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Review article

IPM for *Bemisia tabaci*: a case study from North America ☆

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Abstract

A model of whitefly integrated pest management (IPM) has been proposed that conveniently organizes all *Bemisia tabaci* control tactics into a multi-level, multi-component pyramid and defines three major keys as "sampling", "effective chemical use", and "avoidance". Each component is described along with information about its implementation, adoption, and importance in the low (<700 m) desert agroecosystem of North America, which recently sustained the introduction and expansion of the B biotype during the 1990s. Insect growth regulators (buprofezin and pyriproxyfen; insect growth regulator (IGR)) in cotton and imidacloprid use in vegetables and melons were key chemical tactics, especially in the US, that were fully integrated with formal sampling plans and action thresholds, and resistance management guidelines. In Mexico, tactics of avoidance such as mandatory planting and harvest dates, post-harvest sanitation, and host-free periods along with strategic use of insecticides implemented cooperatively were key to the recovery of this agroecosystem. A concept, "bioresidual", was developed to explain the extended period of suppression possible through the proper use of IGRs. Organized and sustained grower education was key to the areawide adoption and deployment of this successful IPM plan, which has drastically lowered whitefly targeted insecticide use and whitefly related problems since 1996. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: *Bemisia tabaci*; *Bemisia argentifolii*; Cotton; Insect growth regulators; Sampling; Thresholds; Avoidance; Bioresidual; IPM

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☆ Recent evidence suggests that *B. tabaci* represents a species complex with numerous biotypes and two described cryptic species. The binomial *B. tabaci* here is used in the broad sense to represent all members of the species complex unless a more specific designation is indicated.

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1. Introduction

Whiteflies in general, and *Bemisia tabaci* in particular, have a long history of destabilizing agricultural and horticultural production. As a result, there has been intensive investigation into the biology, behavior, and control of this group and the viruses they vector. Many of the tactics used to control *B. tabaci* have been reviewed elsewhere in this volume (Bellotti and Arias, 2001; Faria and Wraight, 2001; Gerling et al., 2001; Hilje et al., 2001; Morales, 2001; Naranjo, 2001; Palumbo et al., 2001). Earlier works have reviewed the components of integrated pest management (IPM) for *B. tabaci* (Gerling, 1990; Gerling and Mayer, 1996) as well as past successes (e.g., Horowitz et al., 1994; Ausher, 1997). Many advances have been made during the last 5–10 years on the formation, implementation and adoption of IPM in the desert regions of North America. This region is a recent center of activity in *B. tabaci* research and control, and one that is currently enjoying some success in the management of *B. tabaci* (Oliveira et al., 2001).

IPM is the integration of tactics as strategic elements of an overall management plan that protects economic, social and environmental interests. While IPM can be a consistent strategy, operationally it should be, and is, implemented and adapted under localized conditions. Thus, IPM is temporally and spatially contextual, which frustrates attempts to easily assess its implementation or adoption.

This case study will show how elements of research, implementation, and education converge to create, develop, and propel IPM in production systems where *B. tabaci* is not only an economic pest but a key constraint to this region's agricultural productivity. As one of the most recent examples of *B. tabaci* IPM in the world, this review will necessarily focus on operational *B. tabaci* IPM present in the low (<700 m elev.) deserts of southwestern US and northwestern Mexico. In the course of this review, we will examine each IPM component, its origin in research, and its implementation and adoption. A large body of work has been conducted on this pest complex around the world which forms the basis for efforts in North America. Some of the literature that supports the IPM programs in this region, on which we will focus, is from Extension and commodity report sources; however, internet locations of these documents are provided where possible.

1.1. Features of the B. tabaci and low desert agroecosystem

There are a number of features of the *B. tabaci* system that challenge attempts at strategic management regardless of the agroecosystem involved. *B. tabaci* is a polyphagous insect with an ability to attack multiple crop, weed, and ornamental hosts (e.g., Watson et al., 1992). Its small size belies its ability to move relatively large distances locally (e.g., Blackmer et al., 1995; Byrne, 1999), placing many hosts within communities at risk of infestation. This ability to disperse is made worse by its extensive movement through commerce of transplant, floricultural, or other greenhouse plants. Small size and rapid reproductive potential are other characteristics that limit options for control. The damage potential of this pest as a direct plant stressor, virus vector, and quality reducer (e.g., by contamination with excreta) is substantial. These attributes, among others, render this species a shared pest within agricultural communities.

Of the over 600,000 ha under irrigated agriculture, cotton is grown on ca. 200,000 ha in the North American low desert regions of Arizona (S. Ariz.), California (SE Calif., Imperial Valley), and Mexico (N. Baja California—Mexicali Valley and San Luis Rio Colorado Region; NW Sonora—Yaqui Valley). These areas are not homogeneous in climate, production seasons, or crop diversity, and just a few of their differences are noted here. Central Arizona is dominated by cotton in rotation with the relatively minor whitefly hosts of alfalfa, corn and small grains. The Yuma Valley of southwestern Arizona has large acreages of melons, lettuces, and other vegetables, in addition to relatively smaller acreages of cotton and other field crops. The Imperial Valley of California also produces significant acreages of melons and vegetables with a landscape dominated by alfalfa, but only a minor acreage devoted to cotton. The Mexicali Valley and nearby areas of Mexico consist mainly of cotton with a diverse array of other crops. The Yaqui Valley of Mexico has had significant acreages of winter wheat, and small acreages of vegetables with soybean and cotton as summer crops.

B. tabaci was an insect known from cotton in this desert region since the 1920s and from other hosts even earlier than this (Russell, 1975); however, the recent outbreak episodes of the 1990s are attributed to a new biotype or cryptic species (see Perring, 2001; Oliveira et al., 2001). The B biotype, capable of inducing silvering symptoms in squash (Costa and Brown, 1991), was likely introduced into this region in the late 1980s. During the 1990s, it rapidly supplanted the old biotype of *B. tabaci* which infrequently required control in cotton, though lettuce infectious yellows and, more rarely, cotton leaf crumple could be constraints on production (e.g., Duffus et al., 1986; Duffus, 1996). Serious infestations of the new biotype in cotton, melons and vegetables began around 1990, intensified in 1991 in southwestern Arizona, southern California, and northwestern Mexico, and reached full outbreak status throughout the low desert production areas of this region by 1992. *B. tabaci* was the largest destructive force on the low Sonoran desert's agricultural industry of any pest of the last decade.

Besides limiting the length of the cotton season during the early 1990s, production of certain crops was curtailed or eliminated in certain regions or during certain production windows; for example, fall melon production in the Imperial Valley of California fell drastically between 1990 and 1992 (Gonzales et al., 1992). In the Mexicali Valley of Baja California, crops such as melon, watermelon, and sesame planted in the summer season were completely destroyed by this pest in 1992. Cotton, one of the major field crops of the region, was nearly eliminated in northern Mexico. The average cotton area planted prior to establishment of the B biotype was ca. 35,000 ha. By 1992, 19,599 ha of cotton were reduced in yield by 50% with high levels of lint contamination by honeydew sugars and sooty mold. In response in 1993, only 714 ha were planted there, but only 653 ha harvested (León López, 1993). The 1992 outbreak led to widespread stickiness in cotton and regionally-discounted lint prices in Arizona that persisted due to market memory for many years (Ellsworth et al., 1999; see also Hendrix et al., 1996).

