Action Thresholds for the Management of *Bemisia tabaci* (Homoptera: Aleyrodidae) in Cotton

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ABSTRACT A 2-yr, multistate project was initiated in 1994 to determine action thresholds for management of *Bemisia tabaci* (Gennadius) Biotype B (=*B. argentifolii* Bellows & Perring) in cotton using chemical insecticides. Identical experimental designs and data collection protocols were used at sites in Brawley, CA, Yuma and Maricopa, AZ, and Weslaco, TX. The prescriptive application of insecticides based on 4 candidate action threshold levels (2.5, 5, 10, or 20 adult *B. tabaci* per leaf) were compared with one another and an untreated control. In general, there were few differences in whitefly populations among action thresholds of 2.5, 5, and 10 adults per leaf at sites in Arizona and California. All insecticide treatments typically reduced population densities below those in untreated control plots. Insecticide applications were generally ineffective in Weslaco, possibly due to reduced insecticide susceptibility or the late onset of pest infestation, and there were few differences in population density among treatments. Yields were higher in sprayed treatments, but there was little difference among threshold levels. Yield differences were not detected among any treatments for Yuma and Weslaco in 1994 and for Maricopa in 1995. The levels of lint stickiness due to honeydew deposition, as measured by thermodetector, were not consistent among sites and were not generally related to pest densities in the different threshold treatments. Levels of stickiness tended to be higher in 1994. There were no treatment effects on other standard measures of lint quality. A simple budgeting analysis assuming $43.24/ha per application for insecticides and $1.59/kg for lint suggested that action thresholds of 5–10 adults per leaf provided the highest net return at most sites.

KEY WORDS *Bemisia tabaci* Biotype B, *Bemisia argentifolii*, *Gossypium hirsutum*, action threshold, pest management, sticky cotton

SINCE THE EARLY 1990s, *Bemisia tabaci* (Gennadius) Biotype B (=*B. argentifolii* Bellows & Perring) has become a key pest of cotton (*Gossypium hirsutum* L. and *G. barbadense* L.) and several other crops in Arizona, California, and the Rio Grande Valley of Texas (USDA 1997). Conservative estimates suggest that this pest is responsible for close to $500 million annually in crop damage in the United States. Economic analyses for the Imperial Valley of California suggest over $400 million in direct crop loss from this pest between 1991 and 1995 and an additional $810 million in associated lost sales and personal income during this same period (Birdsall et al. 1996). *B. tabaci* causes damage by removing plant sap, which reduces plant vigor and lint yields (Naranjo et al. 1996a). The pest also damages cotton lint through the deposition of honeydew. Honeydew provides a medium for growth of sooty molds that stain the lint, and also causes fiber stickiness, a critical problem which hinders ginning and textile processing operations (Hector and Hodkinson 1989). *B. tabaci* is also a vector of cotton leaf crumple virus in the southwest, but historically the disease has not been of economic importance (Butler et al. 1986).

Insecticides are currently the principal method for control of *B. tabaci* and will likely continue to be used until more biologically based management systems can be developed. Decision aids for the rational and efficient use of insecticides will extend the longevity of this important control tactic and will stabilize economic returns while minimizing the potential for unintended environmental impacts. Workers from various parts of the world have suggested operational action thresholds for whitefly control in cotton (e.g., Mabbett et al. 1980, Sukhija et al. 1986, Ellsworth and Meade 1994, Stam et al. 1994). Recently, Naranjo et al. (1996a) estimated economic injury levels for *B. tabaci* in cotton based on experimental studies conducted in the Imperial Valley, CA. The broad applicability of these various thresholds throughout affected areas of the U.S. Cotton Belt is unknown.

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Table 1. Summary of study sites used in the determination of action thresholds for *B. tabaci* in cotton

Year	Agronomic practice	Brawley, CA	Maricopa, AZ	Yuma, AZ	Weslaco, TX
1994	Planting date	7 March	1 April	17 March	23 February
	Cultivar	DP-5415	DP-5415	DP-5415	DP-50
	Defoliation date	1 September	8 September	5 August	22 July
	Harvest date	15 September	17 October	8 September	5 August
	Insecticide use for other pests	None	Vydate C-LV, 10 August	None	Guthion, 28 April
1995	Planting date	10 March	10 April	26 March	24 March
	Cultivar	DP-5415	DP-5415	DP-5415	DP-50
	Defoliation date	29 August	22 September	22 September	26 July
	Harvest date	7 September	30 October	10 October	18 August
	Insecticide use for other pests	None	Vydate C-LV; 26 July	None	Monitor-4, 9 May; Bt Xentari, 22 May; Guthion, 25 May; Bt, Guthion, 20 June

This article reports the results of a 2-yr multistate project to determine action thresholds for the efficient control of *B. tabaci* in cotton. Our approach was to apply insecticides at 4 candidate action threshold levels (2.5, 5, 10, or 20 adult *B. tabaci* per leaf) and to compare pest suppression, yield, and lint quality among these treatments and an untreated control. Studies were conducted in 1994 and 1995 at 4 sites in California, Arizona, and Texas.

Materials and Methods

Study Sites and Experimental Design. Cotton plots were established in 1994 and 1995 at 4 sites: the USDA-ARS Irrigated Desert Research Station in Brawley, CA; the University of Arizona Yuma Agricultural Center in Yuma, AZ; the University of Arizona Maricopa Agricultural Center in Maricopa, AZ; and the Texas A&M University Agricultural Experiment Station in Weslaco, TX. Details of plot establishment and maintenance, and the timing of particular events are given in Table 1. Standard agronomic practices specific to each area were used.

Identical experimental designs and protocols were followed at all sites in both years. There were 4 experimental treatments which consisted of suppressing *B. tabaci* whenever populations exceeded predetermined thresholds of 2.5, 5, 10, and 20 adults per leaf (see *Sampling* below), and an untreated control. Insecticide treatments were a mixture of fenpropathrin and acephate at 0.11 and 0.56 kg (AI)/ha, respectively, applied in 187–290 liter of water per hectare by ground equipment fitted with 2–3 nozzles per row. Insecticide applications were made no more often than weekly and were continued as needed through defoliation. All treatments were replicated 5 times in a Latin square design used to control for anticipated variation caused by soil and irrigation gradients. In the vast majority of analyses at all sites there was significant variation attributable to row or column effects or both, justifying the use of this design. Individual plots were 8–12 rows (1 m spacing by 15.24 m long) and were separated by 2–3 m of bare ground on all sides. Other pests (e.g., *Lygus hesperus* Knight, *Aphis gossypii* Glover, *Spodoptera exigua* (Hübner), *Anthonomus grandis grandis* Boheman) were controlled as needed over the season (Table 1). To the extent possible, these applications were made with materials that were largely ineffective against *B. tabaci* and were applied to all treatment and control plots on the same day at a given site.

Sampling and Treatment Implementation. Densities of eggs, nymphs, and adults of *B. tabaci* were estimated weekly in all plots beginning ≈30 d after planting. Nymph and egg densities were estimated by the method of Naranjo and Flint (1994), which consists of counting individuals on a 3.88-cm^2 disk on the 5th mainstem leaf below the terminal. The densities of adults were estimated by counting individuals on the underside of 5th mainstem node leaves (Naranjo and Flint 1995). Typically, the 5th mainstem node is ≈20 cm below the terminal. Thirty sample units were collected for immatures and adults from the central 4–6 rows of the plot each sample date.

