Status of Whitefly Resistance to Insecticides in Arizona Cotton

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Abstract

We summarize a whitefly resistance crisis that culminated in 1995 in Arizona cotton and that prompted the development of an integrated resistance management strategy. The strategy incorporated two new major elements: once-per-year use of the insect growth regulators (IGRs), Knack® (pyriproxyfen) and Applaud® (buprofezin), and measures to delay use of pyrethroids for as long into the growing season as possible. A three-stage chemical use recommendation was formulated comprising IGRs (Stage I), other non-pyrethroid insecticides (Stage II), and synergized pyrethroid insecticides (Stage III). Results from use of the strategy in the 1996 season were very promising. Insecticide use for control of whiteflies was reduced substantially where IGRs were used. Statewide monitoring of whitefly susceptibility to key insecticides revealed significant reductions in resistance to synergized pyrethroids as well as to non-pyrethroid insecticides. Resistance to Danitol® + Orthene® was shown to decline sharply from the end of the 1995 season to early in the 1996 season at the Maricopa Agricultural Center. Use of Stage I materials (Knack® and Applaud®) and specific Stage II (non-pyrethroid) insecticides in 1996 resulted in only small reductions in susceptibility to synergized pyrethroids. However, one application of Danitol® + Orthene® yielded a large increase in resistance. These findings confirmed the value of the newly-formulated resistance management strategy and indicated that resistance to the synergized pyrethroids can be managed if these insecticides are used sparingly. Additionally, evidence was obtained of collateral resistance buildup and decline in lygus bugs and whiteflies. Substantially reduced susceptibility of lygus bugs was documented in 1995, relative to 1994, coinciding with elevated insecticide use to control resistant whiteflies. Implementation of the 1996 whitefly resistance management program was correlated with increased lygus bug susceptiblity to the insecticides Orthene® and Capture® at most locations monitored throughout Arizona.

Chronicle of a Resistance Crisis

We documented a resistance crisis in Arizona cotton from 1994 to 1995 (Dennehy et al. 1996a). By the end of the 1995 season, pyrethroid insecticides, synergized by organophosphates or carbamates, failed to control whiteflies (*Bemisia argentifolii*) throughout much of Central Arizona cotton (Figs. 1, 2). This resulted from a classic resistance treadmill (Fig. 3), the end result of which was growers in the most seriously affected areas applying in excess of 8-12 whitefly treatments, and cotton discounted by buyers due to honeydew contamination (stickiness), in some cases despite insecticide expenditures of $200-$300 per acre. In this paper we summarize the major elements of the whitefly resistance management program that was devised and implemented in 1996 to overcome resistance. We then overview the outcomes of deployment of this program.

International Collaboration

A speedy response to the Arizona whitefly resistance crisis was made possible by the cooperation offered by scientists from England (Rothamsted Experimental Station) and Israel (Gilat Regional Experiment Station). Rothamsted scientists shared their considerable experience with whitefly bioassay methods, and isolation and description of whitefly resistances (e.g., Byrne et al. 1994, Cahill et al. 1996). Israeli experience with insect growth regulators was pivotal to development of the new strategy in Arizona. In the late 1980s, cotton growers in Israel faced serious whitefly resistance to pyrethroid insecticides. To overcome the problem scientists there formulated a successful resistance management program centered around the strategic use of insect growth regulators (Horowitz 1993). The Arizona cotton program described herein is a derivative of the Israeli strategy. The benefits gained by Arizona cotton from this international collaboration illustrate clearly the value of maintaining a global perspective on insecticide resistance management. Solutions for management of specific resistance problems are invariably contextual and must be adapted to specific production systems. Nonetheless, as shown in the case detailed here, exchange of information from around the world can provide critical insight for responding rapidly to a resistance crisis.

Southwest Whitefly Resistance Working Group

An essential step in Arizona's efforts to manage whitefly resistance has been the formation of the Southwest Whitefly Resistance Working Group. Since 1994, this group has met twice per year to reach consensus on recommendations. Members of the group (Table 1) include university and government workers involved in cotton pest management in the Southwest and representatives from the State and national cotton grower associations.

The Arizona Cotton Growers Association and Cotton Incorporated

The Arizona Cotton Growers Association and Cotton Incorporated have served pivotal roles in resistance management in Arizona cotton. They assisted with formulation of this strategy, production of publications, and have supported educational programs in resistance management around the State. Both organizations have invested heavily into resistance research. Doing so has required the foresight to fund studies prior to the point at which resistance reaches crisis proportions. Additionally, they have been leading participants in negotiations with chemical producers and the Environmental Protection Agency as they related to the Section 18 exemptions (described below). Clearly, the resistance management program we describe herein could not have been developed as rapidly nor delivered as effectively without their assistance.

Arizona's Extension Resistance Laboratory

The Extension Arthropod Resistance Management Laboratory (EARML) at the University of Arizona serves a central role in maintaining applied programs to document and manage pest resistance in Arizona. This first-of-its-kind Extension facility in the U.S. was established in 1994 with funding from the USDA-Western Cotton Research Laboratory, the Arizona Cotton Growers Association, Cotton Incorporated, and the University of Arizona. EARML reflects Arizona's response to the 1985 recommendation of the National Research Council that:

> *"Resistance detection, monitoring and management organizations be formed at the local or regional level and assume responsibility for education, coordination, and implementation of activities to deal with resistance problems."*

EARML activities include routine monitoring of resistance in key pests throughout the State, research to isolate and characterize specific resistances, and long-term evaluation of resistance management strategies. The laboratory is designed to serve as a bridge to basic research groups by providing access to resistant pests isolated by EARML and linkages to a range of applied resistance management studies underway throughout the State. Strong emphasis is placed on educational programs stressing limiting and diversifying chemical use to avoid resistance.

Formulating and Implementing a Strategy

Objectives of The 1996 Whitefly Resistance Management Program for Arizona Cotton were to: 1) conserve natural enemies, 2) limit insecticide use and, 3) diversify the selection of insecticides used against whiteflies. To achieve these goals two new major elements were recommended for whitefly control in Arizona cotton: once-per-season use of each of two selective insect growth regulators (Knack® and Applaud®) and delayed use of pyrethroid insecticides for as long into the growing season as possible. These new measures were incorporated into a three-stage chemical use strategy (Fig. 4) and were coupled with renewed emphasis on whitefly monitoring and thresholds (Ellsworth et al. 1996), and long-standing agronomic and cultural methods for managing whiteflies (Byrne and Bellows 1991). The three stages of whitefly chemical use, insect growth regulators (Stage I), non-pyrethroids (Stage II), and pyrethroids (Stage III), and their respective sampling procedures and treatment thresholds were described in an extension publication (Dennehy et al. 1996b) that included a laminated pocket guide (Ellsworth and Watson 1996) detailing the efficacy of the various options for Stage II and Stage III insecticides.

