has made few inroads in open field crops where insecticidal control is still the norm and augmentation is seen as too costly, unreliable or difficult to implement. Fallow periods free of crop hosts of

B. tabaci and it's vectored viruses have been the basis for successful management in Florida, the Dominican Republic and Israel in recent times, and in cotton and tobacco production in Africa as far back as the 1930s. With the advent of effective control with neonicotinoids and insect growth regulators, area wide management of insecticide use and modification of cropping patterns has been key to maintaining the viability of open field vegetable and cotton production in the face of the continual threat of insecticide resistance. Few efforts at augmentative biological control have been reported from these agroecosystems, although indigenous natural enemies often play an important role in the crop as well as by in reducing pest populations in unsprayed weeds and during fallow periods. Recent advances in implementation of augmentative biological control using predaceous mites in field grown vegetable crops such as eggplant and pepper, and successful integrated control program for cotton in Arizona where native predators contribute significant control, may point the way to more biologically based management strategies in agronomic crops such as alfalfa, soybean and cotton, especially where whitefly-borne virus disease is not a major issue. The challenge in any crop is to integrate management strategies for all potentially damaging pests and diseases into an economically and environmentally viable system. Whitefly control may only be one of many components in such systems, although it is often a key component. Future success will depend on continued advances in application of basic biology and ecology to practical pest management solutions.

Literature Cited

Alomar O, Albajes R. 1996. Greenhouse whitefly (Homoptera: Aleyrodidae) predation and tomato fruit injury by the zoophytophagous predator Dicyphus tamaninii (Heteroptera: Miridae). In *Zoophytophagous Heteroptera: Implications for Life History and Integrated Pest Management*, ed. O Alomar, R Wiedanmann, pp. 155–177. *Proceedings*, Lanham: Thomas Say Publications in Entomology. E.S.A.

Alvarez AJ, Valera DL, Molina-Aiz FD. 2006. A method for the analysis of the geometric characteristics of protection screens. *Acta Hort. (ISHS)* 719:557–564. http://www.actahort.org/books/719/719_65.htm

Ardeh MJ, de Jong PW, van Lenteren JC. 2005. Intra- and interspecific host discrimination in arrhenotokous and thelytokous *Eretmocerus* spp. *Biol. Control* 33:74–80.

Baker GA, Burnham TA. 2001. Consumer response to genetically modified foods: market segment analysis and implications for producers and policy makers. *J. Agric. Resour. Econ.* 26:387–403.

Beachy RN. 1997. Mechanisms and applications of pathogen-derived resistance in transgenic plants. *Curr. Opin. Biotechnol.* 8:215–220.

Belda J, Calvo J. 2006. Eficacia de *Amblyseius swirskii* (Acarii: Phytoseiidae) en el control biológico de *Bemisia tabaci* (Genn.) (Hom. Alerodidae) y *Frankliniella occidentalis* (Pergande) (Thys: Thripidae) en pimiento en condiciones de semi-campo. *Bol. San. Veg. Plagas* 32:283–296.

Bell ML, Baker JR. 2000. Comparison of greenhouse screening materials for excluding whitefly (Homoptera: Aleyrodidae) and thrips (Thysanoptera: Thripidae). *J. Econ. Entomol.* 93:800–804.

Beasley JO. 1940. The origin of American tetraploid *Gossypium* species. *Am. Nat.* 74:285–286.

Berlinger MJ. 1986. Host plant resistance to *Bemisia tabaci*. *Agric. Ecosyst. Environ.* 17:69–82.

Bethke JA, Paine TD. 1991. Screen hole size and barriers for exclusion of insect pests of glasshouse crops. *J. Entomol. Sci.* 26:169–177.

Bi JL, Ballmer GR, Hendrix DL, Hennneberry TJ, Toscano NC. 2001. Effect of cotton nitrogen fertilization on *Bemisia argentifolii* populations and honeydew production. *Entomol. Exp. Appl.* 99:25–36.

Bi JL, Lin DM, Lii KS, Toscano NC. 2005. Impact of cotton planting date and nitrogen fertilization on *Bemisia argentifolii* populations. *Insect Sci.* 12:31–36.

Blua MJ, Perring TM, Nuessly GS, Duffus JE, Toscano NC. 1994. Seasonal cropping pattern effects on abundance of *Bemisia tabaci* (Homoptera: Aleyrodidae) and incidence of lettuce infectious yellows virus. *Environ. Entomol.* 23:1422–1427.

Bolckmans JKF. 1999. Commercial aspects of biological pest control in greenhouses. In *Integrated Pest and Disease Management in Greenhouse Crops*, ed. R Albajes, M Lodovica Gullino, JC van Lenteren, Y Elad, pp. 310–318. Dordrecht, Netherlands: Kluwer Academic Publishers.

Bosclair J, Brueren GJ, van Lenteren JC. 1990. Can *Bemisia tabaci* be controlled with *Encarsia formosa*? *SROP/WPRS Bull.* 5:32–35.

