COTTON IPM IN ARIZONA: A DECADE OF RESEARCH, IMPLEMENTATION & EDUCATION

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Summary

Cotton production in Arizona has been faced with major challenges in insect control during the past decade. These challenges have been met through IPM programs of research, implementation, and education. The decade began (1990) with an outbreak of our key lepidopteran pest, the pink bollworm. Growers sprayed for all pests more than 11 times at a cost of over $113 / A that year. The following years (1991–1995) saw the introduction of and devastation by a serious, quality-reducing insect, the sweetpotato or silverleaf whitefly. Growers sprayed up to 6.6 times (1995) at a cost of over $145 / A to combat this single insect pest. The cotton IPM program at the University of Arizona along with industry, grower, and USDA partners readied farmers for the introduction (1996) of two strategic sets of pest control technology, 'Bt' transgenic cotton and insect growth regulators (IGR). Through an aggressive educational campaign, growers learned about the safe, effective, and sustainable use of these technologies. As a result, cotton growers saw their average spray requirement plummet from 12.5 sprays at $217 / A (1995) to an historic low of 1.91 sprays at $37 / A (1999). Now new threats from an old pest, *Lygus* bugs, pose serious challenges to these staggering advances in cotton IPM. This paper highlights the key advances made in research, implementation, and education during this volatile decade. Furthermore, we conclude with one example how systematic, large-scale, and long-term research can provide insight into the role that new technology and the knowledge to use it properly have on cotton grower and industry success.

Introduction

Pest management in Arizona during the 1990's has been filled with unique challenges and solutions. This tumultuous period was dotted with pest outbreaks, grower adaptation and perseverance, and spectacular recovery and progress. The elements that helped broker these tremendous successes cotton growers now enjoy—at least with respect to pest management—were comprised of multiple groups who worked individually and together towards solutions. The University of Arizona, the Land-Grant University in this state, and Cooperative Extension have been at the center of response to many of these imposing challenges to this important industry. This paper briefly details a historical review of the pest pressures and responses to each in terms of research, implementation, and education. The importance of our mission as a Land-Grant institution has been instrumental in catalyzing a multilateral response to and recovery from insect pest pressures that would most assuredly have been fatal to the cotton industry of this state.

Arizona's Pest Complex: A Historical Review

Arizona's pest complex has shifted over time due to natural and man-influenced factors that are not entirely understood (e.g., Ellsworth & Barkley, 2001). Throughout the last decade, however, the primary pests of concern have not changed: Pink Bollworm (PBW), *Bemisia* whiteflies (SWF), and *Lygus* bugs. These three pests dominate the attention and pest control budgets of our growers. In an analysis of pest control trends over the past 22 years (Table 1), only two occurrences outside of the 1990's appeared in the rankings of severe pest incidences ('years'). Also, no pest other than these three primary pests have ever ranked in the top five most severe pest incidences over nine categories of classification (Table 1: 11 for PBW; 13 for *Lygus*; 21 for SWF).

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The PBW outbreak of 1990 was the third most costly outbreak of all time in AZ (Table 1). More sprays were directed at this pest in that year than for any other pest in any year (6.8). Subsequent to 1990, PBW declined in importance; however, more acres were treated for PBW in 1994 and 1995 than any other pest of the 1990's. PBW has not shown up in these rankings since 1995 (Table 1).

The 1992 SWF outbreak was the second costliest on record and impacted yields more than any other pest (Table 1). Vast areas of cotton plantings were biologically defoliated due to the stress imposed by this insect. By 1993, growers adopted a defensive production strategy that included a much abbreviated season, and this along with other advances in understanding helped to limit the damage by this pest but not without its cost. The largest portion in history of a grower's control budget was spent fighting this pest in that year (Table 1; Fig. 1). The following year (1994) continued a trend of increasing costs to control this pest ($/A; 3rd most expensive on record). But by 1995, SWF became the most costly outbreak of a pest in AZ cotton in history. Foliar spray intensity was higher in 1995 than in any other year of the 1990's and in history (Fig. 1). Altogether, the SWF infestations of 1992–1995 dominate the rankings of pest severity (Table 1) and occupy the No. 1 position in 7 of 9 categories of impact. SWF deposits honeydew, a viscous sugary excrement, that contaminates lint and prevents efficient processing (Ellsworth et al. 1999b). The costs of these quality losses to the industry or the reductions in price to growers for their cotton in this state during this period were not included in any of these analyses. Thus, SWF's economic and historic importance to AZ cotton is even greater than reported here. SWF remains a key pest of our system; however, no occurrences of this pest ranked in the top 5 most severe for the variables measured since 1995 (Table 1).

