Conservation of Predatory Arthropods in Cotton: Role of Action Thresholds for *Bemisia tabaci* (Homoptera: Aleyrodidae)

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ABSTRACT   Studies were conducted in 1994 and 1995 to examine the effects of a range of action thresholds for managing *Bemisia tabaci* (Gennadius) Biotype B (=*B. argentifolii* Bellows & Perring) with insecticides in cotton on populations of arthropod predators in Imperial Valley, CA, and Maricopa, AZ. Application of insecticides significantly reduced population densities of spiders, *Geocoris punctipes* (Say), *G. pallens* (Stål), *Orius tristicolor* (White), *Nabis alternatus* Parshley, *Zelus renardii* Kolenati, *Hippodamia convergens* Guérin-Méneville, *Spanogonicus albofasciatus* (Reuter), *Drapetis* sp., and *Chrysoperla carnea* Stephens in one or both years and sites compared with untreated controls. Use of higher *B. tabaci* thresholds conserved some species and groups relative to lower thresholds. Stepwise regression analyses indicated that reductions in predator populations were generally influenced more strongly by the timing of the first insecticide application than by the total number of sprays necessary to maintain suppression of the pest below any given action threshold. A predation index, which weights the importance of each predator species based on their known frequency of predation on *B. tabaci* and another key pest, *Pectinophora gossypiella* (Saunders), was developed and analyzed. Patterns were similar to results based on changes in abundance alone, but the index generally revealed less severe effects of insecticides on overall predator function. The current action threshold for conventional insecticidal control of *B. tabaci* in Arizona and southern California is five adults per leaf. Results here suggest that predator conservation may be enhanced by raising the initial threshold to delay the first application or initially using more selective materials such as insect growth regulators.

KEY WORDS   *Bemisia tabaci*, *Bemisia argentifolii*, predators, pest management, action thresholds, conservation biological control

A NUMBER OF parasitoid and arthropod predator species naturally inhabit cotton fields (Whitcomb and Bell 1964, van den Bosch and Hagen 1966, Gonzales et al. 1977), and it is generally recognized that natural enemies play an important role in regulating pest populations (Whitcomb 1980). The most severe constraint to realizing the potential of natural enemies in field crops is disruption through the widespread use of insecticides with broad toxicity to both pests and their natural enemies (Stern et al. 1959, Newsom et al. 1976, Croft 1990). Some of the best examples of this problem are found in the cotton ecosystem where insecticide use disrupts the control of key pests and may cause the outbreak of secondary pests (e.g., Leigh et al. 1966, Eveleens et al. 1973, Stoltz and Stern 1978).

The concept that pest control should be based on economic as well as ecological considerations has been a pervasive force in integrated pest management (IPM) over the past four decades (Stern et al. 1959, Stern 1973, Pedigo and Higley 1992). The economic or action threshold is the operational pest density that triggers a remedial action, such as spraying an insecticide, to prevent damage that would exceed the cost of control. Adherence to established action thresholds reduces the unnecessary use of costly control tactics. Implicitly, the use of action thresholds may also contribute to conservation of natural enemies by minimizing the use of disruptive insecticides until they are absolutely necessary (Stern et al. 1959, Newsom et al. 1976, Gonzales and Wilson 1982, Sterling 1984, Hull and Beers 1985). Conceptual and mathematical approaches for directly incorporating natural enemies into pest economic thresholds have been outlined (e.g., Freier 1994, Brown 1997), but there are very few operational examples. Hoffmann et al. (1990) suggested an approach using the ratio of parasitized to unparasitized *Helicoverpa zea* (Boddie) eggs to modify decision aids for insecticidal control of this pest in California processing tomatoes, and further developed sequential sampling plans for field implementation (Hoffmann et al. 1991). More explicit recognition of natural enemies as integral components of pest sup-

pression within decision-based management programs is needed. An understanding of natural enemy conservation within the context of existing IPM programs is a step in this direction that could lead to simple modifications in the decision framework, potentially resulting in enhancement of the role of natural enemies in pest control.

Bemisia tabaci (Gennadius) Biotype B (=*B. argentifolii* Bellows & Perring) is a key pest of cotton and various vegetable crops in the southern tier of the United States. In cotton, *B. tabaci* causes damage by direct feeding on plant sap and indirect damage by contaminating cotton lint through honeydew excretion. The insect may also vector a number of plant viruses, although this has not historically been a significant problems in U.S. cotton production with the exception of sporadic cotton leaf crumple outbreaks (Butler et al. 1986). Population densities of *B. tabaci* can reach extremely high levels during the cotton growing season in western low desert production areas typified by central Arizona and the Imperial Valley of California. A diverse and consistent assemblage of indigenous arthropod predators and parasitoids are present, but these natural enemies are generally insufficient to suppress populations of *B. tabaci* below economically acceptable limits. Thus, insecticides are routinely used to augment control of *B. tabaci* on cotton in Arizona and California.

Minimizing the effects of insecticide on natural enemies requires the use of more selective materials and/or more selective approaches for the application of broad-spectrum insecticides. The insect growth regulators (IGRs), buprofezin and pyriproxyfen, are now available for suppression of *B. tabaci* on cotton in the United States, and extensive research has demonstrated the efficacy and selectivity of these materials (Ellsworth et al. 1997, Ellsworth 1998, Naranjo and Hagler 1997, Naranjo 2001) for management of this pest. Although these materials have been widely adopted in western cotton production systems, broader-spectrum insecticides are still commonly used for control of *B. tabaci* and other pests (Agnew and Baker 2001). For example, after 5 yr of availability of IGRs in Arizona, growers there have, on average, made 0.44 sprays per acre of the IGRs along with 0.74 sprays per acre of conventional materials for whitefly control (Ellsworth and Martinez-Carrillo 2001). Thus, approaches that also focus on more selective application methods may contribute to natural enemy conservation. Such strategies, collectively termed ecological selectivity, include reduced rates of application, use of less persistent materials, temporal and spatial changes in application, and changes in formulation and delivery (Newsom et al. 1976, Hull and Beers 1985, Croft, 1990). Action thresholds, although typically designed to optimize the timing of insecticide application for pest suppression, indirectly help to preserve natural enemies and also reduce selection pressure for insecticide resistance by delaying and/or reducing the total number of applications.

