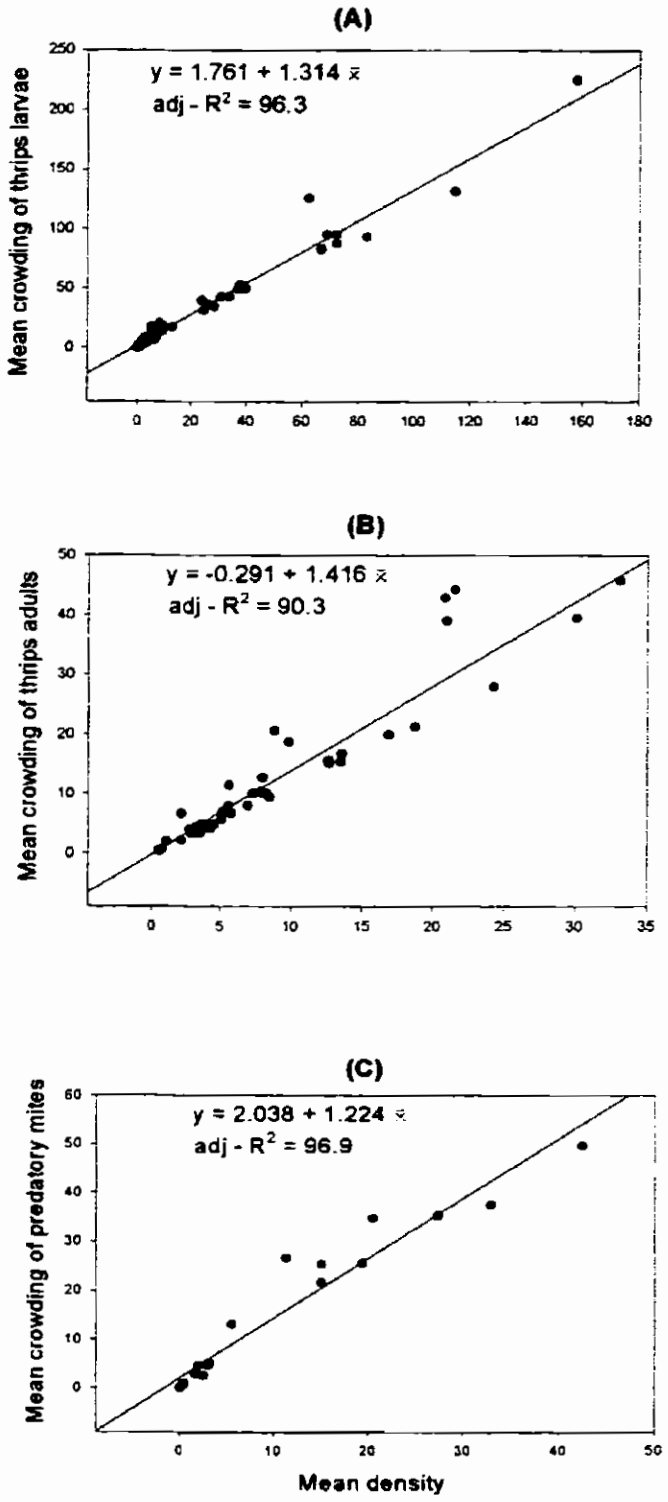

Fig. 3. Iwao's patchiness regression of mean crowding ($\mathring{x}$) on mean density ($\bar{x}$) of *T. tabaci* larvae (A) and adults (B) and *A. cucumeris* (C) in greenhouse cucumbers.

Table 7. T-test of the index of basic contagion (a_r) for significance greater than 0 for *T. tabaci* larvae and adults and *A. cucumeris* in greenhouse cucumbers.

Life stages	Mean ± S.E.M.	t	P $\|t\| > 0$
T. tabaci: Larvae	3.09 ± 1.520	2.04	0.050
Adults	0.15 ± 0.567	0.27	0.400
A. cucumeris	2.70 ± 1.120	2.42	0.160

The values for density contagious coefficient (b_r) are listed in Table 8. The density contagious coefficient for thrips larvae and adults was significantly greater than 1 indicating that the basic components of the thrips larvae and adults are contagiously distributed in greenhouse cucumbers. For the predatory mites, the density contagious coefficient was not significantly greater than1 and therefore, mites do not exhibit contagious distribution, but exhibit random distribution within greenhouse cucumbers. This could be due to the application of these predators in slow release packages at regular intervals, thereby inducing a less aggregated population in the greenhouse.

Table 8. T-test of the density contagious coefficient (b_r) for significance greater than 1 for *T. tabaci* larvae and adults and *A. cucumeris* in greenhouse cucumbers.

Life stages	Mean ± S.E.M.	t	P $\|t\| > 1$
T. tabaci: Larvae	1.30 ± 0.074	4.11	0.007
Adults	1.36 ± 0.087	4.13	0.007
A. cucumeris	1.29 ± 0.075	3.77	0.150

In commercial monitoring programmes, it is more practical to count the total larvae or adults rather than the individual larval instars because it is faster and requires less training for the sampler. Two sequential sampling programmes were calculated; one for combined

first and second instar thrips, and a second plan for adult thrips. The thresholds employed were based on 75 percent of the preliminary estimate of the EIL for cumulative western flower thrips larvae (9.5) and adults (1.7) on the middle leaves of greenhouse cucumbers (Steiner 1990). This estimate can be adopted for onion thrips on greenhouses cucumbers because these species cause similar leaf damage. The economic thresholds were calculated to be cumulative counts of 7.1 larval and 1.3 adult thrips on mature, middle leaves of greenhouse cucumbers.