The density of adult *B. tabaci* was used to determine the need for insecticide application each week. All plots of a given threshold treatment were sprayed with insecticide when the mean from all replicate plots of that threshold ($n = 5$) exceeded the predetermined level (2.5, 5, 10, or 20 adults per leaf). Insecticide applications were made within 1–2 d after thresholds were reached. In 1994 there were some deviations from this threshold protocol. The first 2 insecticide applications were made on an individual plot-by-plot basis at the Weslaco site. Thus, only 1 plot of the 2.5 per leaf treatment was sprayed on 10 June, and only 2 plots in the 5 per leaf treatment were sprayed on 7 July. A substantial deviation occurred at the Brawley site. Here, applications of the fenpropathrin and acephate mixture were applied weekly once the given threshold level was reached. This practice continued until 4 August when the deviation was noted and corrected. Thus, a total of 3, 5, 5, and 5 insecticide applications was made without regard to threshold for the 2.5, 5, 10, and 20 per leaf treatments, respectively. It is difficult to estimate how many treatments were unnecessary; however, given the rapid increase of *B. tabaci* populations in untreated control plots during June and July, it is likely that many of these applications were valid, particularly at the lower threshold levels. The protocols were strictly followed at all sites in 1995.

Yield and Lint Quality. Seed cotton was machine-harvested from the center 4 rows of each plot in both years. A 1,500- to 2,000-g subsample was ginned for turnout (percentage of lint from seed cotton by

Table 2. Seasonal mean (± SEM) densities of *B. tabaci* eggs, nymphs, and adults in relation to different action thresholds, 1994

Stage	Action threshold	Seasonal density[a]			
		Brawley, CA	Yuma, AZ	Maricopa, AZ	Weslaco, TX
Eggs cm^{-2}	2.5/leaf	5.4 ± 0.9a	3.0 ± 1.8a	7.2 ± 2.6a	16.4 ± 4.5a
	5/leaf	5.6 ± 0.4a	2.0 ± 0.5a	7.0 ± 1.7a	18.0 ± 5.1a
	10/leaf	5.4 ± 0.5a	5.5 ± 0.7ab	9.1 ± 1.3ab	17.3 ± 4.9a
	20/leaf	10.1 ± 1.3b	13.8 ± 3.3bc	13.5 ± 3.3b	14.4 ± 4.0a
	Untreated control	24.6 ± 1.5c	22.3 ± 3.6c	44.3 ± 9.3c	13.0 ± 3.1a
	F-value[b]	59.6*	20.2*	39.7*	0.9
Nymphs cm^{-2}	2.5/leaf	1.3 ± 0.3a	1.4 ± 0.5a	2.5 ± 0.8a	3.5 ± 0.2a
	5/leaf	1.1 ± 0.2a	1.1 ± 0.2a	2.5 ± 0.5a	4.3 ± 0.8a
	10/leaf	1.1 ± 0.2a	3.1 ± 0.3b	4.4 ± 0.7b	4.0 ± 0.7a
	20/leaf	2.0 ± 0.3b	7.1 ± 1.8c	5.8 ± 1.5b	3.5 ± 0.6a
	Untreated control	4.5 ± 0.5c	7.4 ± 0.9c	17.2 ± 3.7c	3.0 ± 0.5a
	F-value	32.2*	21.6*	54.1*	1.3
Adults $leaf^{-1}$	2.5/leaf	6.4 ± 0.7a	2.7 ± 0.8a	5.2 ± 1.0a	5.8 ± 1.8a
	5/leaf	11.6 ± 1.4b	2.7 ± 0.5a	6.8 ± 0.4b	5.3 ± 1.6a
	10/leaf	10.2 ± 1.1b	6.6 ± 0.3b	8.1 ± 1.0b	5.7 ± 1.8a
	20/leaf	21.8 ± 2.1c	11.5 ± 2.6bc	15.0 ± 2.3c	4.3 ± 1.2a
	Untreated control	81.7 ± 3.9d	13.8 ± 1.7c	28.5 ± 3.3d	5.3 ± 1.7a
	F-value	120.9*	22.5*	224.0*	0.6

[a] Mean seasonal densities based on sample dates following the first insecticide treatments in the 2.5/leaf threshold plots at each site (n = 5). Inclusive dates were: Brawley, 15 June–31 August; Yuma, 20 June–1 August; Maricopa, 12 July–7 September; and Weslaco, 15 June–18 July.
[b] df = 4, 12, * $P < 0.05$; means followed by different letters within a column are significantly different at $P < 0.05$ (Ryan's Q test [Day and Quinn 1989]).

weight) and used to estimate lint yields on a kg/ha basis. Standard fiber quality measures were determined in duplicate 8-g subsamples of lint from each plot using a high volume instrumentation system at Cotton Incorporated, Raleigh, NC. Additional analyses were conducted to determine lint stickiness and sugar concentrations. In 1994, ≈1500 g of seed cotton was collected from the bulk harvest of the plot and ginned. Lint stickiness was determined on duplicate 2.5-g subsamples of this lint by the thermodetector method (Perkins and Brushwood 1995) at Cotton Incorporated. Concentrations of trehalulose, melezitose, fructose, and glucose were determined on an additional 10-g subsample of lint using a high performance liquid chromatography (HPLC) system (Hendrix and Wei 1994) at the USDA-ARS, Western Cotton Research Laboratory, Phoenix, AZ. Results were expressed as mg/g of lint for each sugar. The collection of subsamples was modified for 1995 based on the high plot-to-plot variability in stickiness ratings found in 1994. Four separate, ≈300 g, seed cotton samples were collected from each plot. After ginning, 5 g of lint was collected from each of the 4 subsamples and combined into a 20-g sample for analysis of sugar concentration by HPLC. Separate thermodetector analyses were then performed on lint from each of the 4 subsamples to arrive at an average for each plot. The HPLC samples for Brawley and Weslaco in storage at Cotton Incorporated were lost because of flooding associated with Hurricane Fran.

Statistical and Economic Analyses. The effect of threshold level on densities of *B. tabaci* (all stages), and on lint yield and quality measures were tested by analysis of variance (ANOVA) separately for each site. All data were tested for normality and were transformed by $\ln(x + 1)$ or $(x+0.5)^{0.5}$ as necessary, but all means are presented as untransformed. Means for significant ANOVA were further separated using the Ryan Q test (Day and Quinn 1989 [implemented as Ryan–Einot–Gabriel–Welsch, SAS Institute 1989]). This multiple range test was chosen because it controls the experimentwise type I error rate while minimizing type II error (Day and Quinn 1989). For insect density, we examined treatment effects for each weekly sample date and for seasonal means. Seasonal means for this latter analysis were based only on sample dates after the 1st insecticide applications in the lowest (2.5 per leaf) threshold treatment.

A simple budgeting analysis was performed to estimate the net return for each threshold treatment. Net return was calculated as the difference between yield (kg/ha) × price ($/kg) and control cost ($/ha per application) × number of applications. We estimated net returns for per application costs of $43.24 ± $5/ha and lint prices of $1.59 ± $0.20/kg to cover a range of realistic values. Lint price was discounted $0.09/kg for treatments in which thermodetector ratings were >5 (Perkins and Brushwood 1995, Schuster et al. 1996).