As part of a regional, 2-yr project to develop action thresholds for *B. tabaci* in cotton using conventional insecticides (Naranjo et al. 1998), we measured the abundance and activity of indigenous natural enemies in Brawley, CA, and Maricopa, AZ, in 1994 and 1995 relative to the timing and frequency of insecticide use prescribed by different action thresholds for *B. tabaci* suppression. The effects of these treatment thresholds on native aphelinid parasitoids were reported by Gerling and Naranjo (1998). Here we evaluated the effects of action threshold regimes on predator abundance and predator function, and further quantified the effects of the timing and number of insecticide applications. The results are used to suggest consideration of simple changes in threshold implementation that could improve arthropod predator conservation in western cotton production systems.

Materials and Methods

Study Site and Experimental Design. Cotton, *Gossypium hirsutum* L., plots were established at the USDA-ARS Irrigated Desert Research Station in Brawley, CA (currently the Imperial County Irrigated Desert Research Station), and the University of Arizona, Maricopa Agricultural Center, Maricopa, AZ. Cotton (cultivar 'Deltapine 5415') was planted on 7 and 10 March and defoliated on 1 September and 29 August in 1994 and 1995, respectively, in Brawley. In Maricopa, Deltapine 5415 was planted 1 April and defoliated 8 September in 1994. Studies were conducted in 1995 at Maricopa, but predator populations were only sampled twice during the season and so these data are not presented. Standard agronomic practices for the respective areas were used.

Experimental designs were similar at both sites. There were five experimental treatments that consisted of suppressing *B. tabaci* whenever populations exceeded thresholds of 2.5, 5, 10, or 20 adult *B. tabaci* per leaf based on weekly sampling, and an untreated control. Insecticide treatments were a mixture of fenpropathrin (pyrethroid class) and acephate (organophosphate class) at 0.11 and 0.56 kg (AI)/ha, respectively, applied by ground equipment fitted with two to three nozzles per row. These insecticides continue to be among most potent and widely used combination of conventional insecticides available for this pest (Ellsworth and Watson 1996, Agnew and Baker 2001). Insecticide applications were continued as needed until defoliation. Treatments were replicated five times in a Latin square design, which was used to control for anticipated variation due to soil and irrigation gradients. Individual plots measured 12, 1-m rows by 15.24 m in length and were separated by 2–3 m of bare ground on all sides. At Maricopa, oxamyl was applied once (10 August 1994) to all plots for control of *Lygus hesperus* Knight (Heteroptera: Miridae); however this spray occurred after predator sampling was discontinued. No additional insecticides were necessary for other pests in Maricopa or any other pests in Brawley.

Bemisia tabaci **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 taken from the fifth mainstem leaf below the terminal. The densities of adults were estimated by counting individuals on the underside of fifth mainstem node leaves (Naranjo and Flint 1995). Thirty sample units were collected for immatures and adults from the central four to six rows of each plot on 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 was an accidental deviation from the protocol at Brawley in which insecticide applications were applied weekly once the given threshold level was initially reached. This practice continued until 4 August when the deviation was noted and corrected. It is difficult to estimate how many of these errant insecticide applications were unnecessary; however, given the rapid increase of *B. tabaci* populations in untreated control plots during June and July, it is likely that many were valid, particularly at the lower threshold levels. Nonetheless, rather than evaluating these treatment regimes on the basis of thresholds per se we examined effects relative to the initial timing and total number of insecticide applications, the two characteristics of any threshold-based regime. For consistency the intended "threshold level" will be used to denote the treatments for this site.

Predator Sampling. Arthropod predators were sampled with a standard 38 cm diameter sweep net. A total of 25 sweeps was taken along one of the center four rows of each plot. In Brawley, samples were taken weekly beginning once the first insecticide treatments were made and continuing until defoliation. Due to resource limitations, predators were sampled from only three treatments (5/leaf, 20/leaf, control) in 1994 (15 plots total); however, all treatment plots were sampled in 1995 at Brawley (25 plots). Again due to resource limitations, a total of four weekly samples was taken in all 25 plots in 1994 at Maricopa beginning 1 wk after the first insecticide application and ending 2 August, 1 wk after the first application at the 20/leaf threshold. Densities of 12 species or groups of arthropod predators were estimated, however, not all species were present at each site in both years. Only larval stages of *Chrysoperla carnea* Stephens (Neuroptera: Chrysopidae) were counted. Immature and adult stages of all other species were pooled when counted.

Predator Function. To further estimate treatment effects on predator function, an index was calculated based on seven of the more common predator species as

$$\sum_{i=1}^{7} W_{ijk}F_i / \sum_{i=1}^{7} W_{ick}F_i,$$

where W_{ijk} is the seasonal density of species i for treatment j (c = control) and replicate k, and F_i is the frequency of predation on *B. tabaci* or *Pectinophora gossypiella* (Saunders) for species i. This frequency was derived from results of gut content immunoassays (Hagler and Naranjo 1994a, 1994b; Naranjo and Hagler 1998) and is estimated as the proportion of sampled predators found positive for prey remains by ELISA in these studies. The predator species and their frequency (F) of predation on *B. tabaci* and *P. gossypiella,* respectively, are as follows: *Geocoris punctipes* (Say) (0.308, 0.136); *G. pallens* (Stål) (Heteroptera: Lygaeidae) (0.329, 0.103); *Orius tristicolor* (White) (Heteroptera: Anthocoridae) (0.383, 0.080); *Nabis alternatus* Parshley (Heteroptera: Nabidae) (0.033, 0.007); *Zelus renardii* Kolenati (Heteroptera: Reduviidae) (0.090, 0.119); *Collops vittatus* (Say) (Coleoptera: Melyridae) (0.490, 0.154): and *Hippodamia convergens* Guérin-Méneville (Coleoptera: Coccinellidae) (0.277, 0.041). The index takes on a value between 0 and 1, with 1 representing no change from the untreated control.

