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Sampling *Bemisia*[1] for Research and Pest Management Applications

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Introduction

The key components of any pest management program are cost-efficient, reliable tools for monitoring pest density and for making decisions regarding the need for population suppression. Ideally, these sampling tools should not only be easy to use and require minimal effort, but also provide accurate and unbiased estimates of pest abundance. Sampling is also a fundamental component of most field research activities that address issues in population ecology, population dynamics, and the development of alternative control systems.

Several useful sampling methods for *Bemisia* have been suggested and implemented for research and management purposes on a number of agricultural crops over the past few decades. The relatively recent emergence of *Bemisia* as a worldwide problem has prompted additional research on sampling this insect on some of its major host crops. This review is not intended to be exhaustive because several good reviews are already available (Butler *et al.*, 1986; Ohnesorge and Rapp, 1986a; Ekbom and Xu, 1990). Instead, this review will focus on the fundamentals of developing and testing sampling methods for use in both research and pest management. Most of the discussion will center around cotton, a major host crop, with emphasis on agriculture in the southwestern deserts of the USA. The concentration on cotton is due to the large amount of literature on sampling in cotton and the author's own research and experience in this area. Nonetheless, the basic components and considerations in

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[1] The generic name *Bemisia* is used whenever no specific affiliation is known or required in the text. See also the introduction to this volume.

Bemisia *1995: Taxonomy, Biology, Damage Control and Management*

developing sampling strategies in cotton can be easily transferred to any of a number of host crops in which *Bemisia* is a significant threat.

General statistical considerations

Several fundamental components need to be addressed in the development of any sampling program. First, the objectives of sampling and the type of data that are being sought need to be defined. This includes such considerations as spatial scale, which life stages are of interest, and whether relative or absolute estimates of density are required. Next, the spatial distribution of the insect should be examined and described at the appropriate spatial scale. This will help define the sampling universe, ensure that sampling will provide representative, unbiased estimates of abundance, and will form the quantitative foundation for formal sampling plans. Third, based on knowledge of spatial dispersion, appropriate sample units can be selected and evaluated in relation to tradeoffs between associated variability and cost. Finally, this information is integrated to formulate specific sampling plans that meet the goals of the sampling program in an efficient manner.

SPATIAL DISTRIBUTION

The spatial dispersion of an insect population is the result of interactions among a complex array of biological, ecological, and physical factors. This spatial patterning further depends on the scale or level of resolution at which the insect population is viewed. The goals of a particular sampling program will determine what spatial scale needs to be examined and how much detail is required. For instance, it is probably not necessary to understand within-leaf or within-plant distribution of *Bemisia* to develop a sampling program for examining areawide movement of adults using yellow sticky traps. However, distributions at these smaller spatial scales would be important for estimating density on a plant or for studying population age structure.

The distribution of *Bemisia* within individual plants is largely a function of the interaction among the ovipositional behavior of adult females, the sessile habit of immature stages, and the dynamics of plant growth. In general, females oviposit on young foliage (Gerling *et al.*, 1980) resulting in a vertical distribution of immatures with eggs and early instar nymphs near terminal growing points and older nymphs on progressively older foliage. Within-plant distributions have been described on a number of host plants, including cotton (Gerling *et al.*, 1980; Mabbett *et al.*, 1980; Melamed-Madjar *et al.*, 1982; von Arx *et al.*, 1984; Ohnesorge and Rapp, 1986b; Butter and Vir, 1990; Rao *et al.*, 1991b; Naik and Lingappa, 1992; Naranjo and Flint, 1994, 1995), cantaloupe (Tonhasca *et al.*, 1994a), peanut (Lynch and Simmons, 1993), cassava (Abisgold and Fishpool, 1990), ornamentals (Liu *et al.*, 1993), tomato (Ohnesorge *et al.*, 1980; Carnero and González-Andujar, 1994) and various vegetables (Simmons, 1994). Distributions of all stages of *Bemisia* are aggregated both within individual leaves and within-plants. *Bemisia* typically inhabits the underside of leaves (reviewed by van Lenteren and Noldus, 1990), although, immature stages may inhabit both leaf surfaces with varying frequency on some host plants (Ohnesorge *et al.*, 1980; McAuslane *et al.*, 1993; Lynch and Simmons, 1993; Simmons, 1994). Consideration of insects on the upper surface is probably not important in developing

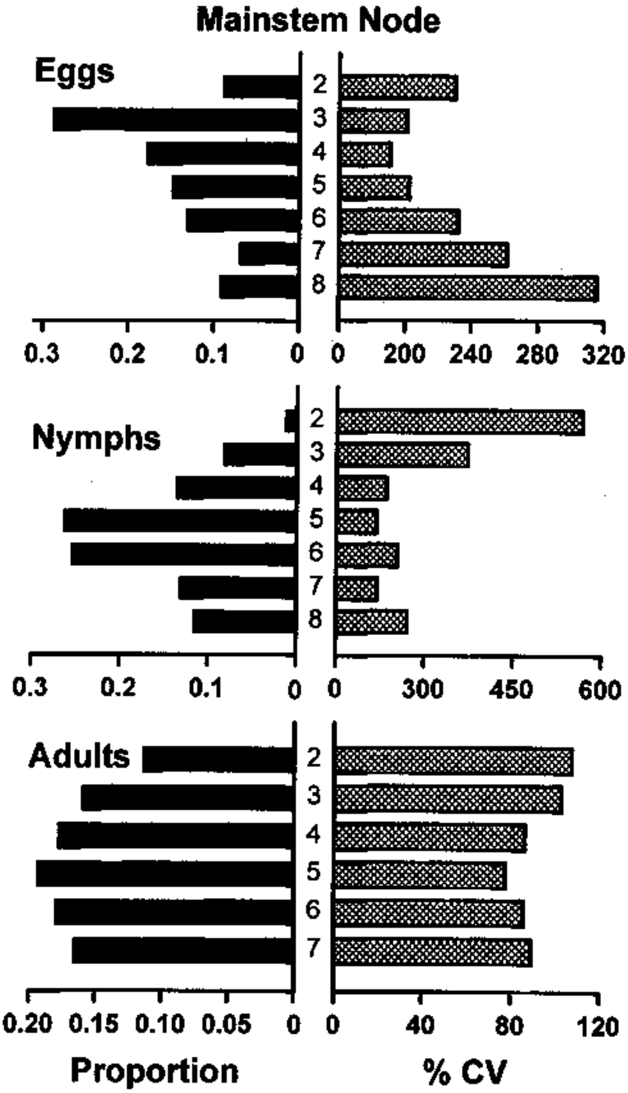

Figure 18.1. Distributions of eggs, nymphs, and adults of *Bemisia* on mainstem leaves of cotton (node 1 = terminal) and associated coefficients of variation (% CV = 100 × SD/mean), Arizona, USA. From Naranjo and Flint (1994, 1995)

relative sampling methods, however, it would be critical if the goal were to estimate absolute population density. This aspect of within-leaf distribution has received little attention and deserves further examination on other host plants.