The *B. tabaci* outbreak of 1992 was the second costliest on record and impacted yields of Arizona cotton more than any other pest (Ellsworth and Jones, 2001). Through rapid and organized research and extension efforts (see Oliveira et al., 2001), improvements in *B. tabaci* management were made possible in cotton, melons and vegetables in 1993 and 1994. Growers adopted a defensive production strategy that included a much abbreviated cotton season, and this along with other advances helped to limit the damage by this pest, but not without its cost (Ellsworth et al., 1993). The largest portion in history of a cotton grower's control budget was spent fighting this pest in 1993 (Fig. 1A). The following year continued a trend of increasing costs to control this pest, and by 1995, *B. tabaci* was in full outbreak status once again, in part due to overreliance on and resistance to synergized pyrethroids (Dennehy and Williams, 1997; Palumbo et al., 2001). Foliar spray intensity and control costs were higher in 1995 than in any other year in history (Fig. 1; Ellsworth and Jones, 2001). Since 1996, however, this region's agricultural production has been restored and proceeds ostensibly unconstrained by the presence of this whitefly.

2. The *B. tabaci* IPM strategy

The IPM program in place over most of this region can be described as a pyramid constructed of building-block components (Fig. 2; see also Naranjo, 2001). The three "keys" to whitefly management are (1) sampling and detection, (2) effective chemical use, and (3) avoidance of the problem. With "Avoidance" as the foundation, virtually all management components can be fit to this paradigm, though some might reside on more than one level. Confronted with a pest crisis, short-term function depends on the upper two levels of the pyramid. However, sustainable, long-term strategies must depend on the development of this solid foundation. At the same time, a pyramid-strategy developed for one pest must be compatible with like strategies in place for all pests of a system (Ellsworth, 1999).

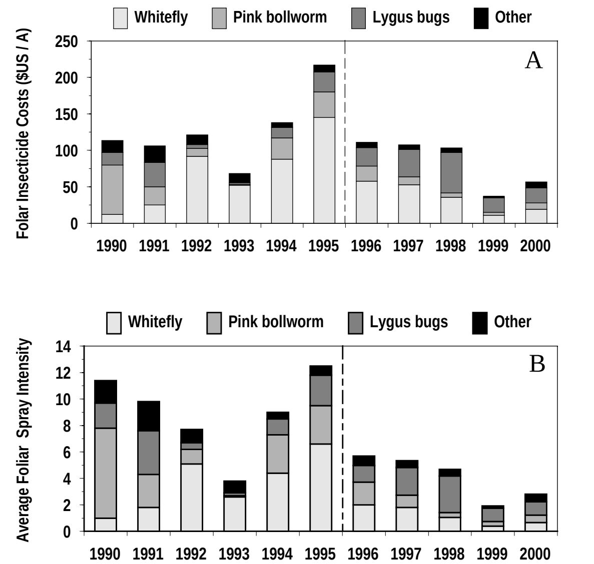


Fig. 1. Statewide average foliar insecticide use statistics for Arizona cotton: (A) average costs per acre (including applications) and (B) number of foliar sprays by pest. Combination sprays targeting multiple pests in a single application are counted for each pest where appropriate. For example, foliar "intensity" was greater than the actual number of foliar applications in 1995. Insect growth regulators effective against whiteflies, Bt transgenic cotton effective against pink bollworms, and a new *B. tabaci* IPM plan and educational campaign were introduced in 1996 (dashed line) (adapted from Ellsworth and Jones, 2001).

2.1. Sampling

Sampling of whiteflies for management application in cotton involves multi-stage, binomial methods of classifying populations and sits at the apex of the pyramid (Fig. 2). This highlights its over-arching importance in the implementation of most insect control tactics. Further, sampling plays a central role in the understanding and refinement of management strategies. Without well-designed sampling tools, progress in all areas of whitefly management would be hampered. Sampling whiteflies for research or pest management has been the subject of numerous studies worldwide and several reviews (Butler et al., 1986; Ohnesorge and Rapp, 1986; Ekbom and Rumei, 1990; Naranjo, 1996). Most approaches to sampling cotton are based on a relationship of "most infested leaf" to main stem leaf position as first analyzed for red-eyed nymphs in

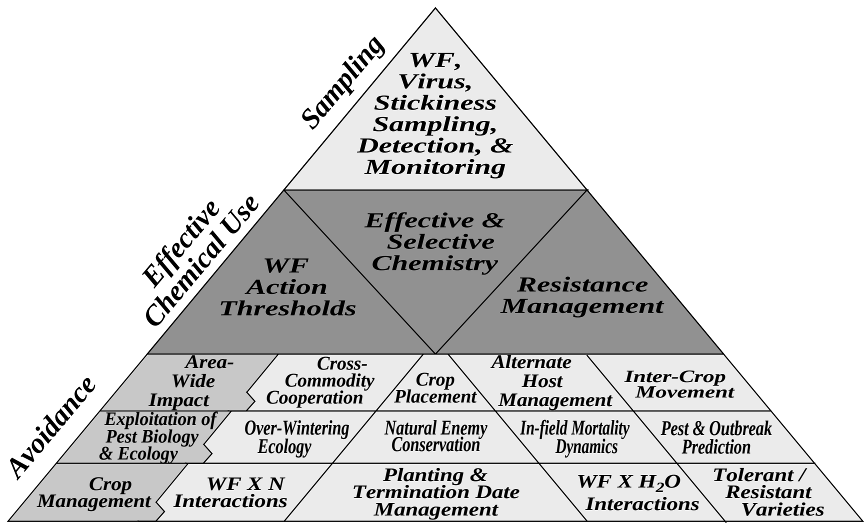


Fig. 2. Conceptual diagram of whitefly IPM, depicting three keys to whitefly management (left): Sampling, Effective Chemical Use, and Avoidance. Avoidance can be further subdivided among three inter-related areas: Areawide Impact, Exploitation of Pest Biology and Ecology, and Crop Management (see text for details).

Sudanese cotton (von Arx et al., 1984). These studies provided useful starting points for the research and development of sampling plans for IPM in the low deserts of North America.

Naranjo and Flint (1994, 1995) described immature and adult distributions in cotton and developed fixed-precision and binomial sampling plans (Naranjo et al., 1996b, 1997). This research was adapted into operational adult sampling plans for commercial use in Arizona, taught to hundreds of growers and pest control advisors (Ellsworth et al., 1995), and implemented and validated within a 7300 ha community (Diehl et al., 1994; Ellsworth et al., 1996b; Naranjo et al., 1997). This methodology was also taught to and adopted by pest control advisors in Mexico and California, where it became the standard sampling method for this pest. With the registration of insect growth regulators (IGRs) that had no direct toxicity on adults, new sampling procedures were developed for nymphal whiteflies. This plan (Ellsworth et al., 1996c) was disseminated throughout the region, implemented on over 3200 ha of commercial cotton (Jech and Husman, 1997), and adapted to an easier to use and more accurate binomial system (Diehl et al., 1997a,b). A sampling count card that integrated both adult and nymphal sampling plans was produced and thousands distributed with a fibrous washer that identified the proper location and area for counting whitefly large nymphs (Diehl et al., 1996).