Statistical Analyses. Analysis of variance (ANOVA) (PROC GLM, SAS Institute 1988) for randomized block (Brawley 1994) or Latin square was performed to test for differences in predator and *B. tabaci* densities by sample date, and seasonal cumulative densities of predators and *B. tabaci* relative to action threshold regimes. Cumulative densities (insect-days) were estimated by numerically integrating the area under the week by week density curves using the trapezoidal rule (Gillett 1984, p. 457). For time series graphs, areas are simply accumulated over consecutive sample dates. *t*-tests were used to examine deviations in the mean predation index for individual threshold treatments from the control value of 1; ANOVA was used to test for differences among the action threshold treatments, excluding the control. Transformations ($[x+0.5]^{0.5}$, $\ln[x+1]$) were used throughout as necessary to achieve normality and homoscedasticity before analysis, but untransformed means are presented. Ryan's Q-test (Day and Quinn 1989), which controls for experiment-wise type I error rates, was used for mean separation throughout.

Further analyses were conducted to examine the effect of the initial timing and number of insecticide applications on densities of predators. Stepwise multiple regression analysis (PROC REG, SAS 1988) was used to regress the proportional reduction in cumulative densities of predators over all sample dates (relative to the untreated control) on two independent variables: the timing of the first applications and the number of applications applied at each action threshold during the predator sampling interval. The timing of application was estimated as degree-days (lower and upper thresholds of 12.8 and 30°C, University of California 1996) after planting. Standardized regression coefficients were calculated to directly compare the strength of the respective responses to timing and application number independent of the numerical scales of these independent variables. Standardized coefficients are calculated as the quotient of the pa-
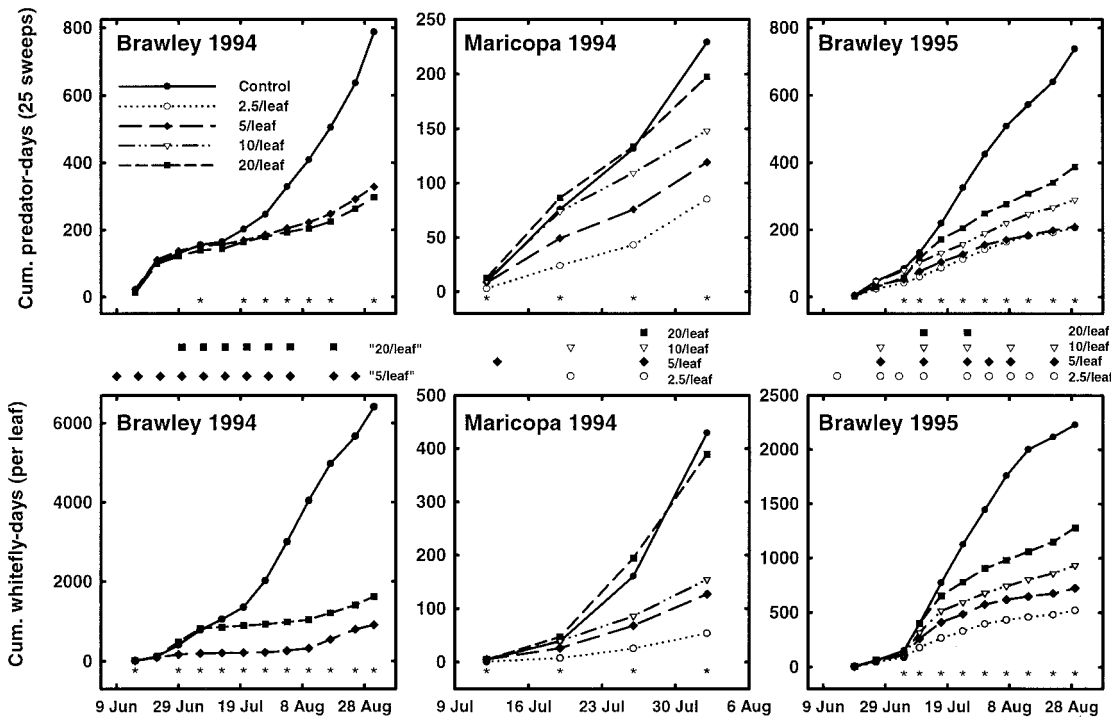
Fig. 1. Cumulative density over the season for all predator species combined and adult *B. tabaci* in relation to different action thresholds for control of *B. tabaci*, Brawley, CA, and Maricopa, AZ, 1994–1995. Symbols between graphs indicate the dates of insecticide treatments, and asterisks within graphs denote dates where significant differences ($P < 0.05$) were found among treatments based on densities for each sample date.

rameter estimate by the ratio of the sample standard deviations of the dependent and independent variables (SAS Institute 1988). These regression analyses used pooled data from all sites and years, excluding control plots ($n = 10$).