The general distribution of eggs, nymphs and adults on the mainstem branch of cotton is summarized in Figure 18.1 from studies in Arizona. On average, eggs are most abundant on leaves from the third node from the terminal whereas adults and nymphs (all stages) are most abundant on leaves from the fifth node. The positions of these most infested leaves change less than one node over the course of the growing season reflecting the synchrony between insect and plant development. Cotton plants produce one new mainstem node about every 4–5 days under well-managed conditions in Arizona (Silvertooth *et al.*, 1992). There is also an interesting relationship between variability and abundance such that leaves with the highest density of insects also have the lowest relative variation (CV). This quality was used in determining the best node for sampling immatures and adults of *Bemisia* (Naranjo and Flint, 1994, 1995).

The next higher level of resolution involves between-plant or within-field distribution. Typically, at this spatial scale, dispersion is described with a theoretical distribution such as the poisson or negative binomial, or with models such as Taylor's power law (Taylor, 1961) or Iwao's patchiness regression (Iwao, 1968) that relate the mean and variance over a range of population densities. Several authors have used mean-variance models to describe the spatial distribution of *Bemisia* immatures and adults (von Arx *et al.*, 1984; Liu *et al.*, 1993; Naranjo and Flint, 1994, 1995; Tonhasca *et al.*, 1994a). Without exception, these analyses indicate that populations of all life stages of *Bemisia* are aggregated, or clumped, in distribution at the resolution of individual fields or greenhouses. Parameters of Taylor's power law for various sample units and all life stages in cotton are shown in Table 18.1.

Table 18.1. Taylor's power law, $S^2 = am^b$, parameters for eggs, nymphs, and adults of *Bemisia* on cotton from Arizona, USA, where S^2 is variance, m is the mean, and a and b are parameters estimated by regression. From Naranjo and Flint (1994, 1995) and Naranjo *et al.* (1995)

Life stage	Sample unit	Power law parameters *a*	*b*	Coefficient of determination (*r*2)
Eggs	Leaf disk	2.99	1.77	0.97
	Leaf sector	2.72	1.67	0.99
	Whole leaf	0.82	1.90	0.98
Nymphs	Leaf disk	2.54	1.69	0.97
	Leaf sector	2.02	1.58	0.99
	Whole leaf	0.55	1.89	0.99
Adult	Whole leaf	2.08	1.67	0.96
	Black pan[a]	0.30	1.90	0.76
	Cylinder trap (ground)[b]	0.22	1.88	0.82
	Cylinder trap (canopy)[b]	0.75	1.70	0.94
	Horizontal trap (ground)[c]	0.45	1.83	0.95
	Horizontal trap (canopy)[c]	1.62	1.49	0.94

[a] Tops of 10 plants beaten over a vegetable oil-coated pan, 23 by 33 by 5 cm deep.

[b] 15.2 by 9.7 cm diameter yellow sticky trap; vertically-oriented.

[c] 7.6 by 7.6 cm yellow sticky trap; exposed surface skyward.

Aside from some general descriptive accounts (e.g. Nelson *et al.*, 1993; Watson *et al.*, 1992; Riley, this volume; Allen, this volume; Ellsworth *et al.*, this volume) there has been little effort to quantitatively describe spatial dispersion of *Bemisia* beyond the level of individual fields.

COST-EFFICIENCY/SELECTION OF SAMPLE UNIT

The resources that can be devoted to sampling are almost always limited, particularly in pest management programs where there are many competing demands for available time and materials. Thus, in the development of sampling plans, there is always a balance between the cost and the quality of information provided by sampling. An efficient sampling plan is one that attempts to maximize precision and minimize cost.

Because eggs and nymphs of *Bemisia* are sessile inhabitants of their host plants, the only method for estimating immature population densities involves direct counting of individuals on leaves. However, information on the distribution of immatures on the plant can greatly reduce the amount of time necessary to achieve an acceptable estimate of abundance (von Arx *et al.*, 1984; Ohnesorge and Rapp, 1986b; Abisgold and Fishpool, 1990; Naranjo and Flint, 1994). For example, the density of eggs and nymphs on the top third of the cotton plant can be accurately estimated by counting only those individuals on the fifth mainstem node leaf (Naranjo and Flint, 1994). Further, the density on a leaf can be accurately estimated by counting individuals on a single leaf sector or a single 4 cm^2 disk extracted near the petiole. The relative merits of sampling a leaf, a sector, or a disk depends on the variability in populations on each of these sample units and the cost (= time) associated with counting insects on each of these sample units. Densities of insects between leaf disks are more variable than those between sectors which are in turn more variable than densities on whole leaves. However, in comparison to a leaf disk, it takes about four times longer to count insects on a leaf sector and about 14 times longer to count insects on a whole leaf. Based on these factors and relative variation among nodes on the mainstem (Figure 18.1) the optimal sample unit for cotton over a wide range of insect densities was determined to be a disk taken from the leaf at the fifth mainstem node (Naranjo and Flint, 1994).