In categories related to yield (Table 1), *Lygus* infestations occupy almost two thirds of the top 5 rankings of most severe losses. The 1998 outbreak was the second most severe loss (%) to an insect pest in history. The El Nino influenced winter of 1997–1998 and the change in crop ecology to include other key hosts (e.g., alfalfa grown for seed) and timing for *Lygus* helped to create conditions conducive to chronic migrations of *Lygus* in localized areas during 1998. With a relatively dry winter yielding very few desert or weed hosts, the 1999 infestation was more restricted to localized areas of alternate host production (e.g., alfalfa and seed alfalfa). With shrinking demand for broad-spectrum insecticides to control PBW and SWF during the latter 1990's, the proportion of spray intensity directed at *Lygus* has risen dramatically (Fig. 1; Ellsworth & Barkley, 2001).

The following discussion by pest outlines the multilateral response to these pest infestations in terms of research, implementation, and education. The years [enclosed in brackets] during which specified activities occurred are provided as a guide.

Pink Bollworm, *Pectinophora Gossypiella* Saunders

In Arizona, the Pink Bollworm (*Pectinophora gossypiella* Saunders) is a pest of tremendous damage potential in its sole host of cotton. Pink bollworm (PBW) first appeared in Arizona in the 1920's after spreading from Egypt to Mexico and Texas a decade earlier. After several declarations of eradication from Arizona, by the mid-1960's, PBW was a serious and widely distributed pest of cotton (Henneberry & Naranjo, 1998). PBW was at least one factor that led to the precipitous decline by 80–90% in acreage in the Imperial Valley of California during the late 1970's through the 1980's (Natwick et al. 1987). In AZ, the 1990's began with the worst PBW outbreak of the decade and since records have been kept (1979; see previous section). In that year, growers sprayed on average 6.8 times at a cost of $60 / A in a losing effort to control this pest and resulted in a tremendous cost to the state of over $48,000,000 (Table 1).

Research

In 1990, the University of Arizona Maricopa Agricultural Center was the site for the first field tests of the first Bt transgenic cottons by USDA and Monsanto (Wilson et al. 1992). In spite of the lack of a desert-adapted variety, the plants performed extremely well with respect to the control of PBW and other lepidopterous pests. This was the beginning of a long road to development of Bt transgenic cottons for commercial use [1996]. In the interim, numerous field tests were conducted by University and USDA scientists to evaluate the potential of this technology in our pest management system. As new families of cotton varieties were developed with the new transgene (Bollgard®; Cry1AC), further testing evaluated agronomic and entomologic performance (Ellsworth et al. 1995c, 1996e). Furthermore, research on efficacy and treatment thresholds revealed that chemical control against PBW would not likely be warranted on Bt cotton once commercialized [1992–] (Watson, 1995; Ellsworth et al. 1995b,c, 1996e). Continued research after introduction included resistance monitoring (Simmons et al. 1998), varietal development and evaluation (Silvertooth & Norton, 1998; Moser et al. 2000), and testing of the second generation of Bt transgenes (Cry2AB alone or in combination with Cry1AC) (Moser 2000; Sieglaff et al. 1999; Marchosky et al. 2001). Research is currently underway to determine the ecological impact of these transgenic systems on non-target arthropods in comparison to conventional systems of lepidopteran control (Hardee & Burris, 2001; Ellsworth, unpubl. data; Naranjo, unpubl. data).

Implementation

Early in the 1990's, cultural practices including reduced season production and plow-down were implemented statewide. These practices were further bolstered through large, areawide programs (Moore et al. 1992; Thacker et al. 1993, 1994a,b; Antilla et al. 1996b; Jech & Husman, 1997); some of which implemented mating disruption technologies and/or pinhead square treatment programs (Ellsworth & Meade, 1994c). Growers adopted Bt transgenic technology at a staggering rate (Fig. 2). After very limited seed grow-outs in Arizona in 1995, there was only limited availability of seed in 1996 which kept adoption low in this first year of commercialization. However, later adoption saw individual growers and communities with rates in excess of 80–85%. Estimates of statewide adoption vary according to source; however, based on multiple industry (70–75%; W. Mullins, pers. comm.) and government sources (56–64%; USDA-AMS, 2001) and grower interactions (e.g., Ellsworth & Jones, 2000), we estimate that ca. 64% of the state's upland acreage was planted to cottons containing the Bt transgene from 1997–2000 (Ellsworth, unpubl. data) (Fig. 2). Meanwhile further research confirmed the efficacy and agronomic performance of Bt cottons on commercial acreages [1994–] (Ellsworth et al. 1995c, 1996e; Silvertooth & Norton, 1998). IPM plans were implemented and tested that integrated the use of Bt cottons with other modern innovations for whitefly management [1996–] (Ellsworth et al. 1997a, b; Silvertooth et al. 1998; Dittmar et al. 1999). Prompted by researchers, growers have begun investigating the viability of various mixed seed tactics as part of a resistance management strategy (e.g., Simmons et al. 1998; Tabashnik et al. 1999).

