Integrated Management of Whiteflies in Arizona

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The Problem

The sweetpotato whitefly, *Bemisia tabaci* Genn., has been present in Arizona since the first cultivation of cotton in the 1920s (Russell 1975). For much of its history, its importance was as a sporadic pest and vector of cotton leaf crumple virus. Meanwhile around the world, outbreaks of whiteflies were recorded in cotton in places like the Sudan, Punjab of India, and Israel. The New World also had outbreaks of whiteflies, though smaller, throughout central America and even in South America (e.g., in Brazil soybeans). The populations responsible for these outbreaks may have been from one or more biotypes of the sweetpotato whitefly. But by the late 1980s, a new whitefly was associated with a silvering syndrome in squash (Costa & Brown, 1991) and later renamed by California workers as the silverleaf whitefly, *B. argentifolii* (Bellows & Perring). Currently, there is a working synonymy between Biotype B of *B. tabaci* and *B. argentifolii* (SWF) (See Perring 2001 for review). It is this biotype or species that invaded Arizona in the early 1990s and has irrevocably altered our integrated pest management (IPM) plans here.

The importance of SWF to Arizona cotton is based not only in its capacity to deplete and disrupt phloem supply to the plant, but in its excretion of a viscous liquid honeydew, which contaminates leaf and lint surfaces with sugars. These sugars render the harvested lint sticky once the lint comes in contact with modern high-speed milling equipment. These sugars also host microbes that produce sooty molds that further weaken and discolor fibers. Because the current USDA grading and marketing system does not measure the levels of sugar contamination, there is no organized method for the marketplace to avoid costly mill shutdowns as a result of acquiring and processing tainted lint. The solution has been instead to avoid purchase of lint from whole regions suspected as having potential to deliver cottons contaminated with unacceptable levels of sugars. This downward market pressure on price has resulted in areas around the world receiving relatively lower prices for their cottons, even if they are free of sugars.

SWFs invaded Arizona in 1990 in the extreme southwestern part of the state. By 1991, that region of vegetable, melon and cotton production was experiencing heavy losses, and the insect began to spread to the low desert valleys of Central Arizona where more than two thirds of the state's cotton is produced. By 1992, Arizona experienced its first epiphytotic of whiteflies with widespread losses throughout the low elevations (< 700 m). This outbreak was exacerbated by a general lack of understanding about the damage potential and control of this pest. Once harvested lint reached the marketplace and buyers began to have problems with its processing, prices for Arizona cotton, when it could be sold, dropped severely. Reductions have been reported as anywhere from $0.02–0.07 per lb of lint during this period (Ellsworth et al. 1999). Management improved greatly in the next two years due to advances in control technologies and the decision support systems that support them. The informal price 'discount' was concomitantly less severe. However, in 1995 Arizona experienced its second major outbreak episode with huge populations invading crop fields as clouds of whiteflies by the end of the cotton season. This outbreak was also associated with major, detectable reductions in efficacy of and susceptibility to synergized pyrethroids, the mainstay of chemical control during the early 1990s (Dennehy & Williams, 1997). The marketplace responded negatively once again by paying reduced prices for Arizona lint.

Years have past since the last great outbreak of 1995, and management has improved dramatically since major changes took place in 1996 (described below). However, even today, Arizona growers of cotton still receive less money for their cotton relative to New York Futures (ca. $-0.02/lb) than they did 15 years ago (ca. $+0.02), preceding the introduction of SWF to our region. Still, our reputation for producing a high quality lint has been restored and continued vigilance by the growing community will hopefully someday erase the memory of 1995 and 1992.

The Response

The response to the crises faced in 1992 and 1995 was multilateral. There were major and immediate shifts in research by the scientific community (University and USDA-ARS) to focus their efforts on the whitefly problem. Grower groups and the agrochemical industry also responded with programs of research and implementation of their own. Finally, there was a concerted, organized effort by educators to develop, implement, and disseminate information to the agricultural sector. Each of these advances provided the building blocks for the successful IPM program that is currently in place.

Organized research programs were planned and implemented in Arizona and throughout the U.S. (see Oliveira et al. 2001 for review). Within and outside of these organized programs, many researchers worked feverishly towards near-term solutions for the SWF problem. These contributions have been summarized in other reviews or volumes (see reviews within Gerling & Mayer, 1996; and Naranjo & Ellsworth, 2001). The areas of major and/or immediate impact included such things as sampling, action thresholds, chemical and cultural controls, application technology/methodology, and resistance management.