Results

Pest Density 1994 and 1995. Complete results of the threshold treatments on *B. tabaci* are detailed in Naranjo et al. (1998) and will only briefly be summarized here. All life stages of *B. tabaci* were found on the first sampling date ≈30–50 d after planting. At Brawley, the first insecticide applications were made on 9 June and 13 June in 1994 and 1995, respectively (Fig. 1). At Maricopa in 1994, the first insecticide applications were made on 6 July. There were few differences in immature or adult *B. tabaci* populations among action thresholds of 2.5, 5, and 10 adults per leaf in either year or site. Population trends over time were similar for adults and immatures of *B. tabaci* and so only adult dynamics are shown (Fig. 1). In general, all threshold treatments significantly reduced pest densities below those in untreated control plots (Tables 1–3). Insecticide applications often resulted in a temporary reduction in pest densities, especially at lower thresholds, and significantly slowed population growth (Fig. 1). Results for Maricopa, AZ, here differ slightly when compared with Naranjo et al. (1998)

because densities of *B. tabaci* here were averaged over shorter intervals of the season.

Predators 1994. *Geocoris punctipes* was the numerically dominant predator in both years at Brawley, while *Drapetis* sp. (Diptera: Empididae), a small predatory fly that attacks adult *B. tabaci* (Butler and Henneberry 1993), was most common at the Maricopa site.

Applications of insecticides significantly reduced population densities of spiders, *G. punctipes*, *G. pallens*, *Z. renardii*, and all predators pooled together at Brawley (Table 1). Clearly, results for all predators combined were largely driven by changes in densities of *G. punctipes*. There were no significant differences among any predator densities between treatment regimes denoted by five and 20 adult *B. tabaci* per leaf. This pattern is very likely related to the deviation from treatment protocols at this site noted above, leading to a relatively small difference in the number of applications between the two treatments. Densities of *C. carnea* larvae significantly increased with increasing intensity of insecticide use (Table 1).

At Maricopa, insecticide applications significantly reduced population densities of *Geocoris* spp., *O. tristicolor*, *C. carnea*, *Drapetis* sp., *Spanogonicus albofasciatus* (Reuter) (Heteroptera: Miridae), and all predators pooled together (Table 2). For *Geocoris* spp. and *O. tristicolor*, seasonal densities did not differ from the control at threshold levels of 10 or 20 adults per leaf;

Table 1.   Mean ± SE density of arthropod predators and *B. tabaci*, in relation to different action thresholds for insecticidal control of *B. tabaci* in 1994, Brawley, CA

	Threshold[a]			F^b	P
	5/leaf (9 June, 11)	20/leaf (30 June, 7)	Control		
Spiders[c]	2.3 ± 1.5a	7.7 ± 3.9ab	15.7 ± 5.6b	8.72	<0.01
Collops vittatus	2.8 ± 1.7a	4.2 ± 2.8a	7.0 ± 2.2a	0.94	0.51
Hippodamia	1.4 ± 1.4a	2.3 ± 1.5a	5.4 ± 3.1a	1.36	0.31
Other Coccinellids	38.5 ± 8.1a	41.2 ± 7.3a	48.7 ± 11.1a	0.22	0.80
Geocoris punctipes	48.5 ± 6.1a	72.9 ± 11.7a	554.1 ± 78.2b	79.9	<0.01
Geocoris pallens	1.4 ± 1.4a	2.1 ± 1.4a	14.7 ± 5.5b	6.46	0.02
Orius tristicolor	145.1 ± 10.2a	138.5 ± 14.8a	96.2 ± 23.5a	3.70	0.07
Zelus renardii	12.1 ± 2.9a	14.7 ± 6.3a	31.5 ± 4.5b	5.62	0.03
Spanogonicus albofasciatus	2.8 ± 2.8a	5.6 ± 2.6a	7.0 ± 3.1a	0.65	0.55
Chrysoperla carnea larvae	35.9 ± 4.5a	24.2 ± 6.4a	5.1 ± 2.2b	11.5	<0.01
Drapetis sp.	1.4 ± 1.4a	6.3 ± 3.2a	7.7 ± 1.3a	2.40	0.15
All predators	297.1 ± 10.5a	328.3 ± 20.8a	786.9 ± 83.3b	33.4	<0.01
B. tabaci immatures	502.3 ± 45.2a	941.6 ± 136.6b	2251.4 ± 126.1c	65.1	<0.01
B. tabaci adults	903.6 ± 111.3a	1620.2 ± 188.3b	6402.8 ± 296.1c	199.3	<0.01

[a] Threshold levels indicate treatment regime (see text for explanation of deviation for this site-year). Figures in parentheses below threshold indicate date of first application and total number of sprays.
[b] df = 2, 8; means within a row followed by a different letter are significantly different (Ryan's Q test; $P < 0.05$).
[c] Predator densities measured as cumulative counts (insect-days) per 25 sweeps; *B. tabaci* immature density measured as cumulative counts of eggs + nymphs per cm² of leaf area; *B. tabaci* adult density measured as cumulative counts of adults per leaf. All densities based on 12 weekly samples from 15 June to 31 August.

for *S. albofasciatus* and *Drapetis* sp., only the treatment based on 2.5 adults per leaf differed from the control. Densities of *C. carnea* larvae were significantly reduced at all threshold levels compared with the control. For all species pooled, threshold levels of 10 adults per leaf or lower caused significant reductions in density compared with the control.

Examination of seasonal patterns for all predator species pooled at Brawley revealed that insecticide applications generally had an immediate and long-term effect on population densities regardless of the insecticide intensity (Fig. 1). Despite the dominance of *G. punctipes*, most of the species which declined significantly with increasing insecticide intensity fol-

lowed a similar trend (not shown). Again, this pattern is largely due to the deviation from treatment protocols at this site which resulted in relatively small differences in the frequency of insecticide use between the two threshold treatments. Populations of predators generally increased over the season in control plots (cumulative curve exponential), but repeated insecticide applications significantly depressed populations and curtailed any growth.