Education

Prior to the introduction of Bt transgenics [1990–1995], educational and regulatory efforts emphasized reduced season approaches (Terry et al. 1991; Brown et al. 1991, 1993) and mandatory termination and plow-down (Antilla et al. 1996b). Grower meetings were conducted statewide on a regular basis to promote these efforts (e.g., Brown et al. 1993). Later, a significant effort was made to heighten awareness in growers and Pest Control Advisors (PCAs) of the manner in which Bt cotton works [1996–]. A campaign of seminars, workshops, and live infield demonstrations taught that small larvae of PBW can and must enter a boll before they can be killed by the toxic Bt protein. Scouting efforts and procedures were modified to place emphasis on detection of large larvae in Bt bolls rather than young larvae [1996–] (Ellsworth et al. 1995b). Extension bulletins were produced and distributed to hundreds of growers (e.g., Ellsworth 1995b,c 1996e). Joint programs between Cooperative Extension and Monsanto were launched in all parts of the state to help explain the technology and ready growers for the implementation of refugia for resistance management [1996–].

Sweetpotato (= Silverleaf) Whitefly, *Bemisia* spp.

The Sweetpotato Whitefly [*Bemisia tabaci* Genn. (Strain B)] [= *Bemisia argentifolii* Bellows & Perring (Silverleaf Whitefly) was likely introduced into Arizona in the late 1980's. During the 1990's in Arizona, SWF rapidly supplanted the old strain of *Bemisia tabaci* which rarely required control. It spread generally throughout most of Arizona in 1991 and broke out in unprecedented numbers in 1992. Whiteflies of both strains were likely present in various portions of Arizona in 1990. By 1991, SWF was well-established in Yuma County, AZ, season-long, and confined mainly to the late season in central AZ. Since 1992, SWF has been widely distributed throughout the cotton growing regions of AZ with the exception of Cochise and Greenlee Counties at our highest cotton elevations. SWF develops earliest (June) at the warmest, lowest elevation locations of Yuma County (nr sea-level). Arizona's central production region experiences initial threshold level populations of SWF during July or August (elev. ca. 1000 ft). At 2000 ft elevation, SWF occasionally reach threshold levels (Pima & portions of Maricopa Counties). The Safford Valley of Graham County is the highest elevation at which threshold level populations are possible, albeit infrequently (ca. 3000 ft). SWF is the largest destructive force on Arizona's cotton industry than any other pest. Besides limiting the length of the cotton season during the early 1990's, certain fall crops were curtailed altogether (Ellsworth et al. 1999b). Cotton production [1991–1992] was reduced in the Mexicali Valley (in Mexico, adjacent to Yuma and Imperial Counties) by over 98% mainly due to the ravages of this pest (R.L. Lopez, pers. comm.). This event was a harbinger of what was to come to central AZ in 1992. The 1992 outbreak was most certainly related, at least in part, to a lack of readiness on the part of the cotton industry including the research/extension community (Ellsworth et al. 1993b). Little was known about the manner in which to sample or control this insect nor about its prodigious ability to overcome insecticides.

