# Comparative Analysis of Selected Sampling Methods for Adult *Bemisia tabaci* (Homoptera: Aleyrodidae) in Cotton

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**ABSTRACT** We evaluated the reliability and efficiency of various sticky traps and 2 direct-count sampling methods for estimating the abundance of *Bemisia tabaci* (Gennadius) adults in cotton, *Gossypium hirsutum* L., during a 3-yr period. Comparing sticky traps of various sizes, orientations, and placements, horizontally oriented traps (7.6 by 7.6 cm) with the upper surface exposed consistently captured the most adults per square centimeter over the season when placed at ground level at field edges followed by those placed within fields at ground level. Before insecticide applications, captures on all trap types and counts using a leaf-turn method and an oiled black pan method were highly correlated with the abundance of immatures in the field the same week, and even better correlated with immatures counted 1 wk later. After insecticide application, correlations were lower and more variable. Regression equations relating adult abundance to immature populations varied significantly between sites and over years for all adult sampling methods. Thus, robust predictive relationships could not be formulated. The 2 direct-count methods were highly correlated with one another, but the leaf-turn method was much less variable between individual samplers than the black pan method when estimating populations in the same field. Accounting for sample sizes needed for an acceptable level of precision and the per unit cost (time) of each sampling method, the black pan method was 3.5 times more costly than the leaf-turn method, and sticky traps were from 3.6 to 19.7 times more costly in estimating populations in the same fields. On average it took ≈6 min to estimate adult populations with a precision (SE/mean) of 0.25 using the leaf-turn method. Based on between-sampler variability, and cost considerations, the leaf-turn method was the most reliable and efficient technique for estimating adult abundance of those examined.

**KEY WORDS** *Bemisia tabaci, Bemisia argentifolii,* cost efficiency, sampling techniques, cotton

SINCE THE EARLY 1990s, the sweetpotato whitefly, *Bemisia tabaci* (Gennadius), has become established as a key pest of various winter, spring, and summer crops in Arizona and southern California. Previous outbreaks of this insect have been documented (Duffus and Flock 1982, Natwick and Zalom 1984, Butler and Henneberry 1986) in the southwestern United States; however, recent population outbreaks are thought to be associated with the introduction of a more virulent strain of *B. tabaci* (USDA 1992) or possibly the introduction of a new species, *Bemisia argentifolii* Bellows & Perring (Perring et al. 1993, Bellows et al. 1994). The sweetpotato whitefly occupies subtropical and tropical environments, is multivoltine, and has a broad host range. These characteristics, along with its ability to transmit plant viruses (Brown and Bird 1992) underlie the destructive capacity of *B. tabaci* to agriculture on a worldwide basis.

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The development and implementation of pest management strategies to control this insect depends on reliable and efficient monitoring tools for estimating pest density. Several sampling methods have been suggested for immature stages (for example, von Arx et al. 1984, Ohnesorge and Rapp 1986a, Naranjo and Flint 1994, Tonhasca et al. 1994); however, because of the difficulty of implementation in the field, these sampling approaches will probably not be useful for whitefly management. Adult whiteflies, in comparison, are relatively easy to sample and much work has been done to develop useful monitoring tools for this stage (Butler et al. 1986, Ohnesorge and Rapp 1986b, Ekbom and Xu 1990). Primarily because of the attraction of *B. tabaci* to the color yellow (Mound 1962, Sharaf et al. 1982), sticky cards have been the most widely studied sampling method for adults. Among the aspects that have been examined are trap size and shape, orientation and placement, and the influence of various environmental variables on capture (Berlinger 1980, Melamed-Madjar et al. 1982, Sharaf 1982, Gerling and Horowitz 1984, Natwick et al. 1984, Byrne et al. 1986, Bellows et al. 1988, Rao et al. 1991, Lynch and Simmons 1993, Liu et al. 1994). Other useful methods, such as visual whole plant or leaf inspection (Mabbett et al. 1980, Gerling and Horowitz 1984, Naranjo and Flint 1995, Palumbo et al. 1995), vacuum sampling (Gerling and Horowitz 1984, Natwick et al. 1992, Palumbo et al. 1995), rating of adult swarms from disturbed plants, and beating plants above vegetable oil-coated pans (Butler et al. 1986) have also been examined.

Although there has been considerable effort in studying and refining adult sampling methods for this insect there has been almost no effort to compare and contrast the performance characteristics of different methods (Natwick et al. 1992, Palumbo et al. 1995). Because the resources devoted to sampling in a pest management program are almost always limited, these performance issues are important in the development of reliable and efficient monitoring tools. Here we describe and quantitatively evaluate the reliability and efficiency of several types of yellow sticky cards and 2 direct-count methods for estimating adult abundance on the plant in cotton, *Gossypium hirsutum* L. Specifically, we examine the capture rate and variability of yellow sticky traps in relation to trap size, orientation and placement, evaluate the utility of sticky traps and 2 direct-count sampling methods for predicting population densities of immature *B. tabaci* in the field, estimate the cost-efficiency of these sampling methods, and measure the sampler to sampler variability associated with use of the 2 direct-count methods.

## Materials and Methods

**General Methods.** We examined several types of yellow sticky cards that indirectly measured adult abundance based on activity, and 2 direct-count sampling methods based on the census of adults on or from the plant. Three basic types of yellow sticky traps (Olson, Medina, OH) were evaluated during the 1992—1994 seasons; vertically oriented cylinders, vertically oriented, 2-sided traps, and horizontally oriented 1-sided traps. The height and placement of traps relative to the field were varied over the study. The cylinder trap was made by wrapping a sticky trap (15.2 by 30.4 cm) around a plastic pipe that was then placed on a wooden stake. The 2-sided trap measured 15.2 by 15.2 cm and was positioned vertically, parallel to the row. The 1-sided trap measured 7.6 by 7.6 cm and was oriented horizontally with the sticky surface facing skyward. For placement in the field, the 1- and 2-sided traps were stapled to plastic pot stakes and then attached to wooden stakes. The stakes were placed within the row, and plants were cleared as necessary to ensure that leaves did not become entangled on the sticky surface. In 1993 and 1994, 1-sided horizontal traps were also placed ≈1 m from the field edge. In instances in which we placed traps at midcanopy or canopy height, trap height was adjusted as needed throughout the season. Ground level traps were placed ≈5 cm above the soil level. All sticky traps were exposed for a 24-h period beginning between 0600 and 1000 hours.

The 2 direct-count sampling methods we examined were the leaf-turn method and the black pan method. In the former, adults were counted on the underside of the 5th mainstem node leaf from the terminal by carefully rotating the petiole or the tip of the leaf blade (Naranjo and Flint 1995). The black pan method is a modification of a technique first described by Butler and Wilson (1986). It consists of tapping the top of a cotton plant 3 times over a black cake pan (22.9 by 33 by 5.1 cm deep) coated with a thin layer of vegetable oil. In total, 10 plants were tapped as the sampler walked down the row, and the trapped whiteflies were then counted. A grid etched into the bottom of the pan aided counting when densities were high. All leaf-turn and black pan counts were made concurrently between 0600 and 1000 hours.