The agricultural community and agroindustry did not sit still during this period. Major developments in new chemistry (e.g., imidacloprid), re-purposed old chemistry (e.g., amitraz), and combinations of current chemistry (e.g., fenpropathrin + organophosphates) were made. Grower groups banded together in large, areawide programs that featured coordinated sampling and timing of sprays (e.g., Antilla et al. 1995).

The educational system was also activated by the SWF crisis (e.g., USDA-Cooperative Extension System and cooperating land-grant Universities). Extension scientists embarked upon organized educational programs that included elements of adaptive research, coordinated implementation, and rapid publication and dissemination of information (e.g., Ellsworth et al. 1996b).

Ultimately, the current solution depended on a central feature made possible through regulatory relief, which was spearheaded by Extension scientists, cotton grower leadership, and collaborating agrochemical registrants. In 1996, Arizona sought and was granted an EPA Section 18 Exemption from registration for two unregistered insecticides. These insect growth regulators (IGR) are center pieces of the IPM plan presented below.

The Arizona Plan

IPM depends on the integration of tactics as strategic elements of an overall management plan that protects economic, social, and environmental interests. The economic costs of SWF to growers in Arizona was well in excess of $10 million per year (Table 1; Ellsworth et al. 1999; Ellsworth & Jones, 2000, 2001). The social costs came in the form of lost jobs (e.g., Gonzales et al. 1992) and reduction in the quality of our rural communities, not to mention the friction that occurred at the urban-agricultural interface where SWF invasions impacted the quality of life of millions of urban residents. The environmental load incurred by the increased use of insecticides during the early 1990s is inestimable; however, the use of foliar cotton insecticides in 1995 marks a 25-year high for the state of Arizona (over 12 sprays / A).

The Arizona plan, first established in 1996, has reduced or eliminated many of the barriers mentioned above, making this one of the more dramatic success stories in IPM of the last century. Insecticide use in Arizona cotton hit a 25-year low in 1999 with just under 2 foliar sprays required for all pests. Using 5-year averages pre- and post-introduction of the current IPM plan, cotton growers alone have saved over $100 million just in SWF control costs (Table 1). Fall melon and vegetable markets, which were once curtailed by SWF presence, are now flourishing in the southwestern part of the state and are expanding to new areas. Friction with urban communities has been all but eliminated, and informal observations are regularly reported on the increased diversity and abundance of arthropod natural enemies in cotton fields.

Whitefly management under this plan depends on three fundamental keys: '*Sampling*', '*Effective Chemical Use*', and '*Avoidance*'. The building blocks which form these three keys to management are organized into a conceptual pyramid and have been reviewed and detailed elsewhere (Ellsworth & Martínez-Carrillo, 2001). The remainder of this paper will briefly outline the structure of this pyramid and its subsidiary pieces (Fig. 1), while highlighting a few of the major accomplishments or understanding achieved in the development of this IPM plan.

All those practices that serve to prevent or maintain pests below economic levels are termed '*Avoidance*', which forms the foundation of this or any IPM plan (Fig. 1). *Avoidance* may be further subdivided with *Crop Management* at its base. Many of the factors within *Crop Management* serve to limit SWF numbers directly or indirectly through uniformity of management, which, for example, limits the migrational movement of SWF adults from one field to another. The second level of *Avoidance* could be casually termed 'know your enemy', because it is only through understanding the pest's biology and ecology that one can exploit its weaknesses. For instance, Arizona grows cotton at various elevations that support varying numbers of generations (e.g., sea level, 400 m, and 800 m) which indicate varying management responses. Because SWFs are polyphagous and highly mobile, *Avoidance* depends on various tactics that have or achieve '*Area-Wide Impact*'. This whole level depends on stable systems of management to be in place for all crops of the agroecosystem (in our case, spring and fall melons, and winter vegetables; e.g., see Palumbo et al. 1994, 2000). Because of our desert climate, Arizona provides for continuous culture of SWF hosts in many areas (Watson et al. 1992). Thus, the common agricultural good is served when growers of diverse commodities interact and cooperate. This might include special attention to crop placement relative to sensitive hosts, post-harvest sanitation (esp. in melons), and awareness of the timing and direction of inter-crop SWF movement. Arizona has major elements of cross-commodity interaction and organization (Palumbo et al. 1999, 2001; Palumbo & Ellsworth, 2002).