Research

After a rapid expansion of range from Florida to California during the 1980's, Arizona was subject to some of the first chronic economic infestations of SWF in cotton in U.S. history. Early research [1991–1993] quickly identified the necessity for mixing pyrethroids with organophosphate or other synergists (Watson, 1993; Ellsworth & Meade, 1994b; Ellsworth et al. 1994b). Pyrethroids or other compounds used alone provided little or no protection against this pest. In spite of this pest's worldwide significance, a systematic sampling plan for cotton had not been developed. Field studies [1993–1994] by the USDA-ARS described immature and adult distributions on cotton useful for designing sampling plans (Naranjo & Flint, 1994, 1995; Ellsworth et al. 1995a; Naranjo et al. 1996b). With these tools for sampling in hand, action levels were first tested and defined [1993] (Ellsworth & Meade 1994a), leading to a multi-state, multi-agency program of thresholds testing [1994–1996] (Naranjo et al. 1998a). Economic injury levels were also defined for the first time in cotton (Naranjo et al. 1996a). Later, field-testing of novel Insect Growth Regulators (IGRs: Knack® and Applaud®) (e.g., Ellsworth et al. 1994a) lead to their landmark emergency registration in 1996 (Ellsworth et al. 1996f; Ellsworth & Diehl, 1996). Research into resistance mechanisms (Prabhaker), resistance monitoring, and resistance management (Dennehy et al. 1996; Ellsworth et al. 1999a) helped to understand the refractory nature of SWF resistances and the need for proactive management to preserve susceptibilities for the future [1991–]. Recent studies [1996–] have begun to identify the factors which make our current system of management so successful (Ellsworth et al. 1997a,b; Ellsworth, 1998; Ellsworth et al. 1998b,c; Naranjo et al. 1998b,c; Ellsworth & Naranjo, 1999; Naranjo &

Ellsworth, 1999, 2000), and may chart a path toward even greater gains in natural enemy conservation and other non-intrusive means of ecological management of SWF.

Implementation

Growers organized community IPM programs (Diehl et al. 1994; Antilla et al. 1995; Diehl & Ellsworth, 1995; Ellsworth et al. 1996b; Jech & Husman, 1997), but were quickly challenged by resistances in SWF to conventional chemistry [1993–1996] (Antilla et al. 1996a; Ellsworth et al. 1996f). These programs include coordinated sampling and sharing of information that helped both individuals and collectives make strategic decisions about insecticide use. Implementation of adult sampling procedures within an 18,000 A community lead to commercial validation of this critical IPM tool [1993–1994] (Diehl & Ellsworth, 1995; Ellsworth et al. 1996b; Naranjo et al. 1997). Proper rotations of conventional chemistry and use of sampling and moderate thresholds were implemented at an unprecedented scale (ca. 210 A) in a multi-agency, commercial-scale experiment [1995] (Fig. 3; Ellsworth et al. 1996d). After the 1995 outbreak, a multi-agency and industry coalition developed a new strategy (Ellsworth et al. 1996a) that included the use of two unregistered, whitefly-specific IGRs. An unprecedented Section 18 Emergency Exemption was granted by EPA [1996–] for both compounds under a strict plan of one-use each, user certification, and mandatory education (Ellsworth et al. 1996a,f). These IGRs with new sampling procedures and action thresholds were subsequently tested in a multi-agency collaboration [1996] (Fig. 4; Ellsworth et al. 1997a,b) and simultaneously implemented on over 13,000 A of commercial cotton farms (Jech & Husman, 1997). Large-scale, demonstrations of IGR's were integrated with other best management practices [1998–2000] (Ellsworth et al. 1998d; Silvertooth et al. 1998; Dittmar et al. 1999). IGR adoption and use was immediate and dramatic with two-thirds of the acres using IGR's in 1996 (Fig. 2). Usage has since declined, but oddly, this is due to increased producer confidence in the SWF control tools at their disposal. Other factors include a generalized decline in severity of ambient populations or areawide suppression (e.g., Fig. 4).