Each time 1 or more adult sampling methods were used at a study site, we also estimated egg and nymph densities using the methods of Naranjo and Flint (1994). This technique consists of cutting a 3.88-$cm^2$ disk from the basal portion of the 5th mainstem node leaf from the terminal and separately counting eggs and all nymphal stages (including pupae) under a dissecting microscope. These counts can be used to accurately predict the density of immatures on the top 3rd of the cotton plant and represent good relative estimators of density.

Studies were conducted from 1992 to 1994 at the University of Arizona, Maricopa Agricultural Center, Maricopa, AZ, and the USDA—ARS, Western Cotton Research Laboratory, Phoenix, AZ. In 1992, sampling data were collected from 24, 0.1-ha plots of upland cotton, ('Deltapine 50' and 'Stoneville 506'), at the Maricopa Agricultural Center. These plots were part of an experiment to evaluate the effect of irrigation scheduling and cultivar on *B. tabaci* population dynamics (Flint et al. 1994a). Plots were planted on 17 April and were managed with standard agronomic practices for the area. No insecticides were used. On each of 5 dates between 16 June and 12 August we placed a cylinder trap and a 2-sided sticky trap (10 m apart) near the center of each plot at canopy top height. We also counted the number of adults using the leaf-turn method on a total of 15 randomly selected leaves per plot. Finally, eggs and nymphs were counted on 15 leaf disks per plot.

In 1993, samples were collected at sites in Maricopa and Phoenix. At the Maricopa Agricultural Center, samples were collected weekly from 9 June through 23 September from 24 0.1-ha plots of Deltapine 50 and 'Pima S7', *G. barbadense* L. These plots were again part of a continuing experiment to examine the effects of irrigation scheduling and cultivar on *B. tabaci* population dynamics (Flint et al. 1994b). Plots were planted on 10 April, and the 1st applications of insecticides were made on 1 August. Different sampling data were collected over different parts of the season. Adults were counted on 15 randomly selected leaves per plot, and eggs and nymphs were counted on 15–20 leaf disks per plot on each week through the season. One black pan sample was collected weekly per plot from 9 June through 2 September. Cylinder sticky traps (1 at ground and 1 at canopy height) were placed in each plot weekly from 16 June through 12 August. One-sided sticky traps (1 each at ground, midcanopy, and canopy height) were placed in each plot weekly from 9 June through 23 September with the exception that midcanopy traps were first placed out on 15 July. One-sided traps were also placed at the edge of each plot at ground and canopy top height. Traps within plots were positioned near the center of the plot and were placed 5–10 m from one another. Edge traps were placed about 5 m apart. Additional leaf-turn (75 per date), black pan (10 per date), and immature leaf disk (20–50 per date) samples were collected randomly on 11 dates between 30 July and 22 October from a 1-ha field of upland cotton (Deltapine 90) at the Western Cotton Research Laboratory. This field was planted on 23 April, and no insecticides were applied.

In 1994, samples were collected at 2 sites in Maricopa and 1 in Phoenix. At 1 site at the Maricop Agricultural Center, leaf-turn (20 per plot) and immature leaf disk (20 per plot) samples were collected randomly on a weekly basis in 24 of the 0.1-ha plots of Deltapine 50 from 31 May through 23 August. In-field and field-edge 1-sided sticky traps were placed weekly (1 each per plot) at ground level starting 8 June. Plots were planted on 5 April and the 1st insecticide applications were made on 20 July. At the 2nd site, black pan (1 per plot) and immature leaf disk (15–25 per plot) samples were collected weekly from 27 June through 29 August in 40 plots (0.04 ha each)of Deltapine 5415. This site was planted 12 April, and insecticides were used in 1/2 of the plots beginning in late June. Similar to 1993, additional leaf-turn (75 per date), black pan (5 per date), and leaf-disk (75-125 per date) samples were collected randomly on 17 dates from 1 July through 17 October from a 1-ha field of Deltapine 5415 at the Western Cotton Research Laboratory. This field was planted 20 April, and no insecticides were used.

At all sample sites, plant densities averaged 65,000/ha with 1.02-m row widths. Insecticide applications consisted of ground sprays of a tank mix of fenpropathrin (0.17 kg [AI]/ha) and acephate (0.56 kg [AI]/ha).

**Comparison of Different Yellow Sticky Traps.** We initially used a repeated-measures analysis of variance (ANOVA) to examine the effect of time of season on differences between trap types for each year (SAS Institute 1988). Based on these results, we then used a factorial ANOVA to examine differences between trap types taking into account day of year, experimental treatments (irrigation frequency or cultivar, or both) and replication within these treatments. Trap effects were tested using trap type by replications within treatments as the error term. Results were summarized by calculating seasonal means and using the Tukey studentized range test to separate comparisons involving >2 means. In all cases, counts were converted to numbers per square centimeter, and these counts were then transformed by $\ln(x + 1)$ to stabilize variances before analysis. All means are presented untransformed. In 1993, various trap types were examined over different portions of the season; therefore, separate analyses were done for the periods from 9 June through 28 July and from 15 July through 16 September.

**Relationship of Immature and Adult Counts.** Correlation analysis (SAS Institute 1988) was used to examine the association of trap catches, leaf-turn counts, and black pan counts with densities of eggs, nymphs, and adult populations at each study site. At all Maricopa Agricultural Center sites where an experimental treatment was involved, we averaged counts of each life stage over each treatment on each sample date and then used these averages in the analysis. For example, in 1992 and 1993 there were 4 experimental treatments and 24 sample plots. Thus, we averaged over the 6 replicates of each treatment to get 4 pairs of data points per date. Furthermore, preliminary analyses suggested that insecticide treatments affected these associations, so we calculated separate correlation coefficients for observations occurring before and after insecticide applications at the Maricopa Agricultural Center sites. Finally, we calculated separate correlation coefficients for associations with immature counts taken 1 wk before, the same week, or 1 wk after adult counts. We further examined these relationships using linear regression analysis (SAS Institute 1988). Analysis of covariance (ANCOVA) was used to test for differences in the regression parameters estimated over different years and sites.

**Variation Among Samplers.** For some of the sample dates in 1993, we estimated the amount of variation caused by individual samplers using the leaf-turn or black pan method. At the Western Cotton Research Laboratory site in Phoenix, 2–3 persons each did leaf-turn and black pan counts at the same time on 2 dates. At the Maricopa Agricultural Center site, 2 individuals did leaf-turn and black pan counts from replicate plots of the same experimental treatment on 10 dates. A nested ANOVA (SAS Institute 1988) was used to estimate the among-sampler portion of total variation.