With agreement reached in late 1995 on the specifics of the strategy, Arizona set forth to obtain approval from the Environmental Protection Agency for the highly unusual request of Section 18 exemptions for two insect growth regulators. University of Arizona's Cotton IPM Team Leader, Dr. Peter Ellsworth, took leadership in compiling materials and drafting documents for the Section 18 request submitted by the Arizona Cotton Growers Association. The exemption was granted in May of 1996, clearing the way for implementation of the strategy. In addition to limiting use of Knack and Applaud to once-per-season, the provisions of the Section 18 required that all applicators obtain a certification that they have been properly trained in the use of these novel insecticides. This involved attending one of the IGR education programs sponsored statewide by the Arizona Cotton Growers Association. Additionally, EPA mandated monitoring of grower compliance with the provisions of the Section 18 exemption. This was done jointly by the Arizona Department of Agriculture and the Arizona Cotton Growers Association.

Evaluating the Strategy

Success of the Arizona whitefly resistance management strategy was evaluated first on the basis of how it overcame the resistance problems that plagued Arizona growers in 1995, i.e. the short-term perspective. In the longer-term, success will hinge on the degree to which the program prolongs the useful lives of the insecticides used in Arizona cotton. Obviously, we can speak confidently at this point in time only about the former criterion. The longer-term question will be evaluated over the course of multiple years through documentation of overall whitefly control in cotton fields, changes in levels of whitefly resistance, and in associated changes in susceptibility of other pests of cotton. Here we provide general summaries of findings to date.

Control Observed

Whitefly control for the 1996 season was excellent at locations employing the 1996 whitefly resistance management strategy (Ellsworth et al. 1997). Many of the same fields that received 8-12 whitefly treatments in 1995 required only 1-4 insecticide applications in 1996 (Simmons et al. 1997). A detailed evaluation of the field performance of the IGRs in 1996 may be found in Ellsworth et al. (1997).

Monitoring of Whitefly Resistance to Insecticides

Whitefly were collected from 19 locations throughout the major cotton production areas of Arizona (Fig. 5). Adult whiteflies were vacuum-collected directly from cotton foliage into plastic vials using a Makita® cordless vacuum (4071D). Samples were transported in ice chests directly to EARML where they were released into cages containing young cotton, *Gossypium hirsutum L.* (DPL-50) plants. Adult whitefly were maintained in these cages until they were placed in bioassays (<7 days). Susceptibility of each population was estimated to the following insecticide treatments: 1) Curacron® (profenofos) + Lorsban® (chlorpyrifos) (1:1 ratio); 2) Curacron + Vydate® (oxamyl) (1:1 ratio); 3) Thiodan® (endosulfan); 4) a fixed concentration of 1,000 µg/ml of active ingredient Orthene® (acephate) combined with varying concentrations of Danitol® (fenpropathrin); 5) Ovasyn® (amitraz); and 6) Ovasyn + Thiodan (1:1 ratio).

A derivative of the Rothamsted leaf disk bioassay method (Rowland et al. 1990) was used. Leaf punches 2.5 cm in diameter were taken from cotton plants (DPL-50) 18 - 26 days old. The leaf disks were dipped for 10 s in formulated insecticide diluted in water. After drying, the disks were placed individually on a base of agar (1.3%) within 20 ml glass scintillation vials. Within 2 h of dipping, 20-30 adult whiteflies were aspirated into each vial. Assays were then held in an incubator at 27°C for 48 h, after which they were scored using a binocular dissecting scope. Vials were tapped on the counter 10 times after which whiteflies not exhibiting repetitive movement of more than one appendage were scored as dead. At least five different concentrations and six bioassay replications per concentration were evaluated for each insecticide tested.

Synergized Pyrethroids. Overall, whiteflies from around the State were more susceptible to the synergized pyrethroid mixture of Danitol + Orthene in 1996 than in 1995. Based on the responses of the relatively susceptible 1995 Yuma whiteflies (Fig. 1), we designated populations as susceptible if they exhibited ≥ 90% mortality in treatments of 10 µg/ml fenpropathrin (+1000 µg/ml acephate) and ≥ 99% mortality in 100 µg/ml fenpropathin treatments (+1000 µg/ml acephate). Five populations (Marana, Mohave Valley, Parker, Somerton, and Thatcher) responded similarly in 1996 to the Yuma susceptible baseline from 1995 (Fig. 6, Table 2a). Contrasts of 1995 and 1996 results from statewide collections showed a significant shift to higher susceptibility to Danitol + Orthene (Fig. 7). Yet, susceptibility to Danitol + Orthene was influenced by local use of pyrethroids. This was illustrated by the somewhat reduced susceptibility of whiteflies at Yuma in 1996. This appears to be the result of elevated pyrethroid use in 1996 in vegetables and cotton at this location.

Significant differences in whitefly susceptibility to synergized pyrethroids continued to be found between regions of Arizona sampled (Fig. 6). Severe resistance to the synergized pyrethroids in 1995 was correlated with substantial (<80%) mortality (Fig. 1) in bioassays of 100 μg/ml fenpropathrin (+ 1000 μg/ml acephate). Such severe levels were not detected in our 1996 survey. In both 1995 and 1996, lowest susceptibility statewide was observed in whiteflies from the Gila Bend area.

Changes in resistance to pyrethroids were documented in 1995 and 1996 at the Maricopa Agricultural Center (MAC), Maricopa, Arizona. Resistance to Danitol + Orthene was shown to be unstable at this location, declining sharply from the end of the 1995 season to the beginning of the 1996 season (Figure 8a). However, susceptibility was not regained fully to levels that existed early in 1995.

Many Arizona growers were able to maintain control of whiteflies in 1996 by using only Stage I and Stage II insecticides. That is, they did not find it necessary to use pyrethroids. Figure 8a demonstrates that the IGRs (Knack® and Applaud®) and non-pyrethroid insecticides used in this MAC trial (Thiodan® + Ovasyn® and Vydate® + Curacron®) resulted in little change in susceptibility to Danitol + Orthene. We conclude that the 1996 whitefly resistance management program has yielded immediate benefits in terms of reductions in resistance to all the synergized pyrethroids used for whitefly control in Arizona cotton.