Brewster CC, Allen JC, Schuster DJ, Stansly PA. 1997. Simulating the dynamics of *Bemisia argentifolii* (Homoptera: Aleyrodidae) in an organic cropping system with a spaciotemporal model. *Environ. Entomol.* 26:203–216.

Butler GD, Jr, Henneberry TJ. 1984. *Bemisia tabaci*: effect of cotton leaf pubescence on abundance. *Southwest. Entomol.* 9:91–94.

Cabrera FJ, Lopez JC, Baeza EJ, Pérez-Parra JJ. 2006. Efficiency of anti-insect screens placed in the vents of Almería greenhouses. *Acta Hort. (ISHS)* 719:605–614. http://www.actahort.org/books/719/719_70.htm

Calvo J, Bolckmans K, Belda JE. 2008a. Controlling the tobacco whitefly *Bemisia tabaci* (Genn.) (Hom.: Aleyrodidae) in horticultural crops with the predatory mite *Amblyseius swirskii* (Athias-Henriot). In *4th International Bemisia Workshop International Whitefly Genomics Workshop*, ed. PA Stansly, CL McKenzie, p. 53. *J. Insect Sci*. 8:4. www.insectscience.org/8.04

Calvo J, Bolckmans K, Stansly PA, Urbaneja A. 2008b. Predation by *Nesidiocoris tenuis* on *Bemisia tabaci* and injury to tomato. *Biocontrol* 54:237–246.

Chen BB, Ren SX, Musa PH, Chen C. 2005. A study on economic threshold of *Bemisia tabaci*. *Acta Agric. Univ. Jiangxiensis* 27:234–237. (in Chinese)

Chu CC, Natwick ET, Henneberry TJ, Lee R. 1998. Effects of pyrethroid insecticides alone and in mixtures on *Bemisia argentifolii* (Homoptera: Aleyrodidae) and cotton, cauliflower, and broccoli yields. *J. Agric. Assn. China* 184:57–66.

Chu CC, Henneberry TJ. 1999. *Bemisia argentifolii*: action thresholds, upland cotton yields and cotton lint stickiness in the Imperial Valley, California. *Southwest. Entomol.* 24:79–86.

Chu CC, Cohen AC, Natwick ET, Simmons GS, Henneberry TJ. 1999. *Bemisia tabaci* (Hemiptera: Aleyrodidae) biotype B colonization and leaf morphology relationships in upland cotton. *Aust. J. Entomol.* 38:127–131.

Chu CC, Henneberry TJ, Natwick ET, Ritter D, Birdsall SL. 2001. Efficacy of CC traps and seasonal activity of adult *Bemisia argentifolii* (Homoptera: Aleyrodidae) in Imperial and Palo Verde Valleys, California. *J. Econ. Entomol.* 94:47–54.

Chu CC, Barnes E, Natwick ET, Chen TY, Henneberry TJ. 2005a. *Bemisia tabaci* population dynamics in the Imperial Valley, California, 1996 to 2002. *Egypt. J. Agric. Res.* 83:89–95.

Chu CC, Natwick ET, Henneberry TJ. 2005b. Okra- and normal-leaf upland cotton *Bemisia tabaci* (Homoptera: Aleyrodidae) colonization, 1996–2002. *Egypt. J. Agric. Res.* 83:109–117.

Chu CC, Barnes E, Natwick ET, Chen TY, Ritter D, Henneberry TJ. 2007. Trap catches of sweetpotato whitefly (Homoptera: Aleyrodidae) in the Imperial Valley, California, from 1996 to 2002. *Insect Sci.* 14:165–170.

Cohen S, Duffus JE, Liu HY. 1992. A new *Bemisia tabaci* biotype in the southwestern United States and its role in silverleaf of squash and transmission of lettuce infectious yellows virus. *Phytopathology* 82:86–90.

Cook CG, Scott AW, Jr. 1995. Registration of C21S781-2 cotton germplasm. *Crop Sci.* 35:598.

Csizinszky AA, Schuster DJ, Polston JE. 1999. Effects of ultraviolet-reflective mulches on tomato yields and on the silverleaf whitefly. *HortScience* 34:911–914.

De Barro PJ, Coombs MT. 2008. Post-release evaluation of *Eretmocerus hayati* Zolnerowich Rose in Australia. *Bull. Entomol. Res.* 24:1–14.

Dennehy TJ, Williams L. 1997. Management of resistance in *Bemisia* in Arizona cotton. *Pestic. Sci.* 51:398–406.

Dimitri C, Oberholtzer L. 2005. Market-led versus government-facilitated growth development of the U.S. and EU organic agricultural sectors. USDA-ARS WRS 0505. http://www.ers.usda.gov/publications/WRS0505/wrs0505.pdf

Dik AJ, Albajes R. 1999. Principals of epidemiology, population biology, damage relationships, and integrated control of diseases and pests. In *Integrated Pest and Disease Management in Greenhouse Crops*, ed. R Albajes, M Lodovica-Gullino, JC van Lenteren, Y Elad, pp. 69–81. Amsterdam, The Netherlands: Springer.