**Comparative Analysis of the Cost of Sampling.** We performed a cost-efficiency analysis to allow comparison among the yellow sticky trap and direct-count sampling methods. For each sampling method we used Taylor's power law (Taylor 1961),

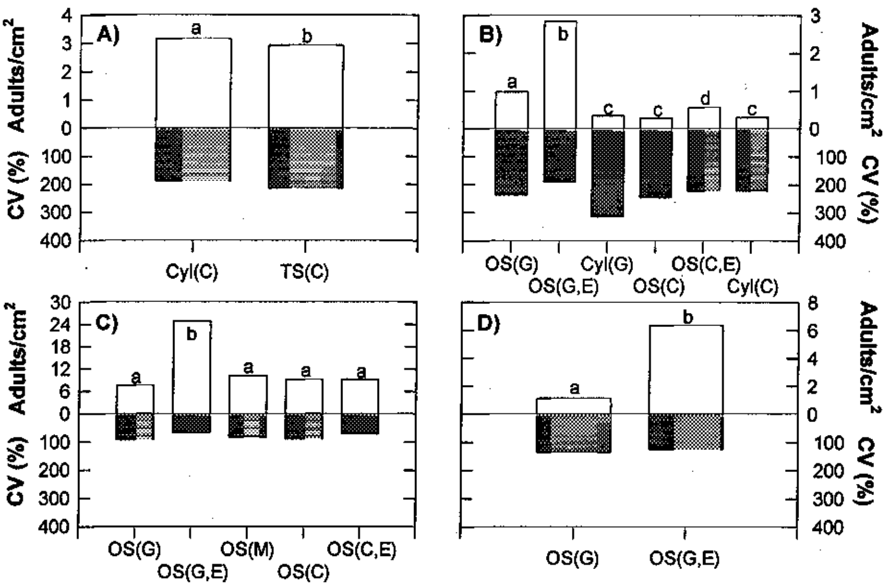


**Fig. 1.** Comparison of mean 24-h captures of adult *B. tabaci* and associated coefficients of variation (CV) on various sticky traps over the season, Maricopa, AZ. Smaller 1-sided traps captured more adults per square centimeter than larger cylindrical traps and 1-sided traps placed on the ground at the field edge consistently captured more adults than any other trap. (A) Sample period 16 June–12 August 1992, (B) sample period 9 June–28 July 1993, (C) sample period 15 July–16 September 1993; (D) sample period 15 June–20 July 1994. Bars labeled with different letters in a given comparison are significantly different ($P < 0.05$). Cyl, cylinder trap; TS, 2-sided trap; OS, 1-sided trap; C, M, G, and E denote placement at canopy top, midcanopy, ground, and edge of field, respectively.

$S^2 = am^b$, to model the relationship between the mean ($m$) and variance ($S^2$) of samples from each study site, where $a$ and $b$ are parameters fit by regressing $\ln(S^2)$ on $\ln(m)$. Following Cochran's (1977) formula for sample size ($n = [S/mD]^2$), where $S$ is the standard deviation and $D$ is precision (measured as the standard error to mean ratio), and substituting $am^b$ for $S^2$ we then estimated the density-dependent number of samples required to achieve a fixed-precision by:

$$n = \frac{am^{b-2}}{D^2}. \quad (1)$$

The cost of sampling at a particular density was then estimated as the product of $n$ and the per unit cost of sampling. We set $D = 0.25$ for all analyses. The cost of sampling (time) was estimated for each sampling method in 1993. The time required to count and record cylinder and 1-sided sticky cards in the laboratory was measured on 3 and 5 dates, respectively, and the time required to place and retrieve a sticky trap in the field was measured on a single date. The time required to enter, count and record leaf-turn or black pan samples, and exit a single plot was measured in 12 and 24 plots on 5 and 6 separate dates, respectively, at the Maricopa Agricultural Center. Regression analysis was used to develop relationships between the density of adults and the time required to complete a single sample using each method.

## Results and Discussion

**Comparison of Different Yellow Sticky Traps.** Repeated-measures analysis indicated that the relative captures of adults on the different traps varied over time in 1993 ($P < 0.05$), but not in 1992 or 1994. These trap × time interactions were strongly influenced by several dates in which the relative order varied among those traps types that did not significantly differ from one another ($P > 0.05$), and also captured the fewest adults over 24 h. Because these interactions did not appear to hold any biological significance, further differences between traps were analyzed with a simpler factorial model. Comparing 2 vertically oriented traps placed at canopy height in 1992, the cylinder trap caught significantly more adult whiteflies ($F = 30.1$; df = 1, 20; $P < 0.001$) and had a slightly smaller coefficient of variation than a 2-sided trap with the same trapping area (466 cm$^2$) (Fig. 1A). In 1993, cylinder traps were compared with smaller, horizontally oriented 1-sided traps (58 cm$^2$). With the exception of 1-sided sticky traps placed at canopy-height within the field, all of these smaller traps captured significantly more whiteflies per square centimeter ($F = 132.6$, df = 5, 32; $P < 0.001$) than cylinder traps (Fig. 1B). The largest number of adults were captured on 1-sided traps at ground level on the edges of fields followed by those at ground level within the field. When densities of whiteflies increased later in the season there was little difference between traps regardless of height or placement in relation to the field (Fig. 1C), except that more adults were still captured on ground level traps at field edges than within the field ($F = 23.3$, df = 4, 28; $P < 0.001$). In general, coefficients of variation were inversely proportional to trap capture and similar among 1-sided sticky traps that captured the fewest adults and cylinder sticky traps. In 1994, sticky traps placed on the field edge captured, on average, >5 times as many adults as within-field traps ($F = 123.0$, df = 1, 22; $P < 0.001$) (Fig. 1D).

Based primarily on their ease of use and ready availability, yellow sticky traps are the most widely used sampling technique for monitoring the abundance of *B. tabaci*. Because capture depends on behavioral activity of the adult, many factors including design, orientation, placement, exposure interval, and weather influence their performance. Previous studies suggest that horizontally oriented traps with the sticky surface skyward capture the greatest number of adults (Sharaf 1982, Gerling and Horowitz 1984, Lynch and Simmons 1993), and that there is a general inverse relationship between capture and height of the trap above the ground (Gerling and Horowitz 1984, Byrne et al. 1986, Rao et al. 1991, Lynch and Simmons 1993, Liu et al. 1994). Our results were generally consistent with these findings, except that we observed no effect of trap height on capture once densities exceeded ≈2 whiteflies per square centimeter on small 1-sided traps in the latter half of the season in 1993 (Fig. 1C). Byrne et al. (1986) found that vertically oriented cylinder traps captured more adults than either horizontal or vertical flat traps of the same surface area when traps were placed at 3 heights on field edges. A similar result was reported for within-field traps by Natwick et al. (1984). Although we consistently captured more adults at field edges (ground height), the generality of this finding is unclear as Melamed-Madjar et al. (1982) reported equal captures on edge and within-field traps. The differing patterns that we observed are probably reflective of the patterns of movement and the mix of crops in the areas in which our study was conducted. Differences also may be related to behavioral differences between biotypes of *B. tabaci*. The studies of Byrne et al. (1986) and Natwick (1984) et al. were conducted before the B biotype was present in Arizona and southern California.