Briefly, the binomial sampling plan with simultaneous sampling of adults and large nymphs to facilitate adoption consists of (Fig. 3): (1) inspecting the undersurface of a main stem leaf located at the fifth position below the terminal for the presence of three or more adults, (2) detaching the leaf and examining a US quarter-sized area (ca. 3.88 sq. cm) located tangentially between the central and left major veins of the leaf for the presence of one or more large nymphs (instars 3 and 4), visible to the naked eye or under weak magnification, (3) calculating the percentage of a 30-leaf sample (for an average-sized field of 16–32 ha) infested with three or more adults and the percentage of disks with one or more large nymphs, and (4) comparing binomial results to numerical estimates. A complete sampling bout for adults and nymphs in an average-sized field takes ca. 7 min. Initial training of scouts can take as little as 1 h (Ellsworth and Diehl, unpubl. data).

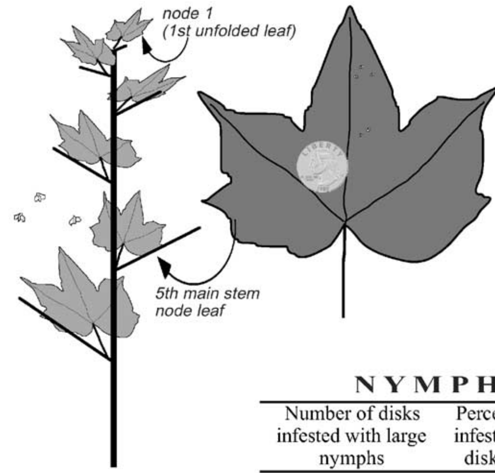
Parallel to these efforts, there were extensive studies designed for the development of sampling plans for melons (Palumbo et al., 1994, 1995; Tonhasca et al., 1994a,b). These tools enabled a systematic examination of yield–injury relationships and gave rise to action thresholds (see Section 2.2.2) for melons (Riley and Palumbo, 1995a,b). However, with the registration of imidacloprid (Admire®; Bayer AG, Leverkusen, Germany; see Palumbo et al., 2001), the majority of growers relaxed dependence on whitefly samples for scheduling this prophylactic approach, though educational efforts continue (Palumbo et al., 2000).

2.2. *Effective chemical use*

IPM, even in its most environmentally benign forms, must be able to call upon chemical controls when other tactics fail to prevent the occurrence of economically damaging levels of pests. Thus, "effective chemical use" is an integral component of IPM, especially for *B. tabaci*, and it consists principally of action thresholds, availability and understanding of selective and effective

ADULTS

Number of leaves infested with 3 or more adults	Percent infested leaves	Average per leaf
1	3.4	0.3
2	6.7	0.6
3	10	0.8
4	13	1.0
5	17	1.3
6	20	1.5
7	23	1.8
8	27	2.1
9	30	2.3
10	33	2.6
11	37	2.9
12	***40***	***3.2***
13	***43***	***3.6***
14	***47***	***3.9***
15	***50***	***4.3***
16	***53***	***4.7***
17	***57***	***5.1***
18	60	5.5
19	63	6.0
20	67	6.5
21	70	7.1
22	73	7.7
23	77	8.4
24	80	9.2
25	83	10.2
26	87	11.3
27	90	12.8
28	93	14.9
29	97	18.4
30	100	34.9



IGR Threshold

NYMPHS

Number of disks infested with large nymphs	Percent infested disks	Average per disk
8	26	0.5
12	***40***	***1.0***
16	52	1.5

<table>
<tr><th colspan="2" rowspan="2">IGR Threshold Decision Matrix</th><th colspan="2">Whitefly Adult Levels</th></tr>
<tr><th>fewer than 3 per leaf</th><th>at least 3–5 per leaf</th></tr>
<tr><td rowspan="2">Whitefly Large Nymph Levels</td><td>fewer than 1 per disk</td><td>Wait and re-sample in 3–7 days</td><td>Wait;
Re-sample in 3 days; or
Use a Stage II adulticide;
or apply Knack</td></tr>
<tr><td>at least 1 per disk</td><td>Wait;
Re-sample in 3 days;
or apply Applaud</td><td>Spray with either IGR</td></tr>
</table>

Fig. 3. The sample units, locations, and binomial conversion tables for *B. tabaci* adults and large nymphs (3rd or 4th instars) in cotton, as well as a threshold decision matrix for IGR use in cotton based on a 30-leaf sample, was taught to hundreds of growers in southwestern US and northwestern Mexico (adapted from Ellsworth et al., 1995, 1996c; Diehl et al., 1996; Naranjo et al., 1996b).

chemistry, and a proactive resistance management plan (Fig. 2). Chemical control, resistance research, and the pivotal role of imidacloprid in melon and vegetable systems are reviewed elsewhere in this volume (Palumbo et al., 2001).

2.2.1. *Effective and selective chemistry*

The availability of selective chemistry and the dramatic impact that imidacloprid has had on the non-cotton sources of *B. tabaci* may have been key to enabling the development of successful whitefly IPM in the low desert system. Bitter local experience taught quickly that conventional materials such as pyrethroids or other compounds used alone provided little or no relief from this pest (Watson, 1993; Martínez-Carrillo, 1996).

Early research in this region quickly identified the necessity for mixing pyrethroids with organophosphate or other synergists (Watson, 1993; Ellsworth et al., 1994; Dennehy et al., 1995a,b; Ellsworth and Watson, 1996; Prabhaker et al., 1998; Palumbo et al., 2001) as was previously established elsewhere around the world (Ishaaya et al., 1987; see review by Horowitz and Ishaaya, 1996). Later, field-tests were conducted with two novel, relatively whitefly specific IGRs, pyriproxyfen (Knack®; Valent USA, Walnut Creek, CA, USA) and buprofezin (Applaud®, Nichino America, Inc., Wilmington, DE, USA), which had been in use in Israel for several years. After the 1995 outbreak, a multi-agency and industry coalition developed a new strategy (Ellsworth et al., 1996a; Dennehy et al., 1996a) that included the use of these two IGRs. An unprecedented Section 18 emergency exemption was granted to Arizona by US-EPA in 1996 for both compounds on cotton. Pyriproxyfen was granted full Section 3 registration in September, 1998, and annual exemption of buprofezin has occurred ever since. The dual Section 18 was also made available in California starting in 1997. In Mexico, buprofezin has been registered for use since 1993, and pyriproxyfen has only recently gained registration

(1999); however, acetamiprid (Rescate®; Aventis Cropscience, Lyon, France), a neonicotinoid with some selectivity, has been registered for use since 1997.