Education

Early educational efforts focussed on instilling understanding in growers of the life cycle, biology, and seasonal ecology of this pest (Watson et al. 1992; Ellsworth et al. 1993a,b). Training sessions were held for Cooperative Extension personnel, Master Gardeners, producers and others [1994] (Goodell et al. 1995). A multi-regional manual on the biology, ecology and control of this pest across multiple crops was produced and distributed in four states (Norman et al. 1996). Community action plans were developed and disseminated within grower groups interested in collective management of this pest (Ellsworth et al. 1996b). Early research into the relative efficacy of insecticidal mixtures and a rudimentary rotational scheme was extended to growers via a laminated pocket guide and brochure (Dennehy et al. 1995a,b). This popular guide was updated to include the IGRs and distributed to hundreds of growers in AZ and translated into Spanish and distributed in N. Mexico (Ellsworth & Watson, 1996; Ellsworth et al. 1996a). A multilateral, grower-endorsed and -imposed, mandated educational campaign was launched [1996–] (Ellsworth et al. 1997c). The focus was stewardship of first-ever, field crop use of IGRs through 1) proper sampling and action thresholds including adults and nymphs (Ellsworth et al. 1995a, 1996c; Diehl et al. 1997a,b,c), and 2) an aggressive, proactive resistance management program that includes 1 use per season IGR limits as part of an overall IPM approach (Ellsworth et al. 1996a). Over 700 PCAs were trained and certified for proper use of IGRs (Ellsworth et al. 1997c). Growers were taught about the lack of adult knockdown with these new products and the need to wait at least 7–10 d after spraying IGRs before observing significant nymphal mortality. Growers were mandated by Section 18 label to wait a minimum period after the use of one IGR before applying the alternate IGR if necessary (Ellsworth & Diehl, 1996; Ellsworth et al. 1996a). A sampling count card was produced and thousands distributed with a fibrous washer that identified the proper location and area for counting SWF large nymphs (Diehl et al. 1996, 1997a,b,c). A dual-component binomial sampling and threshold system was taught to hundreds of PCAs and growers (Diehl et al. 1997b; Ellsworth et al. 1995a). Continued efforts today emphasize cross-commodity cooperation and management of SWF in a sustainable manner (Palumbo et al. 1999).

Lygus Bug, *Lygus Hesperus* (Knight)

Lygus bug (*Lygus hesperus* Knight) is a perennial pest of cotton and other crops. It is well-established here and believed to be native to Arizona as part of a species complex (including *L. elisus* and *L. lineolaris*). It feeds directly on fruiting forms giving this pest the greatest potential for damage. Throughout much of cotton history in Arizona, other key pests have "distracted" attention from *Lygus,* and many sprays against these other pests collaterally or incidentally controlled *Lygus* (Ellsworth & Barkley, 2001). As a result, the apparency of this pest has not been as dramatic as for other cotton pests. Also, historically, AZ and southern CA have enjoyed very long production seasons with long-season type varieties. Work during the 1960's and 1970's minimized the importance of *Lygus* bugs because of the late season compensation that was possible with cotton (e.g., Gutierrez, 1975). Only since production has been pushed towards more efficient, single set fruiting cycles and more determinant varieties has *Lygus* damage potential been fully realized. Furthermore, no modern pest control technologies have been developed for this pest. Thus, *Lygus* has the greatest potential to cause damage to cotton and lead to disruption of other pests in the future.

Research

As successes with other pests increased, research on this third key cotton pest has intensified [1996–] (Antilla et al. 1998; Pacheco, 1998; Ellsworth, 1998, 1999, 2000), but seriously lags behind that of the other two key pests. Decades-old recommendations were revisited with new research into chemical control (Antilla et al. 1998; Pacheco, 1998) and action thresholds [1997–] (Ellsworth, 1998, 1999, 2000). Mixtures, pyrethroids, and all but a few compounds were proven ineffective. Modern compounds (e.g., Provado®) that showed promise with a related species, *Lygus lineolaris*, were shown largely ineffective against AZ *Lygus*. Field trials showed that higher rates of recommended compounds were necessary for economic control of *Lygus*. Critical action levels were redefined and refined. The role of nymphs in yield loss was better recognized and defined [1997–] (Ellsworth & Barkley, 2001). Resistances were identified in different populations throughout AZ [1994–1996] (Dennehy & Russell, 1996); however, chemical control remains dependent on a narrow list of old compounds (Orthene®, Vydate C-LV®, Monitor®, and endosulfan). The disruptive potential of *Lygus* controls was quantified with respect to SWF management [1996–1999] (e.g., Ellsworth & Naranjo, 1999).

Implementation

An organized set of grower trials were initiated by growers and researchers to confirm relative efficacy of various compounds and rates [1997] (Antilla et al. 1998; Ellsworth et al. 1998a). Thresholds were implemented in large-scale integrated demonstration trials [1998–] (Silvertooth et al. 1998; Dittmar et al. 1999). Thousands of hectares of commercial cotton in Mexicali Valley (Mexico) implemented a modification of the AZ sampling and threshold guidelines and minimized yield loss while limiting sprays and maximizing profits [2000] (R. Cinco, pers. comm.). Local growers of multiple crops were organized around large areas for coordinated sampling of *Lygus* across multiple hosts [2000] (Ellsworth et al. 2000).