Dickson RC, Johnson MM, Laird EF. 1954. Leaf crumple, a virus disease of cotton. *Phytopathology* 44:479–480.

Duffus JE, Larsen RC, Liu HY. 1986. Lettuce infectious yellows virus – a new type of whitefly-transmitted virus. *Phytopathology* 76:97–100.

Ellsworth PC, Diehl JW, Dennehy TJ, Naranjo SE. 1995 (Rev. 11/2000). Sampling sweet-potato whiteflies in cotton. *IPM Series No. 2. Publ. No. 194023*. University of Arizona, College of Agriculture and Life Sciences, Cooperative Extension, Tucson, Arizona. http://cals.arizona.edu/crops/cotton/insects/wf/wfsampl.html

Ellsworth PC, Martinez-Carrillo JL. 2001. IPM for *Bemisia tabaci*: a case study from North America. *Crop Prot.* 20:853–869.

Ellsworth PC, Palumbo JC, Naranjo SE, Dennehy TJ, Nichols RL. 2006. Whitefly management in Arizona cotton 2006. Cooperative Extension, IPM Series No. 18. The University of Arizona, Tucson, http://Cals.Arizona.Edu/Pubs/Insects/Az1404.Pdf

Enkegaard A. 1993. *Encarsia formosa* parasitizing the Poinsettia strain of the cotton whitefly, *Bemisia tabaci*, on Poinsettia: bionomics in relation to temperature. *Entomol. Exp. Appl.* 69:251–261.

Faria M, Wraight SP. 2001. Biological control of *Bemisia tabaci* with fungi. *Crop Prot.* 20:767–778.

Flint HM, Naranjo SE, Leggett JE, Henneberry TJ. 1996. Cotton water stress, arthropod dynamics, and management of *Bemisia tabaci* (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 89:1288–1300.

Flint HM, Parks NJ. 1990. Infestation of germplasm lines and cultivars of cotton in Arizona USA by whitefly nymphs (Homoptera: Aleyrodidae). *J. Entomol. Sci.* 25:223–229.

Gerling D, Naranjo SE. 1998. The effect of insecticide treatments in cotton fields on the levels of parasitism of *Bemisia tabaci*. *Biol. Control* 12:33–41.

Gerling D, Alomar O, Arnó J. 2001. Biological control of *Bemisia tabaci* using predators and parasitoids. *Crop Prot.* 20:779–799.

Gilbertson RL. 2007. Introduction of *Cucurbit yellow stunting disorder virus* (CYSDV) into the Imperial Valley (and Yuma, Arizona): assessment of the threat to melon production and disease management. In *California Melon Research Board 2007 Annual Report*, pp. 23–30.

Gill RJ. 2007. Can molecules solve the *Bemisia* conundrum when morphology cannot? A taxonomist's perspective. In *4th International Bemisia Workshop International Whitefly Genomics Workshop*, 2008, ed. PA Stansly, CL McKenzie. *J. Insect Sci*. 8:4.

Godfrey LD, Goodell PB, Natwick ET, Haviland DR. 2008. Insects and mites. In *UC IPM Pest Management Guidelines: Cotton*. UC ANR Publication 3444. http://www.ipm.ucdavis.edu/PMG/r114300311.html

Goettel MS, Hajek AE, Siegel JP, Evans HC. 2001. Safety of fungal biocontrol agents. In *Fungi as Biocontrol Agents: Progress, Problems and Potential*, ed. TM Butt, CW Jackson, N Magan, pp. 347–376. Wallingford, UK: CABI.

Gould J, Waldner D, Colletto N, Merten P. 2008. Release and recovery of four species of *Eretmocerus* against *Bemisia tabaci* biotype B in Arizona. In *Classical Biological Control of*

Bemisia tabaci in the United States – A Review of Interagency Research and Implementation, ed. J Gould, KA Hoelmer, JA Goolsby, Vol. 4, pp. 191–204. Amsterdam, the Netherlands: Springer.

Greenberg SM, Jones WA, Liu TX. 2002. Interactions among two species of *Eretmocerus* (Hymenoptera: Aphelinidae), two species of whiteflies (Homoptera: Aleyrodidae), and tomato. *Environ. Entomol.* 31:397–402.

Gusmao MR, Picanco MC, Guedes RNC, Galvan TL, Pereira EJG. 2006. Economic injury level and sequential sampling plan for *Bemisia tabaci* in outdoor tomato. *J. Appl. Entomol.* 130:160–166.

Hagler JR, Naranjo SE. 1994. Determining the frequency of heteropteran predation on sweetpotato whitefly and pink bollworm using multiple ELISAs. *Entomol. Exp. Appl.* 72:59–66.

Hagler JR. 2002. Foraging behavior, host stage selection and gut content analysis of field collected *Drapetis* nr. *divergens*: a predatory fly of *Bemisia argentifolii*. *Southwest. Entomol.* 27: 241–249.