Seasonal patterns at Maricopa were somewhat different from those at Brawley in 1994, due to a lower number of overall applications and a shorter sampling interval (Fig. 1). Application of insecticides at threshold levels of 2.5 and 5.0 adults per leaf generally de-

Table 2.   Mean ± SE density of arthropod predators and *B. tabaci*, in relation to different action thresholds for insecticidal control of *B. tabaci* in 1994, Maricopa, AZ

	Threshold[a]					F^b	P
	2.5/leaf (6 July, 3)	5/leaf (13 July, 2)	10/leaf (20 July, 2)	20/leaf (27 July, 1)	Control		
Spiders[c]	0.7 ± 0.7a	2.7 ± 1.1a	6.8 ± 1.3a	9.2 ± 4.2a	7.2 ± 3.5a	2.48	0.10
Collops vittatus	0.0 ± 0.0a	0.7 ± 0.7a	0.5 ± 0.5a	1.6 ± 1.6a	1.4 ± 0.9a	0.42	0.79
Geocoris spp.	4.4 ± 1.7a	1.2 ± 0.7a	5.7 ± 2.6ab	6.5 ± 1.6b	11.6 ± 3.7b	3.61	0.04
Orius tristicolor	20.3 ± 5.1ab	12.5 ± 6.1a	33.2 ± 2.6bc	39.9 ± 2.8bc	53.8 ± 10.9c	9.77	<0.01
Zelus renardii	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	0.5 ± 0.5a	4.2 ± 3.3a	1.65	0.23
Spanogonicus albofasciatus	9.1 ± 3.1a	28.5 ± 6.3ab	26.9 ± 4.3ab	37.1 ± 2.5b	42.3 ± 7.4b	5.20	0.01
Chrysoperla carnea larvae	2.8 ± 2.0a	6.0 ± 2.3a	6.8 ± 1.4a	6.7 ± 1.4a	22.8 ± 6.6b	5.52	<0.01
Drapetis sp.	46.8 ± 12.4a	66.8 ± 15.2ab	67.9 ± 7.5ab	95.1 ± 8.6b	86.9 ± 16.9b	3.27	0.05
All predators	85.4 ± 10.3a	119.3 ± 22.3ab	148.1 ± 14.3b	197.6 ± 16.5c	229.2 ± 18.9c	23.9	<0.01
B. tabaci immatures	19.2 ± 5.7a	53.5 ± 11.9a	67.8 ± 6.5a	202.4 ± 71.8b	293.9 ± 77.9b	17.9	<0.01
B. tabaci adults	53.4 ± 15.4a	126.8 ± 16.3b	154.2 ± 25.7b	389.2 ± 65.4c	429.2 ± 41.8c	103	<0.01

[a] Threshold indicates level at which insecticides were applied. Figures in parentheses below threshold indicate date of first application and total number of sprays.
[b] df = 4, 12; means within a row followed by a different letter are significantly different (Ryan's Q test; $P < 0.05$).
[c] Predator densities measured as cumulative counts (insect-days) per 25 sweeps; *B. tabaci* immature density measured as cumulative counts of eggs + nymphs per cm² of leaf area; *B. tabaci* adult density measured as cumulative counts of adults per leaf. All densities based on four weekly samples from 12 July through 2 August.

Table 3. Mean ± SE density of arthropod predators and *B. tabaci*, in relation to different action thresholds for insecticidal control of *B. tabaci* in 1995, Brawley, CA

Group/Species	Threshold[a]					F[b]	P
	2.5/leaf (13 June, 9)	5/leaf (27 June, 6)	10/leaf (27 June, 5)	20/leaf (11 July, 2)	Control		
Spiders[c]	5.8 ± 1.9a	13.5 ± 3.8ab	14.9 ± 5.5ab	17.5 ± 4.0b	28.2 ± 12.0b	5.33	0.01
Collops vittatus	1.4 ± 1.4a	1.4 ± 1.4a	2.8 ± 1.7a	2.8 ± 1.7a	4.2 ± 2.8a	0.27	0.89
Hippodamia convergens	4.2 ± 1.7a	6.5 ± 3.1a	2.7 ± 1.8a	9.1 ± 3.1a	38.7 ± 6.4b	13.1	<0.01
Other Coccinellids	0.9 ± 0.9a	1.4 ± 1.4a	5.5 ± 3.4a	4.2 ± 1.7a	5.0 ± 5.0a	0.71	0.60
Geocoris punctipes	116.8 ± 14.8a	108.6 ± 7.8a	147.2 ± 25.3ab	246.3 ± 36.9b	510.8 ± 55.8c	18.8	<0.01
Geocoris pallens	10.5 ± 5.8a	10.2 ± 3.9a	10.7 ± 6.0a	15.8 ± 7.1a	28.2 ± 3.4b	3.45	0.04
Orius tristicolor	41.5 ± 8.3ab	39.6 ± 6.9ab	60.1 ± 5.3a	23.8 ± 4.7b	34.4 ± 5.4ab	4.33	0.02
Zelus renardii	0.9 ± 0.9a	2.1 ± 0.9a	4.9 ± 2.1ab	9.1 ± 4.6ab	14.7 ± 4.2b	4.63	0.02
Nabis alternatus	11.2 ± 5.7a	11.5 ± 2.2a	19.6 ± 8.7a	42.8 ± 13.1b	45.1 ± 10.1b	6.61	<0.01
Chrysoperla carnea larvae	2.8 ± 1.7a	5.6 ± 4.1a	7.0 ± 3.8a	1.4 ± 1.4a	4.2 ± 2.8a	0.41	0.80
Drapetis sp.	4.4 ± 4.4a	8.4 ± 2.6a	11.4 ± 7.3a	13.3 ± 6.5a	17.5 ± 6.7a	0.83	0.53
All predators	206.5 ± 10.9a	209.4 ± 14.6a	290.2 ± 37.5ab	388.4 ± 34.6b	738.0 ± 68.5c	27.9	<0.01
B. tabaci immatures	508.4 ± 88.2a	639.8 ± 63.1a	614.2 ± 92.2a	1148.4 ± 100.7b	1946.5 ± 275.1c	62.7	<0.01
B. tabaci adults	520.0 ± 92.6a	722.6 ± 51.8ab	933.2 ± 113.9bc	1280.6 ± 125.4c	2229.8 ± 217.2d	45.5	<0.01

[a] Threshold indicates level at which insecticides were applied. Figures in parentheses below threshold indicate date of first application and total number of sprays.