Buprofezin is a chitin synthesis agonist that mainly affects inter-stadial nymph molts (Ishaaya et al., 1988). Pyriproxyfen is a juvenoid with abilities to sterilize eggs prior to blastokinesis either free-living or developing within females and also prevents metamorphosis of the fourth instar into an adult (Ishaaya and Horowitz, 1992). Neither compound kills adults outright, necessitating significant educational efforts with growers and pest control advisors—over 700 were trained and certified for proper use of IGRs in Arizona. They were taught about the lack of adult knockdown and the need to wait at least 7–10 days after spraying before observing significant egg or nymphal mortality and concomitant reductions in populations. In part because of the slow action of the IGRs, growers were mandated by the Section 18 label to wait a minimum period after the use of one IGR before applying the alternate IGR if necessary (Ellsworth et al., 1996a). No other pests are impacted directly in the low desert cotton system, and both compounds are relatively safe for natural enemies (Naranjo, 2001; Palumbo et al., 2001).

2.2.2. *Action thresholds*

A fundamental precept of IPM, especially at its inception as "integrated control" more than 40 years ago, is applying pesticides only as needed (Smith and Allen, 1954). Action thresholds, therefore, are key to implementing an "as needed" strategy to chemical control and indeed IPM. Prior to the 1992 outbreak in North American deserts, there were no established thresholds there for cotton or melons, the two most affected crops. Compared to studies on sampling, there were fewer studies around the world on action thresholds with even fewer formally linked to sampling plans. Comparative research and observation in cotton suggested that two adults per leaf in Thailand (Mabbett et al., 1980), 6–8 adults per leaf in India (Sukhija et al., 1986), and ca. six adults per leaf in the Sudan (Stam et al., 1994) were appropriate action thresholds.

With the proper sampling tools in hand (see Section 2.1), action levels were first tested and proposed in US cotton as between one and ten adults per leaf (Ellsworth and Meade, 1994). Based on a multi-state, multi-agency program of thresholds testing over a three state region, five adults per leaf was deemed the most appropriate action threshold for applying conventional, principally adulticidal, insecticides (Naranjo et al., 1998a). This level protected against yield loss and minimized risks of cotton lint stickiness, a characteristic that leads to regional discounts in the marketplace (Ellsworth et al., 1999). Results from additional testing in California of action thresholds (Yee et al., 1996) and analyses of economic injury levels (Naranjo et al., 1996a) lent additional support for the five adults per leaf threshold, equivalent to 57% of leaves infested with three or more adults (Fig. 3). Furthermore, a replicated experiment of large scale (ca. 85 ha) and collaboration showed that more conservative action thresholds (one or three adults per leaf), as were favored by commercial growers of the time, were no more effective than the five adults per leaf threshold (Ellsworth et al., 1996d). Furthermore, no differences were found between aerially and ground-applied conventional insecticides. This addressed concerns of growers who, dependent on aerial applications, had doubts about recommendations based on ground-applied insecticides and as a result had previously implemented even lower thresholds (5–30 adults per pan or ca. 0.2–1 adult per leaf; El-Lissy et al., 1994). These thresholds were tested in northwestern Mexico, where it was decided to use ten adults per leaf as the action threshold. The recommended threshold for Imperial Valley, California, cotton growers is five adults per leaf; however, the central valley of California uses ten per leaf (Flint, 1996). The recommended threshold for melons using conventional materials is three adults per leaf (Palumbo et al., 1994).

Once IGRs became commercially available in Arizona, new sampling procedures (see Section 2.1; Fig. 3) and nominal action thresholds were tested in a 72 ha, 48-plot factorial design that contrasted application methods, thresholds for initiating IGR use, and insecticide regime (Ellsworth et al., 1997). The nominal thresholds were based on four factors: (1) the levels at which earlier small plot studies showed "acceptable" control (Ellsworth, unpubl. data), (2) the objective of applying the IGR just at the point of inflection of the whitefly population curve, beyond which populations are considered uncontrollable and exponentially growing, (3) the objective of positioning IGRs as first strike alternatives to conventional adulticidal compounds (with action levels of five adults per leaf), and (4) empirical evidence from Israeli practitioners who had prior experience with these IGRs (ca. 10–20 large instars per maximally infested leaf; Kletter, 1993; Horowitz, pers. comm.). The nominal threshold consisted of both adult (3–5 adults per leaf) and nymphal levels (0.5–1 large nymph per disk). The nymphal component was later revised to one large nymph per disk (Diehl et al., 1997a,b). Further testing has corroborated the adequacy of this action threshold in preventing yield or quality losses (Ellsworth and Naranjo, unpubl. data).

Ellsworth et al. (1996c) proposed a decision matrix for the use of IGRs within a sampling and thresholds program (Fig. 3). This matrix illustrates the relative utility of the two compounds; pyriproxyfen may be better for an adult-biased population and buprofezin for a nymphal-biased population. Studies have shown that, while both IGRs generally reduce populations ultimately to similar endpoints, buprofezin acts somewhat more quickly because of its direct action on nymphs (Ellsworth, 1998). Several investigations have found an IGR-based strategy, when compared to a conventional insecticide-based strategy, generally lowers whitefly populations for a longer period of time (Ellsworth, 1998), reduces risk of pest resurgence (Naranjo, 2001) and pest resistance (Dennehy et al., 1996b; Ellsworth, 1998), at about the same or lower overall cost. In a 6-year series of commercial-scale, replicated experiments at one location in central Arizona, IGR-based approaches reduced the number of whitefly targeted sprays by 50% on average (Ellsworth and Jones, 2001).

2.2.3. Resistance management

As part of IPM, new chemical control tactics should be developed along with proactive resistance management programs, which incorporate and integrate guidelines that will preserve susceptibilities of pest populations (Thompson and Head, 2001). These susceptibilities, and indeed the modes of action of the chemistries themselves, are natural resources that should be protected like any other environmental objective of IPM. The principles of resistance management include maximizing each non-chemical tactic for control, limiting the use of all pesticidal agents to the lowest practical level, partitioning uses within crop seasons, and harmonizing uses across multi-crop systems. The literature is replete with accounts of performance-degrading resistances occurring relatively rapidly in some biotypes of *B. tabaci* over the last several decades (see Denholm et al., 1996, 1998; Horowitz and Ishaaya, 1996; Horowitz et al., 1999; Palumbo et al., 2001). These experiences around the world were key to making resistance management in *B. tabaci* a priority for growers in the southwest US.