Hagler JR, Naranjo SE. 2005. Use of a gut content ELISA to detect whitefly predator feeding activity after field exposure to different insecticide treatments. *Biocontrol Sci. Technol.* 15: 321–339.

Hanafi A, Bouharroud R, Amouat S, Miftah S. 2007. Efficiency of insect nets in excluding whiteflies and their impact on some natural biological control agents. *Acta Hort. (ISHS)* 747:383–388. http://www.actahort.org/books/747/747_47.htm

Harmanto HJ, Tantau SVM. 2006. Influence of insect screens with different mesh sizes on ventilation rate and microclimate of greenhouses in the humid tropics. *Agricultural Engineering International: The CIGR Ejournal*. Manuscript BC 05 017. Vol. VIII, http://www.cigrjournal.org/index.php/Ejounral

Henneberry TJ, Jech LF, Hendrix DL. 1998. Seasonal distribution of *Bemisia argentifolii* (Homoptera: Aleyrodidae) honeydew sugars and Pima and Upland cotton lint and lint stickiness at harvest. *Southwest. Entomol.* 23:105–121.

Henneberry TJ, Jech LJ, De La Torre TM. 2002. Effects of cotton plant water stress on *Bemisia tabaci* strain B (Homoptera: Aleyrodidae) honeydew production. *Southwest. Entomol.* 27: 117–133.

Hilje L, Costa HS, Stansly PA. 2001. Cultural practices for managing *Bemisa tabaci* and associated viral diseases. In *Challenges and Opportunities for Pest Management of Bemisia tabaci in the New Century*, ed. S Naranjo, P Ellsworth. *Crop Prot*. 20(9):801–812.

Hilje L, Stansly PA. 2008. Living mulch ground covers for management of *Bemisia tabaci* (Gennadius) (Homoptera: Aleyrodidae) and *Tomato yellow mottle virus* (ToYMoV) in Costa Rica. *Crop Prot.* 27:10–16.

Hoddle MS, van Driesche RG, Elkinton JS, Sanderson JP. 1998. Discovery and utilization of *Bemisia argentifolii* patches by *Eretmocerus eremicus* and *Encarsia formosa* (Beltsville strain) in greenhouses. *Entomol. Exp. Appl.* 87:15–28.

Hoddle MS. 2004. Biological control of whiteflies on ornamental crops. In *Biocontrol in Protected Culture*, ed. K Heinz, RG Van Driesche, MP Parrella, pp. 149–170. Batavia, IL, USA: Ball Publishing.

Hoogerbrugge H, Calvo J, van Houten Y, Bolckmans K. 2007. Biological control of the tobacco whitefly *Bemisia tabaci* with the predatory mite *Amblyseius swirskii* in sweet pepper crops. *IOBC/WPRS Bull.* 28:119–122.

Horowitz AR, Forer G, Ishaaya I. 1994. Managing resistance in *Bemisia tabaci* in Israel with emphasis on cotton. *Pestic. Sci.* 42:113–122.

Howard RJ, Garland JA, Seaman WL. 1994. *Diseases and Pests of Vegetable Crops in Canada, An Illustrated Compendium*, 554pp. Ottawa: The Canadian Phytopathological Society and The Entomological Society of Canada.

Hu JS, Gelman DB, Blackburn MB. 2002. Growth and development of *Encarsia formosa* (Hymenoptera: Aphelinidae) in the greenhouse whitefly, *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae): effect of host age. *Arch. Insect Biochem. Physiol.* 49:125–136.

Hu JS, Gelman DB, Blackburn MB. 2003. Age-specific interaction between the parasitoid, *Encarsia formosa* and its host, the silverleaf whitefly, *Bemisia tabaci* (Strain B). *J. Insect Sci.* 3:28.

Inglis GD, Goettel MS, Butt TM, Strasser H. 2001. Use of hyphomycetous fungi for managing insect pests. In *Fungi as Biocontrol Agents. Progress, Problems and Potential*, ed. TM Butt, CW Jackson, N Magan, pp. 1–8. Wallingford: CABI.

Jaing YX, Zareh N, Walker GP, Teuber LR. 2003. Characterization of alfalfa germplasm expressing resistance to silverleaf whitefly, *Bemisia argentifolii*. *J. Appl. Entomol.* 127:447–457.

Jaing YX, Walker GP. 2007. Identification of phloem sieve elements as the site of resistance to silverleaf whitefly in resistant alfalfa genotypes. *Entomol. Exp. Appl.* 125:307–320.

Jervis MA, Heimpel GE, Ferns PN, Harvey JA, Kidd NAC. 2001. Life-history strategies in parasitoid wasps: a comparative analysis of ‘ovigeny’. *J. Anim. Ecol.* 70:442–458.

Ji YF, Scott JW, Hanson P, Graham E, Maxwell DP. 2007. Sources of resistance, inheritance, and location of genetic loci conferring resistance to members of the tomato-infecting begomoviruses. In *Tomato Yellow Leaf Curl Virus Disease Management, Molecular Biology, Breeding for Resistance*, ed. H Czosnek, pp. 343–362. Amsterdam, The Netherlands: Springer.