Results

Insect Density 1994. Infestations of *B. tabaci* varied among the 4 sites. Based on mean seasonal densities, pest populations in 1994 were relatively high in Brawley and Maricopa, moderate in Yuma, and low in Weslaco (Table 2). With the exception of Weslaco, there were significant differences among treatments for densities of eggs, nymphs, and adults. In general, there were few differences in whitefly populations among action thresholds of 2.5, 5, and 10 adults/leaf. These treatments usually reduced populations below those in untreated plots and those treated at 20 adults/leaf. All threshold treatments significantly reduced

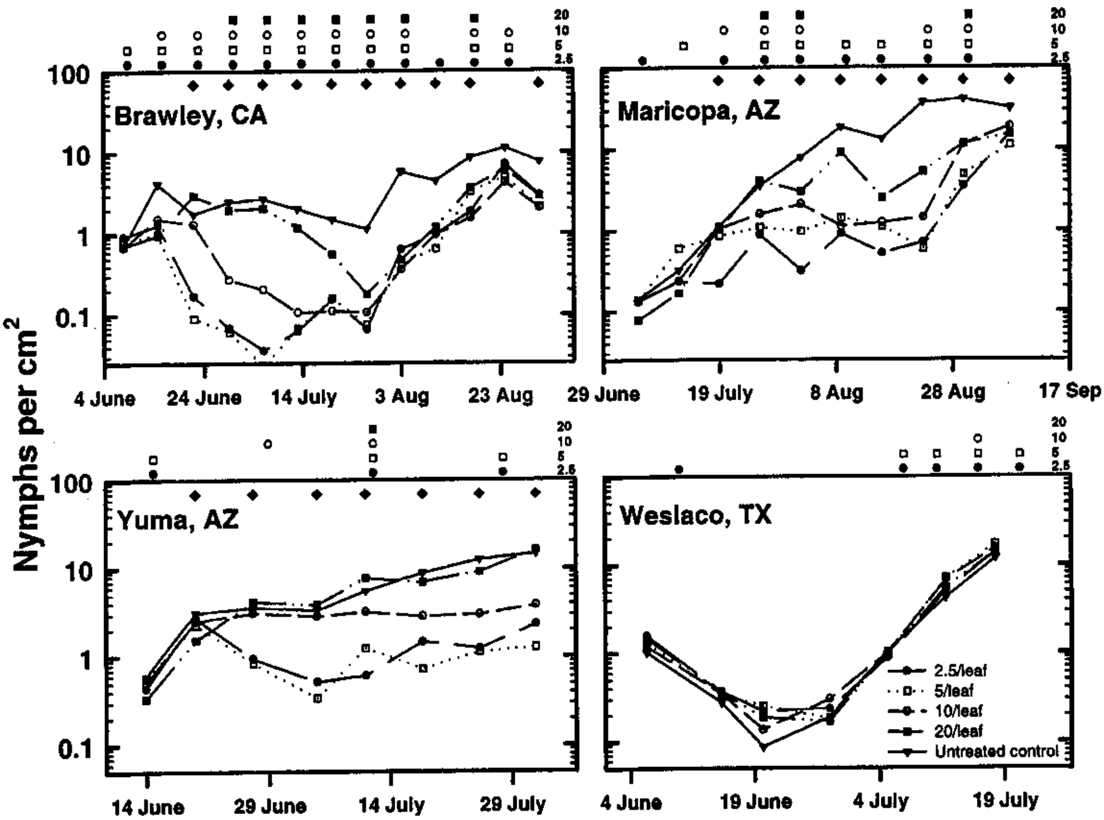

Fig. 1. Seasonal patterns in the density of *B. tabaci* nymphs at 4 study sites in relation to different action thresholds in 1994. Symbols above each graph denote the timing of insecticide applications for each indicated threshold level. Diamonds near the top of each graph denote dates on which significant treatment differences were detected by ANOVA ($P < 0.05$). To improve graphical resolution, weekly densities were plotted starting ≈1–2 d before the 1st insecticide applications at each site.

pest densities below those in untreated control plots at Brawley and Maricopa. Depending on site, applications of insecticides at any threshold reduced seasonal egg, nymph, and adult densities from 4 to 92% compared with the untreated control. Seasonal control was usually better than 50% even at the highest threshold.

For the most part, these patterns of treatment effects and efficacy were evident on a week-by-week basis (Figs. 1 and 2). Seasonal patterns of egg densities were nearly identical to that of nymphs, and only data for this latter stage is presented. Generally, all life stages were found on the 1st sampling date ≈30 d after planting. The dynamics of nymphal population growth were somewhat similar at Brawley, Yuma, and Maricopa, with a steady rise in population density in untreated plots as the season progressed (Fig. 1). Nymphal populations at Weslaco remained very low over an extended portion of the season, then increased quickly during the last 2–3 wk in July. Adult population dynamics were less similar among sites (Fig. 2). Insecticide applications often resulted in a temporary reduction in pest densities, especially at lower thresholds, and significantly slowed population growth at Brawley, Yuma, and Maricopa. The relatively long duration of suppression for the 2.5, 5, and 10 per leaf treatments at Brawley probably resulted from weekly insecticide applications through most of June and July. As with nymphs, the dynamics of adult populations were very different at Weslaco. Population density was low through June then rose rapidly in early July (Fig. 2). Most of the insecticide applications were made late in the season and had little effect on subsequent population growth.

Insect Density 1995. Compared with 1994, population densities of *B. tabaci* in 1995 increased substantially at Weslaco, and increased slightly at Brawley, Yuma, and Maricopa (Table 3). There were significant treatment effects for all life stages at all 4 sites. Similar to 1994, there were few differences in seasonal densities of whitefly using action thresholds of 2.5, 5, and 10 adults/leaf, but most treatments significantly reduced populations below those in the untreated control plots. Again, depending on site, applications of insecticides at any threshold reduced seasonal egg, nymph, and adult densities from 13 to 96% compared with the untreated control. As in 1994, seasonal con-