Ultimately, however, the Arizona plan depends on the upper two levels of the IPM pyramid when damaging numbers of SWF are present. *Sampling* sits atop the pyramid and serves all other layers of management. Our sampling plans are solidly based in research (Naranjo & Flint, 1994, 1995; Naranjo et al. 1996b), thoroughly validated and implemented (Ellsworth et al. 1996b; Naranjo et al. 1997), and routinely taught to growers through publications and demonstration (Ellsworth et al. 1995, 1996c; Diehl et al. 1996, 1997). Our sampling plans are also multidimensional, specific to life stage, and associated with specific action thresholds and stages of chemical use. Determining the need for IGRs and other insecticides depends on a sampling program for adults and large nymphs (Fig. 2). This binomial system is based on scoring leaves or leaf disks as "infested" or "uninfested" from the fifth main stem leaf below the terminal. A 30-leaf/leaf disk sampling bout should take on average just 7 minutes to complete in an average sized management unit (ca. 40–80 A). This sampling plan along with other program elements were taught to over 700 growers and pest control advisors in 1996 as part of an organized educational campaign to launch the new IPM program and prepare the industry for deployment of the new IGRs (Ellsworth & Martínez-Carrillo, 2001).

'*Effective Chemical Use*' is central to an IPM plan that deploys chemistry only as needed and in the most effective manner. With proper sampling, one can apply '*Action Thresholds*' for precise timing of IGRs (i.e., in Stage I; Dennehy et al. 1996a; Ellsworth et al. 1996a) and other SWF insecticides (i.e., in Stage II & III). Research-based SWF thresholds (Naranjo et al. 1996a, 1998a) are key to *Effective Chemical Use* and inform the user of the optimal timing of IGRs, where we teach a dual-system of sampling and decision-making. When 40% of the leaves are infested with 3 or more SWF adults <u>and</u> 40% of the leaf disks are infested with 1 or more large nymphs (instars 3 or 4), IGRs are best timed and should precede the use of any other SWF insecticides. Follow-up timing with conventional, adulticidal sprays is needed when 57% of the leaves are infested with 3 or more adults.

At the center of *Effective Chemical Use*, indeed the entire IPM pyramid, lies '*Selective & Effective Chemistry*.' Knack® (pyriproxyfen, Valent USA), as a juvenoid sterilant, and Applaud® (now known as Courier®, buprofezin, Nichino America), as a molting inhibitor, are highly selective for whiteflies in our system (Ishaaya et al. 1988; Ishaaya & Horowitz, 1992). Admire® (imidacloprid, Bayer AgriSciences), when soil applied in melons and vegetables, is also very effective and selective. The widespread adoption of all three of these compounds has provided an effective, yet selective, approach to reducing SWF populations dramatically throughout our agroecosystem.

Recent ecological studies have shown just how important, yet strategically small, these IGRs are in contributing to SWF mortality (Ellsworth & Naranjo, unpubl. data; Naranjo et al. 1998b;

Naranjo & Ellsworth, 1999). For example, a comparison of unmanaged SWF populations (i.e., leading to outbreak conditions) to IGR-managed populations show that generational survivorship is just over 4% vs. under 1%, respectively. This 3% difference between the outbreak state and the well-controlled state is strategically accomplished by these IGRs and concomitant mortality as a result of natural factors.

Thus, the widespread deployment of IGRs according to rational decision-making protocols interacts with other levels of the IPM pyramid, like *Avoidance*. By studying '*In-Field Mortality Dynamics*', using life table approaches, we have been able to demonstrate significant '*Natural Enemy Conservation*' when IGRs are used properly. As a result, we have developed a new concept, "bioresidual", to explain the unique and dynamic killing power of the selective IGRs. As defined by Ellsworth & Martínez-Carrillo (2001), bioresidual is the overall killing power of an insect control technology including the direct effects of the technology (i.e., chemical residual) plus the associated natural biological or ecological mortality (also see Naranjo 2001). This concept helps explain the long interval of suppression experienced by growers who use IGRs, often more than 30 days for a single IGR application. Furthermore, our studies have measured directly and shown that IGR-based control programs are extended by this bioresidual and are superior to programs based on conventional, mostly adulticidal and broad-spectrum, insecticides. Specifically, we have analytic and field bioassay information that confirms that Applaud and Knack each last no more than 14 days chemically. However, adding the effects of predation and other natural mortality factors, a prolonged period of suppression is possible (up to 7–8 weeks) with just a single spray of Applaud or Knack. Data from our large-scale trials (4-yr average) showed that the average "control" interval for an IGR was 4–8 weeks, while the average control interval with conventional chemistry was only 16 days (Ellsworth & Naranjo, unpubl. data).