Jones DR. 2003. Plant viruses transmitted by whiteflies. *Eur. J. Plant Path.* 109:195–219.

Liu SS, De Barro PJ, Xu J, Luan JB, Zang LS, Ruan YM, Wan FH. 2007. Asymmetric mating interactions drive widespread invasion and displacement in a whitefly. *Science* 318:1769–1772.

Mansor S, Bedford I, Pinner MS, Stanley J, Markham PG. 1993. A whitefly transmitted geminivirus associated with cotton leaf curl diseases in Pakistan. *Pakistan J. Bot.* 25:105–107.

Maynard DN, Cantliffe DJ. 1990. Squash silverleaf and tomato ripening: new vegetable disorders in Florida. *Vegetable Crops Fact Sheet* VC-37, IFAS, University of Florida.

McGregor RR, Gillespie DR, Park CG, Quiring DMJ, Foisy MRJ. 2000. Leaves or fruit? The potential for damage to tomato fruits by the omnivorous predator, *Dicyphus hesperus Entomol. Exp. Appl.* 95:325–328.

Messelink G, van Steenpaal S, van Wensveen W. 2005. *Typhlodromips swirskii* (Athias-Henriot) (Acari: Phytoseiidae): a new predator for thrips control in greenhouse cucumber. *IOBC/WPRS Bull.* 28:183–186.

Messelink GJ, Maanen RV, van Steenpaal SEF, Janssen A. 2008. Biological control of thrips and whiteflies by a shared predator: two pests are better than one. *Biol. Control* 44:372–379.

Mound LA. 1965. Effect of leaf hair on cotton whitefly populations in the Sudan Gezira. *Empire Cotton Growing Rev.* 42:33–40.

Munro JM. 1987. *Cotton*, 2nd Edition, 436pp. UK: Longman Scientific & Technical.

Nannini M. 2001. Experiments on greenhouse whitefly control by the mirid bugs *Macrolophus caliginosus* wagner and *Cyrtopeltis tenuis* (Reuter) in protected winter tomato crops. *Acta Horticulturae* 559:769–774.

Naranjo SE. 2008. Establishment and impact of exotic Aphelinid parasitoids in Arizona: a life table approach. *J. Insect Sci.* 8:36.

Naranjo SE, Akey D. 2005. Conservation of natural enemies in cotton: comparative selectivity of acetamiprid in the management of *Bemisia tabaci*. *Pest Manag. Sci.* 61:555–566.

Naranjo SE, Ellsworth PC. 2005. Mortality dynamics and population regulation in *Bemisia tabaci*. *Entomol. Exp. Appl.* 116:93–108.

Naranjo SE, Ellsworth PC. 2009a. Fifty years of the integrated control concept: moving the model and implementation forward in Arizona. *Pest Manag. Sci.* 65:1267–1286.

Naranjo SE, Ellsworth PC. 2009b. The contribution of conservation biological control to integrated control of *Bemisia tabaci* in cotton. *Biol. Control.* 51:458–470.

Naranjo SE, Flint HM. 1994. Spatial distribution of premaginal *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton and development of fixed-precision, sequential sampling plans. *Environ. Entomol.* 24:254–266.

Naranjo SE, Flint HM. 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 SE, Chu CC, Henneberry TJ. 1996. Economic injury levels for *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton: impact of crop price, control costs, and efficacy of control. *Crop Prot.* 15:779–788.

Naranjo SE, Ellsworth PC, Chu CC, Henneberry TJ, Riley DG, Watson TF, Nichols RL. 1998. Action thresholds for the management of *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton. *J. Econ. Entomol.* 91:1415–1426.

Naranjo SE, Ellsworth PC, Chu CC, Henneberry TJ. 2002. Conservation of predatory arthropods in cotton: role of action thresholds for *Bemisia tabaci* (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 95:682–691.

Naranjo SE, Ellsworth PC, Hagler JR. 2004. Conservation of natural enemies in cotton: role of insect growth regulators for management of *Bemisia tabaci*. *Biol. Control* 30:52–72.

Natwick ET. 1993. Silverleaf whitefly control in cotton using various insecticides in the Imperial Valley of CA. In *Proceeding of the Beltwide Cotton Conference*, ed. DJ Herber, DA Richter, pp. 722–727. Memphis, TN: National Cotton Council.

Natwick ET, Laemmlen FF. 1993. Protection from phytophagous insects and virus vectors in honeydew melons using row covers. *Fla. Entomol.* 76:120–126.

Natwick ET, Robinson F. 1993. Alfalfa host plant resistance to silverleaf whitefly (formerly sweetpotato whitefly strain B). In *Proceedings of the Alfalfa Seed Production Symposium*, ed. S Mueller, pp. 60–63.

Natwick ET, Chu CC, Perkins HH, Henneberry TJ, Cohen AC. 1995. Pima and upland cotton susceptibility to *Bemisia argentifolii* under desert conditions. *Southwest. Entomol.* 20:429–438.