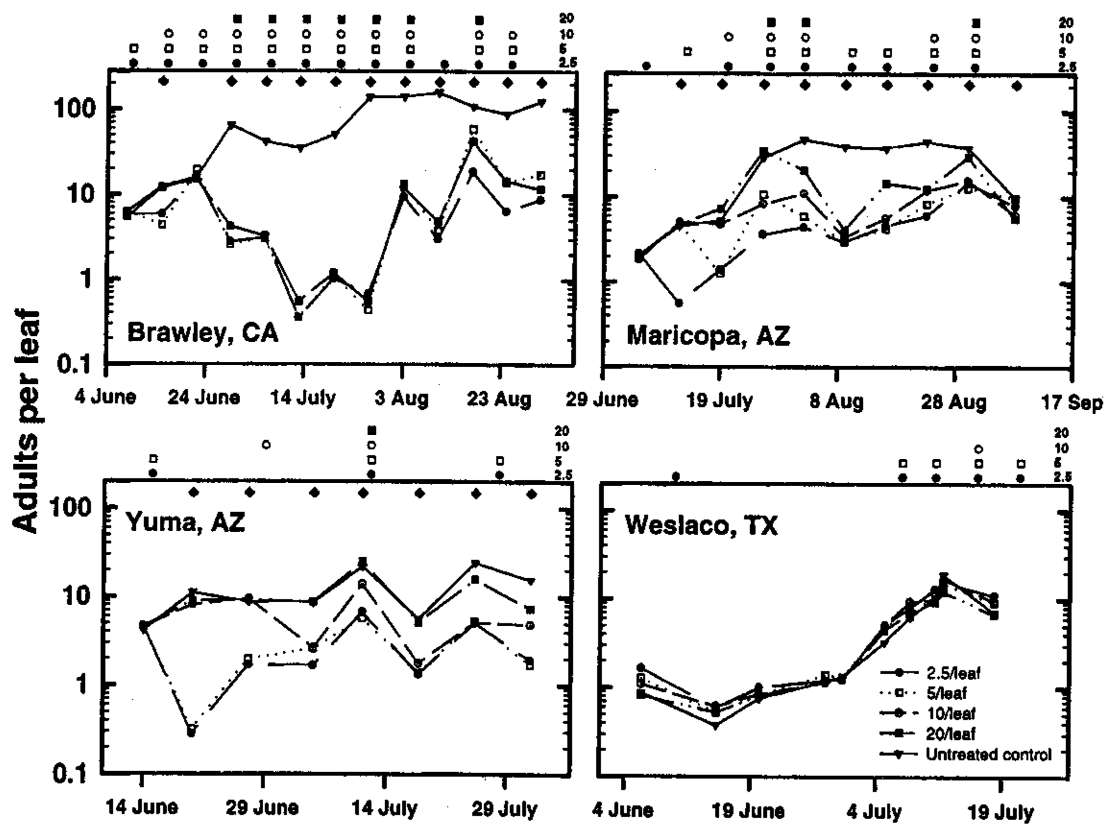

Fig. 2. Seasonal patterns in the density of *B. tabaci* adults at 4 study sites in relation to different action thresholds in 1994. Symbols above each graph denote the timing of insecticide applications for each indicated threshold level. Diamonds near the top of each graph denote dates on which significant treatment differences were detected by ANOVA ($P < 0.05$). To improve graphical resolution, weekly densities were plotted starting ≈1–2 d before the 1st insecticide applications at each site.

trol was usually better than 50% even at the highest threshold.

Again, these patterns of treatment effects and efficacy were evident on a week-by-week basis in 1995 (Figs. 3 and 4). The dynamics of nymphal population growth differed from patterns seen in 1994 and differed more among sites. At Brawley and Yuma, densities of nymphs in untreated plots rose rapidly from low population levels in late June to late July, respectively, and then showed several distinct peaks throughout the rest of the season (Fig. 3). Populations in Maricopa rose very rapidly and then declined in early to mid September. Weslaco was again unique with relatively low nymphal densities throughout much of the season followed by a dramatic increase during the last 2 sample dates in mid-July, probably as a result of pest movement from senescent vegetables and melons.

The dynamics of adult population growth were again different among sites (Fig. 4). Insecticide applications resulted in temporary reductions in pest densities, especially at lower thresholds, and significantly slowed population growth at Brawley, Yuma, and Maricopa. Similar to nymphal populations, adult population growth increased rapidly at Weslaco beginning in late June. Insecticide applications began much earlier at Weslaco in 1995 and initially suppressed whitefly populations, but, as in 1994, they generally failed to significantly suppress pest population growth later in the season (Fig. 4).

Yield and Lint Quality 1994. Cotton yields in Brawley did not differ significantly among threshold treatments of 2.5, 5, and 10 adults per leaf, but yields declined significantly when left untreated or when treated at 20 adults per leaf (Table 4). Yield did not differ among any of the threshold treatments at Maricopa, but all were significantly higher than the untreated control. Yields did not differ among treatments at Yuma where yield potentials were low, or Weslaco where threshold levels were reached very late in the season.

Lint stickiness, as measured by the thermodetector method, was not consistent with the effects of threshold treatments on pest population density (Table 4). At Weslaco, low pest population densities corresponded with low lint stickiness ratings (<5) that did not differ because of treatment effects. However, there also were no significant treatment effects and

Table 3. Seasonal mean (± SEM) densities of *B. tabaci* eggs, nymphs, and adults in relation to different action thresholds, 1995

Stage	Action threshold	Seasonal density[a]			
		Brawley, CA	Yuma, AZ	Maricopa, AZ	Weslaco, TX
Eggs cm^{-2}	2.5/leaf	5.8 ± 1.0a	1.3 ± 0.6a	11.1 ± 3.5a	32.8 ± 5.4a
	5/leaf	7.6 ± 0.8a	1.6 ± 0.8a	11.5 ± 3.4a	29.1 ± 1.9a
	10/leaf	7.4 ± 1.1a	4.5 ± 2.1b	9.8 ± 1.6a	52.1 ± 7.6b
	20/leaf	13.4 ± 0.9b	9.2 ± 3.1b	14.4 ± 3.4a	43.2 ± 7.2ab
	Untreated control	22.0 ± 2.6c	30.7 ± 18.6c	27.7 ± 5.5b	60.4 ± 6.5b
	F-value[b]	53.0*	30.2*	18.1*	11.1*
Nymphs cm^{-2}	2.5/leaf	1.5 ± 0.3a	0.3 ± 0.2a	2.5 ± 0.7a	12.9 ± 1.7a
	5/leaf	1.6 ± 0.1a	0.4 ± 0.1a	3.4 ± 1.3a	12.8 ± 1.5a
	10/leaf	1.5 ± 0.3a	0.8 ± 0.4a	4.5 ± 1.0ab	22.9 ± 2.9b
	20/leaf	3.7 ± 0.4b	2.0 ± 0.6ab	8.2 ± 2.6b	24.1 ± 3.2b
	Untreated control	5.8 ± 1.2c	8.8 ± 6.6b	20.4 ± 6.9c	31.3 ± 4.3b
	F-value	50.5*	8.5*	23.6*	14.8*
Adults $leaf^{-1}$	2.5/leaf	7.2 ± 1.3a	2.3 ± 0.3a	4.5 ± 0.7a	24.3 ± 1.6a
	5/leaf	9.8 ± 0.7b	2.9 ± 0.4a	5.2 ± 0.9a	24.1 ± 3.4a
	10/leaf	12.6 ± 1.5b	5.5 ± 1.2b	9.8 ± 1.5b	34.7 ± 0.5b
	20/leaf	17.6 ± 1.6c	9.4 ± 1.9c	15.7 ± 2.1c	35.6 ± 2.0b
	Untreated control	29.8 ± 2.9d	19.4 ± 4.6d	18.6 ± 2.7c	39.7 ± 4.3b
	F-value	42.8*	39.8*	73.8*	8.9*

[a] Mean seasonal densities based on sample dates following the first insecticide treatments in the 2.5/leaf threshold plots at each site (n = 5). Inclusive dates were: Brawley, 19 June–29 August; Yuma, 3 July–18 September; Maricopa, 24 July–20 September; and Weslaco, 23 May–25 July.