**Relationship of Immature and Adult Counts.** In general, correlations between the abundance of *B. tabaci* in the field and the abundance of adults estimated using various direct and indirect methods were highly significant ($P < 0.01$), particularly before insecticide applications commenced (Table 1). For sticky traps before insecticide application, correlation coefficients were generally greater for the larger traps (cylinder and 2-sided) and placement within the canopy appeared to have no effect. For the smaller, 1-sided traps, those placed on the ground were better correlated with in-field abundance of both immatures and adults determined by the leaf-turn method. Also, with the exception of results from 1992, sticky traps catches usually were more closely associated with the density of immatures estimated 1 wk later. A similar finding was reported by Lynch and Simmons (1993) using yellow sticky traps in peanuts. Correlations between adult counts and the density of immatures estimated 1 wk earlier were consistently lower than correlations the same week or 1 wk after (not shown). Between the direct methods, the leaf-turn method was generally better correlated with the density of immatures than the black pan method; however, both methods were highly correlated with densities of immature before insecticide application, and both methods were generally better correlated with the abundance of immatures 1 wk later. Again the lowest correlations were found between adult counts and immature abundance 1 wk earlier (not shown). This consistent time-lag pattern for all methods suggests that immature populations reflect past adult reproductive activity in the field. As such, this pattern suggests that adult control may play an important role in overall population suppression.

Following the application of insecticides, correlations were lower and more variable for all adult sampling methods. In general, the only methods resulting in consistently significant correlations with field populations were the 1-sided traps at ground level within the field and the leaf-turn method (Table 1). One-sided traps placed at the field edge were not correlated with field populations in any instance and the same was true for black pan counts at the Maricopa Agricultural Center site in 1993. Leaf-turn counts were significantly correlated with immature counts in 3 of 4 cases at this site, however there was no clear pattern in relation to when adult counts were taken relative to immature counts. At the Maricopa Agricultural Center site in 1994, correlations were generally better, and the best correlations were found between adults and immatures on the same week.

With few exceptions, previous studies suggest that captures on yellow sticky traps are closely associated with field estimates of immature and adult population density using more direct methods (for example, leaf count) (Melamed-Madjar et al. 1982, Gerling and Horowitz 1984, Rao et al. 1991) or are closely associated with damage, such as virus infection (Berlinger 1980). Byrne et al. (1986) reported no significant correlations between trap catches and field populations, however, inadequate sample sizes and low populations densities may have been contributing factors. Sticky traps also may be useful indicators of movement and general population increases in an area (Gerling and Horowitz 1984, Youngman et al. 1986); however, their sensitivity is clearly limited. For example, in our analysis of different trap types we failed to detect

**Table 1. Matrix of the Spearman rank correlations between counts of adult *B. tabaci* using various sampling methods and field densities of immature and adult population estimates the same week or 1 wk after adult sampling, Maricopa (MAC) and Phoenix (WCRL), AZ**

| Method[a] | Before insecticide application | | | | | | After insecticide application | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Same wk | | | 1 wk after | | $n$ | Same wk | | | 1 wk after | | $n$ |
| | Adult | Egg | Nymph | Egg | Nymph | | Adult | Egg | Nymph | Egg | Nymph | |
| | | | | | 1992/MAC | | | | | | | |
| Cylinder (C) | 0.92* | 0.94* | 0.97* | 0.78* | 0.89* | 16–20 | — | — | — | — | — | — |
| Two-sided (C) | 0.92* | 0.96* | 0.96* | 0.74* | 0.89* | 16–20 | — | — | — | — | — | — |
| Leaf turn | — | 0.89* | 0.91* | 0.89* | 0.93* | 16–18 | — | — | — | — | — | — |
| | | | | | 1993/MAC | | | | | | | |
| One-sided (G) | 0.89* | 0.85* | 0.81* | 0.90* | 0.91* | 32–40 | 0.38* | 0.38* | 0.51* | 0.53* | 0.48* | 28–32 |
| One-sided (C) | 0.84* | 0.75* | 0.76* | 0.80* | 0.83* | 31–39 | 0.02 | 0.36* | 0.48* | 0.31 | 0.31 | 28–32 |
| Cylinder (G) | 0.92* | 0.94* | 0.93* | 0.96* | 0.97* | 32 | — | — | — | — | — | — |
| Cylinder (C) | 0.94* | 0.94* | 0.94* | 0.96* | 0.97* | 32 | — | — | — | — | — | — |
| One-sided (G, E) | 0.83* | 0.76* | 0.76* | 0.91* | 0.93* | 31–39 | 0.21 | 0.07 | 0.28 | 0.03 | −0.05 | 28–32 |
| One-sided (C, E) | 0.83* | 0.76* | 0.76* | 0.77* | 0.77* | 31–39 | −0.10 | 0.15 | 0.31 | −0.6 | −0.04 | 28–32 |
| Leaf turn | — | 0.95* | 0.93* | 0.95* | 0.96* | 32 | — | 0.40* | 0.04* | 0.61* | 0.24 | 32 |
| Black pan | 0.94* | 0.93* | 0.90* | 0.94* | 0.91* | 36 | 0.26 | 0.53 | 0.15 | 0.37 | 0.48 | 12 |
| | | | | | 1993/WCRL | | | | | | | |
| Leaf turn | — | 0.61* | 0.62* | —[b] | — | 11 | — | — | — | — | — | — |
| Black pan | 0.95* | 0.41 | 0.42 | — | — | 11 | — | — | — | — | — | — |
| | | | | | 1994/MAC | | | | | | | |
| One-sided (G) | 0.97* | 0.79* | 0.89* | 0.85* | 0.97* | 19–23 | 0.34* | 0.52* | 0.49* | 0.52* | 0.63* | 48–60 |
| One-sided (G, E) | 0.94* | 0.82* | 0.85* | 0.81* | 0.93* | 24–28 | −0.18 | 0.01 | 0.06 | 0.12 | 0.22 | 48–60 |
| Leaf turn | — | 0.82* | 0.88* | 0.84* | 0.95* | 20–24 | — | 0.72* | 0.60* | 0.38* | 0.57* | 48–60 |
| Black pan | —[c] | 0.79* | 0.89* | 0.92* | 0.88* | 36–40 | — | 0.86* | 0.75* | 0.78* | 0.85* | 36–40 |
| | | | | | 1994/WCRL | | | | | | | |
| Leaf turn | — | 0.80* | 0.54* | 0.80* | 0.74* | 15–16 | — | — | — | — | — | — |
| Black pan | 0.79* | 0.76* | 0.51* | 0.81* | 0.65* | 16–17 | — | — | — | — | — | — |

Field populations estimated as adults per leaf and eggs or nymphs per 3.88-$cm^2$ leaf disk. Asterisks indicate significant correlation coefficients ($P < 0.05$).