A greater variety of sampling methods have been used to estimate abundance of the non-sessile adult stage, including yellow sticky cards (Berlinger, 1980; Melamed-Madjar *et al.*, 1982; Sharaf, 1982; Gerling and Horowitz, 1984; Natwick *et al.*, 1984; Byrne *et al.*, 1986; Youngman *et al.*, 1986; Rao *et al.*, 1991a; Lynch and Simmons, 1993; Liu *et al.*, 1994), visual plant or leaf inspection (Mabbett *et al.*, 1980; Gerling and Horowitz, 1984; Naranjo and Flint, 1995), vacuum sampling (Gerling and Horowitz, 1984; Natwick *et al.*, 1992), and beating plants above vegetable oil-coated pans (Butler *et al.*, 1986). Yellow sticky cards are widely used and are generally good tools for detecting the presence of whiteflies, estimating relative abundance in a general area, or monitoring dispersive activity. The remaining techniques are more closely

Table 18.2. Comparative cost-efficiency of different sampling methods for estimating the abundance of adult *Bemisia* in cotton. 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

Sampling method	Mean sample size	Mean cost (minutes)	Relative cost[a]
Leaf turn	22.4	5.9	1.0
Black pan[b]	3.3	20.5	3.5
Cylinder trap[c] (ground)	2.2	21.1	3.6
Cylinder trap[c] (canopy)	6.1	61.0	10.3
Horizontal trap[d] (ground)	3.5	21.1	3.6
Horizontal trap[d] (canopy)	10.1	51.3	8.7

[a] Cost of each method relative to the leaf turn method.

[b] Tops of 10 plants beaten over a vegetable oil-coated pan, 23 by 33 by 5 cm deep.

[c] 15.2 by 9.7 cm diameter yellow sticky trap; vertically-oriented.

[d] 7.6 by 7.6 cm yellow sticky trap; exposed surface skyward.

related to abundance on the host-plant. However, until recently, there has been little effort to directly compare various methods (Natwick *et al.*, 1992; Naranjo *et al.*, 1995). A comparative study of various types of sticky cards and two direct sampling methods was recently completed on cotton in Arizona (Table 18.2). Based on evaluation of variability and cost, a simple technique consisting of counting adults on the underside of a fifth mainstem node leaf was found to be the most efficient method by at least a factor of 3.5. Additionally, the density of adults on this leaf can be used to accurately estimate the number of adults on the entire cotton plant (Naranjo and Flint, 1995) and the number of eggs and nymphs on leaf disks from the same field (Naranjo *et al.*, 1995).

Sampling plans for research applications

There has been considerable effort in developing sampling methods for *Bemisia* that have direct application to research problems (see reviews by Butler *et al.*, 1986; Ohnesorge and Rapp, 1986a; Ekbom and Xu, 1990). Although the objectives of sampling for research purposes may vary, some common goals are to achieve unbiased, and precise estimates of population density. An additional requirement for most applications is that estimates of density be achieved with the minimal expenditure of resources, primarily time. Beyond these issues, the level of effort and detail is dictated by research needs. Certain research goals, such as study of population age-structure or estimation of mortality rates, may require absolute estimates of density (numbers/unit of ground area), whereas relative estimates of abundance may suffice for general studies of population dynamics or evaluation of insecticidal, cultural, or biological control practices.

Once the underlying spatial distribution of the insect has been quantitatively described and the optimal sample unit has been identified (see above), the final concern involves determining the number of samples needed to achieve an estimate with acceptable precision. Relatively few studies have formulated specific sampling plans to address this latter aspect. Fixed-precision sequential sampling represents the most efficient way to implement a sampling protocol and several approaches have been developed based on theoretical probability distributions, or on empirical mean-variance relationships (Hutchison, 1994). von Arx *et al.* (1984) used Kuno's (1969) method to develop fixed-precision sequential sampling plans for fourth stage nymphs of *Bemisia* on cotton. Recently, Naranjo and Flint (1994, 1995) formulated fixed-precision sampling plans for eggs, nymphs, and adults based on Green's (1970) method which uses Taylor's power law to model the relationship between the mean and variance (Figure 18.2). A similar set of sequential stop lines was given by Tonhasca *et al.* (1994a) for eggs, nymphs and adults of *Bemisia* on cantaloupe. For immatures in cotton, these sample plans use a 4 cm^2 leaf disk extracted from the fifth mainstem node leaf as the sample unit. As previously noted, these densities can be converted to number per leaf or numbers on the top third of the cotton plant. As such, these plans cannot provide absolute estimates of immature density. Sampling plans for adults use counts on the underside of the fifth mainstem node leaf as the sample unit. These estimates can be converted to absolute density (numbers per unit area) given information on plant density. Although *Bemisia* is seldom present in cotton in most areas of Arizona and California before the five node stage, estimates

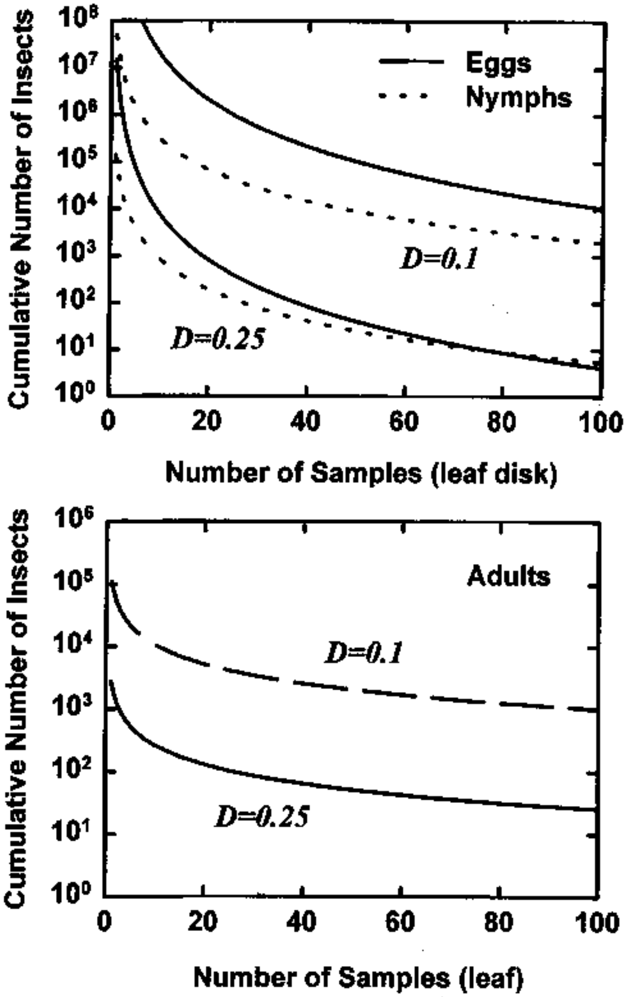

Figure 18.2. Sequential sampling stop lines for estimating the densities of egg, nymphs or adult *Bemisia* with a fixed statistical precision *D* (=SE/mean) of 0.1 and 0.25 based on Green's (1970) method.

of density can be made using the first fully expanded leaf below the terminal on less mature plants.