[b] df = 4, 12, *$P < 0.05$; means followed by different letters within a column are significantly different at $P < 0.05$ (Ryan's Q test [Day and Quinn 1989]).

very low levels of stickiness (<5) at Maricopa, despite relatively high pest pressure (Figs. 1 and 2; Table 2). This was likely the result of September rains or other degradative processes that reduced lint stickiness before harvest. There was no significant difference in lint stickiness among the 4 threshold treatments at Brawley, but all were less sticky than the untreated control. Stickiness was light (5–14 sticky spots) to heavy (>24 sticky spots) for sprayed plots at Brawley, but there was no consistent pattern relative to pest density. Patterns were even less consistent at Yuma. Lint stickiness varied from light to heavy, and stickiness in plots treated at 5, 10, and 20 adults per leaf were not different from one another or the untreated control. The significant difference in stickiness between plots treated at 2.5 and 5 adults per leaf was unexpected because both these treatments received 3 sprays on the same dates. All the inconsistencies noted here may reflect more basic problems with the measurement of lint stickiness.

The analyses of individual sugar components by HPLC (Hendrix and Wei 1994) were generally consistent with thermodetector ratings (Table 4). At Brawley, concentrations of trehalulose, melezitose, glucose, and fructose were relatively low and did not differ significantly among sprayed plots; however, all sprayed plots differed from the untreated control. At Yuma, there were significantly higher concentrations of trehalulose and melezitose in untreated plots and in plots treated at 20 adults per leaf compared with those sprayed at the 3 lower thresholds. There were no significant differences for glucose and fructose; and unlike thermodetector ratings, no differences were observed between the 2.5 and 5 adult per leaf treatments for any sugar at Yuma. Consistent with thermodetector results, there were no significant differences in sugar concentrations among treatments at Maricopa or Weslaco.

Yield and Lint Quality 1995. Overall, cotton yields were lower at Brawley, Maricopa, and Weslaco, and higher at Yuma, compared with 1994 (Table 5). Again, there were few differences in yield between plots treated at 2.5, 5, and 10 adults per leaf and no difference between those treated at 20 adults per leaf and the untreated controls. Although there was a pattern of increased yields at lower thresholds at Maricopa, which may have been related to incidental *L. hesperus* control, there were no significant treatment effects at this site. There was again no general relationship between the thermodetector ratings and threshold levels at any site, but stickiness ratings overall were much lower in 1995 in comparison with 1994. Stickiness readings did not differ among treatments at Weslaco, Maricopa, or Yuma, with many treatments having thermodetector counts <5. Only results from Maricopa were affected by rain showers before harvest. No differences were detected in Brawley among any of the sprayed plots, and plots treated at 2.5, 5, and 10 adults per leaf had thermodetector counts ≤5. Results from sugar concentration analyses from the 2 sites where samples were available were consistent with thermodetector counts (Table 5).

Lint quality, as measured by high volume instrumentation, was not significantly affected by threshold treatments in either year (data not shown), but it did vary among sites. In general, USDA classer grades were good to excellent (41–21), except at Weslaco (51 and 61), where color discounts were applicable in both years. Lint lengths (1.07–1.14 inches) and strength (26–29 G/tex) were acceptable to excellent; however, in 6 of 8 site-years, micronaire exceeded 5.0. Many factors can affect micronaire including fiber

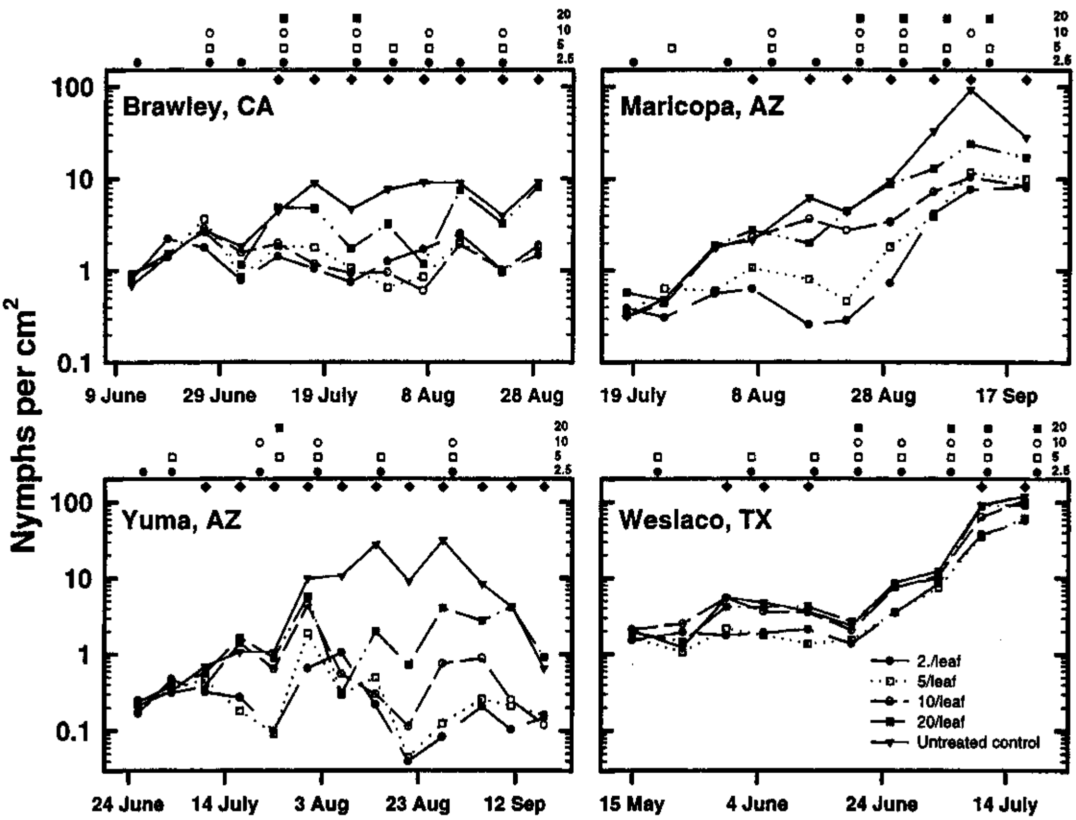

Fig. 3. Seasonal patterns in the density of *B. tabaci* nymphs at 4 study sites in relation to different action thresholds in 1995. Symbols above each graph denote the timing of insecticide applications for each indicated threshold level. Diamonds near the top of each graph denote dates on which significant treatment differences were detected by ANOVA ($P < 0.05$). To improve graphical resolution, weekly densities were plotted starting ≈1–2 d before the 1st insecticide applications at each site.

maturity, length of season, and temperature (Gipson and Joham 1968).

Insecticide Applications. As expected, the number of insecticide treatments increased with the use of lower thresholds (Table 6). In 1994, as few as 3 treatments were needed at a threshold of 2.5 per leaf at Yuma, and as many as 8 were needed for this threshold in Maricopa. Twelve applications were made in Brawley at this lowest threshold; however, as noted earlier, this site deviated from protocols. At the highest threshold, a total of 3 sprays was needed at Maricopa, whereas no sprays were applied at Weslaco. In 1995, as few as 6 treatment were needed at 2.5 adult per leaf in Yuma and as many as 9 treatments were made at this threshold in Brawley. At the highest threshold as many as 4 applications were needed at Maricopa and Weslaco, whereas only 1 or 2 applications were needed at Yuma and Brawley, respectively.