Precision is important in IPM because it assures the sampler that the estimated pest density is relatively close to the true pest density (Legg and Moon 1994). An error level of 0.1 was used in the calculation of the upper and lower acceptance limits of the sequential sampling plans (Fig. 4). After each sample, the cumulative number of thrips larvae or adults is compared with the appropriate sequential sampling plan. A decision is based on whether this number is smaller or larger than the acceptance limits. If the number is smaller than the lower limit, sampling is stopped and the grower is advised not to treat. On the contrary, if the cumulative number is larger than the upper limit, sampling is stopped and the grower is advised to treat. Sampling continues until one of the acceptance limits is crossed or the maximum number of samples is reached (Fig. 4). If no decision can be made when the maximum number of samples is reached, the sampler can either arrive at the decision according to the closest limit, or return in a few days to repeat the process and determine if the population has changed to a level upon which a clear decision can be made.

The maximum number of samples required before sampling can be terminated varies with the economic threshold, the size of d, and the error level associated with d. The changes

in *d* are necessary to maintain the sampling size manageable for commercial monitoring programmes (Boivin *et al.* 1991). The maximum sample number (n_{max}) to be taken before terminating sampling for thrips larvae at a *d* level of 1.2 and α level of 0.1 was calculated to be 66 samples. If, after this many samples are taken, the cumulative number of thrips larvae has not crossed the acceptance limits, the population estimate is then ET $\pm$ *d*, *i.e.* 7.1 $\pm$ 1.2 larvae per leaf with an error level of 0.1. The n_{max} calculated for adult thrips when the *d* value was reduced to 0.3 but the error level remained at 0.1. was calculated to be 46. In all cases, it is recommended that at least 10 samples are examined before a decision is made (Nyrop and Simmons 1984).

When issuing recommendations, caution must be employed when interpreting the results obtained with higher error levels (Boivin *et al.* 1991). The producer's notion of a pest threat can be quite different than that of a researcher or IPM advisor (Bechinski 1994). The information must be presented in such a way that the user can understand and balance the risk of making a Type I or a Type II error. If the population is overestimated, a Type I error occurs which results in an unnecessary pesticide application that reduces economic efficiency and potentially has some environmental impact. If the population density is underestimated, a Type II error is made which results in missing a necessary pesticide application which obviously results in an increased pest population and possibly higher yield losses. To the producer, this may be economically catastrophic (Cuperus and Berberet 1994).

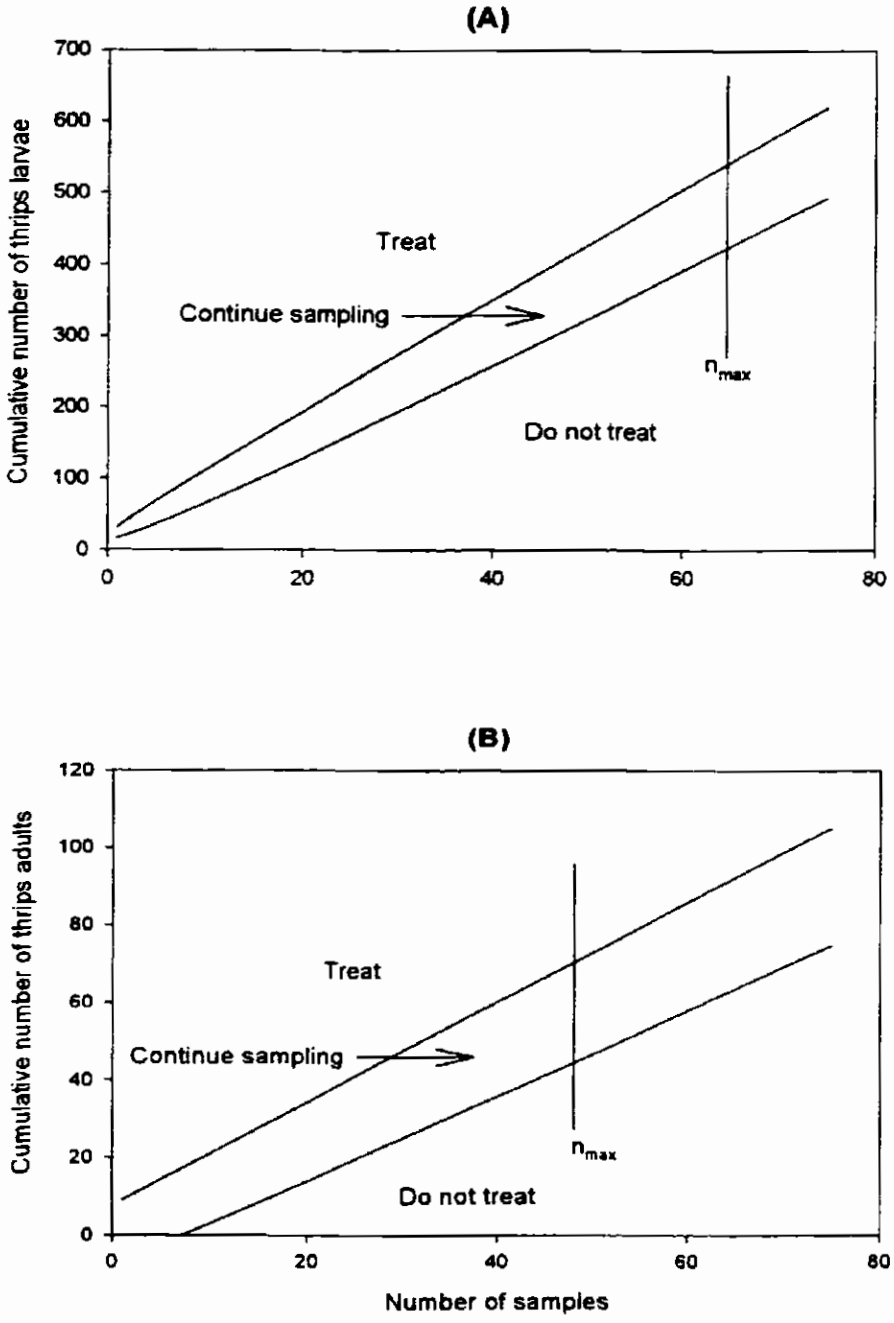

Fig. 4. Iwao's sequential sampling plan for *T. tabaci* larvae (A) and adults (B) in greenhouse cucumbers.