Education

Integrated crop and insect monitoring workshops [1993–] were conducted statewide and extended to N. Mexico where the '15:4' threshold (Ellsworth & Barkley, 2001) was readily adapted and adopted by growers [2000]. Joint industry-University *Lygus* workshops were conducted throughout AZ [1997–2000]. Extension bulletins were produced and distributed widely (Diehl et al. 1998; Ellsworth & Diehl, 1998). Growers began to forego mixtures in favor of higher rates of recommended materials [1997–] (National Cotton Council, unpubl report; Agnew & Baker, unpubl. data; Agnew & Baker, 2001). Exclusive reliance on Orthene (acephate) began to give way to other effective compounds (Vydate, endosulfan) (Pacheco, 1998) as growers learned about the efficacy of these other compounds and the need to rotate chemistry for resistance management (Agnew & Baker, 2001; unpubl. data). The relative importance of adults and nymphs to yield loss was reinforced through frequent seminars, workshops, and field days. The latter highlighted situations where *Lygus* were responsible for up to 5-fold reductions in yield that could be prevented through implementation of recommended guidelines for sampling and thresholds. Area growers learned through a series of meetings and newsletters that *Lygus* are a by-product of our local crop ecology and winter moisture conditions [1999–] (Ellsworth et al. 2000).

"What if...?"

As with any historical account, it becomes difficult to state with certainty causation, especially with respect to biological phenomena such as insect infestations or outbreaks. As a result, it begs the question, "What if...?" What if certain practices or technologies or teachings had not occurred? Would the course of pest management and cotton production been different? Undoubtedly some things would be different, but it is difficult to establish alternative scenarios with any degree of certainty. However, in at least one case (SWF), we can get a comparative glimpse into potential alternative outcomes through a series of large-scale, systematically replicated trials (Fig. 3–4).

Whitefly population dynamics have been systematically studied on large, commercial-scale, yet experimental, acreages since 1995 prior to the introduction of the Insect Growth Regulators (IGRs). At that time, our best management practices included a rotation of non-pyrethroid and pyrethroid combinations ('95IRM') applied on an adult threshold of 5 adults / leaf (the University recommendations; Dennehy et al. 1995a,b; Ellsworth et al. 1995a). This approach has been maintained in a comparative manner in replicated large-scale plots through 1999. In 2000, fiscal constraints prevented true replication; however, one 21-A field was divided into thirds that were assigned to one of three regimes (IGRs, conventional chemistry, and an untreated check). All other pests were managed normally—pink bollworm was controlled by the Bt transgenic variety (DP33B except in 2000, DP458B/RR) and *Lygus* bugs were sprayed as needed with single compounds (usually once or twice in July).

The results allow us to make comparative observations over this 6-year period (1995–2000). As seen by Figure 3, adult levels were similar among years with few exceptions. In 1996, adults reached threshold sooner than in any other year requiring a total of 5 conventional sprays. In 1995, the last severe outbreak year, atypical adult dynamics were not seen until September when populations exploded in spite of 6 conventional sprays. In 2000, the second earliest onset of threshold levels was observed; however, a combination of rains, time, and other weather factors probably mitigated any potential for outbreak levels of whiteflies or stickiness.

Since 1997, whiteflies have been successfully managed with this conventional rotation using only 1–3 sprays. This past year (2000) might have required more than the 2 sprays used, if it had not been for the rather active monsoon season that contributed to dramatic reductions in whitefly populations. Put another way, had there been a weak monsoon with very dry weather as was more typical in the earlier 1990's, 4 or 5 conventional sprays might have been required in 2000. In general, however, 1995–1997 required 5–6 conventional sprays, while 1998–2000 required only 1–3 conventional sprays. The specific reason for these differences is under investigation but likely was a result of weather, predation, and unknown factors (Ellsworth, 1998; Ellsworth et al. 1998b,c; Naranjo et al. 1998b,c; Ellsworth & Naranjo, 1999; Naranjo & Ellsworth, 1999, 2000) as well as the surrounding ambient density of SWF.

The IGR regime performed exceptionally well in all years requiring usually just 1 spray to manage SWF season-long (Fig. 4). The IGR regime required on average 1–3 fewer sprays against SWF than did the conventional regime. Only in 1998 were the spray requirements the same (1). The SWF dynamics in this year were extraordinary in that threshold levels were present statewide during the first week of August, but then spontaneously crashed even in untreated plots and commercial fields. As measured by large nymph densities (Fig. 4; Ellsworth et al. 1996c), threshold levels of SWF were reached at distinctly different times each year. Due to the time lag effects inherent to IGR's, the peak nymphal densities were always reached about 1 week after IGR use. The characteristic precipitous decline thereafter was often followed by 3–7 weeks of subthreshold SWF densities.