Optimism regarding the future of pyrethroids for whitefly control in Arizona cotton should be tempered by our finding that a single treatment of Danitol+ Orthene resulted in a significant increase in pyrethroid resistance (Fig. 8b). This confirmed our conclusion from 1995 that areas with histories of pyrethroid resistance were unlikely to obtain satisfactory results for more than two applications of synergized pyrethroids per season. This finding now can be extended to essentially all the pyrethroids used in Arizona for whitefly control. Sivasupramaniam et al. (1997) found that resistance to Danitol + Orthene conferred cross-resistance to all of the pyrethroids evaluated for controlling whiteflies in Arizona. Our strategy continues to emphasize holding the synergized pyrethroids in reserve to be used as a last resort, should they be needed late in the season when the crop is at greatest risk of being contaminated by honeydew.

Non- Pyrethroid Insecticides. Results of statewide monitoring of whitefly susceptibility to specific non-pyrethroid insecticide treatments are given in Tables 2b-f. We continued in 1996 to monitor susceptibility to endosulfan (Table 2b) and amitraz (Table 2c); overall susceptibility of Arizona whiteflies to these insecticides increased significantly from 1995 to 1996 (Figs. 9, 10). In addition, we monitored for the first time in 1996 susceptibility to three non-pyrethroid mixtures that showed promise (Sivasupramaniam et al. 1997) for controlling pyrethroid-resistant whiteflies (Tables 2d, e, f).

Collateral Susceptibility Changes of Lygus Bugs

Lygus bugs (principally *Lygus hesperus)* are a key pest of Arizona cotton, causing economic losses through feeding on young floral buds, flowers and young bolls. Since 1994 we have been estimating susceptibility of lygus populations throughout Arizona to the pyrethroid, Capture® (bifenthrin), and the organophosphate, Orthene® (acephate). Contrasts of lygus and whitefly susceptibility data provided evidence of collateral resistance buildup and decline on a statewide basis. We reported substantially reduced susceptibility of lygus bugs in 1995, relative to 1994 (Dennehy and Russell 1996). This reduction coincided with elevated use of synergized pyrethroids during the 1995 whitefly resistance crisis (Fig. 11a, b). Implementation of the 1996 whitefly resistance management program was correlated with significantly increased lygus bug susceptibility at most locations monitored throughout Arizona. These data strengthen the validity of the resistance treadmill concept. The whitefly resistance problem appeared to have made it more difficult to control lygus bugs, thereby exacerbating further the economic losses associated with whitefly resistance.

Sustaining and Improving the Strategy

The whitefly resistance crisis in Arizona cotton was remedied by introduction of effective, selective insect growth regulators. These insecticides show clear signs of having re-established a degree of biological harmony in Arizona cotton (Naranjo and Hagler 1997). The IGRs now occupy a keystone position in our cotton IPM program. Yet, concerns about resistance development of IGRs appear to be warranted. Elsewhere in the world where these compounds have been used they have been found to be of relatively high resistance risk (Cahill et al. 1996, Horowitz et al. 1994). Therefore, it is prudent for the Arizona cotton industry to take directed efforts to sustain its successful whitefly control program. Combating resistance to the IGRs necessitates limiting their use through label restrictions and maintaining reliance on the non-chemical whitefly control measures detailed in the Arizona strategy (Dennehy et al. 1996b, Ellsworth et al. 1996). Maintaining statewide resistance monitoring provides a way of tracking the future success (or lack of it) of the whitefly resistance management program and allows it to be modified promptly should resistance to the IGRs emerge.

From the wider perspective, what we are attempting to do is to fundamentally change the manner in which insecticides are used in Arizona cotton. Each year insecticides represent one of the cotton growers' largest variable production costs. Arizona growers know that they cannot maintain profitable cotton production in the face of the high costs associated with resistance crises such as beset them in 1995. Harmonizing chemical use to avert such problems will require limiting and diversifying insecticides. Limiting IGR use to once-per-season and delaying or eliminating pyrethroid use constitutes a big step in that direction. Finally, we are striving to advance the program detailed herein to achieve cross-commodity cooperation to manage chemical use on a multi-crop basis. Doing so broadens the scope of the successful whitefly resistance management program in Arizona to that of striving to sustain efficacy of all the critical insecticides used in cotton and vegetables.

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Table 1. Contributors to the Southwest Whitefly Resistance Working Group

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Table 2a. Mortality (± std. dev.) of Arizona whitefly populations collected in 1996 and tested in leaf-disk bioassays with variable concentrations of Danitol (fenpropathrin) combined with a fixed concentration of Orthene® (acephate). Summary results of statewide monitoring conducted in 1995 with the same insecticides are contrasted below.

	Concentration fenpropathrin (µg/ml) + 1000 µg/ml acephate				
Site	**0**	**0.1**	**1**	**10**	**100**
Buckeye	0 (0)	4.7 (5.5)	15 (12)	45 (20)	98 (3.6)
Casa Grande	3.0 (4.0)	4.5 (7.4)	37 (11)	62 (13)	92 (6.5)
Coolidge	3.7 (3.9)	10 (8.1)	26 (8.9)	59 (14)	96 (9.3)
Gila River Basin #1	2.6 (2.9)	8.7 (7.7)	33 (14)	59 (14)	94 (4.5)
Gila River Basin #2	1.6 (2.7)	3.3 (3.7)	8.2 (7.1)	27 (14)	86 (17)
Laveen	3.0 (3.6)	3.1 (3.7)	19 (13)	53 (17)	99 (1.6)
Litchfield Park	14 (9.5)	14 (8.6)	23 (12)	52 (7.1)	94 (9.0)
Marana	0 (0)	7.2 (3.8)	75 (9.7)	96 (1.8)	100 (0)
Maricopa Ag. Ctr.	2.0 (2.2)	16 (12)	40 (13)	75 (11)	96 (2.9)
Mohave Valley	3.0 (3.6)	10 (8.7)	55 (19)	92 (3.2)	100 (0)
Painted Rock	0.76 (1.9)	2.7 (4.6)	5.5 (3.3)	46 (7.9)	71 (11)
Paloma	0.69 (1.7)	1.3 (2.1)	25 (10)	48 (5.4)	100 (0)
Parker	17 (10)	15 (8.3)	48 (22)	94 (6.8)	100 (0)
Peters Corner	1.4 (2.2)	3.0 (3.6)	31 (6.0)	59 (15)	95 (6.5)
Roll	2.0 (3.4)	8.3 (9.4)	57 (9.9)	83 (10)	97 (3.7)
Somerton	3.6 (1.8)	2.5 (2.7)	63 (16)	96 (3.4)	100 (0)
South Harquahala Valley	0.72 (1.8)	6.6 (5.6)	41 (11)	81 (11)	100 (0)
Thatcher	4.8 (3.8)	6.5 (8.4)	85 (9.6)	98 (2.5)	100 (0)
Yuma Valley Ag. Ctr.	1.5 (2.4)	6.9 (9.8)	68 (17)	94 (4.6)	92 (7.6)
1996	*Summary*	*Statistics*			
N	19	19	19	19	19
MEAN	3.5	7.2	40	70	95
MEDIAN	2.0	6.6	37	62	97
MINIMUM VALUE	0	1.3	5.5	27	71
STD. DEV.	4.6	4.5	22	21	6.8
1995	*Summary*	*Statistics*			
N	13	13	13	13	13
MEAN	7.6	6.2	31	57	91
MEDIAN	3.6	4.4	27	54	96
MINIMUM VALUE	0	1.3	2.7	7.8	66
STD. DEV.	9.5	5.2	29	38	11