4.3.2 Binomial sequential sampling plan: The relationship between the $\log_{10}$(variance) and $\log_{10}$ (mean) were significantly linear for all life stages of onion thrips and the predatory mites (Table 9 and Fig.5). For thrips life stages and the predatory mites, the index of aggregation, *b*, from TPL was determined to be significantly greater than 1 (Table 10), indicating that all were contagiously distributed in greenhouse cucumbers. The thrips larvae and adults results are in accordance with Iwao's density contagious coefficient. The discrepancy between the aggregations of the predatory mites may be due to IPR using each visit per site to develop a regression line for that site (therefore two b_r data points) while *b* of the TPL can be calculated for each visit (20 data points). In this situation, the aggregation based on TPL would be more robust than IPR. When more sites are sampled, IPR may show similar results.

Table 9. Statistics of the regression of $\log_{10}$ variance on $\log_{10}$ mean for captures of *T. tabaci* larvae and adults, and the predatory mite, *A. cucumeris*, in greenhouse cucumbers.

Life Stages	Intercept	Slope	Adjusted-R^2	Correlation coefficient[1]	n
T. tabaci: Larvae	0.265	1.554	96.1	0.981	43
Adults	-0.060	1.670	87.2	0.936	43
A. cucumeris	0.321	1.446	97.1	0.986	20

[1]Correlation coefficient significant at $\alpha = 0.01$.

The estimates of the *a* and *b* parameters of TPL were used to establish the relationship between thrips mean density and the proportion of plants infested in the formula by Wilson and Room (1983). These relationships appear in Fig. 6.

The sequential sampling programmes were based on the same economic thresholds as Iwao's sequential sampling programmes, 7.1 larvae and 1.3 adults per leaf. The proportion

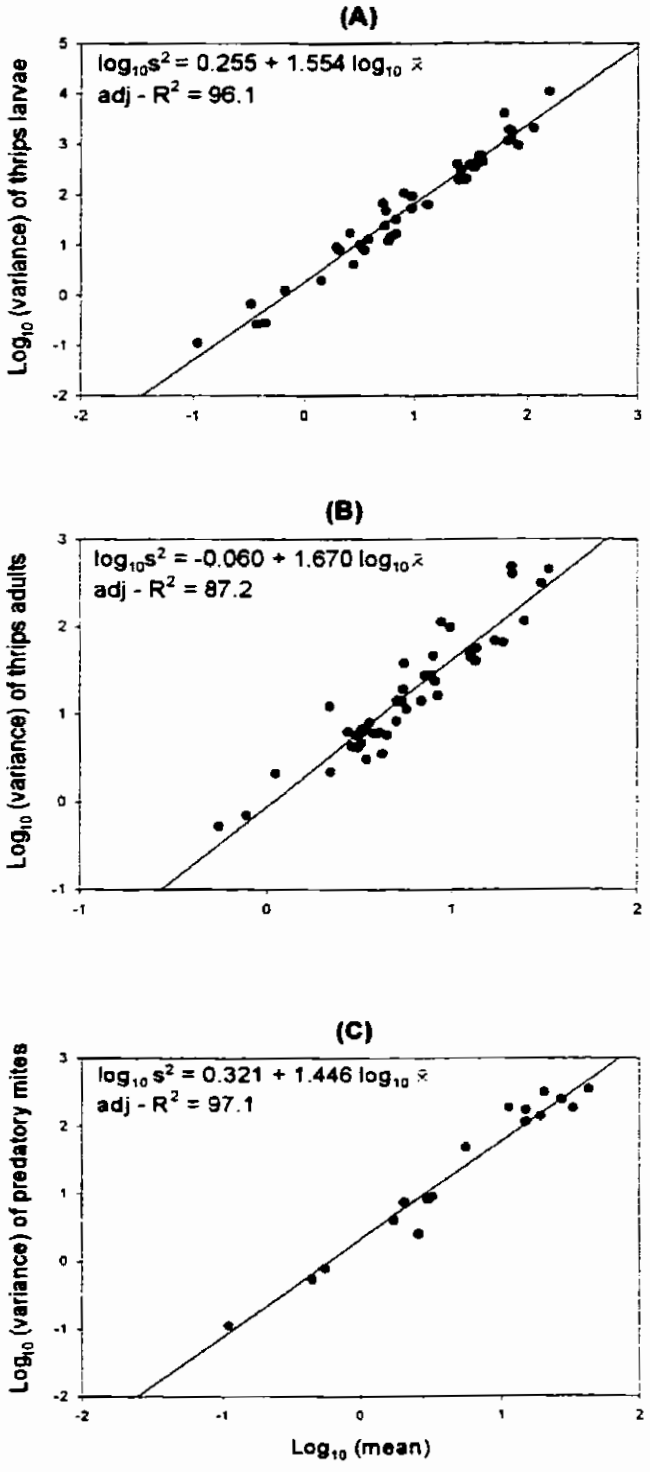

Fig. 5. Taylor's power law regression of $\log_{10}$ (variance) on $\log_{10}$ (mean) of *T. tabaci* larvae (A) and adults (B) and *A. cucumeris* (C) in greenhouse cucumbers.

