in a randomized complete block design with five replications. Guard plants were placed at the ends of each row to avoid edge effects. The total number of plants was 130 plants resulting in a spacing of 0.89 plants·m^{-2}. To establish an onion thrips population in the crop, plants were infested with one thrips per plant at the two leaf stage.

The 1997 summer crop was also not considered this time due to crop failure. Plants were seeded 27 March and placed in the greenhouse 9 April and were subjected to cold shock. A heavy infestation of the greenhouse whitefly, *Trialeurodes vaporariorium* [Homoptera: Aleyrodidae] further weakened the plant. Warming temperatures encouraged *Pythium* species, which, in combination with the other stresses, caused the ultimate demise of the crop. Plants were removed from the greenhouses 12 and 18 June. The whiteflies were eradicated with a nicotine sulfate application 19 June. The greenhouses were thoroughly cleaned by rinsing the lines and tubs with a 10 percent virucidal disinfectant[19] (50 percent potassium monopersulphate, potassium bisulphate, potassium sulphate) solution followed by a 3.0 percent bleach[20] (commercial 5.25 percent sodium hypochlorite concentrate) solution and finished with two final flushes of water. This is important to note as our goal was to limit as much as possible, residual thrips populations (of any species) and to have a command over the initial *Thrips tabaci* population for the subsequent attempt.

A second crop was seeded 18 June and moved into the greenhouse 7 July. There were five cucumber cultivars represented: Corona, Exacta, Pinnacle, Pyralis, and Titleist. These were placed randomly in the greenhouse with all cultivars represented equally in each

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[19]Virkon®: Noraid Laboratories Inc., Joliette, Quebec.

[20]Javex®: Colgate-Palmolive Canada Inc., Toronto, Ontario.

house. Rows were divided into five plots of five plants each with guards at the ends of each row. The total number of plants in each house was 135 with a final plant spacing of 0.93 plants·m^{-2}. *T. tabaci* was acquired from a local culture[21] and applied at a rate of approximately two per plant one week after placement in the greenhouse and allowed to establish. The greenhouse whitefly was controlled with its specific biological control agent, *Encarsia formosa*. Powdery mildew was treated with a solution of 0.5 g·L^{-1} benomyl[22] [methyl 1-(butylcarbamoyl)-2-benzimidazole carbamate] and 0.25 g·L^{-1} etradiazole [23] [1, 2, 4-thiadiazole, 5-ethoxy - 3 (trichloromethyl)] on 12 August and 1.0 g·L^{-1} sulfur on 28 August.

3.2.2 Volatile chemicals: ρ-Anisaldehyde (4-methoxybenzaldehyde) and ethyl nicotinate (nicotinic acid ethyl ester, 3-pyridinecarboxylic acid) were purchased directly[24]. Subsamples were diluted to a concentration of 1:1000 scent:ethanol[25]. Ethanol was used in the trials as a control. A volume of 50 µL of the scents were pipetted into a nalgene slow release dispenser and attached to the trap with a metallic and plastic twist tie. Paper twist ties were not used to avoid possible absorption of attractants.

3.2.3 Sticky traps: Blue and yellow sticky traps measuring 10 cm x 26 cm were acquired from a Canadian distributor[26]. Clear sticky traps were cut from clear acetate to the same

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[21]Nova Scotia Agricultural College, Truro, Nova Scotia.

[22]Benlate® 50WP: Du Pont Inc., Agricultural Products, Mississauga, Ontario.

[23]Truban® 30WP: Scotts-Sierra Crop Protection Co., Marysville, Ohio.

[24]Sigma Chemical Co., St. Louis, Missouri.

[25]Commercial Alcohols Inc., Boucherville, Quebec.

[26]Aero-kure International, Sherbrooke, Quebec.

dimensions as the commercially available traps and coated on both sides with commercial insect trapping adhesive[27].

3.2.4 Volatile Chemical Attractant Experiments

3.2.4.1 Trial 1: commercial greenhouse: In the commercial greenhouse (Stokdijk), the traps were installed with the base approximately 10 cm above the crop canopy perpendicular to the row and attached to supporting chains with wooden clothes pins. Spacing between traps was 6.4 m within rows and 7.4 m between rows. The trials were designed as a randomized complete block, split plot with two replications (one replication in each section), and was repeated four times throughout the cropping season. To accommodate air currents within the greenhouse, the scent variable was designated as the main plot and placed within the same row to avoid mixing of scents. The subplots were trap colour, *i.e.* yellow, blue, and clear. Thrips captures were counted and both traps and scents were replaced daily for ten days. A time lapse of at least one week was allowed between trials to allow dissipation of remaining scent within the area.