Economic Analysis. We performed a simple budgeting analysis to evaluate the comparative benefits associated with the 4 action thresholds we tested (Table 6). The thresholds that provided the highest net returns did not change as we varied per unit control costs and lint prices at any site. Thus, we report results for average values only.

Net returns were consistently highest for action thresholds of 5–10 adults per leaf at Brawley, Yuma, and Maricopa. At Weslaco, the plots treated at 10 adults per leaf and the untreated control plots had almost identical net returns in 1994, and in 1995 the best net return was associated with the untreated control plots. For Brawley, Yuma, and Maricopa, the benefits of spraying at specific thresholds varied among sites and between years. The net return increased 57% over the untreated control in the 5 per leaf treatment at Brawley in 1994. This was despite the deviation from protocol, which probably lead to several unnecessary treatments at this site. In 1995 at Brawley, the net return for plots treated at 10 adults per leaf were 61.9% higher than the untreated control. The differences in net return between the treated and untreated plots were lower for the Yuma and Maricopa sites. Applying insecticides at 5 adults per leaf in Yuma increased net returns over 19% and nearly 43% over the untreated control in 1994 and 1995, respectively. In Maricopa, net returns were increased 23.4%

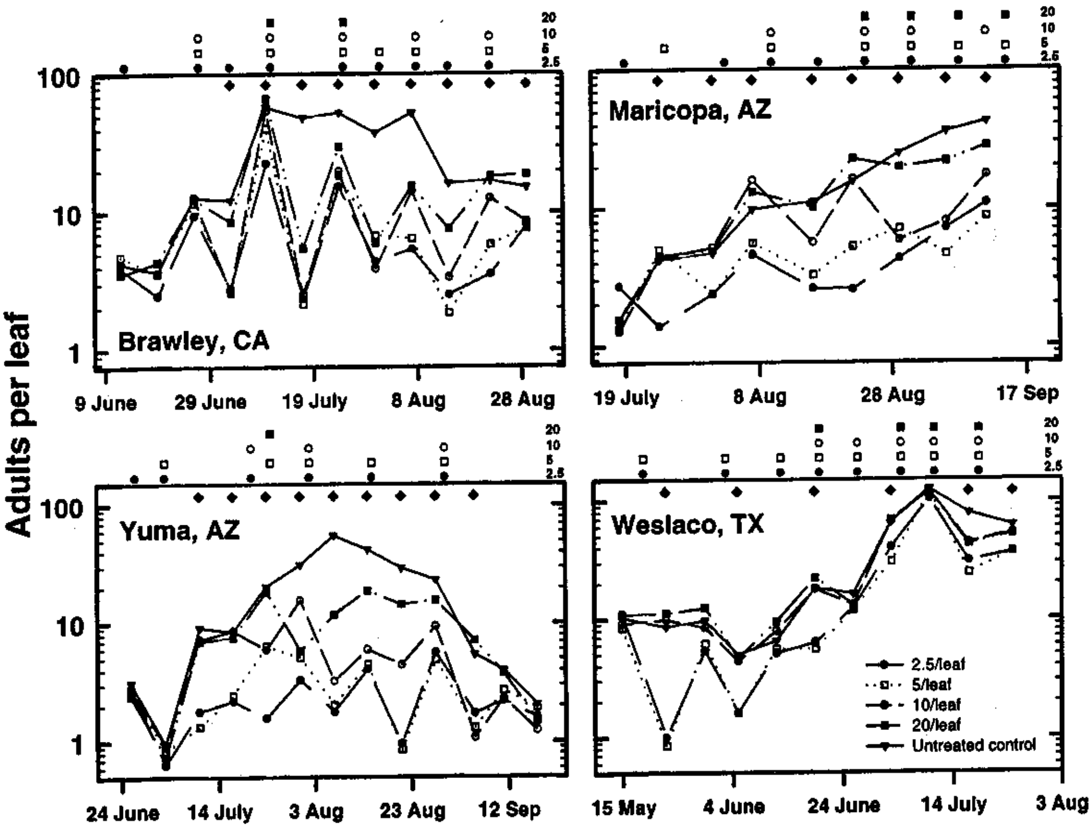

Fig. 4. Seasonal patterns in the density of *B. tabaci* adults at 4 study sites in relation to different action thresholds in 1995. Symbols above each graph denote the timing of insecticide applications for each indicated threshold level. Diamonds near the top of each graph denote dates on which significant treatment differences were detected by ANOVA ($P < 0.05$). To improve graphical resolution, weekly densities were plotted starting ≈1–2 d before the 1st insecticide applications at each site.

at 10 adults per leaf in 1994 and 7.5% at 5 adults per leaf in 1995, when compared with untreated control plots.

Discussion

Our results suggest that action thresholds can provide a cost-effective method for timing insecticide applications necessary for the suppression of *B. tabaci* at most of the sites studied. In an area such as the Imperial Valley of California, where populations of *B. tabaci* can reach very high densities in cotton, pest suppression enhanced yields by as much as 84% in 1994 and 67% in 1995 when insecticide treatments were made at action thresholds of 5–10 adults per leaf. Considering average costs of insecticides and returns on yield, these thresholds resulted in net returns 57 and 62% greater than that in untreated control plots in 1994 and 1995, respectively (Table 6). Yield enhancements and net returns were less dramatic at Yuma and Maricopa, but still demonstrated that use of action thresholds of 5–10 adults per leaf is more profitable than treating at higher or lower thresholds. Yields in Yuma were untypically low for the area and probably resulted largely from late season water stress caused by problems in scheduling timely irrigations. Peculiar population dynamics, particularly in 1994, and possibly reduced susceptibility to the fenpropathrin and acephate mixture (Wolfenbarger and Riley 1994) limited the utility of this pest suppression tactic at Weslaco. The lack of yield differences in 1994 at Weslaco was probably related to the late arrival of *B. tabaci*, which would have had little or no effect on fruit production.

Overall, it is important to recognize that it is difficult to isolate and test for the effects of 1 pest in multiple-pest systems. For example, sprays for *B. tabaci* in Maricopa and Yuma, where *L. hesperus* is a perennial threat, no doubt provided some incidental control of *L. hesperus*. Additional sprays specifically for *L. hesperus* were made at Maricopa in both years, but not Yuma, and this too may have contributed to lower overall yields at this latter site in 1994. In 1995, despite additional insecticide applications at Weslaco, the impact of other pest species (*A. gossypii*, *S. exigua*, *A. grandis*) may have limited yields and compromised our ability to discern differences caused by *B. tabaci* infestations. The results of our study should be interpreted with these limitations in mind.