[b] df = 4, 12; means within a row followed by a different letter are significantly different (Ryan's Q test; $P < 0.05$).

[c] Predator densities measured as cumulative counts (insect-days) per 25 sweeps; *B. tabaci* immature density measured as cumulative counts of eggs + nymphs per cm^2 of leaf area; *B. tabaci* adult density measured as cumulative counts of adults per leaf. All densities based on 11 weekly samples from 19 June through 29 August.

pressed populations of predators, while the delay in insecticide use afforded by higher thresholds allowed predator populations to be maintained at levels similar to the untreated control for a longer portion of the season. This pattern was indicative of most individual species that showed declining trends with lower threshold levels (not shown).

Predators 1995. In Brawley, the application of insecticides significantly reduced population densities of spiders, *H. convergens*, *G. punctipes*, *G. pallens*, *Z. renardii*, *N. alternatus,* and all predators pooled together (Table 3). Differences due to treatment thresholds were apparent for some species or groups. Significant reductions in spiders, relative to the control, were only found at the lowest threshold level, and reductions in *Z. renardii* were observed only in the two lowest threshold plots. Densities of *N. alternatus* were not significantly reduced from the control at the highest threshold level. Populations of *G. punctipes* were reduced in all treated plots, but reductions were significantly greater in plots treated at 2.5, or five adult *B. tabaci* per leaf. A similar result was observed for all predators combined which was again strongly influenced by patterns for *G. punctipes*.

As seen in 1994, insecticide applications in Brawley generally had an immediate and long-term effect on population densities of all predators pooled regardless of the *B. tabaci* threshold level used (Fig. 1). Predator population densities were affected to a lesser extent in plots treated at 10 and 20 adult *B. tabaci* per leaf compared with those treated at 2.5 and 5.0 per leaf. Again, similar patterns were observed in most of the individual species (not shown).

Timing and Number of Sprays. A multiple regression approach was used to further examine the overall effect of insecticide application timing and frequency on predator populations. Regressions of proportional reductions in cumulative densities of natural enemy populations (relative to the untreated control) on the timing and number of insecticide applications were significant for six of the 10 species or groups examined and for all predators pooled (Table 4). The stepwise analysis indicated that the timing of the first insecticide application generally had a strong negative effect on most predator populations with earlier applications leading to greater reductions in predator densities. Thus, delaying the first spray progressively reduces the impact of insecticides on predator populations. In contrast, the total number of applications failed to meet the $P < 0.50$ criterion for entry into the model for all species or groups except *O. tristicolor*, *C. carnea*, and *S. albofasciatus*, suggesting that insecticide initiation alone is sufficient to predict the impact of insecticides on most species or groups. For the former two species the coefficient was negative, indicating that the increasing number of applications resulted in lower proportional reductions in population density. Examination of the standardized coefficients for *C. carnea* indicated that the number of applications had a stronger influence than timing of the first application. For *O. tristicolor*, the timing of application failed to meet the $P < 0.50$ criterion for entry into the model at all. These results are consistent with findings for *C. carnea* at Brawley in 1994 in which populations of this predator increased with higher intensity of insecticide use (Table 1). The number of applications entered into the model for *S. albofasciatus*, but standardized coefficients indicated that timing of the first spray had a comparatively greater influence on population reduction.

Predator Function. The functional impact of different *B. tabaci* thresholds levels was evaluated by weighting the relative value of seven species (see *Materials and Methods*) as predators of two of the three

Table 4. Regression of proportional reductions in mean cumulative seasonal densities of predatory arthropods (relative to the control) on the timing and number of insecticide applications as prescribed by four different action thresholds for control of *B. tabaci*, Brawley, CA, and Maricopa, AZ, 1994–1995

Group/Species	Regression coefficient[a]			Standardized coefficients[b]			*F*-value	*P*	r^2	n^e
	Intercept	First spray[c]	No. sprays[d]	Intercept	First spray[c]	No. sprays[d]				
Spiders	2.1184	−0.0015	NS	0.0	−0.7898	0.0	13.3	<0.01	0.62	10
Collops vittatus	1.3778	−0.0008	NS	0.0	−0.5200	0.0	2.96	0.12	0.27	10
Coccinellids	0.6115	NS	NS	0.0	0.0	0.0	-	-	-	6
Geocoris spp.	1.6532	−0.0009	NS	0.0	−0.7883	0.0	13.1	<0.01	0.62	10
Orius tristicolor	0.5617	NS	−0.1110	0.0	0.0	−0.7369	9.51	0.02	0.54	10
Nabis alternatus	2.3682	−0.0019	NS	0.0	−0.8932	0.0	7.89	0.11	0.80	4
Zelus renardii	0.7886	NS	NS	0.0	0.0	0.0	-		-	10
Spanogonicus albofasciatus	3.1383	−0.0021	0.0647	0.0	−1.5635	1.0042	7.32	0.07	0.83	6
Chrysoperla carnea	14.8342	−0.0099	−0.9962	0.0	−0.8167	−1.4435	14.3	<0.01	0.80	10
Drapetis sp.	1.8141	−0.0013	NS	0.0	−0.9343	0.0	54.9	<0.01	0.87	10
All predators	1.4213	−0.0008	NS	0.0	−0.8859	0.0	29.2	<0.01	0.78	10

[a] Coefficients determined with stepwise multiple regression; NS indicated that the variable failed to meet the 0.5 significance level for entry into the model.