Prior to the introduction of the IGRs and neonicotinoids to North America, the range of chemistries and modes of action effective against *B. tabaci* were quite limited. They consisted primarily of an array of pyrethroid mixtures and a few non-pyrethroid mixtures. Given these limitations, a rudimentary rotational scheme was extended to growers via a laminated pocket guide and brochure (Dennehy et al., 1995a,b) and tested in a commercial-scale trial in 1995 (Ellsworth et al., 1996d). By this time, serious resistances had been documented to the synergized pyrethroids in Arizona (Dennehy et al., 1996a, Dennehy and Williams, 1997; Denholm et al., 1998; Sivasupramaniam and Watson, 2000), though the prevalence of resistances in the Imperial Valley of California was ostensibly lower (Castle et al., 1996a,c). In California, a program of regional resistance monitoring was deployed for inferring field efficacy and making near real-time chemical efficacy recommendations to growers via a weekly newsletter (Castle et al., 1996a,c). In the Yaqui Valley of northwestern Mexico, resistance management recommendations based in prevention of pyrethroid resistance in *Heliothis virescens* emphasized use of pyrethroids in a window during the middle of the season (Martínez-Carrillo, 1990). Using a vial technique, researchers there showed similar trends as in Arizona with highest LC50 values during 1994 and 1995. These resistances declined by 1996, where they have remained ever since. This recovery was attributed to a relaxation of selection pressures on summer populations there (Martínez-Carrillo, 1998). Other resistance research conducted in the low deserts in support of resistance management recommendations has been reviewed elsewhere (Dennehy and Williams, 1997; Dennehy and Denholm, 1998; Castle et al., 1999; Palumbo et al., 2001).

US-EPA granted the IGR exemptions under a strict plan of one-use per season for each IGR, user certification, and mandatory education. The one use per IGR restriction was sought because of the desire to proactively manage or prevent resistances to this valuable set of new chemistries, and because neither IGR was believed to provide for season-long control of whiteflies when used alone. This multilateral, grower-endorsed, and mandated educational campaign focused on stewardship of these IGRs through (1) proper sampling and action thresholds including adult and nymphal whiteflies (see Sections 2.1 and 2.2.2), and (2) an aggressive, proactive resistance management program as part of an IPM approach (Dennehy et al., 1996a; Ellsworth et al., 1996a). As part of this resistance management program, all whitefly insecticides including the IGRs were organized and partitioned into a three-stage (IGRs, non-pyrethroids, pyrethroid mixtures) approach described in more detail by Palumbo et al. (2001).

2.3. Avoidance

Adoption of IPM depends on, in part, the simplicity of the message. The paradigm proposed here (Fig. 2) categorizes all those practices that serve to limit pest populations below economic levels as "avoidance". This concept can be easily taught to practitioners who innately understand the essence of this objective. Scientifically, this can be the most difficult set of practices to develop, research, and implement. They are, however, the foundation blocks to sustainable or "least intrusive" IPM. The broader this base of tactics is and the more they are adopted, the less reliant IPM is on the upper portions of this pyramid.

Due to the inherent complexity of this level of IPM, "avoidance" can be further subdivided or organized into multiple layers. Three are provided here that represent key areas of whitefly IPM development: Crop Management, Exploitation of Pest Biology and Ecology, and Areawide Impact (Fig. 2).

2.3.1. Crop management

Practitioners and researchers of IPM, past and present, recognize the importance of crop health to the successful avoidance of damaging pest populations (see Kogan, 1998). The North American low deserts are characterized by scant rainfall with virtually all agricultural production under irrigation. The complex insect–plant–water interaction has been examined by a number of researchers. Findings include: (1) water-stressed plants sustain higher whitefly densities (Flint et al., 1994, 1995, 1996) possibly mediated by elevated leaf temperatures and/or altered nutrition (Blackmer and Byrne, 1999); (2) rainfall, especially associated with high winds and dust as is typical of this region's summer monsoon season, serves to lower adult (Henneberry et al., 1995) and immature densities (Naranjo and Ellsworth, unpubl. data), and stickiness (Henneberry et al., 1995); (3) supplemental overhead sprinkler irrigation can also lead to lower whitefly densities (Castle et al., 1996b; Palumbo, unpubl. data); (4) more consistent delivery of water to meet the plants' needs, such as with drip irrigation or shorter irrigation intervals, limits whitefly population development relative to alternating cycles of saturation and drying (Mor, 1987; Leggett, 1993; Flint et al., 1994, 1995, 1996); and (5) termination of irrigations in cotton earlier in the season reduces risks of late season infestation and damage by whiteflies (Nuessly et al., 1994). The practical result of this research on IPM and guidelines (Ellsworth et al., 1993; Flint, 1996) is somewhat limited. However, growers are advised to closely observe plant–water relations and limit any water stress on the crop especially when whiteflies are present in large numbers, to incorporate any practices that will "buy time" (such as first use of IGRs in cotton) and thereby increase the cumulative chance of significant weather disturbances that can lower whitefly populations, and to meet the water and other needs of the cotton crop during the primary fruiting cycle and expediently terminate irrigations without pursuing a late season, compensatory or secondary fruiting cycle. Growers of high value crops like vegetables and melons rarely, if ever, subject their crops to water-stress. However, watermelon cultivation and markets are such that growers often withhold water after an initial harvest in order to gauge, time, or assess future more favorable markets. This practice results in water-stressed vines, an environment favorable to *B. tabaci* development and dispersal (Blackmer and Byrne, 1999).

Plant–nitrogen–whitefly interactions are also the subject of much investigation, especially with respect to whitefly nutrition (e.g., Blackmer and Byrne, 1999). The evidence of the role of nitrogen (N) in regulating whitefly populations is equivocal (see Hilje et al., 2001); however, there is evidence to suggest that excess N in the cotton system can lead to conditions more favorable to whitefly population development (Blua and Toscano, 1994; Watson et al., 1994; Bi et al., 2001). Further work is necessary here; however, growers are once again advised to plan for the N needs of their crop and, in cotton, provide supplemental N through post-plant, split-applications up to peak flowering only (Silvertooth and Norton, 1996). This recommendation limits N losses through volatilization or leaching and prevents excesses in the plant (Norton and Silvertooth, 1998).

Planting and termination date management represents one of the more powerful tactics of avoidance that a grower can control directly. The benefits of these practices are more fully realized when deployed over large areas (see below); however, even a single grower can impact their risk of whitefly infestation through skilled manipulation of their production season. In general, practices that favor earliness in cotton production reduce exposure of the crop to damaging whitefly populations (Nuessly et al., 1994). Early optimum plantings, timely irrigation termination, and prompt chemical defoliation have been standard recommended practices for low desert cotton production for years. However, with the onset of *B. tabaci* through the early 1990s, growers adopted these tactics at an accelerated rate in order to avoid overwhelming, late summer populations of whiteflies (Nuessly et al., 1994). Growers now better match maturity classes of cotton to various planting windows to ensure timely termination in the fall (Unruh and Silvertooth, 1997). Prior to *B. tabaci* in this region, there were some growers in central Arizona who continued irrigations through October and harvests through December. Later, but prior to the IGRs, growers routinely terminated irrigations in August or earlier, if possible. The Imperial Valley of California had a system of mandatory cultural requirements, developed for *Pectinophora gossypiella* management, that provided for early irrigation and chemical terminations as well as prompt harvest and post-harvest plowdown (Chu et al., 1996). The Yuma Valley of Arizona has a fall vegetable and melon market-induced, compressed cotton season, where growers attempt to double crop cotton with these valuable fall crops (Silvertooth, pers. comm.). In the Mexicali Valley, water shortages there often preclude late season cultivation of cotton (R. León López, pers. comm.). Planting dates have been successfully manipulated in Mexico to help facilitate *B. tabaci* management (Hernández and Pacheco, 1998a, b). Some growers there have experimented with warming soils using plastic and planting cotton in December as an earliness measure to avoid whiteflies. In the Yaqui Valley of Sonora, Mexico, cotton has been planted one month earlier (in December) in order to avoid whitefly populations. Even though low temperatures could be a problem, the benefits in whitefly management were greater (Hernández and Pacheco, 1998a,b). All these practices, whether actively deployed for whitefly management or not, serve to limit the crop exposure and risk to whitefly populations and the viruses they vector. While cotton leaf crumple was rarely a production constraint in cotton of this period, other diseases of vegetables were affected by seasonal cropping patterns and timing (Blua et al., 1994).