Table 10. T-test of the index of aggregation, *b*, greater than 1 for *T. tabaci* larvae and adults and *A. cucumeris* in greenhouse cucumbers.

Life stages	Mean ± S.E.M.	*t*	P $\|t\| > 1$
T. tabaci: Larvae	1.53 ± 0.065	8.15	0.000
Adults	1.36 ± 0.082	4.38	0.000
A. cucumeris	1.45 ± 0.075	5.99	0.000

of plants infested corresponding to these economic thresholds were determined from the equation of Wilson and Room (1983) to be 0.17 for larvae and 0.47 for adults. To ensure accuracy of the pest density estimate, the corresponding proportion of infested samples should not exceed 80 percent (Southwood 1978) because the maximum detectable densities tend to be below the economic threshold. These proportions are incorporated into the formula for the acceptance limits based on the formula of Bechinski and Stoltz (1985) and are presented in Fig. 7. The y-axis indicates the maximum allowable number of plants infested with one or more thrips corresponding to the number of samples taken. Parallel to Iwao's sequential sampling plans, if either of these lines are crossed before the maximum sample number is reached, sampling is terminated and a decision to either treat (upper limit) or not to treat (lower limit) is made.

The proportion of infested leaves corresponding to the economic threshold is also incorporated into the formula for maximum sample number by Karandinos (1976), and was determined to be 39 samples for larvae and 67 samples for adults. The conditions of the error terms (α=0.1) and minimum sample number suggested by Nyrop and Simmons (1984) also applies to the binomial sequential sampling.

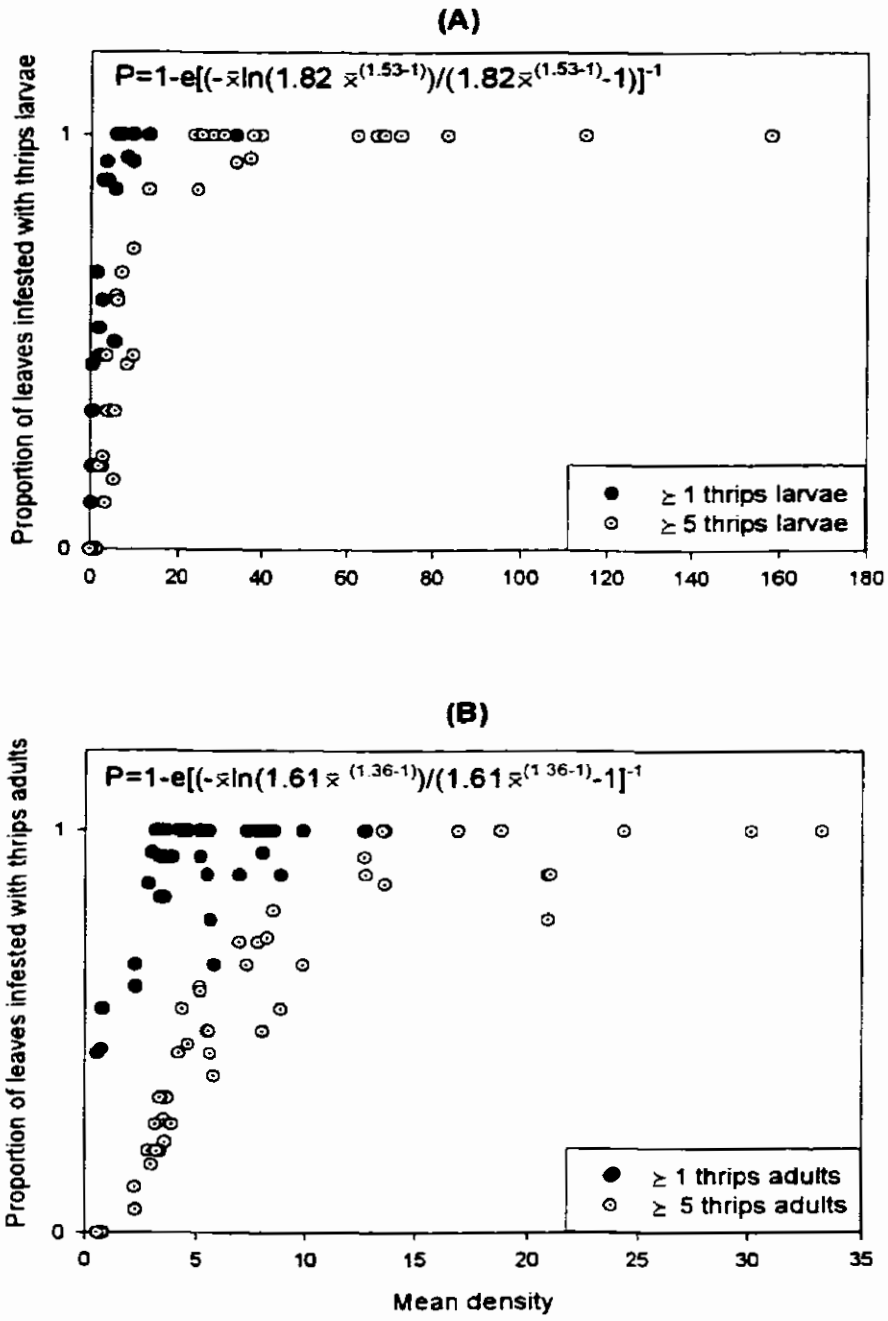

Fig. 6. The relationship between proportion of leaves infested with ≥ 1 and ≥ 5 thrips larvae (A) and thrips adults (B) in greenhouse cucumbers.