In practice, sequential stop lines are often summarized in tabular form so that they can be more readily interpreted for field application. This can be easily done for the various life stages using parameter values listed in Table 18.1 and Green's formula (see Naranjo and Flint, 1994). Sample size requirements increase considerably when higher levels of precision (e.g. 0.10) are required (Figure 18.2). There are no hard and fast rules for the selection of a specific value of *D* (=SE/mean). Southwood (1978) suggests that a precision of 0.05 is necessary for population studies; however, a value between 0.1 and 0.25 is probably adequate in most cases. Ultimately, the level of precision chosen typically depends on the balance between the needs of the researcher and the amount of time that can be devoted to sampling.

Sampling plans for pest management applications

Immatures are probably the best indicators of plant damage; however, they are also difficult and time-consuming to count even when sampling methods have been optimized (e.g. von Arx *et al.*, 1984; Abisgold and Fishpool, 1990; Naranjo and Flint, 1994). In contrast, adults are relatively easy to sample and a number of good sampling tools are available. Consequently, it is likely that the adult stage will continue to be the center of focus for pest management application (Mabbett *et al.*, 1980; Melamed-Madjar *et al.*, 1982; Musuna, 1986). One major drawback to this approach is the dispersive ability and intercrop movement of adults which complicate the interpretation of pest infestation data.

The primary goal of sampling for pest management is to classify the pest population as either above or below some specified level denoted by an action or economic threshold. Sampling plans developed for research (discussed above) could be used for this purpose; however, a high level of precision is seldom required, particularly when pest density is considerably above or below a damaging density. One of the most widely used sampling approaches for pest management application is binomial sampling (Binns and Nyrop, 1992). In this approach, mean population density is estimated from the proportion of sampling units infested with at least a predetermined number of insects (tally count). Because it is not necessary to enumerate all insects in a sample unit, sampling can generally be accomplished in a much shorter period of time with acceptable accuracy. Binomial sampling may also be easier to implement in scouting programs because, typically, less training and experience are needed.

Binomial sampling models have been developed for adult *Bemisia* in both cotton (Naranjo *et al.*, 1994) and cantaloupe (Tonhasca *et al.*, 1994b). Both of these models are based on an empirical mathematical equation (Gerrard and Chiang, 1970; Nachman, 1984) that relates mean density (m) to the proportion of sample units infested with

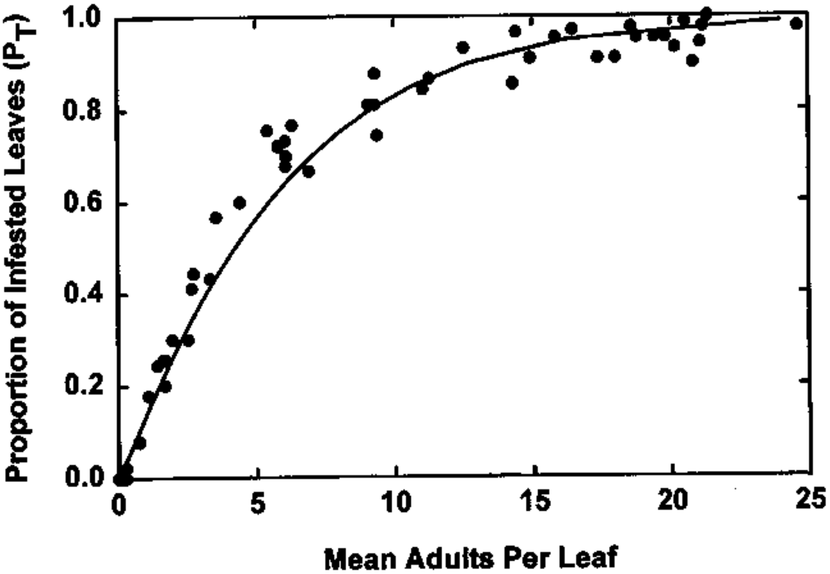

Figure 18.3. An empirical model relating the mean density of adult *Bemisia* per leaf to the proportion of leaves infested with at least three adults (P_T).

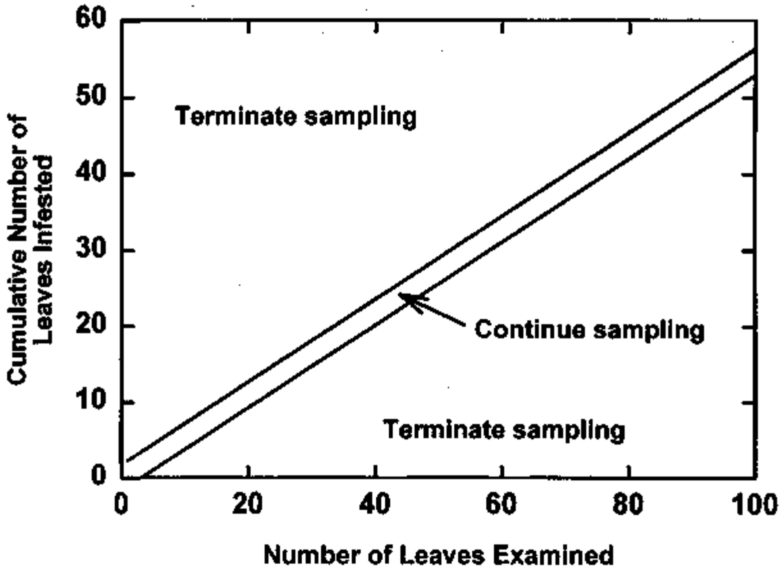

Figure 18.4. Binomial sequential sampling stop lines for an action thresholds of 5 adults per leaf based on Wald's (1947) sequential probability ratio test and a tally threshold of three adults per leaf. Upper and lower bounds encompass ± 2 adults per leaf. Nominal α and β errors set at 0.1.