Tolerant or resistant varieties (Fig. 2) or host plant resistance is a major, often preventative tactic in IPM. Much research has been done on *B. tabaci* and host–plant interactions that might lead to varieties that are tolerant or resistant to the insect or to the viruses they vector (see Bellotti and Arias, 2001; Morales, 2001). While desert cotton varieties resistant to *B. tabaci* have yet to be identified, much has been reported on the positive relationship of leaf hairiness to whitefly population development (Chu et al., 1995; Heinz and Zalom, 1995; Lambert et al., 1995, 1997; McAuslane et al., 1995; McAuslane, 1996). As a result, and early in the *B. tabaci* expansion to this region, growers were advised to plant glabrous varieties of cotton (Ellsworth et al., 1993). Most of this region already used glabrous varieties (1989–1991: ca. 9% planted non-smooth cultivars) due to the market dominance of one company; however, with the onset of *B. tabaci* in Arizona cotton (1991), even more growers chose to plant glabrous varieties (1992–1993; ca. 4.3% planted non-smooth cultivars). With recent advances in chemical controls, varietal decisions by growers have returned to depend more on traditional traits like yield and quality and new transgenic traits than on susceptibility to whiteflies (1996–2000: ca. 15.1% planted non-smooth varieties) (Moser and Ellsworth, unpubl. data). Nevertheless, new whitefly-tolerant varieties of alfalfa have been developed for this region of production (Teuber et al., 1996). In the Imperial Valley, California, where alfalfa is a spatially dominant crop, the impact of wide-spread use of these new varieties on areawide levels of whiteflies could become significant. Also, two whitefly-tolerant soybean varieties have been developed for northwestern Mexico (Castillo et al., 1998). Though they have not been used commercially, the impact of re-introducing significant summer soybean production in northern Mexico on whitefly seasonal dynamics and management could be significant.

2.3.2. Areawide impact

Areawide impact (Fig. 2) entails a number of avoidance practices that are best implemented within communities over multiple crops or fields, and cropping cycles; most have a significant spatial and/or temporal element (see Kogan, 1998). This level of IPM is closely related to and may even overlap with other levels of avoidance (e.g., crop management) or with the upper tiers of the IPM pyramid (e.g., effective chemical use; Fig. 2). Areawide impact can be achieved either actively through organized programs or more passively through areawide adoption of key tactics or education.

Tactics such as crop placement and intercrop movement are difficult to test in an IPM context. However, research on the dispersal abilities of *B. tabaci* (e.g., Blackmer et al., 1995; Isaacs and Byrne, 1998), localized weather patterns including wind direction (Brown et al., 1995), and producer experience have led to a greater sensitivity about crop placement and proximity to source hosts that generate dispersing populations of adults (e.g., Flint, 1996). Many growers in the region now attempt to avoid placement of cotton immediately adjacent to spring melons, and alternatively, fall melons or vegetables near cotton, and in Mexico, soybeans near cotton. The relative scale of these crops makes it difficult to completely isolate susceptible hosts. However, producers and their pest control advisors use this understanding of whitefly intercrop movement to more intensely monitor and manage nearby host crops. In Mexico, agricultural areas have organized monitoring for whitefly movement using yellow sticky cards. This information is summarized and provided to pest control advisors who use this information to identify crops or areas at risk of infestation.

Alternate host management or source reduction is another key tactic of avoidance in IPM. During the early 1990s, producers of cotton had difficulty with spring melon crops that were grown and then abandoned. These abandoned fields produced large numbers of whitefly adults that migrated to nearby cotton crops. Even with proper post-harvest destruction of these fields, summer rains sometimes germinated melon seeds that subsequently hosted huge numbers of whiteflies before ultimately drying up. These lessons in alternate host management have led to regular recommendations to growers of all crops to initiate timely and complete post-harvest residue destruction. In Mexico, these recommendations, which include planting and harvest dates by region and rules for post-harvest sanitation, are the cornerstone of a mandated strategy.

It was not until the registration of imidacloprid in 1993 (see Palumbo et al., 2001) that melon and vegetable growers finally had a significantly more effective means to manage whiteflies within these crops, often considered significant spring sources of *B. tabaci*. One cannot overestimate the impact that the areawide application of imidacloprid has had on the overall source reduction of *B. tabaci* in the low desert agricultural system of North America. However, experiences after the registration of imidacloprid also showed that this singular tactic alone was not enough to protect cotton from severe losses to *B. tabaci* (e.g., in 1995; Fig. 1A; Ellsworth and Jones, 2001).

Arizona has been on the forefront of the development of areawide and communitywide programs, though usually they have been confined to a single crop (cotton) within an agricultural valley or community. Those directed at *B. tabaci* were sometimes derivative of organization that was originally developed to combat other cotton pests such as the boll weevil or pink bollworm (e.g., Antilla et al., 1995, 1996b). While other tactics of "avoidance" were promoted within these programs, the active components were coordinated sampling and sharing of information that helped both individuals and collectives make strategic decisions about insecticide use. Some then took over responsibility for applying insecticides including IGRs on behalf of the collective (Antilla et al., 1995, 1996b). Other programs were organized around growers who took individual action based on regional sampling and discussion (Diehl et al., 1994; Ellsworth et al., 1996b; Jech and Husman, 1997). These programs, too, served as fertile areas for much needed validation and implementation research on sampling and thresholds (Ellsworth et al., 1996b; Naranjo et al., 1997) and resistance development (Antilla et al., 1996a).

In Mexico after the whitefly crisis of 1992, INIFAP and other University and government scientists developed and promoted a system of avoidance tactics through areawide implementation and legal mandate. They established local whitefly committees that organized growers and supported them with several conferences, so that everyone could be trained and would follow the recommended and/or mandated practices. These included destruction of all crop residues, changes in planting dates and windows, control of weeds, and host-free periods. Fall melons and watermelons (planted during the summer; ca. 1173 ha in 1991; León López, pers. comm.) and sesame (ca. 7451 ha in 1991; León López, pers. comm.) were eliminated from production in the Mexicali Valley of Baja California, Mexico, by 1992. Soybeans in northwestern Mexico declined from ca. 100,000 (1992–1994) to 25,000 ha (1995) and then to nothing in 2000–2001, in part due to market forces and drought (E. Gutierrez, pers. comm.). The areawide impact of these practices including elimination of key hosts or planting windows was likely key to the successful reduction in whitefly problems in Mexico after 1995.