[b] Standardized coefficients weight the relative contribution of each variable independent of their original numerical scale.

[c] Degree-days after planting (upper and lower thresholds of 12.8 and 30°C, respectively) when first insecticide applications were made; range 785–1,426.

[d] Total number of insecticide applications; range 1–11.

[e] There was a total of 10 site-year observations; however, sample size was reduced due to absence of some species at each site during the two years of the study. *G. punctipes* and *G. pallens* were combined because the two species were not separated at the Maricopa site; *H. convergens* was combined with all other coccinellids due to low densities of these groups at both sites.

keys pests of cotton in Arizona, based on predator density and previous immunological analyses of predator feeding behavior. Data on frequency of predation on the third key pest, *L. hesperus*, are not available. Compared with the controls there was a large and significant decline in the predation index for both prey in all threshold treatments at all sites and years (Fig. 2). The general patterns of change in predation indices reflected those seen for relative changes in predator density alone (unweighted index), but quantitative values differed. At the Brawley site in both years, predation indices suggest that insecticide effects on predator function are consistently smaller than those predicted from changes in abundance alone (Fig. 2). At Maricopa in 1994, the predation index for both prey species suggested a greater impact of insecticides than would be predicted from changes in abundance alone for the lowest threshold, but a lesser or equal effect for the three higher threshold levels (Fig. 2).

Discussion

Not unexpectedly, our results clearly show that use of a broad-spectrum, pyrethroid/organophosphate mixture reduced populations of most predator species and groups examined irrespective of the action threshold level. This pattern was especially marked for the Brawley site, where high densities of *B. tabaci* occurred relatively early in the crop cycle and numerous applications were needed even at higher threshold levels. Nonetheless, our findings indicate that conservation of many species and groups of arthropod predators could be enhanced by the use of higher action threshold levels. For example, in comparisons where significant treatment differences were observed, population densities of *Geocoris* spp., *O. tristicolor*, *N. alternatus*, *Drapetis* sp., *Z. renardii*, and spiders in plots

treated at 10 and/or 20 adults per leaf were not statistically different from untreated control plots in one or more site-years. In certain instances, densities of predators in all thresholds were lower than the control, but the higher thresholds were less detrimental than lower thresholds. These overall patterns were more definitive for the Maricopa site, but the full-season impact of the different threshold regimes could not be ascertained at this site because predator sampling was terminated before completion of all prescribed insecticide treatments. However, our regression analyses suggest that the timing of initial applications at each threshold level are a stronger predictor of predator population reduction than the total number of sprays prescribed by each threshold level. Thus, the general patterns observed for the Maricopa site may have remained unchanged by additional sampling.

Populations of several predator species appeared to be unaffected by insecticide applications relative to the control and various factors could be involved. First, these populations could truly be insensitive to the insecticides used in this study. However, results are inconsistent among years. For example, *H. convergens* was unaffected by treatment regime at Brawley in 1994 but showed high sensitivity to insecticides in 1995 at this site. Densities of *S. albofasciatus* were reduced by insecticide use at Maricopa, but not Brawley in 1994. Movement among the relatively small plots by these species could be a contributing factor. However, this too is an inconsistent explanation, and even though inter-plot movement may have occurred it did not seem to affect discrimination among treatments for many species, many of which are relatively large and mobile. Finally, in almost all instances where treatment differences were not observed, predator densities were extremely low. This resulted in high
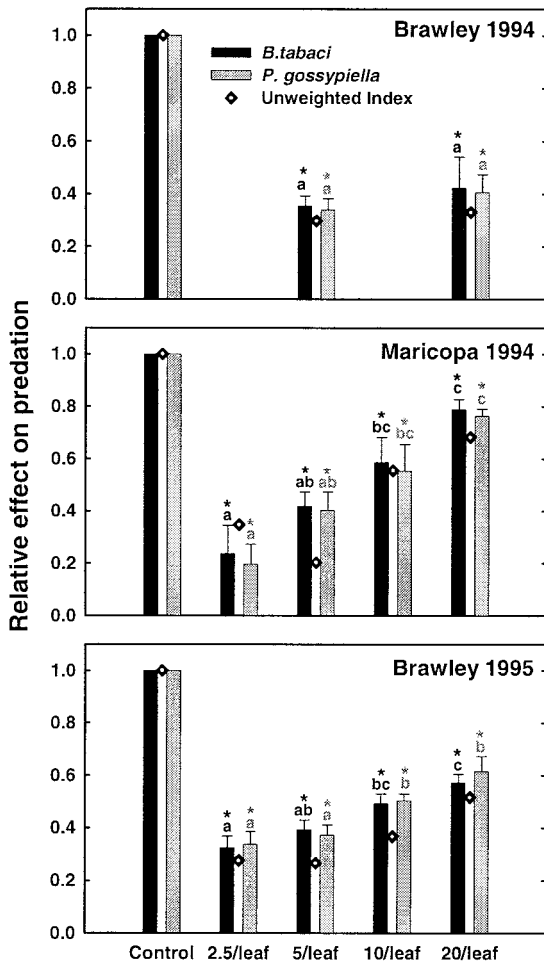
Fig. 2. Relative effect on predation of *B. tabaci* and *P. gossypiella* when using different action thresholds for control of *B. tabaci*, Brawley, CA, and Maricopa, AZ, 1994–1995. The index is based on seasonal density and known frequency of predation by seven predator species (see text for details). Asterisks denote differences from the control (=1), letters denote differences among threshold levels, and diamonds between bars denote values of the index unweighted for predation frequency (equivalent to changes in density only). Error bars denote 95% confidence intervals.

sampling variance and thus poor discrimination among treatments. This explanation is supported in part by the fact that changes in density, even though not statistically significant, generally showed a decreasing trend with increasing intensity of insecticide use. Increased power of treatment discrimination may have been possible with additional replicates or a larger number of sweeps per plot.