at least T adults (P_T) as $\ln(m) = a + b\ln(-\ln(1-P_T))$, where a and b are fitted parameters and T is the tally threshold. An example of this relationship is shown in Figure 18.3 for cotton using the fifth mainstem node leaf as the sample unit, and using a tally count of 3 adults/leaf. For cantaloupe, the binomial sampling plan is implemented by sampling 200 terminal leaves per field (50 per quadrant) and recommending control when the proportion of leaves infested with one or more adults (T=1) exceeds 65% (Palumbo *et al.*, 1994). The intervention proportion is based on an action threshold of 3 adults/leaf and the sample size was determined to maximize the precision of the estimated density. A somewhat different approach was taken for cotton. To further improve the efficiency of sampling in cotton, Wald's (1947) sequential probability ratio test was used to formulate sequential binomial sampling plans based on action thresholds of 5 or 10 adults/leaf (see Nyrop and Binns, 1991 for equations). Monte Carlo simulation (Nyrop and Binns, 1991) was then used to estimate expected sample sizes and probabilities of error based on using different tally counts (Naranjo *et al.*, 1994). These simulations draw repeated samples from a probability distribution and take into account the stochastic variability associated with predicting the mean density from the proportion of infested sample units. Results from these analyses suggested that a tally count of three was optimal in terms of the number of samples that would be needed to make a control decision (on average, < 30), and in terms of making the correct decision relative to the action threshold. Research is currently underway to more accurately define the action threshold for adults in cotton (Nichols *et al.*, 1994, Chu *et al.*, 1995). The current recommendation for cotton in Arizona is to initiate control at 5 adults/leaf (Ellsworth *et al.*, 1994). The sequential decision stop lines associated with this density are shown in Figure. 18.4. The binomial sampling plan for adults in cotton is presently implemented for a fixed sample size of 30 leaves (15 each in two areas of the field; Ellsworth *et al.*, 1994). This fixed-sample-size model was easier to implement and ensures that at least two sites per field are visited by the scout or grower.

Validation of sampling plans

Validation and evaluation of sample plan performance are critical, but often overlooked, phases in the development and implementation of sampling models. Sampling plans are often developed from a restricted range of observations from a small geographic area, but are then used over a wide area representing a novel array of environmental and agronomic conditions. The performance of fixed-precision sequential sampling plans depends on the accuracy of the underlying model that predicts the variance from the mean. Many factors are known to affect the parameters of this model including host crop, geographic range, and environmental heterogeneity (Trumble *et al.*, 1989; Jones, 1990). Likewise, the distributional pattern represented by the empirical mean-proportional infestation model may vary in time and space.

The desired precision specified in a sequential sample plan is not the precision that will result from any one set of samples in a field, but instead is the average precision that would be expected over a large number of individual sampling bouts (Hutchison *et al.*, 1988; Nyrop and Binns, 1991). Likewise, error rates associated with making the proper decision to control a pest population are those that would be expected, on average, over a large number of trials. There are two primary sources of error: 1) variation associated with Taylor's power law regression or that associated with the empirical mean-proportional infestation model, and 2) the inherent variability in the sequential selection of samples from a field.

There are two basic approaches for assessing the expected performance of sampling plans in the field: Monte Carlo simulation and bootstrap, or resampling analysis. In Monte Carlo simulation (Nyrop and Binns, 1991), samples are drawn at random from a theoretical distribution, such as the negative binomial, until the sequential stop lines are satisfied. This exercise is repeated many times (≥500) over a range of densities, and then statistics such as the average precision and average sample size can be calculated for each mean density. The limitation of this approach is that one must assume a specific distribution. A more robust procedure is to randomly resample actual data sets collected independently from those used to develop the sample plan (Hutchison, 1994). Thus, the underlying distribution is defined by the data set rather than by a theoretical model. By resampling these data sets on a computer, the average behavior of the sample plan for that data set can be determined given that the individual samples from a field could have been collected in any order.

As part of a community-wide pest management program (Ellsworth *et al.*, this volume), the cotton sampling plans described above were implemented and tested within a 3,500 ha cotton growing area in central Arizona, USA. In 1994, samples were taken weekly in 190 commercial cotton fields from mid-May through mid-August. In approximately half of these fields, adults were completely enumerated on 25 leaves from each of four quadrants for a total of 100 samples per field. A subset of 105 date/field observations from this data set, representing a density range of 0.1 to 20 adults/leaf, was selected for further analyses. Three sampling plans were evaluated: 1) fixed-precision sequential sampling for estimating adult density, 2) sequential binomial sampling and 3) fixed-sample-size binomial sampling for classifying adult density relative to an action threshold of 5 adults/leaf. Each of the 105 data sets was resampled 500 times for each sampling model.

The stochastic nature of fixed-precision sequential sampling is readily apparent (Table 18.3). Rarely did the mean precision calculated from 500 resamplings of a data set equal the specified level of precision of 0.25. Also, there was considerable variation in the actual level of precision achieved. Nonetheless, over a wide range of densities, the actual levels of precision fell between 0.2 and 0.3 much of the time and in many instances actual precision was better than that specified. The sequential sampling model was generally conservative, requiring more samples than necessary before terminating sampling. In contrast to precision, the number of required samples varied relatively little for any adult density and, as expected from the sampling model, sample size requirements dropped quickly with increasing density (Table 18.3). On average, less than 25 samples were needed to achieve estimates of adult density greater than 4–5 adults/leaf with a target precision of 0.25.

Table 18.3. Performance of fixed-precision sequential sampling plans for estimating the density of adult *Bemisia* derived from a resampling analysis of 105 independent field data sets from Arizona, USA. Sequential stop lines were set for a precision of 0.25. Each data set was resampled 500 times and the minimum sample size was set to 10

			% of Actual precision values		
Density range (adults/leaf)	Average sample size	Average precision[a]	< 0.20	0.20–0.30	> 0.30
0–1	44.5	0.28	11.9	56.9	31.2
1–2	30.2	0.22	46.3	46.8	7.0
2–3	25.7	0.23	44.0	45.4	10.6
3–4	23.1	0.21	52.3	39.6	8.1
4–5	21.2	0.21	45.2	40.8	14.0
5–6	19.9	0.22	44.5	51.1	4.4
6–7	18.8	0.21	51.0	40.1	9.0
7–8	18.3	0.27	31.7	33.6	34.7
8–10	17.4	0.23	44.6	43.5	11.9
10–15	15.1	0.25	20.9	66.8	12.3
15–20	12.7	0.20	53.9	42.9	3.3

[a] Precision measured as the standard error to mean ratio.