Natwick ET, Turini T, Gilbertson R. 2008. Whitefly transmitted virus diseases in southeastern California. *CAPCA Advisor* 11(1):24–27.

Nava-Camberos U, Riley DG, Harris MK. 2001. Density-yield relationships and economic injury levels for *Bemisia argentifolii* (Homoptera: Aleyrodidae) in cantaloupe in Texas. *J. Econ. Entomol.* 94:180–189.

Nomikou M, Janssen A, Schraag R, Sabelis MW. 2001a. Phytoseiid predators as potential biological control agents for *Bemisia tabaci*. *Exp. Appl. Acarol.* 25:270–290.

Nomikou M, Janssen A, Schraag R, Sabelis MW. 2001b. Phytoseiid predators suppress populations of *Bemisia tabaci* on cucumber plants with alternative food. *Exp. Appl. Acarol.* 27:57–68.

Nomikou M, Janssen A, Sabelis MW. 2003. Phytoseiid predators of whiteflies feed and reproduce on non-prey food sources. *Exp. Appl. Acarol.* 31:15–26.

Norman JW, Jr, Sparks AN, Jr. 1997. Cotton leaf hairs and silverleaf whiteflies in the lower Rio Grande Valley of Texas. In *Proceedings Beltwide Cotton Conferences*, ed. P Dugger, DA Richter, pp. 1063–1064. Memphis, TN: National Cotton Council.

Nuessly GS, Meyerdirk DE, Coudriet DL, Henneberry TJ. 1994. The effect of short season cotton production schedules on *Bemisia tabaci* (Gennadius). *Southwest. Entomol.* 19:209–217.

Nyoike TW, Liburd OE, Webb SE. 2008. Suppression of whiteflies, *Bemisia tabaci* (Hemiptera: Aleyrodidae) and incidence of *cucurbit leaf crumple virus*, a whitefly-transmitted virus of zucchini squash new to Florida, with mulches and imidacloprid. *Fla. Entomol.* 91:460–465.

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

Ozores-Hampton M, McAvoy E, Simonne E, Stansly P. 2008. Evaluation of TYLCV virus-resistant varieties under commercial conditions in Southwest Florida. In *Proceedings of the Florida Tomato Institute*, pp. 12–16. http://gcrec.ifas.ufl.edu/tomatoproceedings08.pdf

Palumbo JC, Ellsworth PC, Dennehy TJ, Umeda K. 1999. Cross commodity management of whiteflies and chemical efficacy in Arizona. In *Vegetable Report.* Series P-117, AZ 1143, ed. DN Byrne, pp. 108–120. The University of Arizona, College of Agriculture, Tucson, AZ.

Palumbo JC, Toscano NC, Blua MJ, Yoshida HA. 2000. Impact of *Bemisia* whiteflies (Homoptera: Aleyrodidae) on alfalfa growth, forage yield, and quality. *J. Econ. Entomol.* 93:1688–1694.

Palumbo JC, Ellsworth PC, Dennehy TJ, Nichols RL. 2003. Cross-commodity guidelines for neonicotinoid insecticides in Arizona, *IPM Series No. 17*, Cooperative Extension, The University of Arizona, Tucson, http://cals.arizona.edu/pubs/insects/az1319.pdf

Palumbo JC, Horowitz AR, Prabhaker N. 2001. Insecticidal control and resistance management for *Bemisia tabaci*. *Crop Prot.* 20:739–765.

Pollard DG, Saunders JH. 1956. Relations of some cotton pests to jassid resistant Sakel. *Empire Cotton Growing Rev.* 33:197–202.

Polston JE, Anderson PK. 1997. The emergence of whitefly transmitted geminiviruses in tomato in the western hemisphere. *Plant Dis.* 81:1358–1369.

Polston JE, Cohen L, Sherwood TA, Ben-Joseph R, Lapidot M. 2006. *Capsicum* species: symptomless hosts and reservoirs of tomato yellow leaf curl virus (TYLCV). *Phytopathology* 96:447–452.

Polston JE, Lapidot M. 2007. Management of tomato yellow leaf curl virus: US and Israel perspectives. In *Tomato Yellow Leaf Curl Virus Disease Management, Molecular Biology, Breeding for Resistance*, ed. H Czosnek, pp. 252–262. Amsterdam, The Netherlands: Springer.

Qui YT, van Lenteren JC, Drost YC, Posthuma-Doodeman CJAM. 2004. Life history parameters of *Encarsia formosa*, *Eretmocerus eremicus* and *E. mundus*, aphelinid parasitoids of *Bemisia argentifolii* (Homoptera: Aleyrodidae). *Eur. J. Entomol.* 101:83–94.

Raya V, Parra M, Cid MC. 2006. Influence of changes in cover and height on the climate of Canary-screenhouses for tomato growth: preliminary results. *Acta Hort. (ISHS)* 719:535-542. http://www.actahort.org/books/719/719_62.htm

Riley DG, Palumbo JC. 1995. Action thresholds for *Bemisia argentifolii* (Homoptera: Aleyrodidae) in cantaloupe. *J. Econ. Entomol.* 88:1733–1738.