The proper timing of insecticide applications can be an effective means of realizing insecticide selectivity (Newsom et al. 1976). Thus, the strong relationship between the timing of first applications and the longer-term effects on populations of predators was not surprising. Predators, like all other arthropods in cotton, must colonize fields anew each year, and popu-

lation growth is driven by further colonization and in-field reproduction. Our results clearly demonstrate that broad-spectrum insecticides disrupt population growth immediately after the first application, regardless of threshold (see Fig. 1). The trajectory of predator population growth over the season is thus strongly correlated with the timing of the first disturbance leading to progressively lower reductions in population densities with progressively later dates of initial applications. Although subsequent applications may further reduce predator populations and disrupt recolonization, they appear to be relatively less important within the experimental arenas examined here.

The number of applications was a significant and negative variable in the regressions for *C. carnea* and *O. tristicolor* indicating a counterintuitive pattern of reductions in populations of these predators with a decreased frequency of insecticide usage. For *C. carnea* this pattern also was apparent at Brawley in 1994 where populations densities were significantly higher in treated plots compared with the control (see Table 1). Generalist predators such as *Z. renardii*, *Nabis* sp., and *Geocoris* spp. have been observed feeding on larval *C. carnea* in cotton fields (Cisneros and Rosenheim 1997, Rosenheim et al. 1999). Increases of *C. carnea* density could be associated with reductions in densities of these intraguild predators in treated plots at Brawley in 1994. However, densities of *C. carnea* decreased in response to insecticide use at Maricopa in 1994, and were unaffected by threshold treatment at Brawley in 1995 despite the presence of *Zelus*, *Nabis* and *Geocoris*. Thus, factors other than intraguild predation, perhaps movement of adult *C. carnea* or a reduction in competition for prey may be involved. Likewise, *O. tristicolor* is readily fed upon by *G. punctipes* and *Z. renardii* in cotton (S.E.N., unpublished data). However, patterns of *O. tristicolor* density relative to threshold treatments are inconsistent across sites and years. This species could be relatively insensitive, or even somewhat resistant, to the insecticides and application methods used in our study, or again, perhaps inter-plot movement or reduced competition for prey are involved.

The overall benefit of particular strategies for conserving natural enemies should be measured not only by simple abundance of particular species, but also their ecological role. Here we attempted to further examine the overall impact of different action threshold levels by weighting the value of different predator species on the basis of prior knowledge of their feeding behavior in the field on two key pests of cotton. Our results generally showed that this weighted index indicated a smaller effect than that determined by simple changes in population density relative to action threshold levels. The index also clearly delineated the two lower thresholds from the two higher thresholds analyzing both *B. tabaci* and *P. gossypiella* as target prey (see Fig. 2). Results here are based on only seven species for which feeding behavior information were available; however, this includes those that are among the most common and abundant species in cotton in desert production areas of Arizona and California. Our

findings suggest that the inclusion of some measure of predator function could enhance the robustness of many studies that involve evaluation of insecticide effects on natural enemy populations.

Pest management of *B. tabaci* in cotton in the western United States has steadily evolved since the first severe population outbreaks of this pest in the early 1990s (Ellsworth and Martinez-Carrillo 2001). Based largely on the results of a multi-state study (Naranjo et al. 1998), currently recommended thresholds are five adults per leaf in Arizona and southern California when using conventional insecticides (Ellsworth et al. 1995, University of California 1996). Further refinements followed the introduction of two new insect growth regulators, buprofezin and pyriproxyfen, in 1996 which emphasizes the use of these selective materials for initial treatments (Ellsworth et al. 1996). This strategy delays the use of broader-spectrum insecticides and provides for the significant contribution of conservation biological control to season-long suppression of *B. tabaci* (Naranjo 2001). Results of our study suggests further refinement of existing action thresholds are worthy of consideration, especially when producers choose to use conventional insecticides for initial suppression of *B. tabaci.* We showed that use of higher action thresholds enhanced conservation of predatory arthropods primarily by delaying chemical control. Although the current action threshold for conventional insecticides is five adults per leaf, Naranjo et al. (1998) found that levels of 5–10 adults per leaf were practically indistinguishable in terms of pest suppression and provided similar net returns. Raising the threshold to 10 adult *B. tabaci* per leaf or higher could potentially enhance conservation of predatory arthropods important to control of *B. tabaci* and other important pests in the cotton system. Such an approach will need to be weighed against the potential risks of economic damage on a broader scale, particularly when quality considerations such as sticky cotton from honeydew contamination are so critical. Further research should evaluate thresholds of 10 per leaf or higher for first use of conventional insecticides followed by the same or lower thresholds for subsequent applications. These more dynamic regimes could lower overall insecticide inputs while still achieving economically acceptable yields and quality.

The emphasis here was to examine conservation of natural enemies within the context of an existing IPM framework that bases insecticide use strictly on pest population densities. Ideally, the decision to apply remedial control agents such as insecticides also should be based on knowledge of the abundance and potential activity of natural enemies in the system. This approach will require a much greater understanding of interactions of the pest with its natural enemies, and the development or adaptation of methods for estimating natural enemy abundance. Future research that refines and expands on such approaches will enable biological control to assume a more central role in future IPM strategies.

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