With respect to *Effective Chemical Use* and proper deployment of IGRs, our recommendations are three-pronged. 1) Use IGRs first (1 use each only) according to the IGR threshold of 40% adult and 40% large nymph infestation; 2) Use IGRs without mixing with other chemicals, if possible, thereby maximizing the bioresidual; and 3) Delay the use of follow-up sprays for 14–21 days to allow at least one generation of SWFs to develop and be impacted by these slow-acting regimes (Ellsworth et al. 1996a).

Clearly when an IPM program is dependent on key effective and selective chemistry, actions must be taken to preserve the efficacy of these compounds. Thus, we carry a shared responsibility for '*Resistance Management*.' SWF losses of susceptibility to synergized pyrethroids in 1995 taught us the importance of developing and adopting strict resistance management guidelines (Dennehy & Williams, 1997). All SWF insecticides are placed into a three stage system with IGRs first to gain maximum advantage of bioresidual. Each IGR is recommended for usage no more than once (Ellsworth et al. 1996a; Palumbo et al. 2001). There have been no major shifts in susceptibility to either compound since their introduction in 1996 (e.g., Ellsworth et al. 1999b; Dennehy et al. 2002). The three stage strategy continues to protect the pyrethroid class by reserving its use until the last stage (III: pyrethroid combinations) and by limiting pyrethroid usage to no more than 2 uses per season (against all pests). Stage I includes no more than one use each of both IGRs; Stage II includes all non-pyrethroids and are recommended for use at least once prior to choosing from Stage III materials. No active ingredient should be used more than twice for all pests under this plan (Ellsworth et al. 1996a; Ellsworth & Watson 1996).

Protection of chemistry through strict resistance management guidelines is all for naught if applied in only one crop, when a polyphagous pest like SWF is involved. Thus, recent efforts have focussed on harmonizing use among multiple commodities, which share SWF as a pest and share much of the same chemistry. A review of this effort has already been published (Palumbo et al. 2001). Briefly, the cross-commodity system depends on a categorization of agroecosystems in Arizona as either "Cotton-intensive Communities" or "Multi-crop Communities". Much of Arizona might be called cotton intensive (typified by the Buckeye area), and the IGRs play a proportionately larger role there. However, there are many small areas of intensive, multi-crop production, throughout the state, similar to the large, Yuma area adjacent to Mexico and California. The guidelines are developed for these two different types of communities (see Palumbo & Ellsworth, 2002). The community unit is subjective, but should be based on localized knowledge of SWF movement and interaction among crops. Certainly, a grower of cotton immediately adjacent to a spring or fall melon producer must consider himself/herself within a multi-crop community, even if the larger community is monocultural.

The resulting *Resistance Management* guidelines serve to limit and separate uses of key active ingredients. For example, Applaud, which is registered in multiple crops, is suggested for limits of 1 use per crop season and 3 uses per year (in a multi-crop area) with an interval of at least 4 weeks or 2 SWF generations between uses. Neonicotinoids such as thiamethoxam, acetamiprid, thiacloprid, and dinotefuron, as well as the original, imidacloprid, are also extremely valuable in low-desert whitefly (and aphid) control. Registration trajectories would suggest that once all are available, individual fields could be legally sprayed 4–8 times with this class of chemistry. Because Admire use in melons and vegetables is critical to the success of our IPM plan in cotton and to the viability of these other crops, there are great incentives for there to be cross-commodity agreements about limiting the use of this class of chemistry. Currently, we are proposing that the foliar neonicotinoids not be used at all on cotton in multi-crop communities, and used no more than twice (non-consecutively) on cotton in cotton-intensive communities, and even then only in Stage II after the use of an IGR (Palumbo & Ellsworth, 2002). Several advisory groups and some of the affected companies have already endorsed these recommendations.

Sustainability?

The recent decade has seen calls for greater sustainability of our production systems. The definition is certainly subject to interpretation; however, the central feature of sustainability is longevity. How long has the current Arizona plan been effective? How much longer will it remain effective? To the first question, our surveys of insecticide use and other practices would suggest that the Arizona IPM plan has been functioning for at least 6 years, since 1996 when it was introduced (Ellsworth & Jones 2000, 2001). To the second question, we can only speculate. Last year (2001), localized incidences of sticky cotton were identified in Arizona and California. Some of this was blamed on depressed prices and therefore depressed incentives for careful production and SWF inputs. However, there is no question that complacency is a factor, too. Growers began to consider SWF as a minor pest, despite past experience, and certainly as one that was “easily” managed. The ecological features of 2001 led to an unusually early infestation in cotton and many growers failed to either recognize this or, once recognized, failed to respond appropriately.