Recent efforts in Arizona have been made to coordinate whitefly management among multiple crops and to harmonize usage of key active ingredients like buprofezin and the novel neonicotinoid class (Palumbo et al., 1999, 2001). Buprofezin has registered uses in Arizona on cucurbits (1999) and cotton (1996). The neonicotinoid class of chemistry is currently available to cotton producers as Actara® (thiamethoxam; 2001) in the US and Rescate (acetamiprid; 1997) in Mexico, and to melon and vegetable producers as imidacloprid. Clearly, agreements must be sought among the proponents of whitefly IPM whereby chemistry can be rationally shared among commodities without exacerbating resistances or the economic management of whiteflies (see Palumbo et al., 2001 for a review of these efforts). Losses of effectiveness of either group of chemistry could seriously destabilize IPM efforts in this region (Denholm et al., 1998, 1999; Li et al., 2000).

2.3.3. *Exploitation of pest biology/ecology*

"Biological-" or "ecologically-based" IPM seeks new and better ways for exploiting a pest's biology and ecology (National Research Council, 1996). While the need for increased efforts in this area still exist, the original concept of "IPM" already accommodates this fundamental building block of avoidance (Kogan, 1998). It is likely only through these and similar tactics of avoidance that less intrusive or sustainable systems of IPM are possible. As "chemically-based" as whitefly IPM would seem to be currently, there are major elements of avoidance, including ecological features, that are integrated into this system's success.

Controlled studies conducted under commercial cotton conditions in Arizona dramatically demonstrated the impact that the IGRs have on whitefly population dynamics (Ellsworth and Naranjo, unpubl. data). In 1996 and 1997, buprofezin or pyriproxyfen led to subthreshold levels for 4–6 weeks. In 1998, populations never rebounded after treatment providing 8+ weeks of suppression with a single application—though the untreated check also stayed below threshold for about 6–7 weeks. In 1999 and 2000, buprofezin or pyriproxyfen each provided for around 6–7 weeks of subthreshold suppression.

The source of this long-lasting suppression has been the subject of much conversation among growers, the industry, and scientists. Because these compounds are known to be longer-lasting biochemically than most conventional alternatives, most speculate that these materials are present in the system for long periods of time (i.e., in excess of a month). This conclusion persists in spite of the knowledge that pyriproxyfen does not move within the plant except translaminarly (Horowitz and Ishaaya, 1996). Thus, new tissue grows out of the treated zone as the cotton plant develops vertically up to 2.5 nodes per week. Analytical data would suggest much shorter chemical residual than 30 d for each of these IGRs (up to 14 d: Ellsworth and Naranjo, unpubl. data; 3.5–16.5 d cotton field dissipation: Knack IGR Tech. Info. Bull., Valent, USA). While these studies confirm the longevity of suppression possible with either compound, the population dynamics are not sufficient to ascribe causality. For this, a more detailed approach is needed (see Riley et al., 1996; Naranjo, 2001).

Starting in 1996, detailed life table studies were initiated to examine whitefly mortality dynamics in these IGR systems in comparison to conventional whitefly control systems and an untreated check (Ellsworth et al., 1998; Naranjo et al., 1998b; Naranjo and Ellsworth, 1999; Naranjo, 2001). Interacting sources of mortality were: weather (dislodgement by severe winds, dust or rain), predation (usually by sucking predators like *Orius* and *Geocoris*), parasitoids, physiological inviability (in eggs and nymphs), and insecticides. Results showed clearly that once the IGRs are applied, their major direct effects (i.e., insecticidal morality) are present mainly during the first generation of exposure (Ellsworth and Naranjo, unpubl. data; Ellsworth et al., 1998; Naranjo and Ellsworth, 1999; Naranjo et al., 1998b). Subsequent generations exhibit low rates of insecticidal mortality due to IGRs (usually less than 5%) which is insufficient to explain the staying power of the IGR control regimes. Predation, however, was a large source of whitefly mortality during most cohorts, but especially 3–6 weeks after IGR use, and especially in the fourth instar. For the first time since these compounds have been registered anywhere in the world, direct evidence of their killing power can be partitioned between two major factors: direct insecticidal mortality and mortality due to other factors, primarily predation. The two together provide >50% more mortality than in a conventional chemistry regime that depended on an average of three sprays (Ellsworth and Naranjo, unpubl. data). The IGRs exert more influence over the pest population than conventional chemistry as a result of a "bio-residual". This bio-residual is defined as the overall killing power of an insect control technology including the direct effects of the technology as well as the associated natural biological mortality. In the case of the IGRs, the major distinguishing features of their bioresidual are their highly effective insecticidal effects on the generation of exposure and their selective nature that preserves the existing predator fauna. Thus, when growers report 30 d "residual" of their IGR, they benefit from bio-residual that includes ca. two weeks insecticidal mortality and mortality inflicted by predators that have been preserved in the system selectively (see Naranjo, 2001). Furthermore, the extended interval provided by this selective approach increases the cumulative chance of significant weather events that provide additional mortality.

The consequences of knowing this about our IGRs in the cotton–whitefly system are significant and not simply academic. It re-enforces the three major recommendations for the usage of the IGRs in cotton (e.g., Ellsworth et al., 1996a).

(1) *Use IGRs first when indicated by sampling and associated thresholds*: This recommendation stems from the recognition that these compounds are not broad spectrum and thus preserve the existing natural enemy community. By starting a whitefly management program with the IGRs, an extension of the period during which predator populations can continue to grow and function is assured. Chances of mortality as a result of inclement weather also are increased.

(2) *Use IGRs singly without mixing with other whitefly control chemicals*: This recommendation follows the same logic as above. By avoiding the broad-spectrum, conventional mixtures, predators are given every chance to function. These studies suggest that aggressive mixing of chemicals at this stage in the population development would be tantamount to throwing away half of the bioresidual of the IGRs, in essence wasting money.

(3) *Delay the use of follow-up treatments for 14–21 days after the IGRs*: This recommendation is with respect to the longer residual and slower action of the IGRs which must be given time to work. The life table work described above sheds new light on why this interval is helpful in recognizing gains in population suppression. Especially when compared to conventional spray regimes, the predator : host ratio is more favorable to predator function in the second whitefly generation after the IGR is used. This takes a minimum of 14 d under most summer conditions in the low deserts of North America.

The ramifications of these life table and dynamics studies with IGRs in contrast to unmanaged systems are manifold. Through better understanding of in-field mortality dynamics of *B. tabaci* and the functional roles of natural enemies, concepts such as bioresidual in the system can be developed (see also Naranjo, 2001) and taught to growers and practitioners of whitefly IPM. Furthermore, these type of studies can be extended to the cool-season cropping cycles that exist in the agriculturally intensive North American low deserts (Cañas, Naranjo, and Ellsworth, unpubl. data). Given the year-round cropping system of this region and the important host-shift in this biotype to include winter-grown crucifers and cole crops (Perring, 1996), these investigations are needed to understand the overwintering ecology of *B. tabaci* as a means to develop new biologically-based control tactics and to foster an understanding that should lead to the ability to better predict pest outbreak conditions. This is a burgeoning area of whitefly IPM that will undoubtedly also make use of innovations in landscape ecology (e.g., Brewster et al., 1999).