[a] Designations following sticky traps denote canopy-top level (C), ground level (G), and 1 m from field edge (E).

[b] Samples were taken on an irregular basis.

[c] Leaf-turn and black pan samples were taken from different field plots and could not be directly compared.

any significant ($P > 0.10$) difference between the experimental treatments at the various sites we used. These same treatment differences were highly significant ($P < 0.01$) using leaf-disk counts for immatures and leaf-turn and or black pan counts for adults (Flint et al. 1994a, b; unpublished data). A similar result was reported for sticky traps in cantaloupes (Palumbo et al. 1995).

The analyses above suggest that it may only be possible to predict the density of populations in the field with acceptable accuracy before the application of insecticides. We used regression analysis to further explore relationships between the various sampling methods and field population density during this restricted period. Because we wanted to determine the consistency of these relationships we examined only those adult sampling methods that were evaluated at >1 site or over >1 yr (cylinder traps at canopy height, 1-sided traps at ground height, leaf-turn method, and black pan method). We used ANCOVA to test for differences in the regression coefficients (slopes and intercepts) between sites-years and then pooled all observations to estimate coefficients of determination for each sampling method. In general, we found that the slopes ($F > 4.6$; df $> 1, 44$; $P < 0.05$) and intercepts ($F > 6.4$; df $> 1, 44$; $P < 0.05$) varied significantly between site-years regardless of the sampling method, whether egg or nymphal density was being predicted, or whether immature populations were being estimated the same week or 1 wk later than adult counts. Thus, although coefficients of determination for individual site-years exceeded 80% in many instances, the inconsistency in regression parameters between site-years resulted in poor coefficients of determination for pooled data. Over all site-years, leaf-turn counts were the best predictors of immature abundance; still, coefficients of determination ranged from 19 to 21% for eggs and 13 to 61% for nymphs. Our results suggest that none of the adult sampling methods we evaluated would be useful in consistently and accurately predicting immature population density in cotton.

Regression equations also were determined to relate adult density, measured as adults per leaf, to other adult sampling methods (Table 2). Although ANCOVA revealed that both slope and intercept parameters varied among sites and years, regressions based on pooled data yielded relatively high coefficients of determination for several sampling methods. Predictions of adult abundance from 1-

**Table 2. Linear regression parameters relating counts from adult sampling methods to adult density in the field (adults per leaf)**

| Method[a] | Slope | Intercept | $r^2$ | $n$ | Among site–years $F^b$ | | |
|---|---|---|---|---|---|---|---|
| | | | | | Slope | Intercept | df |
| Cylinder (C) | 0.009* | 2.471* | 0.87 | 50 | 6.3* | 5.2* | 1, 46 |
| One-sided (G) | 0.042* | −0.493 | 0.42 | 61 | 0.8 | 8.0* | 2, 55 |
| One-sided (G, E) | 0.006* | 0.013 | 0.29 | 59 | 98.5* | 40.3* | 1, 55 |
| Black pan | 0.037* | −0.219 | 0.77 | 58 | 5.3* | 4.5* | 2, 52 |

Analyses were only conducted for methods with at least 2 site years of data and only for observations from plots not treated with insecticides, Maricopa and Phoenix, AZ, 1992–1994.

Asterisks indicate that the slope or intercept of regression were significantly different than zero, or that slopes and intercepts were significantly different between sites or years ($P < 0.05$).

[a] Designations following sticky traps denote canopy-top level (C), ground level (G), and 1 m from field edge (E).

[b] ANCOVA to test for heterogeneity of regression parameters among different sites–years. Cylinder (C), 2 site–years; 1-sided (G) and 1-sided (G, E), 2 site–years each; black pan 4 site–years.

sided sticky traps was poor ($r^2 < 42\%$), however, both cylinder sticky traps and black pan counts accounted for at least 77% of the variation in adult abundance in the field. Based on a trapping surface of 466 $cm^2$, cylinder traps and leaf-turn counts were related by a ratio of ≈1:111 (range, 1:58–1:122). Likewise, based on tapping 10 plants three times each into a black pan (22.9 by 33 cm), our results indicate that, on average, leaf-turn and black pan counts were related by a ratio of ≈1:27 (range, 1:20–1:34).

The significant variability in regressions between sites for eggs and nymphs was not unexpected and reflects the effect of site-specific and yearly factors such as weather, crop mix, and crop spatial patterning that in turn influence the dynamics and age-structure of whitefly populations. Such complex interactions cannot be adequately described by simple regression. These same factors do not influence relationships among adult sampling methods to the same degree. Instead, these relationships are probably affected by differential changes in plant size and attractiveness, and prevailing weather conditions during sampling. It may be possible to develop more reliable relationships for predicting immature density from adult abundance through the use of population dynamics models. In the meantime, we should be cautious of relationships for predicting immature or adult abundance developed from empirical data collected at single sites for only one season.

The ability of adult sampling methods to accurately reflect immature populations is only 1 of the criteria by which we should judge the utility of a sampling method. Clearly, adult sampling would be inadequate for any study requiring accurate estimates of immature populations, for example, biological control studies involving nymphal parasitoids. However, because nymphs as well as adults of *B. tabaci* feed on the cotton plant and produce honeydew, both are considered to be damaging stages. Thus, either stage could arguably be sampled for pest management purposes. The emphasis on adult sampling for pest management is mainly a function of the relative ease of censusing this stage in comparison with immatures. In any case, adult sampling techniques have been successfully used in a number of pest management programs geared toward maintaining populations of this pest below economically damaging levels (Mabbett et al. 1980, Melamed-Madjar et al. 1982, Ellsworth and Meade 1994, Stam et al. 1994). Thus, the accurate prediction of immature populations may not necessarily be an important requisite for pest management application.

**Variation Among Samplers.** The amount of variation attributable to different persons sampling the same population ranged from 0 to 21% for the leaf-turn method and from 0 to 81% for the black pan method, depending on the date of sampling and site (Table 3). These results were based on samplers with equal experience in using each technique. There was no clear relationship between this variation and population density, and the variation was similar between the 2 sites examined. Pooling all dates at each site, only 6.6–9.1% of the variation in counts could be attributed to sampler for the leaf-turn method, whereas the sampler contributed 26.7–31.2% of the variation using the black pan method.