Table 2b. Mortality (± std. dev.) of Arizona whitefly populations collected in 1996 and tested in leaf-disk bioassays with Gowan Thiodan® (endosulfan). Summary results of statewide monitoring conducted in 1995 with endosulfan are contrasted below.

	Concentration endosulfan (µg/ml)				
Site	0	1	10	100	1000
Buckeye	1.9 (3.8)	1.7 (3.6)	24 (12)	100 (0)	100 (0)
Casa Grande	1.3 (2.1)	5.2 (4.1)	32 (15)	98 (2.3)	100 (0)
Coolidge	6.2 (6.9)	13 (7.3)	56 (17)	97 (7.2)	100 (0)
Gila River Basin #1	12 (17)	20 (18)	81 (19)	100 (0)	100 (0)
Gila River Basin #2	1.1 (2.9)	2.2 (3.4)	38 (13)	100 (0)	100 (0)
Laveen	2.9 (3.7)	9.8 (4.4)	37 (16)	94 (7.7)	100 (0)
Litchfield Park	5.2 (4.4)	21 (15)	47 (17)	92 (14)	100 (0)
Marana	5.7 (7.0)	7.1 (6.9)	42 (7.7)	100 (0)	100 (0)
Maricopa Ag. Ctr.	2.0 (2.2)	7.2 (4.9)	53 (16)	98 (2.3)	100 (0)
Mohave Valley	22 (15)	41 (37)	100 (0)	100 (0)	100 (0)
Painted Rock	0 (0)	0 (0)	40 (26)	100 (0)	100 (0)
Paloma	2.7 (4.8)	2.3 (2.6)	41 (11)	100 (0)	100 (0)
Parker	22 (15)	21 (8.8)	51 (17)	99 (2.1)	100 (0)
Peters Corner	4.9 (4.8)	7.3 (3.2)	64 (20)	100 (0)	100 (0)
Roll	3.3 (2.6)	8.9 (7.3)	58 (34)	100 (0)	100 (0)
Somerton	4.5 (2.9)	27 (24)	38 (18)	97 (3.4)	100 (0)
South Harquahala Valley	7.4 (7.7)	13 (18)	79 (25)	100 (0)	100 (0)
Thatcher	6.1 (6.9)	13 (7.3)	56 (17)	97 (7.2)	100 (0)
Yuma Valley Ag. Ctr.	4.9 (6.5)	11 (6.2)	23 (4.6)	99 (2.1)	100 (0)
1996	*Summary*	*Statistics*			
N	19	19	19	19	19
MEAN	6.2	12	50	98	100
MEDIAN	4.9	9.8	47	100	100
MINIMUM VALUE	0	0	23	92.0	100
STD. DEV.	6.3	10	19	2.1	0
1995	*Summary*	*Statistics*			
N	13	13	13	13	13
MEAN	4.5	8.8	40	97	99
MEDIAN	3.6	8.1	42	99	100
MINIMUM VALUE	0.64	2.2	17	86	99
STD. DEV.	3.7	5.8	16	4.4	0.28

Table 2c. Mortality (± std. dev.) of Arizona whitefly populations collected in 1996 and tested in leaf-disk bioassays with Ovasyn® (amitraz). Summary results of statewide monitoring conducted in 1995 with amitraz are contrasted below.

	Concentration amitraz (µg/ml)				
Site	**0**	**1**	**10**	**100**	**1000**
Buckeye	6.2 (8.0)	12 (9.9)	16 (13)	90 (7.0)	100 (0)
Casa Grande	3.3 (3.0)	4.7 (6.4)	19 (9.3)	82 (2.3)	100 (0)
Coolidge	19 (20)	8.9 (7.0)	43 (20)	83 (16)	97 (3.6)
Gila River Basin #1	0.83 (2.0)	9.9 (2.8)	48 (14)	92 (6.9)	100 (0)
Gila River Basin #2	1.1 (2.9)	3.3 (5.6)	11 (12)	82 (9.7)	100 (0)
Laveen	1.5 (2.4)	2.0 (2.3)	10 (4.2)	91 (6.2)	99 (1.9)
Litchfield Park	0.72 (1.8)	4.6 (4.4)	23 (22)	83 (14)	97 (3.2)
Marana	12 (6.2)	11 (8.2)	18 (15)	95 (3.8)	99 (1.5)
Maricopa Ag. Ctr.	0.64 (1.6)	2.8 (2.2)	3.0 (3.7)	85 (9.5)	100 (0)
Mohave Valley	16 (17)	14 (12)	40 (11)	96 (5.0)	98 (2.5)
Painted Rock	1.9 (3.8)	0 (0)	0 (0)	66 (28)	96 (4.4)
Paloma	1.3 (3.4)	3.0 (4.0)	3.8 (3.7)	59 (19)	98 (2.3)
Parker	11 (9.4)	28 (13)	41 (15)	86 (18)	99 (1.9)
Peters Corner	2.3 (2.5)	6.3 (5.7)	40 (19)	95 (8.1)	99 (1.5)
Roll	5.3 (8.2)	1.4 (2.2)	25 (13)	84 (20)	100 (0)
Somerton	2.8 (2.2)	8.3 (9.1)	26 (15)	92 (8.4)	100 (0)
South Harquahala Valley	5.5 (6.3)	5.1 (4.9)	9.7 (5.2)	90 (4.6)	98 (3.7)
Thatcher	2.3 (4.1)	5.5 (5.9)	20 (20)	98 (2.5)	100 (0)
Yuma Valley Ag. Ctr.	0.88 (2.1)	1.6 (2.6)	11 (15)	87 (11)	100 (0)
1996	***Summary***	***Statistics***			
N	19	19	19	19	19
MEAN	5.1	7.0	21	86	99
MEDIAN	2.3	5.1	19	87	99
MINIMUM VALUE	0.6	0	0	59	96
STD. DEV.	5.7	6.5	15	9.8	1.1
1995	***Summary***	***Statistics***			
N	12	12	12	12	11
MEAN	6.4	6.4	13	51	94
MEDIAN	4.5	3.4	7.8	48	96
MINIMUM VALUE	0.66	0.66	3.3	30	75
STD. DEV.	6.0	7.6	15	18	7.0