Rojas MR, Kon T, Natwick ET, Polston JE, Akad F, Gilbertson RL. 2007. First report of *Tomato yellow leaf curl virus* associated with tomato yellow leaf curl disease in California. *Plant Dis.* 91:1056.

Roltsch WJ, Hoelmer KA, Simmons GS, Andress E. 2008. Release and recovery of exotic natural enemies of *Bemisia tabaci* (biotype "B") (Hemiptera: Aleyrodidae) in Imperial Valley. In *California Classical Biological Control of Bemisia tabaci in the United States – A Review of Interagency Research and Implementation*, ed. J Gould, KA Hoelmer, JA Goolsby, Vol. 4, pp. 205–224. Amsterdam, The Netherlands: Springer.

Sanchez JA. 2008. Zoophytophagy in the plantbug *Nesidiocoris tenuis*. *Agric. For. Entomol.* 10:75–80.

Schuster DJ, Stansly PA, Polston JE. 1996. Expressions of plant damage from *Bemisia*. In *Bemisia 1995: Taxonomy, Biology, Damage Control and Management*, ed. D Gerling, RT Mayer, pp. 153–165. Andover, Hants, UK: Intercept Ltd.

Schuster DJ, Evans GA, Bennett FD, Stansly PA, Jansson RK, Leibee GL, Webb SE. 1998. A survey of parasitoids of *Bemisia* spp. whiteflies in Florida, the Caribbean, and Central and South America. *Int. J. Pest Manag.* 44:255–260.

Schuster DJ. 2002. Action threshold for applying insect growth regulators to tomato for management of irregular ripening caused by *Bemisia argentifolii* (Homoptera: Aleyrodidae). *J. Econ. Entomol.* 95(2):372–376.

Schuster DJ, Stansly PA, Polston JE, Gilreath PR, McAvoy E. 2007. Management of whiteflies, whitefly-vectored plant virus, and insecticide resistance for vegetable production in southern Florida. *ENY-735 (IN695)*, IFAS Extension, University of Florida, Gainesville.

Seo YS, Zhou YC, Turini TA, Cook CG, Gilbertson RL, Natwick ET. 2006. Evaluation of cotton germplasm for resistance to whitefly and cotton leaf crumple (CLCr) disease and etiology of CLCr in California's Imperial Valley. *Plant Dis.* 90:877–884.

Shipp JL, Wang K. 2006. Evaluation of *Dicyphus hesperus* (Heteroptera: Miridae) for biological control of *Frankliniella occidentalis* (Thysanoptera: Thripidae) on greenhouse tomato. *J. Econ. Entomol.* 99:414–420.

Soler-Gamborena R, van Lenteren JC. 2004. Reproduction and development of *Eretmocerus eremicus* (Hymenoptera: Aphelinidae) on *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae). In *Proceedings of the Section Experimental and Applied Entomology of the Netherlands Entomological Society (NEV)* 15, ed. R Soler-Gamborena, JC van Lenteren, pp. 111–117.

Stansly PA. 1996. Seasonal abundance of silverleaf whitefly in Southwest Florida vegetable fields. *Proc. Fla. State Hort. Soc.* 108:234–242.

Stansly PA, Schuster DJ, Liu TX. 1997. Apparent parasitism of *Bemisia argentifolii* (Homoptera: Aleyrodidae) by Aphelinidae (Hymenoptera) on vegetable crops and associated weeds in South Florida. *Biol. Control.* 9:49–57.

Stansly PA, Sanchez PA, Rodriguez JM, Canizares F, Nieto A, Lopez-Leyva MJ, Fajardo M, Suarez V, Urbaneja A. 2004a. Prospects for biological control of *Bemisia tabaci* (Homoptera, Aleyrodidae) in greenhouse tomatoes of southern Spain. *Crop Prot.* 23:701–712.

Stansly PA, Calvo FJ, Urbaneja A. 2004b. Biological control of *Bemisia tabaci* (Homoptera, Aleyrodidae) in protected tomato and pepper culture in southern Spain. In *Proceedings of the VII Internatational Symposium on Protected Cultivation in Mild Winter Climates: Production, Pest Management and Global Competition*. Vol. I, *Acta Hort*. 659:383–394. http://www.actahort.org/books/659/659_51.htm

Stansly PA, Calvo J, Urbaneja A. 2005a. Augumentative biological control of *Bemisia tabaci* biotype "Q" in greenhouse pepper using *Eretmocerus* spp. (Hym. Aphelinidae). *Crop Prot.* 24:829–835.

Stansly PA, Calvo J, Urbaneja A. 2005b. Release rates for control of *Bemisia tabaci* (Homoptera: Aleyrodidae) Biotype "Q" with *Eretmocerus mundus* (Hymenoptera: Aphelinidae) in greenhouse tomato and pepper. *Biol. Control* 35:124–133.