Table 4. Cotton lint yield, stickiness, and sugar content in relation to different action thresholds, 1994

Site	Threshold	Lint yield (kg/ha)	Thermodetector rating[a]	Trehalulose (mg/g)	Melezitose (mg/g)	Glucose (mg/g)	Fructose (mg/g)
Brawley, CA	2.5/leaf	2132 ± 114a	10.6 ± 2.6a	0.36 ± 0.08a	0.23 ± 0.03a	0.31 ± 0.02a	0.15 ± 0.02a
	5/leaf	2166 ± 44a	14.9 ± 4.9a	0.24 ± 0.05a	0.17 ± 0.04a	0.24 ± 0.03a	0.11 ± 0.02a
	10/leaf	1935 ± 122a	9.4 ± 2.1a	0.35 ± 0.05a	0.22 ± 0.02a	0.27 ± 0.02a	0.13 ± 0.01a
	20/leaf	1438 ± 179b	26.7 ± 8.1a	0.89 ± 0.29a	0.43 ± 0.08a	0.27 ± 0.04a	0.22 ± 0.08a
	Untreated control	1178 ± 73b	71.7 ± 12.9b	6.44 ± 1.74b	1.71 ± 0.32b	0.66 ± 0.09b	0.76 ± 0.13b
	F-value[b]	39.1*	18.9*	14.3*	23.5*	14.9*	23.1*
Yuma, AZ	2.5/leaf	798 ± 107a	11.6 ± 2.8a	0.21 ± 0.02a	0.26 ± 0.01a	0.26 ± 0.05a	0.40 ± 0.07a
	5/leaf	882 ± 95a	27.4 ± 6.4b	0.20 ± 0.05a	0.25 ± 0.06a	0.21 ± 0.04a	0.38 ± 0.11a
	10/leaf	764 ± 67a	15.2 ± 4.0ab	0.29 ± 0.05a	0.36 ± 0.05a	0.28 ± 0.04a	0.53 ± 0.18a
	20/leaf	699 ± 70a	32.2 ± 7.7b	0.98 ± 0.40b	0.64 ± 0.19b	0.35 ± 0.05a	0.74 ± 0.11a
	Untreated control	665 ± 83a	35.6 ± 12.3b	0.83 ± 0.19b	0.59 ± 0.09b	0.29 ± 0.05a	0.58 ± 0.12a
	F-value	2.7	3.9*	5.2*	4.5*	1.9	3.0
Maricopa, AZ	2.5/leaf	1840 ± 33a	2.5 ± 0.5a	0.06 ± 0.04a	0.11 ± 0.03a	0.18 ± 0.04a	0.15 ± 0.03a
	5/leaf	1710 ± 120a	2.9 ± 0.9a	0.10 ± 0.03a	0.12 ± 0.03a	0.17 ± 0.03a	0.10 ± 0.01a
	10/leaf	1793 ± 40a	2.8 ± 1.1a	0.14 ± 0.02a	0.16 ± 0.02a	0.16 ± 0.03a	0.13 ± 0.02a
	20/leaf	1604 ± 36a	1.6 ± 0.5a	0.12 ± 0.01a	0.15 ± 0.01a	0.18 ± 0.02a	0.15 ± 0.02a
	Untreated control	1343 ± 28b	1.3 ± 0.6a	0.09 ± 0.03a	0.15 ± 0.01a	0.19 ± 0.02a	0.14 ± 0.01a
	F-value	12.3*	0.8	1.0	1.0	0.2	1.0
Weslaco, TX	2.5/leaf	1106 ± 92a	2.4 ± 1.0a	0.00 ± 0.00a	0.13 ± 0.01a	0.48 ± 0.04a	0.65 ± 0.06a
	5/leaf	989 ± 17a	2.9 ± 0.7a	0.02 ± 0.02a	0.14 ± 0.01a	0.45 ± 0.04a	0.62 ± 0.05a
	10/leaf	1065 ± 50a	3.7 ± 1.2a	0.01 ± 0.01a	0.15 ± 0.01a	0.47 ± 0.06a	0.64 ± 0.13a
	20/leaf	895 ± 34a	3.7 ± 0.5a	0.04 ± 0.01a	0.13 ± 0.03a	0.39 ± 0.05a	0.49 ± 0.10a
	Untreated control	1036 ± 60a	3.3 ± 1.3a	0.00 ± 0.00a	0.15 ± 0.01a	0.46 ± 0.04a	0.61 ± 0.08a
	F-value	2.1	0.3	2.5	0.3	1.0	1.5

[a] Ratings <5 are considered non-sticky, ratings from 5–14 are considered lightly sticky, ratings from 15–24 are considered moderately sticky, and those >24 are considered heavily sticky (after Perkins and Brushwood 1995).
[b] df = 4, 12, $*P < 0.05$; means (±SEM) followed by different letters within a column are significantly different at $P < 05$ (Ryan's Q test [Day and Quinn 1989]).

Worldwide, various action thresholds have been suggested for management of *B. tabaci* in cotton. Mabbett et al. (1980) suggested an action threshold of 2 adults per leaf for *B. tabaci* in Thailand based on observations that economic damage was associated with higher population densities. Sukhija et al. (1986) recommended an action threshold of 6–8 adults per leaf from mid-July onward on the basis of field studies

Table 5. Cotton lint yield, stickiness, and sugar content in relation to different action thresholds, 1995

Site	Threshold	Lint yield (kg/ha)	Thermodetector rating[a]	Trehalulose (mg/g)	Melezitose (mg/g)	Glucose (mg/g)	Fructose (mg/g)
Brawley, CA	2.5/leaf	1600 ± 97a	2.3 ± 0.6a	—	—	—	—
	5/leaf	1448 ± 55ab	4.2 ± 1.0a	—	—	—	—
	10/leaf	1566 ± 69a	5.1 ± 1.8a	—	—	—	—
	20/leaf	1130 ± 92bc	9.2 ± 1.8ab	—	—	—	—
	Untreated control	936 ± 119c	12.6 ± 1.6b	—	—	—	—
	F-value[b]	9.7*	5.7*				
Yuma, AZ	2.5/leaf	1253 ± 124a	1.5 ± 0.3a	0.06 ± 0.04a	0.20 ± 0.04a	0.16 ± 0.05a	0.14 ± 0.04a
	5/leaf	1243 ± 128a	1.1 ± 0.2a	0.08 ± 0.04a	0.23 ± 0.03a	0.23 ± 0.02a	0.19 ± 0.05a
	10/leaf	1069 ± 67ab	1.5 ± 0.3a	0.07 ± 0.05a	0.22 ± 0.04a	0.25 ± 0.01a	0.19 ± 0.04a
	20/leaf	965 ± 82bc	1.2 ± 0.3a	0.13 ± 0.02a	0.24 ± 0.03a	0.19 ± 0.05a	0.18 ± 0.04a
	Untreated control	776 ± 87c	1.6 ± 0.4a	0.11 ± 0.05a	0.22 ± 0.04a	0.23 ± 0.01a	0.20 ± 0.03a
	F-value	15.8*	0.5	0.7	0.6	1.1	1.5
Maricopa, AZ	2.5/leaf	1348 ± 100a	6.2 ± 1.9a	0.58 ± 0.04a	0.69 ± 0.04a	0.38 ± 0.03a	0.37 ± 0.02a
	5/leaf	1404 ± 42a	4.7 ± 0.5a	0.58 ± 0.09a	0.65 ± 0.05a	0.43 ± 0.02a	0.40 ± 0.03a
	10/leaf	1221 ± 87a	5.1 ± 1.2a	0.51 ± 0.06a	0.61 ± 0.06a	0.35 ± 0.02a	0.37 ± 0.04a
	20/leaf	1277 ± 68a	4.6 ± 0.7a	0.53 ± 0.10a	0.59 ± 0.07a	0.33 ± 0.02a	0.37 ± 0.03a
	Untreated control	1224 ± 49a	7.7 ± 1.2a	0.51 ± 0.16a	0.51 ± 0.16a	0.28 ± 0.07a	0.32 ± 0.08a
	F-value	2.1	2.5	0.3	0.7	2.3	0.6
Weslaco, TX	2.5/leaf	854 ± 41a	1.4 ± 0.3a	—	—	—	—
	5/leaf	878 ± 33a	1.7 ± 0.5a	—	—	—	—
	10/leaf	720 ± 29b	2.2 ± 0.2a	—	—	—	—
	20/leaf	714 ± 43b	2.3 ± 0.3a	—	—	—	—
	Untreated control	726 ± 51b	1.4 ± 0.3a	—	—	—	—
	F-value	8.8*	1.3				