3. Adoption and evaluation

Previous accounts of IPM have attempted to identify sentinel practices as proxies for IPM such as pesticide usage or quantity, or acres employing a professional scout. While these are useful studies of individual systems and practices, it is rare that such an effort adequately describes the IPM system or its adoption. So, too, insecticide use statistics or adoption rates of IGRs, where available, do not fully describe adoption rates of IPM in the North American low desert agroecosystem. Unfortunately, short of an organized survey or sociological study, we cannot know precisely how well implemented this IPM program is, except for the accounts of the successful results with respect to whitefly management (e.g., Ellsworth and Jones, 2001). Most other evidence is anecdotal, but supportive of large changes in producer behaviors and understanding of whitefly IPM. It is important to realize, too, that all components of the program described herein do not necessarily have to be consciously implemented by growers in order to be "adopted". For example, some growers may not deploy IGRs with the conscious intent of conserving natural enemies; however, by systematically adopting all the related recommendations for their use—sampling, thresholds, waiting period, single-use, limited mixing with broad-spectrum insecticides, resistance management—they in fact benefit from the bioresidual of the IGRs.

The IGRs were not initially as well-accepted in Mexico, in part because their inability to knockdown adults was not well-understood among growers [note: use rates were lower there, too (125 g a.i./ha buprofezin vs. 393 g a.i./ha in the US) and multiple applications were encouraged]. As a result, buprofezin has been used on only a limited amount of cotton (ca. 10–30% on average in Mexicali Valley) and ornamental hectarage, and pyriproxyfen was unavailable until relatively recently. Instead, the implementation of an IPM program that depended heavily on a set of avoidance tactics implemented areawide by legal mandate in the Mexicali Valley, B.C., Mexico, led to a return in cotton plantings since 1996 (15,000–55,000 ha) with little evidence of serious whitefly infestations. Also, by eliminating fall production of key whitefly hosts like melons, watermelons, and sesame, this area has created a host-free period of sorts. When chemical controls are needed, growers there make full use of the sampling and threshold guidelines and depend more on the neonicotinoid, acetamiprid, than the IGRs. Similarly, the Yaqui Valley of Sonora, Mexico, which has only a minor hectarage in cotton (ca. 8391 ha in 2001), escapes major problems from *B. tabaci* through the elimination of a key summer host, soybeans, and adherence to other cultural recommendations (Martínez-Carrillo et al., 1998).

In the US, IGRs are elected for use on over half the acreage in Arizona cotton (1996–1999), and the average number of foliar sprays against *B. tabaci* have steadily declined since the introduction of the IGRs (Fig. 1B; Ellsworth and Jones, 2001). Indeed, since 1996, foliar insecticide intensity for all pests has reached a 22-year low in 1999 (1.91 sprays; 0.4 for whiteflies) down from 1995s record-setting 22-year high (12.5 sprays; 6.6 for whiteflies). The average number of sprays made against whiteflies in Arizona cotton since 1996 (5-year ave.) has been just 1.18 (down from 4.1 for the previous 5 years); 0.44 of these were IGRs. Econometric studies of adoption of the IGRs in Arizona showed that net reductions in costs of whitefly control in cotton by IGR-adopters averaged \$73.26/ha or about \$11,000 per farm (Agnew et al., 2000). Large scale adoption of key chemical tactics, like IGRs in cotton and imidacloprid in melons and vegetables, was supported by intensive educational programs in Arizona and California. As a result, growers report wholesale, areawide reductions in pest densities even on the minority of non-adopting acres. The collateral benefits of this effect along with large-scale adoption of Bt cotton (ca. 64%) have been substantial. Many cotton growers in Arizona have reported on individual fields each year that have escaped the need for any foliar insecticide use during the last three seasons (Ellsworth, unpubl. data).

4. Conclusion

A model of whitefly IPM has been proposed that conveniently organizes all *B. tabaci* control tactics into a multi-level, multi-component pyramid. This approach logically arranges the ecologically and biologically rational aspects of IPM at the base or foundation of the structure, Avoidance. Sampling and Effective Chemical Use remain critical components of IPM, especially when dealing with an outbreak condition such as occurred with the introduction of biotype B to the low deserts of North America. This flexible model may be useful for organizing, viewing, and even assessing and teaching IPM for whiteflies or other pests in other regions of the world.

The severe and shared nature of the B biotype of *B. tabaci* in the low deserts of North America's many crops demanded an integrated solution to the outbreak crises that faced growers during the early 1990s. Cotton, as a dominant occupant of the agricultural landscape and principal summer host for *B. tabaci*, is the focus of intense research and extension that has led to rapid formation, implementation and adoption of this IPM plan. The near universal adoption of source reduction tactics in vegetables and melons (including the use of imidacloprid and post-harvest sanitation) and the near simultaneous deployment of IGRs among many cotton growers have led to a putative areawide impact or lowering of pest density to levels at which other tactics become more effective (e.g., natural enemy conservation, crop placement, crop management). Arguably, this is a "chemically based" IPM strategy. However, the IGRs may also be viewed as ecorational based on recent studies that have begun to identify the factors which make the current system of management so successful. These findings emphasize the importance of natural enemy conservation within a selective IGR approach and may chart a path toward even greater gains in natural enemy conservation and other non-intrusive means of ecological management of *B. tabaci* through similar studies of cool-season dynamics in multiple hosts. As a result, a new concept, "bioresidual", has been proposed (also see Naranjo, 2001) that advances our understanding of the integration of chemical and biological control tactics. Selective chemistry, and specifically the IGRs, will likely become major, if not sustainable, features of other whitefly management programs if deployed properly and if the biological and ecological elements of IPM are known and exploited.

Organized educational programs that stimulated widespread knowledge and adoption were critical to the success of IPM in the US and Mexico. Growers will continue to need education and commercially relevant guidelines in order to keep up with the constant changes in pest control technologies as well as advances in our understanding of the agroecosystem within which they work. Major catastrophic change, like the introduction of biotype B to this region, can and will happen again. With *B. tabaci* entrenched as a resident of the low deserts of North America, it would seem to be a matter of time before some whitefly-vectored, exotic or locally derived virus becomes a major production challenge to one or more crops of this region.

The future of IPM research for *B. tabaci* will likely find fertile ground in various landscape approaches (see Riley et al., 1996) that make ample use of new information coming from direct observational studies such as life tables (see Naranjo, 2001). Furthermore, a better understanding of whitefly dynamics at extremely low (e.g., near localized extinction), cool-season, densities will likely provide new insight into habitat manipulation or other non-crop practices that will limit population outbreaks.

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