Table 2d. Mortality (± std. dev.) of Arizona whitefly populations collected in 1996 and tested in leaf-disk bioassays with a 1:1 ratio of Gowan Thiodan® (endosulfan) + Ovasyn® (amitraz).

	Concentration endosulfan+amitraz (µg/ml)				
Site	**0**	**1**	**10**	**100**	**1000**
Buckeye	2.0 (4.2)	49 (27)	97 (5.6)	100 (0)	100 (0)
Casa Grande	2.7 (3.4)	38 (11)	82 (14)	100 (0)	100 (0)
Coolidge	10 (9.0)	32 (13)	76 (16)	100 (0)	100 (0)
Gila River Basin #1	5.9 (3.8)	50 (10.8)	95 (4.2)	100 (0)	100 (0)
Gila River Basin #2	1.3 (3.4)	15 (12)	89 (7.5)	99 (2.6)	100 (0)
Laveen	1.3 (2.0)	10 (17)	55 (18)	100 (0)	100 (0)
Litchfield Park	9.4 (9.7)	43 (11)	77 (18)	99 (1.9)	100 (0)
Marana	1.3 (2.2)	34 (18)	63 (13)	92 (8.6)	100 (0)
Maricopa Ag. Ctr.	0 (0)	4.1 (5.2)	76 (9.9)	100 (0)	100 (0)
Mohave Valley	4.1 (3.8)	34 (11)	70 (11)	97 (4.7)	100 (0)
Painted Rock	1.5 (2.5)	21 (6.3)	92 (7.2)	100 (0)	100 (0)
Paloma	1.4 (2.3)	17 (11)	81 (11)	100 (0)	100 (0)
Parker	12 (11)	- (-)	38 (21)	90 (14)	100 (0)
Peters Corner	3.9 (3.7)	54 (15)	96 (2.5)	100 (0)	100 (0)
Roll	1.5 (2.4)	21 (12)	62 (20)	94 (4.4)	100 (0)
Somerton	2.1 (2.4)	2.4 (2.7)	28 (26)	90 (11)	100 (0)
South Harquahala Valley	3.3 (1.6)	8.9 (13)	46 (20)	94 (4.6)	100 (0)
Thatcher	2.6 (3.1)	95 (4.6)	99 (1.8)	100 (0)	100 (0)
Yuma Valley Ag. Ctr.	5.1 (11)	8.0 (4.2)	41 (26)	86 (10)	100 (0)
1996	*Summary*	*Statistics*			
N	19	18	19	19	19
MEAN	3.8	30	72	97	100
MEDIAN	2.6	27	76	100	100
MINIMUM VALUE	0	2.4	28	86	100
STD. DEV.	3.4	23	21	4.2	0

Table 2e. Mortality (± std. dev.) of Arizona whitefly populations collected in 1996 and evaluated in leaf-disk bioassays with a 1:1 ratio of Curacron® (profenofos) + Lorsban® (chlorpyrifos).

	Concentration profenofos+chlorpyrifos (μg/ml)				
Site	**0**	**10**	**32**	**64**	**100**
Buckeye	6.4 (8.6)	61 (36)	98 (3.1)	100 (0)	100 (0)
Casa Grande	1.4 (3.6)	7.9 (12)	93 (13)	100 (0)	100 (0)
Coolidge	15 (8.1)	45 (24)	100 (0)	100 (0)	100 (0)
Gila River Basin #1	1.6 (2.6)	58 (20)	100 (0)	100 (0)	100 (0)
Gila River Basin #2	0 (0)	39 (30)	100 (0)	100 (0)	100 (0)
Laveen	1.5 (2.4)	77 (21)	95 (6.5)	100 (0)	100 (0)
Litchfield Park	5.8 (2.3)	22 (20)	99 (1.9)	100 (0)	100 (0)
Marana	8.6 (5.4)	89 (14)	100 (0)	100 (0)	100 (0)
Maricopa Ag. Ctr.	2.0 (3.4)	17 (16)	79 (12)	100 (0)	100 (0)
Mohave Valley	7.0 (8.2)	8.7 (3.8)	74 (20)	98 (3.0)	100 (0)
Painted Rock	0.83 (2.0)	28 (17)	98 (2.8)	100 (0)	100 (0)
Paloma	2.0 (2.2)	2.1 (2.4)	99 (1.9)	100 (0)	100 (0)
Parker	10 (7.5)	18 (15)	82 (17)	99 (1.6)	100 (0)
Peters Corner	3.2 (3.9)	19 (6.8)	98 (3.4)	100 (0)	100 (0)
Roll	1.6 (2.5)	61 (17)	99 (2.1)	100 (0)	100 (0)
Somerton	7.1 (12)	8.3 (7.4)	97 (3.8)	100 (0)	100 (0)
South Harquahala Valley	1.3 (2.0)	18 (21)	94 (7.3)	100 (0)	100 (0)
Thatcher	5.0 (5.8)	58 (11)	100 (0)	100 (0)	100 (0)
Yuma Valley Ag. Ctr.	2.5 (4.2)	4.3 (7.0)	77 (19)	100 (0)	100 (0)
1996	***Summary***	***Statistics***			
N	19	19	19	19	19
MEAN	4.4	34	94	99	100
MEDIAN	2.5	22	98	100	100
MINIMUM VALUE	0	2.1	74.	98	100
STD. DEV.	4.0	26	8.6	0.30	0

Table 2f. Mortality (± std. dev.) of Arizona whitefly populations collected in 1996 and tested in leaf-disk bioassays with a 1:1 ratio of Curacron® (profenofos) + Vydate® (oxamyl).