Analysis of the binomial sequential model for pest management application indicated that pest density can be classified as either above or below an action threshold with even fewer samples (Table 18.4). Fewer than 20 samples, on average, were required to classify populations at or near an action threshold of 5 adults/leaf. Considerably fewer samples were required at higher or lower densities. Even in the most extreme cases, fewer than 40 samples were necessary to make a decision regarding pest control. Analysis of the sequential model led to the development of a fixed-sample-size model based on examining 30 leaves per field. This model is relatively conservative if control is to be initiated when the density exceeds 5 adults/leaf.

Regardless of the sampling model used, sample size requirements are very modest, but the question remains: how accurate is the decision based on these samples? Two types of errors need to be considered: α error, which is the chance of taking action

Table 18.4. Number of samples needed to make a decision using a binomial sequential sampling plan for classifying the density of adult *Bemisia* relative to a action threshold of 5 adults/leaf. Results were derived from a resampling analysis of 105 independent field data sets from Arizona, USA. Each data set was resampled 500 times and the minimum sample size was set to 10

	Number of samples		
Density range (adults/leaf)	5th percentile	Average	95th percentile
0–1	10	10.0	10.0
1–2	10	10.5	12.4
2–3	10	12.6	22.5
3–4	10	17.4	37.5
4–5	10	18.1	37.9
5–6	10	17.7	35.9
6–7	10	14.2	26.5
7–8	10	13.8	23.3
8–10	10	13.3	22.0
10–15	10	12.3	20.7
15–20	10	10.1	10.4

when none is warranted, and the more critical β error, which is the chance of taking no action when control is needed. Results from the resampling analysis indicate that both the sequential and the fixed-sample-size models are extremely accurate in terms of decision-making (Table 18.5). Both models provided the correct decision greater than 86% of the time and made critical β errors only 6% of the time. It is worth noting that nominal α and β errors for the sequential model were originally set at 10%.

Although not technically part of sample model validation, it is equally important to evaluate other operational aspects of sample plan performance. These factors include evaluation of the total time needed to carry out sampling in relation to other ongoing sampling activities, variation in the estimation of pest densities among samplers, determination of the robustness of the method in relation to time-of-day, and overall adoption of the sampling method by the agricultural community. These aspects are discussed in some detail for the Arizona cotton sampling plan by Ellsworth *et al.* (this volume).

Table 18.5. Error rates associated with use of a sequential binomial sampling model or a fixed sample size (N=30) binomial model for making treatment decisions in cotton relative to an action threshold of 5 adults/leaf. Results derived from a resampling analysis of 105 independent field data sets from Arizona, USA

		Percent of decisions	
Decision area	Outcome	Sequential model	Fixed sample size model
No action needed	No treatment	54.9	56.9
Action needed	Treatment	30.8	30.1
No action needed	Treatment (α error)	8.9	6.9
Action needed	No treatment (β error)	5.4	6.1

Summary

Sampling is a fundamental component of most field research projects and is the foundation of integrated pest management programs based on prescriptive pest control. Research over the past several decades has provided much of the basic information needed to develop reliable and efficient sampling strategies for *Bemisia* on several major crops. Detailed knowledge of spatial distributions, along with additional information on the variability and costs associated with different sample units or sampling methods can be used to optimally balance precision and cost in the estimation of population density. Efficiency can be further enhanced through the development of numerical or binomial sequential sampling approaches which automatically terminate sampling after a preset level of precision is reached or a population can be classified relative to an action threshold. These considerations were exemplified by recent research which has resulted in the development of cost-efficient and reliable methods for estimating the abundance of immature and adult *Bemisia* in cotton. An essential, but often neglected, component of sample plan development is careful validation and evaluation of the plan's performance under actual field conditions. The resampling approach exemplified in this review represents the most robust technique available to carry out this important task.

Although considerable progress has been made in developing reliable and efficient sampling plans for some crops, most notably cotton, sampling of *Bemisia* on many other important host crops has received relatively little attention. Because of factors such as polyphagy and high reproductive potential, it seems clear that management of this pest will be most efficiently and effectively accomplished through an ecosystem perspective. Thus, we not only need efficient monitoring methods for all the effected host crops in a region, but also better tools for assessing and estimating regional population densities. Many of the components and approaches outlined here could be useful in accomplishing these goals.

References

ABISGOLD, J.D. AND FISHPOOL, L.D.C. (1990). A method for estimating population sizes of whitefly nymphs (*Bemisia tabaci* Genn.) on cassava. *Tropical Pest Management* **36**, 287–292.

ARX, R.V. VON, BAUMGÄRTNER, J. AND DELUCCHI, V. (1984). Sampling of *Bemisia tabaci* (Genn.) (Sternorrhyncha: Aleyrodidae) in Sudanese cotton fields. *Journal of Economic Entomology* **77**, 1130–1136.

BERLINGER, M.J. (1980). A yellow sticky trap for whiteflies: *Trialeurodes vaporariorum* and *Bemisia tabaci* (Aleyrodidae). Entomologia *Expermentalis et Applicata* **27**, 98–102.

BINNS, M.R. AND NYROP, J.P. (1992). Sampling insect populations for the purpose of IPM decision making. *Annual Review of Entomology* **37**, 427–453.

BUTLER, G.D., JR., HENNEBERRY, T.J. AND HUTCHISON, W. D. (1986). Biology, sampling and population dynamics of *Bemisia tabaci*. *Agricultural and Zoological Review* **1**, 167–195.

BUTTER, N.S. AND VIR, B.K. (1990). Sampling of whitefly *Bemisia tabaci* (Genn.) in cotton. *Journal of Research (Punjab Agricultural University)* **27**, 615–619.