[a] Ratings <5 are considered non-sticky, ratings from 5–14 are considered lightly sticky, ratings from 15–24 are considered moderately sticky, and those >24 are considered heavily sticky (after Perkins and Brushwood 1995).
[b] df = 4, 12, $*P < 0.05$; means (±SEM) followed by different letters within a column are significantly different at $P < 05$ (Ryan's Q test [Day and Quinn 1989]).

Table 6. Comparison of economic benefits in relation to different action thresholds, 1994–1995

Site	Threshold	1994			1995		
		Total insecticide applications	Net return ($/ha)[a]	% Increase over untreated control	Total insecticide applications	Net return ($/ha)[a]	% Increase over untreated control
Brawley, CA	2.5/leaf	12	2679.12	51.6	9	2154.84	53.5
	5/leaf	11	2773.36	57.0	6	2042.88	45.5
	10/leaf	10	2470.10	39.8	5	2273.74	61.9
	20/leaf	7	1854.32	4.9	2	1608.52	14.6
	Untreated control	0	1767.00		0	1404.00	
Yuma, AZ	2.5/leaf	3	1067.28	7.0	6	1732.83	40.4
	5/leaf	3	1193.28	19.6	5	1760.17	42.7
	10/leaf	2	1059.52	6.2	3	1569.99	27.2
	20/leaf	1	1005.26	0.8	1	1491.11	20.9
	Untreated control	0	997.50		0	1233.84	
Maricopa, AZ	2.5/leaf	8	2579.68	20.8	8	1676.08	−8.7
	5/leaf	7	2416.22	13.1	6	1972.92	7.5
	10/leaf	5	2634.67	23.4	4	1768.43	−3.7
	20/leaf	3	2420.64	13.4	4	1857.47	1.2
	Untreated control	0	2135.37		0	1836.00	
Weslaco, TX	2.5/leaf	4.2	1576.93	−4.3	8	1011.94	−12.3
	5/leaf	3.4	1425.49	−13.5	8	1050.10	−9.0
	10/leaf	1	1650.11	0.2	5	928.60	−19.6
	20/leaf	0	1423.05	−13.6	4	962.30	−16.6
	Untreated control	0	1647.24		0	1154.34	

[a] Net return calculated as lint yield (kg/ha) × $1.59/kg − No. applications × $43.24/ha; a discount of $0.09/kg was applied to lint with a sticky cotton thermodetector rating >5 (see Tables 4 and 5).

in the Punjab, India. A similar threshold was recommended by Stam et al. (1994) in the Sudan. Their studies demonstrated little to no yield loss or lint stickiness when using a threshold of 6 adults per leaf. Field studies in Arizona in which weekly applications of insecticides were initiated once adult populations exceeded prescribed thresholds suggested that action thresholds between 1 and 10 adults per leaf resulted in yields and levels of lint quality typical of the area (Ellsworth and Meade 1994). These studies resulted in the initial recommendation of 5–10 adults per leaf as operational thresholds for Arizona and California (Ellsworth et al. 1994). All these thresholds are surprisingly similar despite differing evaluation and sampling techniques, differing pest populations (including the possibility of different biotypes or species) and use of a wide array of insecticide types. The close correspondence among all of these studies indicates that we may be close to defining economically damaging population levels of *B. tabaci* in cotton that are broadly applicable.

The results of this study are corroborated by the recent independent study of Naranjo et al. (1996a) to determine economic injury levels for *B. tabaci* in cotton. Based on roughly equivalent crop prices and control costs, they estimated economic injury levels ranging from 5.9 to 15.3 adults per leaf depending on factors such as efficacy of control and potential crop yield. The economic or action threshold would be the pest density at which control should be initiated to prevent populations from exceeding the economic injury level (Poston et al. 1983, Pedigo et al. 1986). Given knowledge of sampling variation (e.g., Naranjo and Flint 1995, Naranjo et al. 1996b) and other management considerations that determine how quickly an insecticide treatment could be made, 5–10 adults per leaf would appear to represent a reasonable action threshold.

In addition to the effect of *B. tabaci* on cotton yields, the pest has a very important direct effect on lint quality through the deposition of honeydew. Stickiness in cotton lint is a major problem for fiber processing and thus a major impediment to the marketing of cotton that is perceived to be at risk of exhibiting stickiness. Although the committee on Cotton Testing Methods of the International Textile Manufactures Federation adopted the Sticky Cotton Thermodetector (Gutknecht et al. 1988) as the reference method for determining stickiness in cotton lint, the method is relatively slow and has not been adopted for general testing of commercial cotton. Accordingly, stickiness problems are frequently first encountered at the textile mill. Thereafter, the cotton causing the stickiness problems is identified by area of origin, and the area or region is then subjected to a reduction in price basis reflective of the risk associated with the probability and severity of lint stickiness.

Unlike the rather straightforward relationship between pest density and yield, there was no consistent relationship between stickiness rating determined by thermodetector and pest population densities resulting from our threshold treatments. All cotton from treatments at Brawley and Yuma were sticky in 1994, whereas none was sticky at Maricopa and Weslaco in 1994, and cotton from very few treatments was sticky at any location in 1995. Clearly, the timing of onset and duration of the whitefly infestations, as well as absolute population densities contribute to the level of stickiness. The occurrence of rainfall during the period when bolls are open (e.g., Maricopa in 1994) and the occurrence of high relative humidities that abet the growth of sooty mold both affect stickiness (Henneberry et al. 1994), and 1995). Further work will be needed to more accurately define the association of pest density and stickiness before information on lint stickiness can be used for improving decision aids for pest management. Clarifying this relationship will require critical examination of the thermodetector method itself and the scaling system that has been suggested for categorizing lint stickiness (Perkins and Brushwood 1995).

The results of our study now form the basis for statewide recommendation in Arizona and California for the insecticidal management of *B. tabaci* (Ellsworth et al. 1994, 1995). In addition, extensively tested, accurate, and cost-efficient sampling protocols are available for implementing these action thresholds on commercial farms (Ellsworth et al. 1996a, Naranjo et al. 1997). The likely registration of insect growth regulators for control of *B. tabaci* in the United States has already forced modifications in current thresholds, primarily through the addition of nymphal-based sampling and thresholds (e.g., Ellsworth et al. 1996b). The techniques and approaches demonstrated here are invaluable in the continuing development of decision aids for effective management of *B. tabaci*.

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