	Concentration profenofos+oxamyl (µg/ml)				
Site	0	10	32	100	320
Buckeye	0 (0)	5.7 (3.9)	11 (15)	96 (7.7)	100 (0)
Casa Grande	2.9 (2.4)	2.7 (3.3)	18 (14)	83 (10)	100 (0)
Coolidge	19 (13)	18 (5.6)	32 (7.5)	98 (2.4)	100 (0)
Gila River Basin #1	0.67 (1.6)	1.4 (2.2)	15 (8.0)	100 (0)	100 (0)
Gila River Basin #2	4.0 (3.1)	7.9 (2.7)	23 (15)	92 (9.4)	100 (0)
Laveen	3.4 (4.8)	2.8 (3.4)	9.6 (7.3)	68 (22)	100 (0)
Litchfield Park	8.3 (7.5)	13 (12)	31 (21)	97 (2.3)	100 (0)
Marana	9.2 (4.7)	6.9 (6.6)	17 (9.1)	55 (17)	99 (1.9)
Maricopa Ag. Ctr.	2.4 (2.8)	1.2 (3.0)	7.3 (8.6)	62 (22)	100 (0)
Mohave Valley	9.6 (4.3)	14 (9.1)	26 (18)	100 (0)	99 (1.8)
Painted Rock	0.93 (2.3)	0 (0)	16 (11)	65 (16)	99 (0)
Paloma	1.0 (2.6)	2.9 (3.3)	13 (19)	93 (9.1)	100 (0)
Parker	6.2 (2.7)	7.1 (4.7)	37 (19)	85 (20)	99 (1.2)
Peters Corner	2.0 (2.3)	4.2 (2.2)	12 (4.0)	80 (14)	100 (0)
Roll	4.93 (5.4)	3.5 (4.6)	55 (27)	100 (0)	100 (0)
Somerton	2.9 (5.1)	6.8 (9.7)	27 (22)	85 (19)	100 (0)
South Harquahala Valley	9.1 (6.4)	13 (6.6)	90 (9.0)	99 (1.7)	100 (0)
Thatcher	7.9 (6.1)	16.9 (13)	41 (20)	99 (1.9)	99 (1.6)
Yuma Valley Ag. Ctr.	13 (9.7)	7.92 (7.5)	23 (23)	88 (14)	100 (0)
1996	*Summary*	*Statistics*			
N	19	19	19	19	19
MEAN	5.7	7.2	27	86	99
MEDIAN	4.0	6.8	23	92	100
MINIMUM VALUE	0	0	7.3	55	99
STD. DEV.	5.1	5.5	19	14	0.31

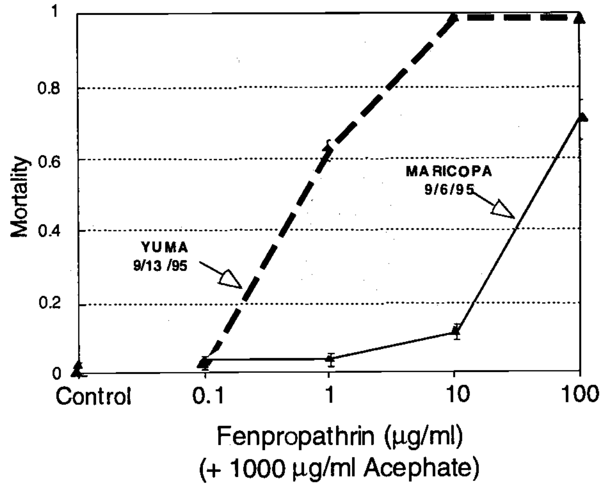


Figure 1. Intensity of whitefly resistance to synergized pyrethroids as depicted by laboratory bioassays of susceptibility to mixtures of variable concentrations of Danitol® (fenpropathrin) + fixed concentrations of Orthene® (acephate) of populations sampled from Yuma and Maricopa Counties in 1995. (From Simmons and Dennehy 1996).

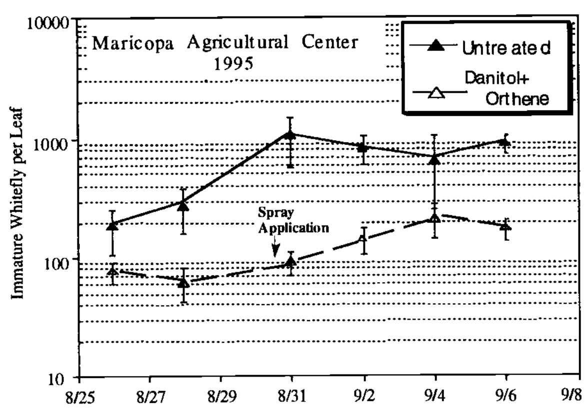


Figure 2. Illustration of the severe loss of efficacy of synergized pyrethroids against whiteflies in 1995. The arrow indicates the date of a field treatment of Danitol® (fenpropathrin) + Orthene® (acephate) using conventional application rates and equipment. (From Simmons and Dennehy 1996).

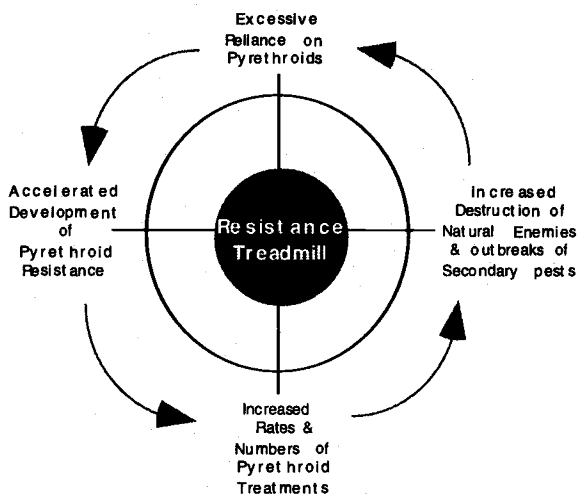


Figure 3. Conceptualized resistance treadmill which led to the loss of efficacy of the synergized pyrethroids against whiteflies in Arizona in less than three years.

Stage I: Insect Growth Regulators

***Threshold:* 0.5–1 large nymph per leaf disk**
AND
3–5 adults per leaf

Use IGR of choice when whitefly counts exceed threshold

IGR	Use Rate	Restrictions	Mode of Action
Applaud (70 WP)	8 oz./A	Use only once per season. Apply no sooner than 21 days after Knack.	Chitin synthesis inhibitor. Effective against nymphs.
Knack (0.86EC)	8 fl. oz./A	Use only once per season. Apply no sooner than 14 days after Applaud.	Juvenoid. Sterilizes adults and eggs. Prevents adult emergence.