BYRNE, D.N., VON BRETZEL, P.K. AND HOFFMAN, C.J. (1986). Impact of trap design and placement when monitoring for the bandedwinged whitefly and the sweetpotato whitefly (Homoptera: Aleyrodidae). *Environmental Entomology* **15**, 300–304.

CARNERO, A. AND GONZÁLEZ-ANDUJAR, J.L. (1994). Spatial and temporal distribution of fourth-instar larvae of *Trialeurodes vaporariorum* and *Bemisia tabaci* in tomato plants. *Phytoparasitica* **22**, 317.

CHU, C.C., HENNEBERRY, T.J., AKEY, D.H., NARANJO, S.E., PERKINS, H.H., PRABHAKER, N. AND MACKEY, B.E. (1995). Sweetpotato whitefly: development of an action thresholds for chemical control on cotton. *Proceedings Beltwide Cotton Production Conference*, pp. 873–874, National Cotton Council of America, Memphis, Tennessee.

EKBOM, B.S. AND XU, R. (1990). Sampling and spatial patterns of whiteflies. In *Whiteflies: their Bionomics, Pest status and Management* (D. Gerling, Ed.), pp. 107–121. Intercept, Andover, Hants.

ELLSWORTH, P., DIEHL, J., DENNEHY, T. AND NARANJO, S. (1994). Sampling sweetpotato whiteflies in cotton. *University of Arizona, IPM Series Number 2.*

GERLING, D. AND HOROWITZ, A.R. (1984). Yellow traps for evaluating the population levels and dispersal patterns of *Bemisia tabaci* (Homoptera: Aleyrodidae). *Annals of the Entomological Society of America* **77**, 753–759.

GERLING, D., MOTRO, U. AND HOROWITZ, R. (1980). Dynamics of *Bemisia tabaci* (Gennadius) (Homoptera: Aleyrodidae) attacking cotton in the coastal plain of Israel. *Bulletin of Entomological Research* **70**, 213–219.

GERRARD, D.J. AND CHIANG, H.C. (1970). Density estimation of corn rootworm egg populations based upon frequency of occurrence. *Ecology* **51**, 237–245.

GREEN, R.H. (1970). On fixed precision sequential sampling. *Researches on Population Ecology* **12**, 249–251.

HUTCHISON, W.D. (1994). Sequential sampling to determine population density. In *Handbook of sampling methods for arthropod pests in agriculture* (L. Pedigo and G. Buntin, Eds). pp. 207–243. *CRC Press*, Boca Raton, FL.

HUTCHISON, W.D., HOGG, D.B., POSWAL, M.A., BERBERET, R.C. AND CUPERUS, G.W. (1988). Implications of the stochastic nature of Kuno's and Green's fixed-precision stop lines: sampling plans for the pea aphid (Homoptera: Aphididae) in alfalfa as an example. *Journal of Economic Entomology* **81**, 749–758.

IWAO, S. (1968). A new regression method for analyzing the aggregation pattern of animal populations. *Researches on Population Ecology* **10**, 1–20.

JONES, V.P. (1990). Developing sampling plans for spider mites (Acari: Tetranychidae): those who don't remember the past may have to repeat it. *Journal of Economic Entomology* **83**, 1656–1664.

KUNO, E. (1969). A new method of sequential sampling to obtain the population estimates with a fixed level of precision. *Researches on Population Ecology* **11**, 127–136.

LENTEREN, J.C. VAN AND NOLDUS, P.J.J. (1990). Whitefly-plant relationships: behavioral and ecological aspects. In *Whiteflies: their Bionomics, Pest status and Management* (D. Gerling, Ed.), pp. 47–89. Intercept, Andover, Hants.

LIU, T.X., OETTING, R.D. AND BUNTIN, G.D. (1993). Distribution of *Trialeurodes vaporariorum* and *Bemisia tabaci* (Homoptera, Aleyrodidae) on some greenhouse-grown ornamental plants. *Journal of Entomological Science* **28**, 102–112.

LIU, T.X., OETTING, R.D. AND BUNTIN, G.D. (1994). Temperature and diel catches of *Trialeurodes vaporariorum* and *Bemisia tabaci* (Homoptera, Aleyrodidae) adults on sticky traps in the greenhouse. *Journal of Entomological Science* **29**, 222–230.

LYNCH, R.E. AND SIMMONS, A.M. (1993). Distribution of immatures and monitoring of adult sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Homoptera: Aleyrodidae), in peanut, *Arachis hypogaea*. *Environmental Entomology* **22**, 375–380.

MABBETT, T.M., NACHAPONG, M. AND MEKDAENG, J. (1980). The within-canopy distribution of adult cotton whitefly (*Bemisia tabaci* Gennadius) incorporating economic thresholds and meteorological conditions. *Thai Journal of Agricultural Science* **13**, 97–108.

MCAUSLANE, H.J., JOHNSON, F.A. KNAUFT, D.A. AND COLVIN, D L. (1993). Seasonal abundance and within-plant distribution of parasitoids of *Bemisia tabaci* (Homoptera: Aleyrodidae) in peanuts. *Environmental Entomology* **22**, 1043–1050.

MELAMED-MADJAR, V., COHEN, S., CHEN, M., TAM, S. AND ROSILIO, D. (1982). A method for monitoring *Bemisia tabaci* and timing spray applications against the pest in cotton fields in Israel. *Phytoparasitica* **10**, 85–91.

MUSUNA, A.C.Z. (1986). A method for monitoring whitefly, *Bemisia tabaci* (Genn.), in cotton in Zimbabwe. *Agriculture Ecosystems and Environment* **17**, 29–35.

NACHMAN, G. (1984). Estimates of mean population density and spatial distributions of *Tetranychus urticae* (Acarina: Tetranychidae) and *Phytoseiulus persimilis* (Acarina: Phytoseiidae) based upon the proportion of empty sampling units. *Journal of Applied Ecology* **21**, 903–913.

NAIK, L.K. AND LINGAPPA, S. (1992). Distribution pattern of *Bemisia tabaci* (Gennadius) in cotton plant. *Insect Science and Application* **13**, 377–379.