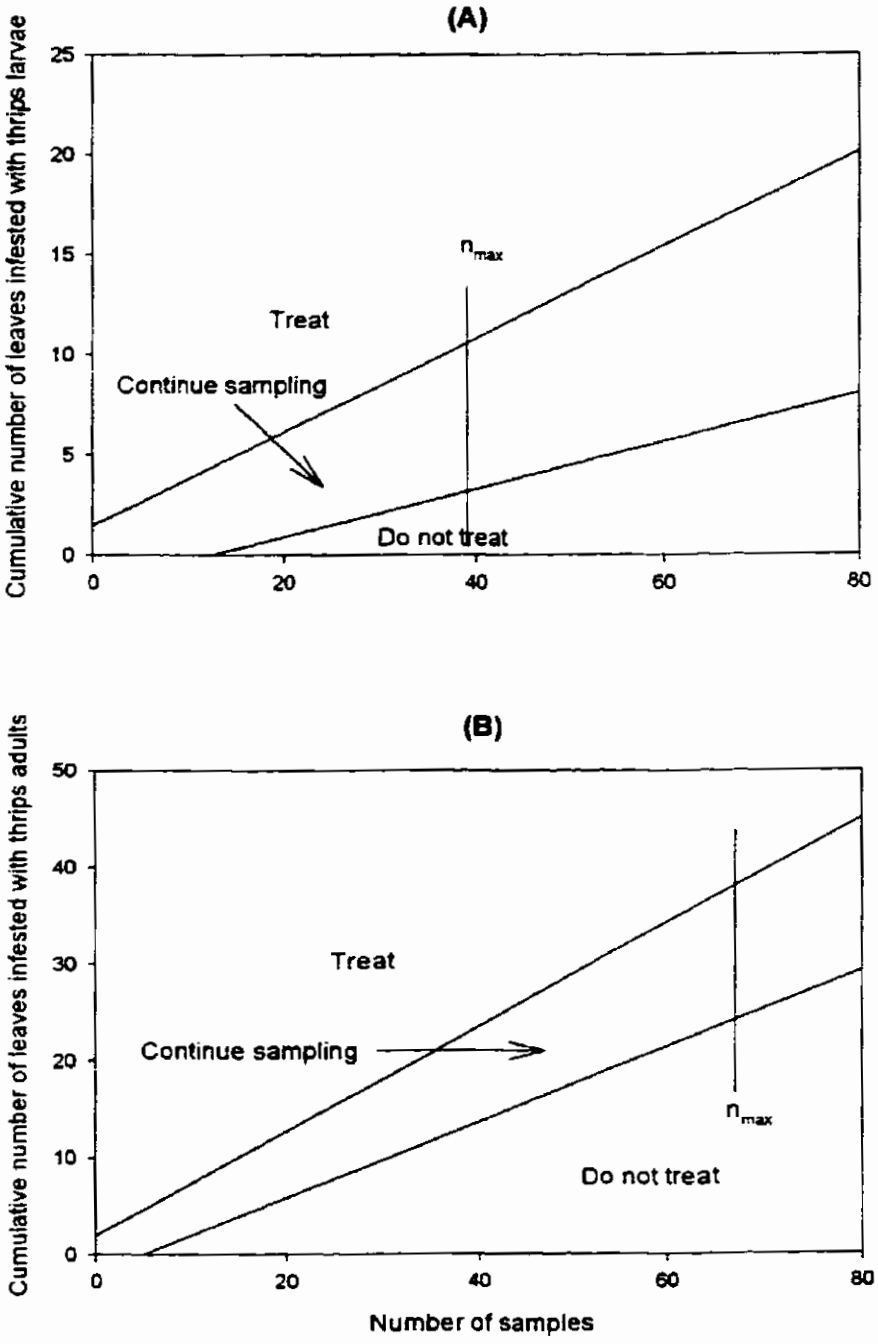

Fig. 7. Binomial sequential sampling plan for *T. tabaci* larvae (A) and adults (B) in greenhouse cucumbers.

4.4 Recommendations and Future Research

There is considerable criticism of the variance-mean relationship models of Iwao and Taylor. Iwao's patchiness regression is based on deductive reasoning of the parameter estimates and these parameters were originally derived with close reference to theoretical distribution models, thus allowing ecological implications of the parameters to be estimated (Kuno 1991). Taylor's index of aggregation is purely an empirical model with no definite theoretical background. Taylor *et al.* (1978) defended the descriptive capability of this parameter by comparing multiple sets of extensive data and concluded that this model was superior to the patchiness regression parameters. Kuno (1991) noticed that in these comparisons, the R^2 value is sufficiently high in both models for the practical purpose of describing the populations. Many researchers comparing IPR and TPL have found that TPL fits data better than the IPR. A disadvantage to IPR is that it is not sensitive to density dependent changes in spatial patterns that may induce some non-linearity to the regression (Kuno 1991). Taylor (1978) insisted that the index of aggregation is a definite 'species' specific characteristic that reflects the mode of density dependent dispersal of that species, being entirely independent of other factors such as sampling scale and quadrat size. These studies have shown that these models have equally high adjusted-R^2 values and correlation coefficients (Tables 7 and 10) to be equally valid in their descriptive ability of onion thrips in greenhouse cucumbers.