Stage II: Non-Pyrethroids

***Threshold:* 5 adults per leaf**

1. When populations average more than five adults per leaf, use Stage II materials at least once before using Stage III materials, in order to delay the use of pyrethroid insecticides.
2. Rotate among classes of insecticides and among different insecticides within classes.
3. Do not use mixtures of more than two compounds.
4. Avoid using any active ingredient more than twice per season.

Stage III: Pyrethroid Mixtures

***Threshold:* 5 adults per leaf**

1. Delay pyrethroid use for as long as is practical in the growing season.
2. Use pyrethroid insecticides no more than twice per season.
3. Rotate the classes of insecticides mixed with pyrethroids

Figure 4. The three stages of chemical use incorporated into The 1996 Whitefly Resistance Management Program for Arizona Cotton. (adapted from Dennehy et al. 1996b).

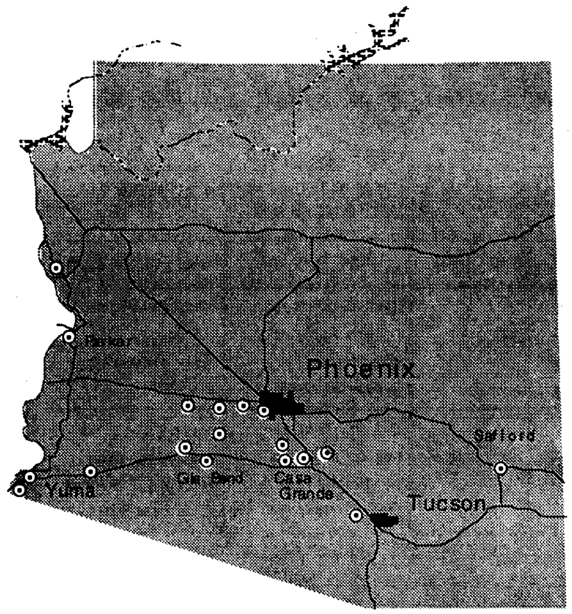


Figure 5. Arizona locations from which whiteflies were collected and tested for susceptibility to key insecticides in 1996.

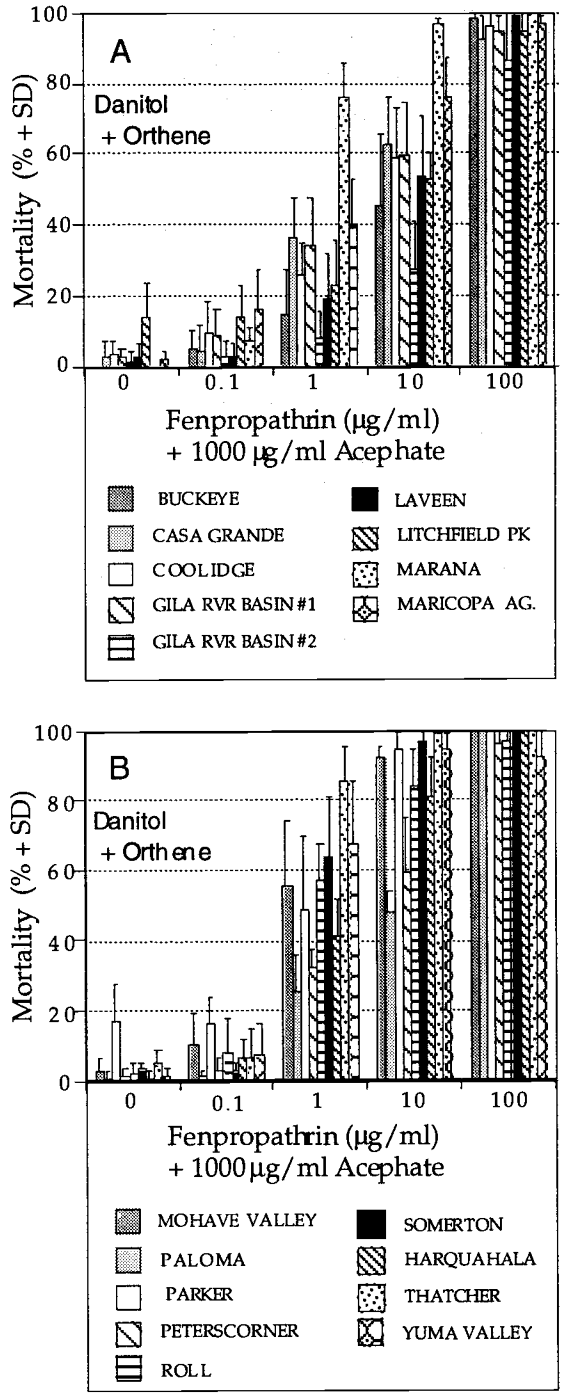


Figure 6. Susceptibility of Arizona whitefly populations in 1996 to mixtures of Danitol® (fenpropathrin) + Orthene® (acephate) in leaf-disk bioassays. a) locations 1-9; b) locations 10-18.

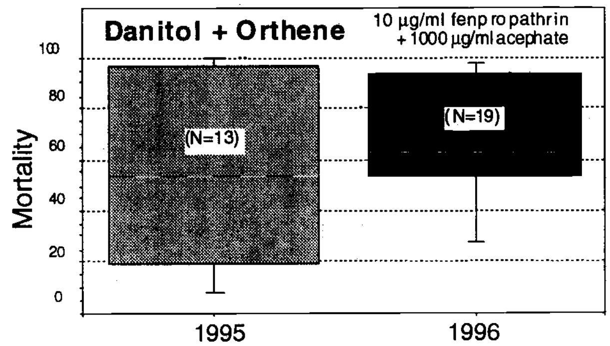


Figure 7. Box plots illustrating the significant increase observed in susceptibility of Arizona whitefly populations to Danitol® (fenpropathrin) + Orthene® (acephate) from 1995 to 1996. The median of each batch of data is marked with a horizontal hatched line. The upper and lower quartiles, i.e. the middle half of each data set, are denoted by the box. The 'whiskers' (i.e., 'error bars') denote the outer quartiles. Points falling outside of the box and 'whiskers' are outliers.