This historical comparison is useful in re-evaluating University recommendations within a commercial-scale context and for re-visiting the relative utility of conventional chemistry vs. IGRs, a choice growers face each year. Also, this comparison provides a useful 'what if' situation where we can see the importance of properly deployed IGRs in combatting SWF more economically and more eco-rationally. Furthermore, it is apparent from this exercise that this integrated use of IGRs and all the associated research, implementation, and education are likely mostly responsible for the staggering reductions in insecticide use against SWF in Arizona cotton. This conclusion is supported by independent analyses of pesticide use trends (Agnew et al. 2000).

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Literature Cited

Many of the citations below by necessity are from the Extension literature as well as other informal or less accessible sources. As a result, World Wide Web URL addresses are provided at the end of each citation, where possible, to facilitate access to this literature. Most of these stem from one home page: *http://ag.arizona.edu/crops*.

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Table 1. Ranking of top 5 pest-years for each insect loss statistic from the last 22 years (data from Ellsworth & Jones, 2000). Notes: 'Total Economic Loss' does not include losses in fiber quality or other non-control or non-yield related losses. Control costs include the foliar insecticide plus application costs. '% of Insect-Related Yield Loss' and '% of Insect Control Costs' are relative to the total loss or costs due to insects that year. '% of Acres Treated' may or may not include Pima cotton acreage depending on year (see Ellsworth & Jones, 2000). Economic figures are not adjusted for inflation or for fluctuations in cotton acreages. The following control costs are not included in this analysis: soil insecticides, seed treament, transgenic seed or technology costs, or any other non-foliar insecticide-related costs. ## = 19##, the year of production; WF = *Bemisia* whiteflies; PBW = Pink Bollworm; Lyg = *Lygus* bugs.

Rank	No. 1	No. 2	No. 3	No. 4	No. 5
Total Economic Loss	95 WF	92 WF	90 PBW	94 WF	95 Lyg
(in $millions)	64.0	59.1	48.6	30.7	17.2
Total Control Costs	95 WF	92 WF	90 PBW	94 WF	93 WF
(in $millions)	59.8	39.0	32.1	27.5	19.3
Total Yield Loss	92 WF	95 Lyg	90 PBW	96 Lyg	98 Lyg
(in $millions)	20.1	19.3	16.5	16.3	14.7
% of Insect-Related	92 WF	98 Lyg	93 WF	90 PBW	99 Lyg
Yield Loss	87.0	78.3	75.5	74.8	72.9
	92 WF	98 Lyg	95 Lyg	94 Lyg	96 Lyg
Yield Loss (%)	8.54	7.00	6.09	4.81	4.75
% of Insect Control	93 WF	92 WF	95 WF	94 WF	90 PBW
Costs	76.1	75.8	66.9	63.7	60.0
	95 WF	92 WF	94 WF	90 PBW	98 Lyg
Control Costs ($ / A)	145.20	91.80	88.00	68.00	55.20
	90 PBW	95 WF	87 PBW	92 WF	94 WF
No. of Applications	6.8	6.6	5.8	5.1	4.4
	87 PBW	94 PBW	95 PBW	98 Lyg	97 Lyg
% of Acres Treated	97	96	95	93	91

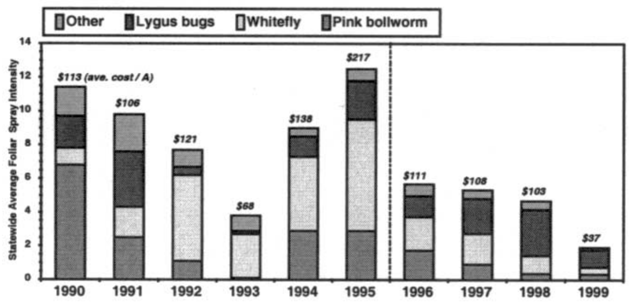

Figure 1. Statewide average foliar insecticide use statistics for Arizona cotton: number of foliar sprays by pest (bars) and average costs per acre (including applications; above) (Ellsworth & Jones, 2000; Williams et al. 2001). Foliar sprays are more a measure of insecticide use intensity than literal passes or applications over fields. Combination sprays targeting multiple pests in a single application are counted for each pest where appropriate. For example, 1995 was a high intensity of use year with virtually all applications consisting of multiple combinations of insecticides targeting one or more pests. Thus, foliar "intensity" was greater than the actual number of foliar applications in 1995. In years of lower use of insecticide mixtures, foliar intensity should approach the actual number of foliar applications. Bt transgenic cotton effective against pink bollworms, insect growth regulators effective against whiteflies, and a new IPM plan and educational campaign were introduced in 1996 (dashed line) (see Fig. 2).