These results follow directly from the nature of the sampling methods. With the black pan, insects must be displaced from the plant and then captured. Thus, it is a more subjective sampling technique because slight individual differences in how hard or how quickly the plant is struck, and where the plant is struck, can influence the result. Further, the technique is subject to error associated with changing plant size over the season which may subtly change the size of the sample unit. These same aspects do not influence the leaf-turn method to the same degree. With this method a constant sample unit size is maintained regardless of plant size. Also, because of the relatively even distribution of adults over the top 3rd of the plant (Naranjo and Flint 1995), improper selection of the 5th leaf (for example, 4th or 6th leaf) from the terminal has little effect on the density estimate. Still, the care with which the leaf is turned over and the accuracy of counting before the insects are

**Table 3. ANOVA of counts of adult *B. tabaci* using 2 different sampling methods at Maricopa and Phoenix, AZ, 1993**

| Date | Leaf-turn method | | | | Black pan method | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean density | Among-sampler variation, % | Total variation | df | Mean density | Among-sampler variation, % | Total variation | df |
| | | | | Maricopa[a] | | | | |
| 159 | 0.03 | 0.0 | 0.03 | 359 | 2.38 | 25.4 | 0.77 | 23 |
| 167 | 0.04 | 0.0 | 0.04 | 359 | 3.38 | 8.6 | 0.43 | 23 |
| 174 | 0.06 | 0.4 | 0.06 | 359 | 3.75 | 27.6 | 0.64 | 23 |
| 188 | 1.01 | 11.5 | 0.66 | 359 | 34.83 | 0.0 | 0.18 | 23 |
| 195 | 1.92 | 1.4 | 0.82 | 359 | 60.50 | 6.5 | 0.29 | 23 |
| 202 | 3.46 | 21.1 | 1.12 | 359 | 80.50 | 0.0 | 0.23 | 23 |
| 209 | 12.96 | 18.8 | 1.92 | 359 | 374.87 | 48.9 | 0.82 | 23 |
| 223 | 9.88 | 13.6 | 1.99 | 359 | 129.83 | 30.1 | 1.65 | 23 |
| 230 | 18.54 | 5.2 | 1.78 | 359 | 96.21 | 34.7 | 1.34 | 23 |
| 245 | 14.09 | 3.9 | 1.69 | 359 | 434.87 | 74.5 | 0.80 | 23 |
| All dates | 6.20 | 9.1 | 3.11 | 3599 | 122.11 | 26.7 | 7.41 | 239 |
| | | | | Phoenix[b] | | | | |
| 211 | 1.35 | 19.9 | 0.87 | 92 | 100.80 | 46.7 | 0.23 | 9 |
| 224 | 3.67 | 0.0 | 1.10 | 90 | 464.10 | 81.3 | 0.63 | 9 |
| All dates | 2.51 | 6.6 | 1.10 | 183 | 282.45 | 31.2 | 2.43 | 19 |

Insect counts transformed by $\ln(x + 1)$ before analysis.
[a] Total variation includes that caused by treatment effect, among-sampler, and within-sampler components.
[b] Total variation includes that caused by among-sampler and within-sampler components.

**Table 4. Taylor power law parameters for different sampling methods for adult *B. tabaci* on cotton at Maricopa (MAC) and Phoenix (WCRL), AZ**

| Sample method/site[a] | $a$ | $b \pm$ SE | $r^2$ |
|---|---|---|---|
| Leaf turn | | | |
| 1993-MAC | 2.08 | 1.67 ± 0.05 | 0.96 |
| 1994-MAC | 1.88 | 1.53 ± 0.03 | 0.97 |
| 1993-WCRL | 1.53 | 1.71 ± 0.03 | 0.95 |
| 1994-WCRL | 1.68 | 1.70 ± 0.06 | 0.98 |
| Black pan | | | |
| 1993-MAC | 0.46 | 1.75 ± 0.07 | 0.92 |
| 1994-MAC | 0.19 | 1.99 ± 0.05 | 0.95 |
| 1993-WCRL | 2.83 | 1.66 ± 0.32 | 0.74 |
| 1994-WCRL | 0.65 | 1.68 ± 0.15 | 0.89 |
| Cylinder (C) | | | |
| 1993-MAC | 1.00 | 1.70 ± 0.06 | 0.98 |
| 1994-MAC | 0.67 | 1.68 ± 0.10 | 0.90 |
| Cylinder (G) | | | |
| 1993-MAC | 0.22 | 1.88 ± 0.16 | 0.82 |
| Two-sided (C) | | | |
| 1992-MAC | 1.02 | 1.72 ± 0.06 | 0.98 |
| One-sided (G) | | | |
| 1993-MAC | 0.43 | 1.89 ± 0.06 | 0.94 |
| 1994-MAC | 0.26 | 1.84 ± 0.18 | 0.83 |
| One-sided (C) | | | |
| 1993-MAC | 1.43 | 1.51 ± 0.06 | 0.93 |
| One-sided (G, E) | | | |
| 1993-MAC | 0.66 | 1.73 ± 0.06 | 0.96 |
| 1994-MAC | 0.40 | 1.86 ± 0.07 | 0.96 |
| One-sided (C, E) | | | |
| 1993-MAC | 2.08 | 1.47 ± 0.05 | 0.97 |

[a] Designations following sticky traps denote canopy-top level (C), ground level (G), and 1 m from field edge (E).

disturbed are important considerations. Our results for the leaf-turn method are consistent with those of Diehl et al. (1995) who demonstrated that samplers with variable degrees of experience consistently estimated similar densities in the same field using this technique.

**Efficiency of Sampling.** The comparative efficiency of the various sampling methods varied widely (Figs. 2 and 3). The time required to correctly identify and count adult *B. tabaci* on a single yellow sticky trap varied depending on the density of adults and size of the trap. The relationship between density ($d$) and time ($t$) in minutes for cylinder or 2-sided traps (465 $cm^2$) is given by $t = 5.67 + 0.0044d$ ($n = 72$, $r^2 = 0.64$) and for 1-sided traps (58.1 $cm^2$) as $t = 1.14 + 0.0061d$ ($n = 262$, $r^2 = 0.93$). An additional (mean ± SD) 3.73 ± 0.25 min ($n = 12$) were needed for placement and retrieval of either trap type in the field. The time required to complete a single pan count in the field is given by $t = 1.87 + 0.012d$ ($n = 144$, $r^2 = 0.80$) and a single leaf-turn count is given by $t = 0.14 + 0.013d$ ($n = 62$, $r^2 = 0.67$). These equations include the time required to enter and exit the field.