Development of sequential sampling plans is a varied and sometimes complicated procedure. Producers often make decisions affecting crop and livestock commodities worth thousands of dollars without adequate information, seemingly because they are unaware of

sampling protocols, or these protocols are perceived as being too complex and having unacceptable risk of an erroneous decision (Cuperus and Berberet 1994). The adoption of sampling protocols must demonstrate to the producer a relative advantage over the existing practices to the producer and the protocols must be compatible and readily integrated with the overall operation. Effective communication and cooperation among researchers, extension specialists, and consultants are essential to the task of information transfer and technologies implementation. Both of these sequential sampling plans have the advantage of not requiring a theoretical mathematical model approaching the true spatial distribution of the insect. An advantage to the binomial sequential sampling plan is the ease and efficiency with which sample units can be classified and its robustness in spite of a few unusual observations. Fournier *et al.* (1995) found that binomial sequential sampling was as reliable as Iwao's for this species in field onions.

Validation of these sequential sampling plans will determine which type of sequential sampling plan is best suited for onion thrips in greenhouse cucumbers. It is of the utmost importance that these plans be validated before any attempt to apply them to a commercial situation is made. This may be accomplished in the field, *i.e.* commercial greenhouses, or by simulation. Field validation is best because there are multiple sources of uncertainty inherent in the development and implementation of a sampling procedures.. Although field validation is more expensive than simulation, it best represents this uncertainty (Hutchinson 1994). Sampling a large number of greenhouses allows the representation of a variety of growing conditions and may provide more robustness to the estimates of the pest number (Higley and Pedigo 1997) and the pest's behaviour in that system. This validation could be achieved by

using the plans in several greenhouses and computing the number of times the plan provided early valid recommendations over the total number of trials. Boivin *et al.* (1991) tested their plans for tarnished plant bugs in 30 commercial celery fields and obtained satisfactory results in 26 of these fields. This is an example that validation of a sequential sampling plan can put to test a large network of resources. Failure to validate a proposed sampling plan in large scale commercial operations is probably the single most important reason that such programmes are not adopted (Trumble 1994).

Accurate quantification of the relationship between pest number and crop damage is crucial to the development of economic injury levels and has been a major preoccupation of agricultural entomologists (Higley and Pedigo 1997). For greenhouse crops, there is almost a complete lack of economic injury level (EIL) or economic thresholds (ET) for greenhouse pests (Shipp *et al.* 1997). The ET is always set below the EIL (also called action threshold) to allow lag time for the chosen control measure to operate and prevent the EIL from being reached and/or surpassed (Metcalf and Luckman 1982). This lack of quantitative yield loss-feeding damage functions provides an inherent source of variability or uncertainty because the sequential sampling plan based on these values are only as accurate as the values themselves. The concept of EIL is very straightforward. EIL represents the point where costs equal benefits. Costs are the losses associated with pest action and the cost of managing the pest. Benefits are the losses prevented by management. Hidden in this simple statement is considerable biological complexity and the application of EIL to specific pest problems adds further complexity. Consequently, EIL is an expression of both economic and biological parameters (Higley and Pedigo 1997). Development of these values are complex

and variances associated with these functions will probably always be higher than those for statistical sampling plans and much less predictable due to the complex interaction of the plant and its environment (Jones 1994). While development of EIL has been one of the most important and useful concepts in pest management, these limitations prevent their complete development and implementation (Higley and Pedigo 1997).

5. Conclusion

These studies have examined specific aspects of an integrated pest management programme for a single pest on greenhouses cucumbers. However, the host, pest and environment create an interplay, representing a moving surface upon which timing and monitoring approaches for sampling must contend (Higley and Peterson 1994). There is a compelling need for reexamination and recommitment of the basic tenets of pest management because sequential sampling for IPM purposes has the potential to enhance such programmes in a multitude of directions.

Time sequential sampling requires a mathematical model of data over time, classification limits of outbreak and non-outbreak populations, and levels of acceptable risk in making classification errors (Pedigo 1994). If knowledge of the population growth is available, sample information can be combined with this knowledge to forecast future density. Such monitoring protocols determine whether the pest density exceeds an intervention threshold and if density is less than the threshold, the protocols determine how long one can wait before sampling the pest population again and be reasonably sure that the density will not have grown to exceed an intervention threshold (Nyrop and van der Werf 1994).

Biological control is a key factor in many current IPM programmes. The key to using biological control agents in pest management is to identify when natural enemies are sufficiently abundant to prevent herbivores from inflicting economic loss (Nyrop 1994). By incorporating the prediction or monitoring biological control into the sampling plan, the ratio of pest-natural enemy can sometimes be used to determine whether natural enemies are sufficiently abundant to control pest populations. This same ratio may not always be used as

an index of the likelihood of biological control because other factors may influence the index, more than one natural enemy may be involved in the interaction and the relative species mix may influence the ratio, or it may not be practical to measure the natural enemy density (Nyrop and van der Werf 1994).

Ultimately, there must be a change in management philosophy for systems which have more than one herbivore that simultaneously feed upon a crop. Guilds of arthropods, established on their physiological mode of injury to the host, will be managed better collectively rather than as a single species (Hutchins 1994). One can rarely develop a sampling plan which does more than estimate the abundance each herbivore and each entomophage. Basic field data can be incorporated into crop-herbivore-natural enemy models that estimate and forecast the interaction between these trophic levels (Wilson 1994). The most widely adopted IPM programmes are those practised in commercial sweet pepper and cucumber crops throughout north-west Europe and Canada. In Ontario, a Harrow Greenhouse Crop Manager™ software has been developed for greenhouse cucumbers which provides advice on identification and control of pests and physiological disorders and the latest information on production practices and management strategies. This system aids producers in reducing operational expenses such as fertilizer and pesticides and allows the user to maintain a database on all aspects of their operation. A communication interface has been added that ultimately makes it possible to develop the forecast module for predicting potential pest and disease outbreaks and advises measures to be taken to avoid them (Shipp *et al.* 1997). This system provides the producer with the necessary categories of a complete IPM programme so that an informed and accurate decision can be made.