The elements of the Arizona IPM pyramid are still functioning and available to all growers. As new chemistry (like the neonicotinoids) or other new developments arise, they can be easily incorporated into the conceptual framework of this plan—the hallmark of any successful IPM plan is its adaptability. Millions of dollars have been saved through the development and deployment of this IPM plan. This has helped stabilize the agricultural sector of the desert southwest US, and markets have been restored, at least partially. Also, an environment has been fostered whereby even other pests may be managed in the future through more ecologically-intensive tactics. Complacency remains the enemy of IPM sustainability, both in the end-user and in scientific communities. Continued innovation will be necessary if we are to avoid a future, more intractable problem with *Bemisia*-vectored disease agents. Even though statewide average spray requirements for SWF are only around 1 spray per acre, further ecological research should be conducted to develop even better systems of *Avoidance*, which could further drive down the need for remedial SWF inputs.

Conclusion

In summary, the major features of the Arizona IPM plan include multiple elements of “*Sampling*”, and “*Effective Chemical Use*”, built upon a foundation of “*Avoidance*”. The principal aspects that have led to 6 years of successful SWF management have been explicit, research-based guidelines for sampling and action thresholds, access to the powerful and selective IGRs with proven guidelines for their use, and the extended action of this selective strategy known as bioresidual, which maximizes the natural mortality factors of the SWF. Further, the entire program was activated by an aggressive and comprehensive educational outreach program that taught directly to growers and pest control advisors these specific tools and fostered a culture of shared responsibility for resistance management. Altogether, the effect of equipping the end-users with science-based tools and the knowledge to deploy them appropriately has led to an important element of areawide impact, where, in some cases, even fields that have never been sprayed escape damage by SWF. Areawide impact also depends on similarly sophisticated programs of management to be in place for all sensitive crops simultaneously (e.g., spring and fall melons, winter vegetables, and cotton). Thus, areawide impact can be both an active exercise as was the case in the past with several grower-sponsored programs around the state, or a passive result of an industry responding in concert to use the proper tools and technology to address a problem. In this manner, each grower monitors and addresses the SWF situation individually according to the articulated IPM plan, and an areawide lowering of pest density is often the result, yielding better than expected results for all.

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Table 1. Statewide average cotton SWF control, loss, and economic information for the five year period preceding and five year period following the introduction of the Arizona IPM plan. Based on these five year averages, no. of applications have declined over 71% for a total economic impact (yield loss + cost of control) of over $100 million saved Arizona cotton growers.

Year	*No. of Applications*	*Control Costs ($US / A)*	*Yield Loss (%)*	*Total Yield Loss ($US millions)*	*Total Control Costs ($US millions)*	*Total Economic Loss ($US millions)*
Pre Introduction of Arizona IPM Plan						
1991	1.80	$25.20	0.31	$1.1	$11.6	$12.7
1992	5.10	$91.80	8.54	$20.1	$39.0	$59.1
1993	2.60	$52.00	3.26	$8.4	$19.3	$27.8
1994	4.40	$88.00	1.76	$4.7	$27.5	$32.1
1995	6.60	$145.20	1.31	$4.2	$59.8	$64.0
5-yr Ave	4.10	$80.44	3.04	$7.7	$31.5	$39.2
Post Introduction of Arizona IPM Plan						
1996	2.00	$57.86	2.11	$7.2	$18.2	$25.4
1997	1.81	$52.72	1.03	$3.2	$17.1	$20.3
1998	1.05	$35.70	0.28	$0.6	$8.9	$9.4
1999	0.40	$10.91	0.17	$0.3	$2.9	$3.2
2000	0.66	$19.29	0.52	$1.6	$5.4	$6.9
5-yr Ave	1.18	$35.30	0.82	$2.6	$10.5	$13.1
Change	**-71%**	**-56%**	**-73%**	**-66%**	**-67%**	**-67%**