Combining the information on per unit sampling times with the sample size requirement derived from the Taylor power law (Table 4; equation 1) we estimated the total time needed to complete sampling on each date at each site using various sticky traps (Fig. 2). In general, less time was required to achieve estimates with a fixed precision of 25% as adult populations increased over the season. There was little difference in efficiency between cylinder and 2-sided traps in 1992 (Fig. 2, A1). Differences in efficiency were more marked

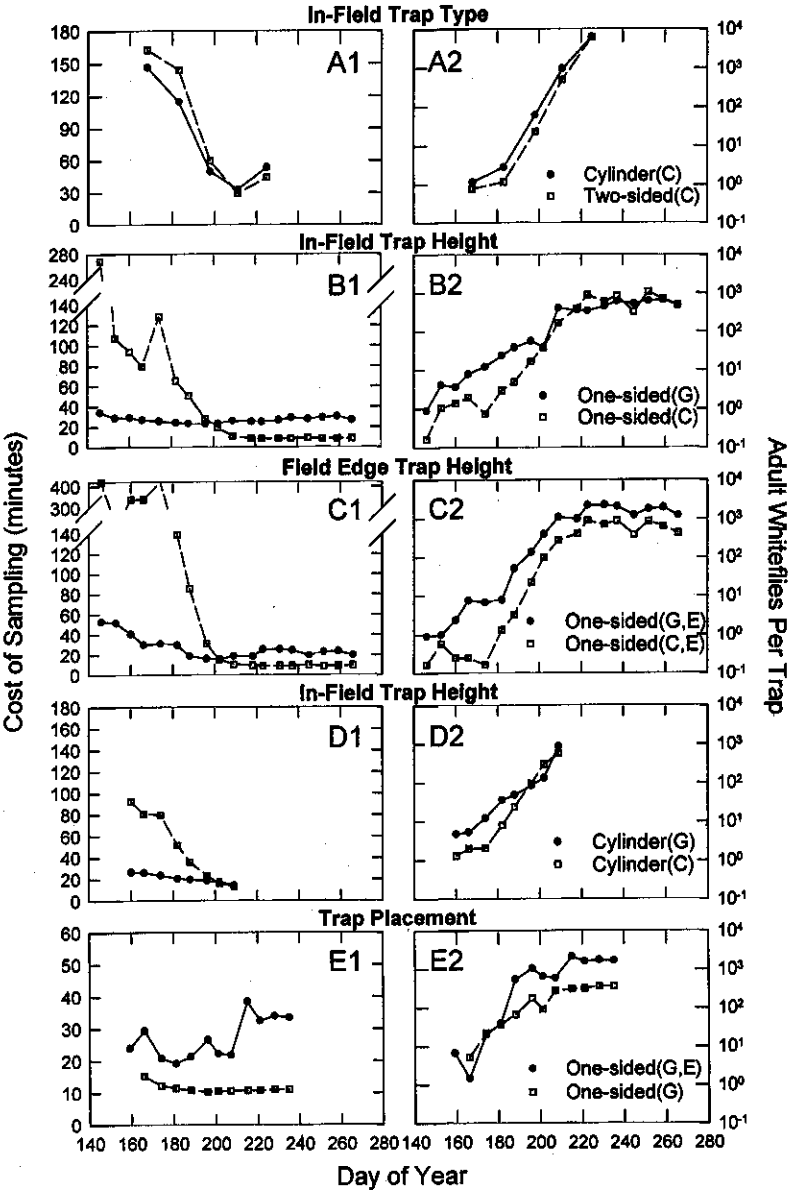


**Fig. 2.** Comparison of the cost of sampling for adult *B. tabaci* using various types of yellow sticky traps in Maricopa, AZ. Cost of sampling was estimated as the product of the density-dependent time need to collect and count traps, and number of traps needed to achieve a sampling precision of 0.25 based on equation 1. (A1) Cost of sampling and (A2) adults per trap for vertically oriented cylinders or 2-sided cards within the field at canopy-height, 1992. (B1) Cost of sampling and (B2) adults per trap for horizontally oriented, 1-sided cards placed within the field at 3 heights within the canopy, 1993. (C1) Cost of sampling and (C2) adults per trap for horizontally oriented, 1-sided traps placed 1 m from the field edge at 2 heights, 1993. (D1) Cost of sampling and (D2) adults per trap for vertically oriented cylinders within the field at 2 heights in the cotton canopy, 1993. (E1) Cost of sampling and (E2) adults per trap for horizontally oriented, 1-sided traps placed at ground level within the field or 1 m from the field edge, 1994. The cost of sampling generally declined with population density and overall cost efficiency was highest for traps placed at ground level. C, G, and E denote placement at canopy top, ground, and edge of field, respectively.

for the smaller, horizontally oriented, 1-sided traps in 1993 (Fig. 2, B1 and C1). Traps placed at canopy height were comparatively inefficient, particularly during the 1st half of the season and if the trap was placed at the field edge. Traps placed at ground level were more efficient and there was relatively little change in efficiency over the entire season. The same pattern resulted using the larger cylinder trap, with traps placed near ground level being much more efficient (Fig. 2, D1). Finally,

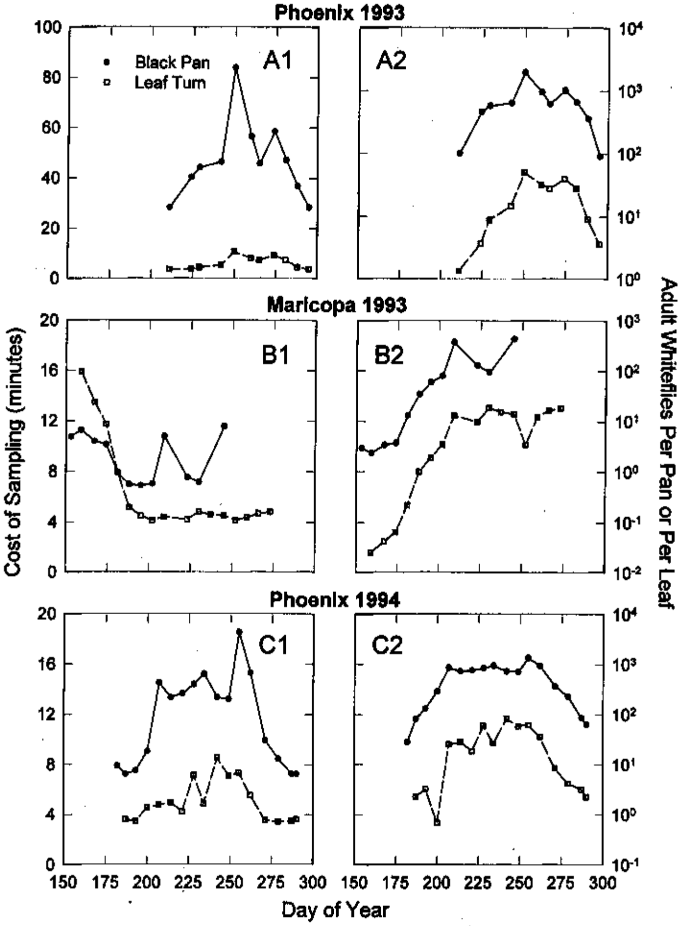


**Fig. 3.** Comparison of the cost of sampling for adult *B. tabaci* using 2 direct-count methods. Cost of sampling was estimated as the product of the density dependent time need to count adults, and number of traps needed to achieve a sampling precision of 0.25 based on equation 1. (A1) Cost of sampling and (A2) adults per leaf or pan at Phoenix, 1993. (B1) Cost of sampling and (B2) adults per leaf or pan at Maricopa, 1993. (C2) Cost of sampling and (C2) adults per leaf or pan at Phoenix, 1994. The cost of sampling generally declined with population density and the leaf-turn method was more cost efficient over a broad range of densities.

results from 1994 (Fig. 2, E1) support those in 1993 in which traps placed at the field edge were less efficient than those placed within the field.