APPENDIX

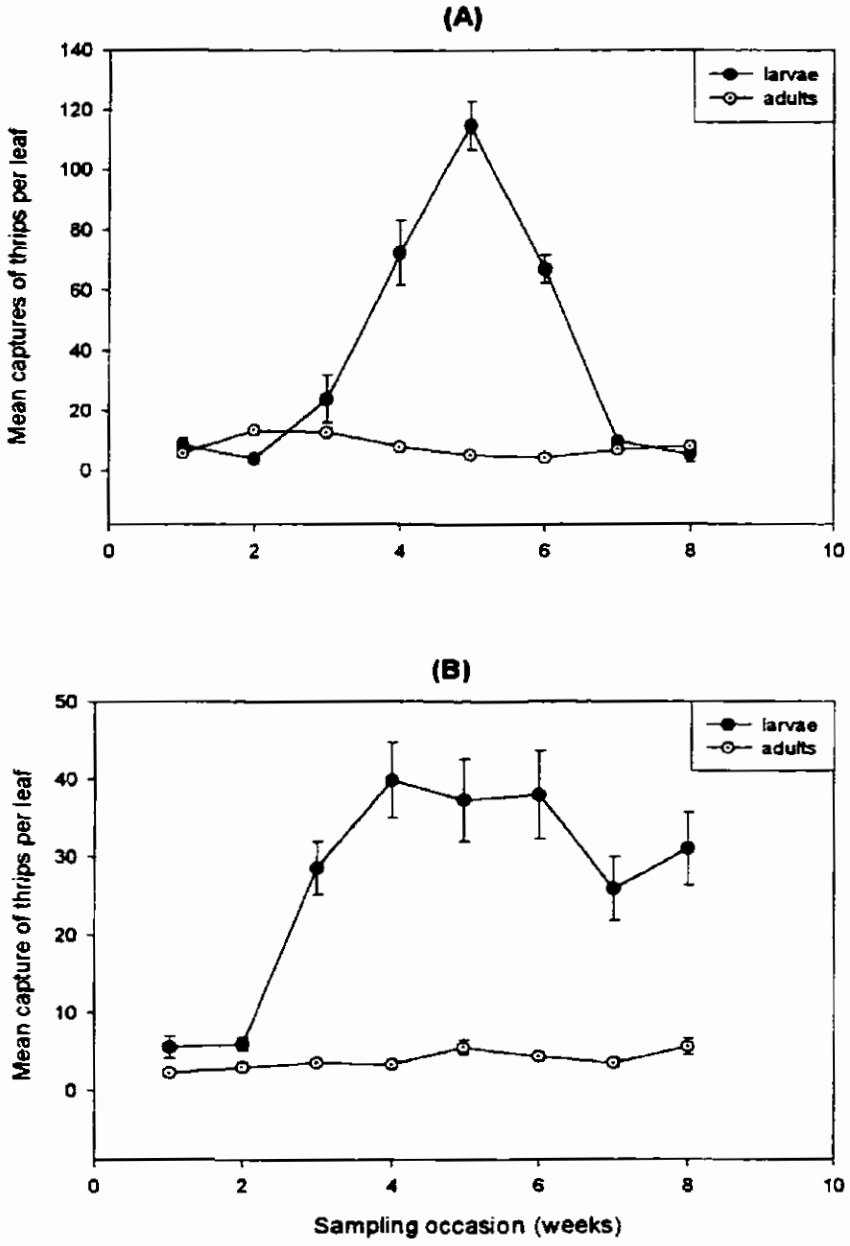

Fig. A.1. Mean captures of *T. tabaci* larvae and adults per cucumber leaf at Harlow research greenhouse 1 (A) and 2 (B) - NSAC, Fall 1996.