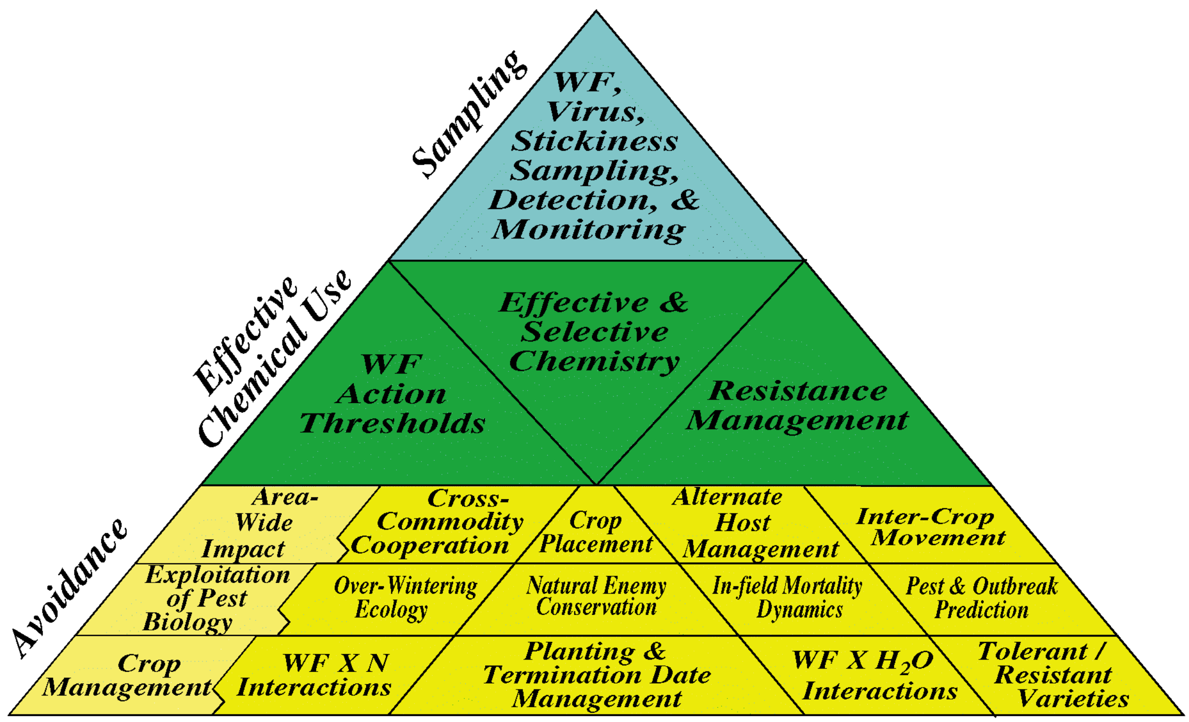
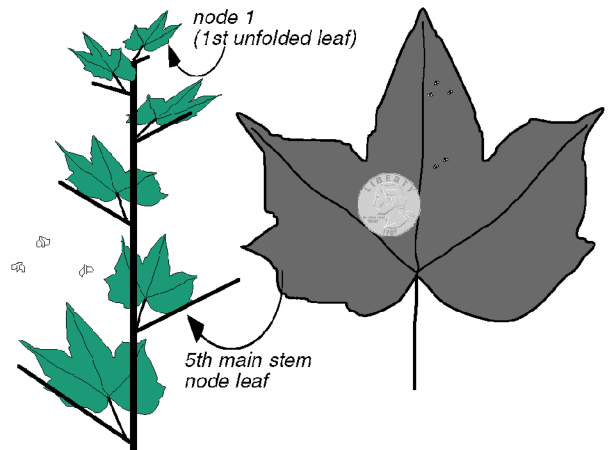


Figure 1: Conceptual diagram of whitefly IPM, depicting three keys to whitefly management (left): *Sampling*, *Effective Chemical Use*, and *Avoidance*. *Avoidance* can be further subdivided among three inter-related areas: *Areawide Impact*, *Exploitation of Pest Biology & Ecology*, and *Crop Management* (from Ellsworth & Martínez-Carrillo, 2001).

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

IGR Threshold Decision Matrix		***Whitefly Adult Levels***	
		fewer than 3 per leaf	**at least 3–5 per leaf**
Whitefly Large Nymph Levels	**fewer than 1 per disk**	Wait and re-sample in 3–7 days	Wait; Re-sample in 3 days; **or** Use a Stage II adulticide; **or** apply Knack
	at least 1 per disk	Wait; Re-sample in 3 days; **or** apply Applaud	Spray with either IGR

Figure 2: 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, were taught to hundreds of growers in southwestern U.S. and northwestern Mexico (from Ellsworth & Martínez-Carrillo, 2001) (adapted from Ellsworth et al., 1995, 1996c; Diehl et al., 1996; Naranjo et al., 1996b).