Stansly PA, Castillo J. 2009. Control of broad mite *Polyphagotarsomeus latus* and the whitefly *Bemisia tabaci* in open field pepper and eggplant with predaceous mites. In *Proceedings of the Working Group "Integrated Control in Protected Crops, Mediterranean Climate"*, ed. C Castañe, D Perdikis. *IOBC WPRS Bull*. 49:145–152.

Stapleton JJ, Summers CG. 2002. Reflective mulches for management of aphids and aphid-borne virus diseases in late season cantaloupe (*Cucumis melo* L. var. *cantalupensis*). *Crop Prot.* 21:891–898.

Stern VM, Smith RF, van den Bosch R, Hagen KS. 1959. The integrated control concept. *Hilgardia* 29:81–101.

Szabo P, van Lenteren JC, Huisman PWT. 1993. Development time, survival and fecundity of *Encarsia formosa* on *Bemisa tabaci* and *Trialeurodes vaporariorum*. *IOBC/WPRS* 16:173–176.

Tal C, Coll M, Weintraub PG. 2007. Biological control of *Polyphagotarsonemus latus* (Acari: Tarsonemidae) by the predaceous mite *Amblyseius swirskii* (Acari: Phytoseiidae). *IOBC/WPRS Bull.* 30:111–115.

Teitel M. 2006. The effect of screens on the microclimate of greenhouses and screenhouses – a review. *Acta Hort*. (ISHS) 719:575–586. http://www.actahort.org/books/719/719_67.htm

Teuber LR, Rupert ME, Gibbs LK, Taggard KL. 1997. Breeding resistant alfalfa holds promise for silverleaf whitefly management. *Calif. Agric.* 51(3):25–29.

Urbaneja A, Tapia G, Stansly PA. 2005. Influence of host plant and prey availability in the developmental time and survival of *Nesidiocoris tenuis* Reuter (Het: Miridae). *Biocontrol Sci. Technol*. 15:513–518.

Urbaneja A, Sanchez E, Stansly PA. 2007. Life history of *Eretmocerus mundus* Mercet (Hym.: Aphelinidae), a parasitoid of *Bemisia tabaci* Gennadius (Hom: Aleyrodidae), on tomato and sweet pepper. *Biocontrol* 52:25–39.

Van der Blom J. 2007. Control de plagas en hortícolas protegidas: el año de la transición. *Horticultura* 200:36-43. http://www.horticom

van Driesche RG, Hoddle MS, Lyon S, Sanderson JP. 2001. Compatibility of insect growth regulators with *Eretmocerus eremicus* (Hymenoptera: Aphelinidae) for whitefly (Homoptera: Aleyrodidae) control on poinsettias. II. Trials in commercial poinsettia crops. *Biol. Control* 20:132–146.

van Driesche RG, Lyon S, Jacques K, Smith T, Lopes P. 2002. Comparative cost of chemical and biological whitefly control in poinsettia: is there a gap? *Fla. Entomol.* 85:488–493.

Van Lenteren JC, Woets J. 1988. Biological and integrated control in greenhouses. *Annu. Rev. Entomol.* 33:239–269.

Vestergaard S, Cherry A, Keller S, Goettel M. 2003. Safety of hyphomycete fungi as microbial control agents. In *Environmental Impacts of Microbial Insecticides: Needs and Methods for*

Risk Assessment, ed. HMT Hokkanen, AE Hajek, pp. 35–62. The Netherlands, Dordrecht: Kluwer Academic publisher.

Vidal C, Fargues J, Rougier M, Smits N. 2003. Effect of air humidity on the infection potential of hyphomycetous fungi as mycoinsecticides for *Trialeurodes vaporariorum*. *Biocontrol Sci. Technol.* 13:183–198.

Walker GP, Natwick ET. 2006. Resistance to silverleaf whitefly, *Bemisia argentifolii* (Hem., Aleyrodidae), in *Gossypium thurberi*, a wild cotton species. *J. Appl. Entomol.* 130:429–436.

Watson TF, Silvertooth JC, Tellez A, Lastra L. 1992. Seasonal dynamics of sweetpotato whitefly in Arizona. *Southwest. Entomol.* 17:149–167.

Yee WL, Toscano NC, Palumbo JC, Blua MJ, Yoshida HA. 1997. Seasonal population trends of *Bemisia argentifolii* (Homoptera: Aleyordidae) on alfalfa in southern California and Arizona. *Environ. Entomol.* 26:241–249.

Yokomi RK, Hoelmer KA, Osborne LS. 1990. Relationship between the sweetpotato whitefly and the squash silverleaf disorder. *Phytopathology* 80:895–900.

Zimmerman G. 2008. The entomopathogenic fungi *Isaria farinosa* (formerly *Paecilomyces farinosus*) and the *Isaria fumosorosea* species complex (formerly *Paecilomyces fumosoroseus*): biology, ecology and use in biological control. *Biocontrol Sci. Technol.* 18:865–901.