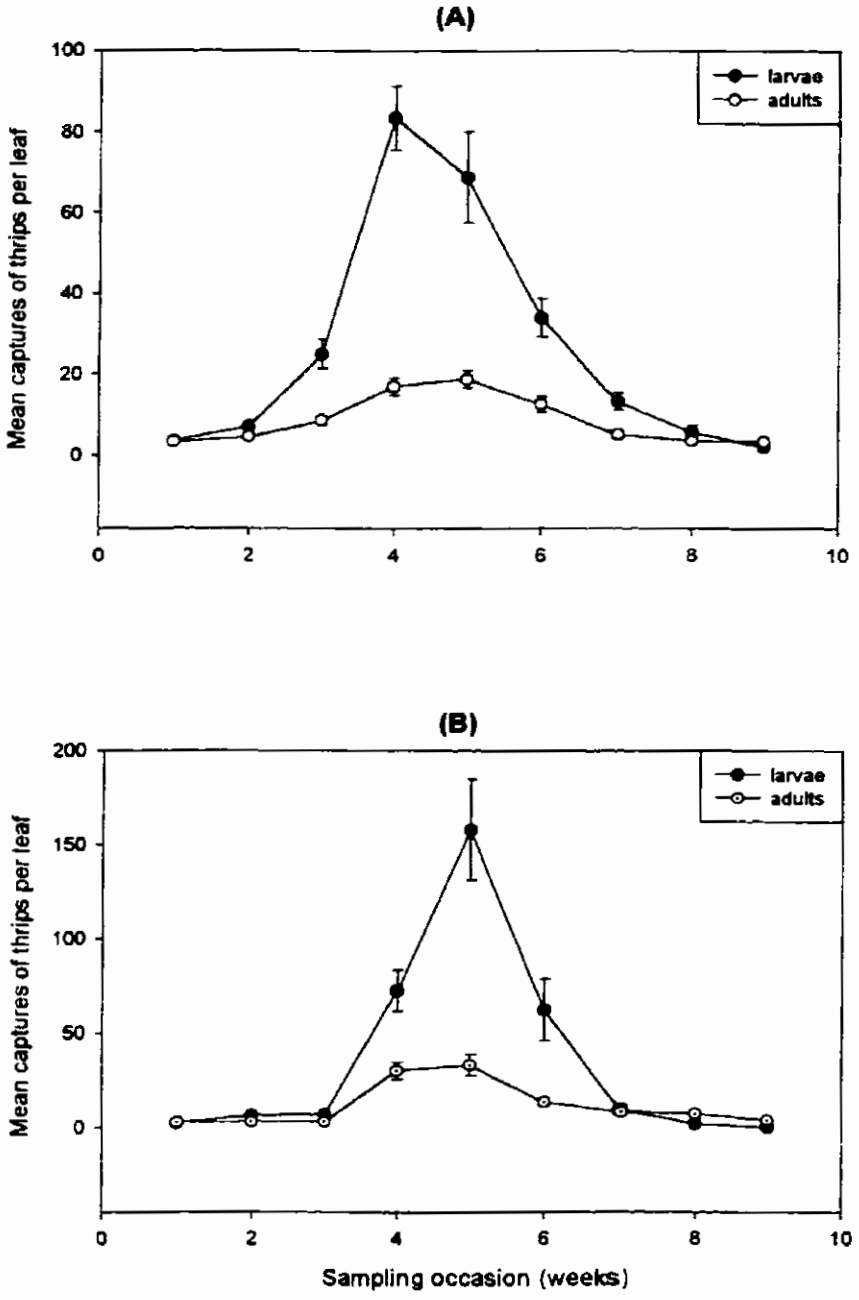

Fig. A.2. Mean captures of *T. tabaci* larvae and adults per cucumber leaf in Harlow research greenhouse 1(A) and 2 (B) - NSAC, Fall 1997.

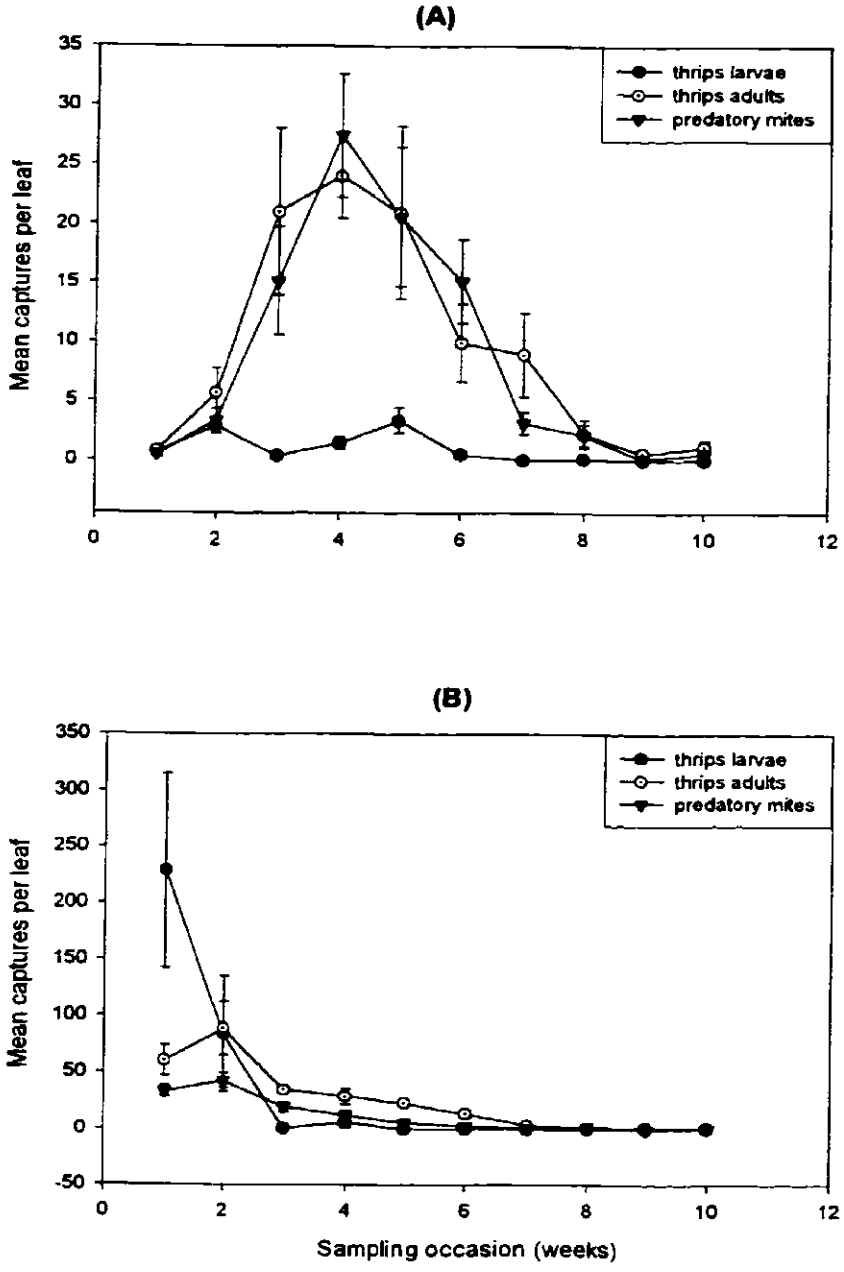

Fig. A.3. Mean captures of *T. tabaci* larvae and adults and *A. cucumeris* per cucumber leaf in Stokdijk Greenhouses, crops 1 (A) and 2 (B) - Beaverbrook, Fall, 1997.

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