3.2.4.1.1 Correlation trial: Leaf samples as per the method developed by Steiner (1990), detailed in Section 4.2.2, were taken within one metre of the traps to correlate trap captures to standard leaf counts to determine if trap captures were indicative of populations of adult thrips on leaves.

3.2.4.1.2 *Orius* captures: Traps with volatile chemicals would be useful as a supplement for other biocontrol methods and it is therefore important to examine the effect of traps with

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[27]Tangle Trap: The Tanglefoot Co., Grand Rapids, Michigan.

volatile chemicals have on other controls (Teulon *et al.* 1993). To that end, the number of minute pirate bug predators, *Orius* spp., captured on the traps was also recorded.

3.2.4.2 Trial 2: research greenhouses: In the research greenhouses (Harlow) during the second crop of 1997, traps were hung with string from the supporting frames approximately 10 cm above the crop canopy perpendicular to the row. Spacing between traps was 2.5 m within row and 3.0 m between rows. Only coloured sticky traps were used in these trials because it had been determined in the previous experiment that the clear traps did not significantly interact with scent to increase thrips capture. Air currents were not a significant factor in these houses; therefore, the experimental design was modified to a randomized complete block with two replications (one in each house). This was repeated three times throughout the cropping season and thrips captures were recorded daily for five successive days and only scent was replaced on a daily basis.

3.2.5 Statistical analysis: Recorded data were subjected to analysis of variance (ANOVA) using the general linear model (GLM) procedure of SAS[28]. Significance differences between treatment means were determined using p-values from ANOVA. P-values <0.01 were considered highly significant, ≥ 0.01 and ≤ 0.05 were considered marginally significant, and >0.05 were not significant. The population of thrips in the vicinity of the traps may also influence trap capture (Parker and Skinner 1997). Immediately prior to trial establishment, the mean of two leaf counts of adult thrips in the area of the trap placement was used as a covariate in the initial statistical analyses of the commercial greenhouse data. The covariate did not improve the R^2 value or the mean squares significantly and was therefore removed.

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[28]Statistical Analysis System, SAS Institute, Cary, North Carolina.

Individual analyses were performed on the commercial data replicated over ten days. Inconsistent results prompted another analysis to distinguish between the effects during pre-fruit and post-fruit production. A final combined analysis was then performed on the four trials. In all cases, examination of the residuals revealed that the data were not normally distributed and did not exhibit constant variance. A natural logarithmic transformation of the data restored normality and constant variance and improved the R^2 value. In trials containing counts of 0, the transformation ln(x+1) was used. A second analysis was performed on the transformed data. Results in tables are presented in original units.

For the commercial greenhouse experiments, correlation analyses were performed between the mean counts of adult thrips captured on leaf samples and the mean number of thrips captured on the three trap colours tested. The data for the *Orius* study were transformed using the natural log and was analysed in the same manner as adult thrips captures were. These results are also presented in original units.

3.3 Results and Discussion

3.3.1 Trial 1: commercial greenhouse: The effect of scent within the individual replications was not consistent. This may be a consequence of chemical attractants exhibiting differential effectiveness during different growth stages of the plant. Attractants may not be competitive with flowers or ripening fruit. A second analysis was performed which separated the replications into pre-fruit and post-fruit production categories. The effect of scent was not significant in the pre-fruit analysis ($p=0.0797$), nor the post-fruit analysis ($p=0.3946$). The interactive effect of scent by colour was also not significant for the pre-fruit ($p=0.2785$) nor

the post-fruit ($p=0.4926$) production. It was concluded that growth stage did not affect the attractiveness of these chemicals alone or in interaction with colour and these effects were therefore, only discussed in the combined analysis.

In all the analyses, the effect of colour was consistent. Blue traps caught significantly more thrips than yellow, and yellow caught significantly more thrips than the clear traps. Some authors suggest that thrips respond to different colour hues and levels of ultraviolet reflectance in different crops or surroundings. In grasses, *T. tabaci* prefer white water traps over shades of yellow and blue, and in field crops, yellow was the colour of choice. It has been constant in the literature that western flower thrips captures are highest on a specific blue hue over yellow or white in the greenhouse environment (Brødsgaard 1993, Le Blanc 1993). The results from the current trials are concurring for *T. tabaci*.