NARANJO, S.E. AND FLINT, H.M. (1994). Spatial distribution of preimaginal *Bemisia tabaci* (Homoptera: Alyerodidae) in cotton and development of fixed-precision, sequential sampling plans. *Environmental Entomology* **23**, 254–266.

NARANJO, S.E. AND FLINT, H.M. (1995). Spatial distribution of adult *Bemisia tabaci* (Homoptera: Alyerodidae) in cotton, and development and validation of fixed-precision sampling plans for estimating population density. *Environmental Entomology* **24**, 261–270.

NARANJO, S.E., FLINT, H.M. AND HENNEBERRY, T.J. (1994). Progress in the development of sampling plans for *Bemisia tabaci* : evaluation of binomial sampling methods. *Proceedings Beltwide Cotton Conference*, pp. 875–877, National Cotton Council of America, Memphis, Tennessee.

NARANJO, S.E., FLINT, H.M. AND HENNEBERRY, T.J. (1995). Comparative analysis of selected sampling methods for adult *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton. *Journal of Economic Entomology* **88**, 1666–1678.

NATWICK, E.T., LEIMGRUBER, W., TOSCANO, N.C. AND YATES, L. (1992). Sampling adult sweetpotato whitefly in cotton. *Proceedings of the Beltwide Cotton Production Research Conference*, pp. 693–697, National Cotton Council of America, Memphis, Tennessee.

NATWICK, E.T., ZALOM, F.G. TOSCANO, N.C. AND KIDO, K. (1984). Monitoring of the cotton whitefly, *Bemisia tabaci* (Gennadius): Studies in the insect's development and control in cotton. *Proceedings of the Beltwide Cotton Production Research Conference*, pp. 197–202, National Cotton Council of America, Memphis, Tennessee

NELSON, M., ORUM, T., BYRNE, D., EL-LISSY, O., ANTILLA, L. AND STATEN, R. (1993). Preliminary investigation of sweetpotato whitefly population dynamics across Arizona. *Arizona Agricultural Experiment Station* **P-94**, 197–205.

NICHOLS, R.L., CHU, C.C., ELLSWORTH, P.C., HENNEBERRY, T.J., NARANJO, S.E., RILEY, D.G., TOSCANO, N.C. AND WATSON, T.F. (1994). Determining an action threshold to prevent whitefly outbreaks. *Phytoparasitica* **22**, 349.

NYROP, J.P. AND BINNS, M. (1991). Quantitative methods for designing and analyzing sampling programs for use in pest management. In *Handbook of Pest Management in Agriculture, vol. 2* (D. Pimentel, Ed.). pp. 67–132. *CRC Press*, Boca Raton, Florida.

OHNESORGE, B. AND RAPP, G. (1986a). Monitoring *Bemisia tabaci*: a review. *Agriculture Ecosystems and Environment* **17**, 21–27.

OHNESORGE, B. AND RAPP, G. (1986b). Methods for estimating the density of whitefly nymphs (*Bemisia tabaci* Genn.) on cotton. *Tropical Pest Management* **32**, 207–211.

OHNESORGE, B., SHARAF, N. AND ALLAWI, T. (1980). Population studies on the tobacco whitefly *Bemisia tabaci* Genn. (Homoptera, Aleyrodidae) during the winter season. I. The spatial distribution on some host plants. *Journal of Applied Entomology* **90**, 226–232.

PALUMBO, J.C., TONHASCA, A., JR. AND BYRNE, D.N. (1994). Sampling plans and action thresholds for whiteflies on spring melons. *University of Arizona IPM Series Number 1.*

RAO, N.V., REDDY, A.S. AND RAO, K.T. (1991a). Monitoring of cotton whitefly, *Bemisia tabaci* with sticky traps. *Madras Agricultural Journal* **78**, 1–7.

RAO, N.V., REDDY, A.S., RAO, B.R. AND SATYANARAYANA, G. (1991b). Intraplant distribution of whitefly *Bemisia tabaci* (Genn.) on cotton *Gossypium hirsutum* L. *Journal of Insect Science* **4**, 32–36.

SHARAF, N.S. (1982). Determination of the proper height, direction, position, and distance of a yellow sticky trap for monitoring adult sweetpotato whitefly populations (*Bemisia tabaci* Genn., Homoptera: Aleyrodidae). *Dirasat* **9**, 169–182.

SILVERTOOTH, J.C., BROWN, P.W. AND MALCUIT, J.E. (1992). Cotton crop growth and development patterns. *Arizona Agricultural Experiment Station* **P-91**, 9–24.

SIMMONS, A.M. (1994). Oviposition on vegetables by *Bemisia tabaci* (Homoptera: Aleyrodidae): temporal and leaf surface factors. *Environmental Entomology* **23**, 381–389.

SOUTHWOOD, T.R.E. (1978). *Ecological methods*, 2nd ed., Chapman & Hall, London.

TAYLOR, L.R. (1961). Aggregation, variance and the mean. *Nature* **189**, 732–735.

TONHASCA, A., PALUMBO, J.C. AND BYRNE, D.N. (1994a). Distribution patterns of *Bemisia tabaci* (Homoptera: Aleyrodidae) in cantaloupe fields in Arizona. *Environmental Entomology* **23**, 949–954.

TONHASCA, A., PALUMBO, J.C. AND BYRNE, D.N. (1994b). Binomial sampling plans for estimating *Bemisia tabaci* populations in cantaloupes. *Researches on Population Ecology* **36**, 159–164.

TRUMBLE, J.T., BREWER, M.J., SHELTON, M.J. AND NYROP, J.P. (1989). Transportability of fixed-precision sampling plans. *Researches on Population Ecology* **31**, 325–342.

WALD, A. (1947). *Sequential Analysis*. John Wiley & Sons, New York.

WATSON, T.F., SILVERTOOTH, J.C., TELLEZ, A. AND LASTRA, L. (1992). Seasonal dynamics of sweetpotato whitefly in Arizona. *Southwestern Entomologist* **17**, 149–167.

YOUNGMAN, R.R., TOSCANO, N.C., JONES, V.P., KIDO, K. AND NATWICK, E.T. (1986). Correlations of seasonal trap counts of *Bemisia tabaci* (Homoptera: Aleyrodidae) in Southeastern California. *Journal of Economic Entomology* **79**, 67–70.