The same efficiency analysis applied to the direct-count methods showed that leaf-turn counts were consistently more efficient than black pan counts except during the 1st 3 sample dates in 1993 at the Maricopa Agricultural Center (Fig. 3, B1). During this period of time the density of adults was less than 0.05 per leaf or 3.7 per pan. Populations are typically at this level for only a brief period in the early part of the cotton-growing season. This, combined with the substantial sampler to sampler variation found for the black pan method at these low densities (see Table 3) suggests that this higher efficiency holds little significance in the practical application of the sampling technique. Again, as with sticky traps, sampling effort was inversely proportional to adult abundance using either method.

One of the main factors contributing to the variable differences in efficiency between the 2 direct-count methods among sites was the variability in the underlying mean–variance relationship for the black pan method (Table 4). ANCOVA indicated that both the slope ($F = 5.05$; df = 3, 148; $P < 0.01$) and intercept ($F = 6.12$; df = 3, 148; $P < 0.01$) of the Taylor power law regressions for the black pan method varied among sites. The same was not true of the leaf-turn method where parameters of the power law regressions remained relatively consistent among sites ($P > 0.07$). This could be an important consideration in the development of robust sequential or binomial sampling plans (for example, Green 1970, Wilson and Room 1983) which use the Taylor power law to model the mean–variance relationship.

**Table 5. Summary of cost-efficiency analyses of different sampling methods for estimating the abundance of adult *B. tabaci* in cotton**

| Sampling method | No. observations | Mean ± SD[a] | | | Relative cost |
|---|---|---|---|---|---|
| | | Density | Sample size | Cost, min | |
| Leaf turn | 43 | 18.1 ± 20.2 | 22.4 ± 21.8 | 5.9 ± 2.8 | 1.0 |
| Black pan | 40 | 447.6 ± 443.7 | 3.3 ± 2.1 | 20.5 ± 18.5 | 3.5 |
| Cylinder trap (ground) | 8 | 150.4 ± 295.2 | 2.2 ± 0.5 | 21.1 ± 4.2 | 3.6 |
| One-sided trap (ground) | 29 | 232.8 ± 225.4 | 3.5 ± 1.5 | 21.1 ± 8.0 | 3.6 |
| One-sided trap (ground, edge) | 30 | 856.5 ± 842.0 | 3.6 ± 2.7 | 27.2 ± 9.4 | 4.6 |
| One-sided trap (canopy) | 18 | 310.1 ± 371.1 | 10.1 ± 14.1 | 51.3 ± 67.3 | 8.7 |
| Cylinder trap (canopy) | 13 | 644.8 ± 1,731.5 | 6.1 ± 4.6 | 61.0 ± 40.2 | 10.3 |
| Two-sided trap (canopy) | 5 | 1,365.5 ± 2,763.8 | 8.5 ± 7.4 | 88.2 ± 60.9 | 14.9 |
| One-sided trap (canopy, edge) | 18 | 315.8 ± 353.7 | 23.5 ± 32.5 | 116.4 ± 156.5 | 19.7 |

Results are based on the number of samples needed to achieve a statistical precision of 0.25 and density-dependent costs associated with each sampling method.

[a] Means of individual observations shown in Figs. 2 and 3.

We summarized the findings shown in Figs. 2 and 3 by averaging results over all sampling dates, sites and years (Table 5). The leaf-turn method was the most efficient method for estimating the abundance of adults by at least a factor of 3.5. The least efficient method was a 1-sided sticky trap placed at canopy height on the edge of a field, which was, on average, 19.7 times more costly than the leaf-turn method. All of the sticky card methods that involved placement of traps at ground level were roughly equal in efficiency to the black pan method and were more than twice as efficient as traps placed at canopy level. However, it should be noted that the cost of the traps themselves and the extra trip to the field site 24 h after placement were not included in cost estimates for sticky traps. Thus, although sticky traps may be useful tools in the detection and monitoring of movement and regional population levels, our results suggest that they are comparatively inefficient.

On average, 22 leaf-turn samples were required to estimate the density of adults with a precision of 0.25 and this sample took ≈6 min to complete. Taking into consideration the small size of our plots and the variable number of samples required on each date, our sample times for the leaf-turn method were comparable to those estimated by Diehl et al. (1995) in which 30 leaf-turn counts were done at 2 sites per field with fields 17–34 ha in size. In comparison, only 3 black pan samples were required, on average, to assess the density of populations in the same plots, but it took > 20 min to complete the sample using this method.

In conclusion, we used 3 independent criteria to evaluate various adult *B. tabaci* sampling methods for use in cotton. The methods we examined were well correlated with immature and adult infestations in the field before the use of insecticides. However, only the leaf-turn method was consistently significantly correlated (albeit poorly) with field populations after insecticide use. Although correlations were good, further regression analysis revealed that none of the adult sampling method could be used to accurately predict field populations of immatures. Of the sticky traps evaluated, horizontally oriented, 1-sided traps placed near the ground captured the most adult whiteflies and generally were the least variable regardless of where they were placed relative to the field. From a cost-efficiency perspective, these horizontal ground traps were also among the most efficient over most of the season, especially if they were placed within the field. Regardless of trap type, sticky traps were from 3.5 to 19.7 times less cost-efficient than the leaf-turn method. Excluding trap costs and extra trips to the field, the average efficiency of the best sticky traps were roughly the same as the black pan method. Both the leaf-turn and the black pan methods are in wide use in Arizona, southern California, and northern Mexico (Natwick et al. 1992, El-Lissy et al. 1994, Diehl et al. 1995). Our findings suggest that the 2 methods are highly correlated; however, we conclude that the leaf-turn method had the best overall performance. The leaf-turn method was less variable among individual samplers, and less costly in terms of the amount of time needed to estimate population density with acceptable statistical precision. These qualities suggest that it would be a more consistent and efficient method for comparing populations of *B. tabaci* among cotton fields and over time. Finally, because the leaf-turn method uses a relatively small sample unit it is useful in the development of binomial count methods which are based on the presence or absence of insects to estimate population density.

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