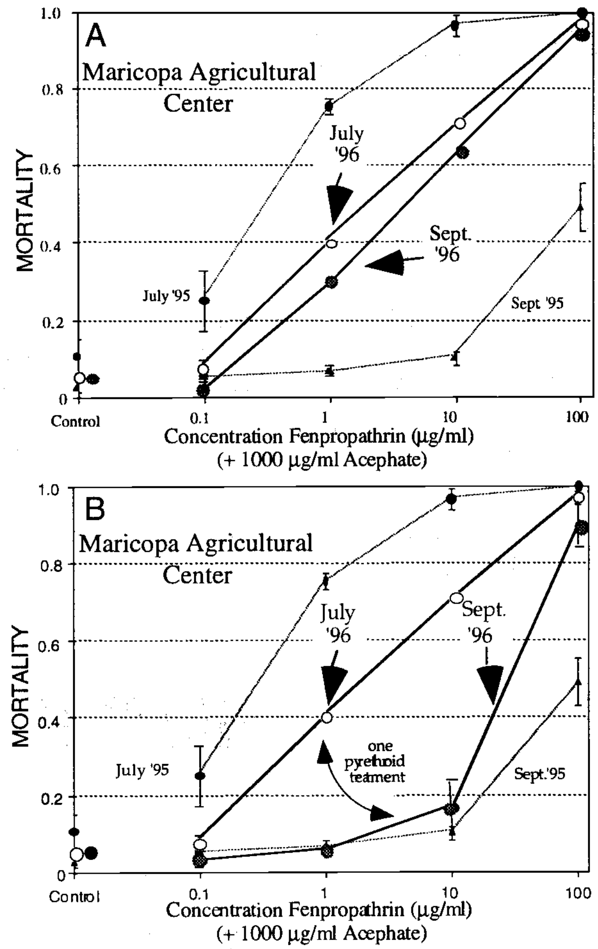


Figure 8. Changes in susceptibility of whiteflies at the Maricopa Agricultural Center between 1995 and 1996. Shown is mortality observed in leaf-disk bioassays of mixtures of Danitol® (fenpropathrin, variable concentrations) + Orthene® (acephate, 1000 µg/ml): a) representative results from plots in which only stage I chemicals (Applaud® and Knack®) or Stage II chemicals (Thiodan® + Ovasyn® and Vydate® + Curacron®) were used in 1996; b) after one application of a mixture of Danitol® + Orthene® in 1996.

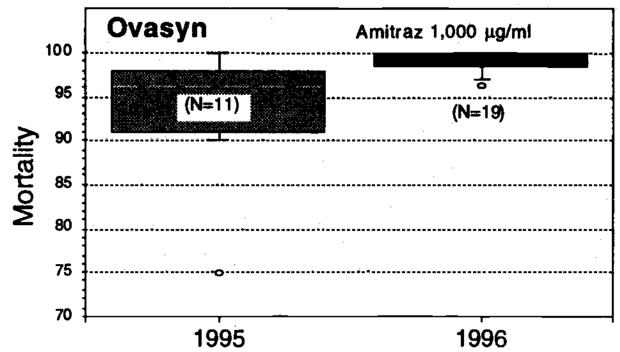


Figure 9. Box plots illustrating the significant increase observed in susceptibility of Arizona whitefly populations to Ovasyn® (amitraz) from 1995 to 1996. The median of each batch of data is marked with a horizontal hatched line. The upper and lower quartiles, i.e. the middle half of each data set, are denoted by the box. The 'whiskers' (i.e., 'error bars') denote the outer quartiles. Points falling outside of the box and 'whiskers' are outliers.

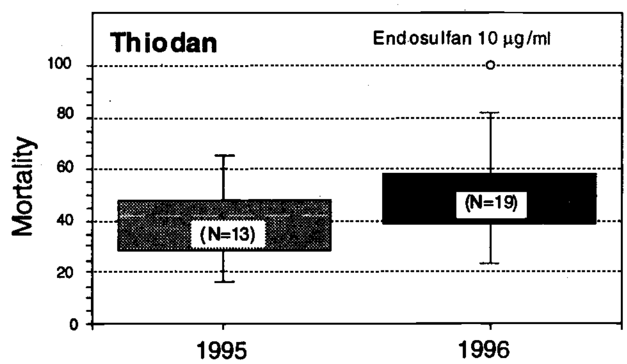
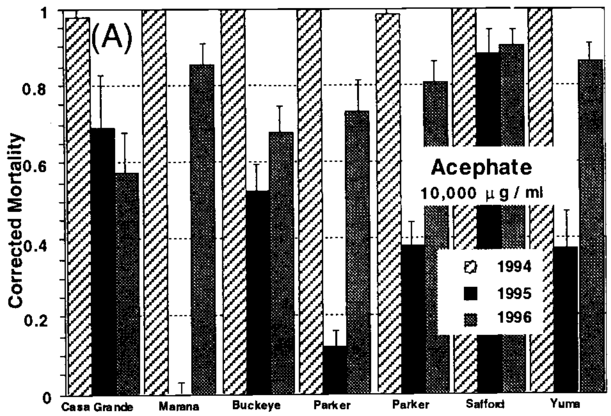


Figure 10. Box plots illustrating the small but significant increase observed in susceptibility of Arizona whitefly populations to Thiodan® (endosulfan) from 1995 to 1996. The median of each batch of data is marked with a horizontal hatched line. The upper and lower quartiles, i.e. the middle half of each data set, are denoted by the box. The 'whiskers' (i.e., 'error bars') denote the outer quartiles. Points falling outside of the box and 'whiskers' are outliers.



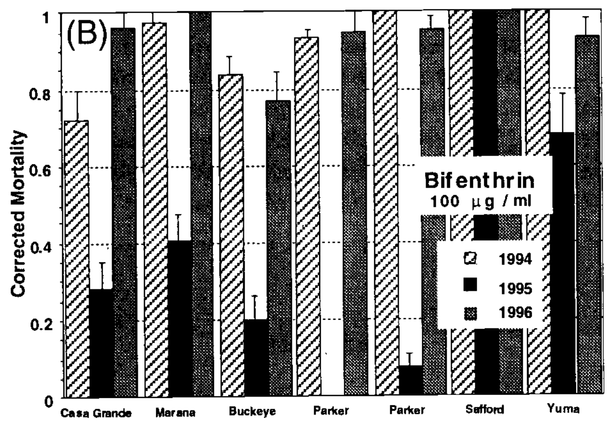


Figure 11. Reductions in Arizona lygus bug susceptibility to insecticides coinciding with the whitefly resistance crisis that occurred in 1995. Shown is mortality observed from 1994 through 1996 in vial bioassays of: a) Orthene® (10,000 µg/ml acephate); and b) Capture® (100 µg/ml bifenthrin). (From Russell et al. 1997).