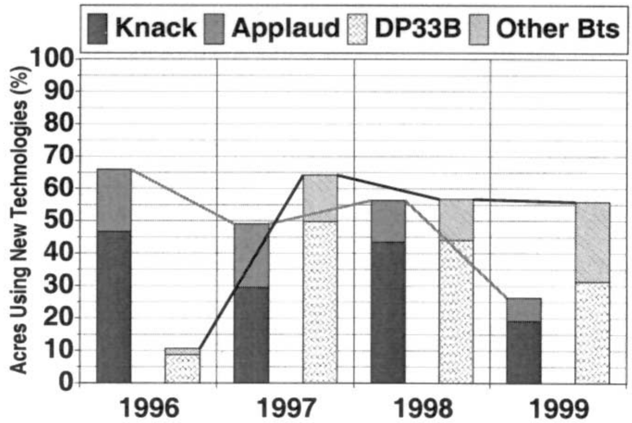

Figure 2. Estimates of adoption rates for new pest management technologies in Arizona cotton. The IGRs, Knack and Applaud, selective against whiteflies were made available under Section 18 Emergency Exemption starting in 1996 (Ellsworth et al. 1996a,f; Ellsworth & Diehl, 1996). Estimates of IGR usage based on sales reports, user reports (Agnew & Baker, 2001), and cotton insect loss survey results (Ellsworth, unpubl. data; Ellsworth & Jones, 2000; Williams et al. 2001). Transgenic Bt cottons were commercially introduced in 1996 with limited availability in limited varietal backgrounds. DP33B dominated Bt varieties planted in Arizona. Estimates of acres planted to Bt varieties from AMS reports (USDA-AMS, 2001). Actual adoption is likely slightly higher (ca. +6%) than reported here (ave. ³ 64%; see text).

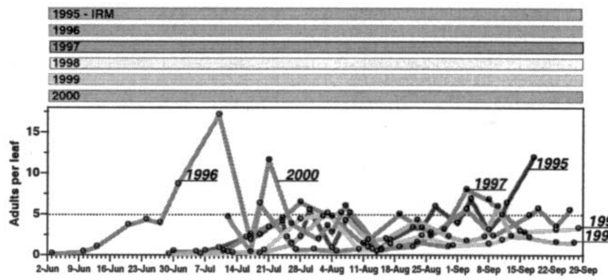

Figure 3. Historical trends in whitefly populations dynamics (adults per leaf) and conventional spray requirements from large-scale, replicated experiments. The same sequence of insecticides was used in each year according to a rotational regime identified in 1995 for resistance management (Ellsworth et al. 1996d). Conventional sprays were made when adult levels reached 5 per leaf (grid line) (Ellsworth et al. 1995a). Arrows above chart indicate frequency and timing of conventional sprays by year. Numbered points on lines correspond to the last digit of the year (e.g., '8' for 1998).

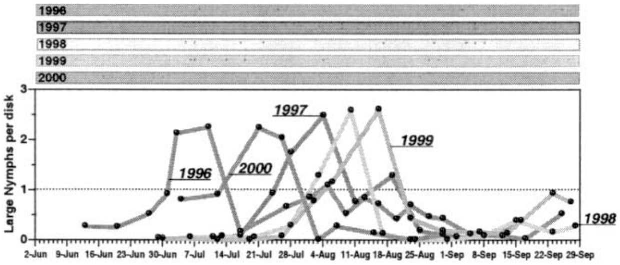

Figure 4. Historical trends in whitefly population dynamics (large nymphs per disk) from large-scale, replicated experiments. Insect growth regulators (IGRs) were used before conventional chemistry in each year (data for Knack first shown only). Sprays were made when large nymph levels reached 1 per disk (grid line) (Ellsworth et al. 1996c). Arrows above chart indicate frequency and timing of sprays by year. Cloud-bursts above chart denote rain events for each year. Numbered points on lines correspond to the last digit of the year (e.g., ‘8’ for 1998).