In the combined analysis, anisaldehyde baited traps captured significantly more thrips ($p=0.0459$) than either ethyl nicotinate or the control (Table 2). Ethyl nicotinate did not increase thrips captures over non-baited traps. Again, the effect of colour was highly significant ($p=0.0001$) with the same trend as in the individual analysis (Table 3). The interaction between scent and colour was not significant ($p=0.9405$) at this location.

Table 2. The effect of scent on captures of *T. tabaci* in a commercial cucumber greenhouse.

Scent	Mean captures
Anisaldehyde	35.45[a]
Control	30.79[b]
Ethyl nicotinate	21.33[b]

Values followed by the same letter are not significantly different (α=0.05), LSMeans, pdiff.

Table 3. The effect of trap colour on captures of *T. tabaci* in a commercial cucumber greenhouse.

Trap colour	Mean captures
Blue	56.72[a]
Yellow	25.83[b]
Clear	5.02[c]

Values followed by the same letter are not significantly different (α=0.05), LSMeans, pdiff.

3.3.2 Trial 2: research greenhouses: Only a combined analysis was performed at this location. There was a marginal significant interaction between scent and colour (p=0.0491). The combination of yellow traps baited with ethyl nicotinate captured 1.6 times as many thrips as the unscented blue traps which produced the next highest level of captures (Table 4). Brødsgaard (1989) supports Kirk (1987) in the statement that a strong visual appearance may reduce the effect of scent. In the present study, the effect of a sub-optimal colour for thrips attraction, yellow, in combination with a non-floral volatile attractant, ethyl nicotinate, resulted in a heightened attraction for *T. tabaci*.

When interpreting of the efficiency of traps containing attractants, caution must be employed. Composition and concentration of volatiles are affected by temporal and spatial

Table 4. The interactive effect of scent x colour on captures of *T. tabaci* in research cucumber greenhouses.

Scent	Colour	Mean captures
Ethyl nicotinate	Yellow	33.93^{a}
Control	Blue	21.30^{ab}
Anisaldehyde	Blue	20.53^{abc}
Ethyl nicotinate	Blue	17.80^{bcd}
Anisaldehyde	Yellow	17.47^{bcd}
Control	Yellow	12.10^{e}

Values followed by the same letter are not significantly different (α=0.05), LSMeans, pdiff.

factors (Dobson 1994). If the traps are in proximity to each other, baited traps may draw thrips away from nearby non-baited traps or from traps baited with chemicals that induce a weak response. The contrary may also occur, *i.e.* traps baited with chemicals that induce a strong response may draw thrips towards an area containing a non-baited trap or a trap containing a chemical that induces a weak response, resulting in these less attractive traps capturing more thrips than these would in isolation (Teulon *et al.* 1993). The distance over which such a response occurs is unknown; however, it will be affected by wind speed and direction (Lewis 1997c). The possible effects of air movement, speed and direction, and the proximity of the baited traps was considered when designing the commercial greenhouse trial, therefore, it is unlikely that these effects occurred at this location. Teulon *et al.* (1993) suggested that the slightest breeze is likely to influence the direction of thrips movement. Thrips capability of exerting a degree of choice as to where to alight may be reflected in their distribution patterns (Lewis 1997b). This occurs with the selection between trap colours; consequently, when mixing of the scents within a trial is not a factor, thrips should be able to

exhibit this same level of choice when exposed to chemical attractants. Within the Harlow trials, traps were in closer proximity; however, there was very little air movement to diffuse the scent. The use of dental roll and filter paper wicks and painting the attractant directly on the trap is reported to leave a strong, lingering scent in the greenhouse (Teulon *et al.* 1993). This was not the case with the slow release dispenser used in these trials. Only in close proximity (< 1 m) could the scent be detected by human means and the scent did not linger when the baited traps were removed.

The variation in results between those of the commercial greenhouse and the ones of the research greenhouses could be a reflection of the type of response mechanism involved in thrips host selection. Teulon *et al.* (1993) found that thrips responded to ethyl nicotinate in both windy (open fields) and calm (greenhouse) conditions, therefore, host-finding behaviour of thrips is unlikely to involve directional host-finding responses, *e.g.* anemotaxis or odour-induced visual response. Conversely, Visser and Piron (1995) stated that in insects' search for host plants, their perception of host-plant odour triggers positive anemotaxis, thus increasing the probability of encountering host plants. Insect responses in flight are often anemotactic and would be impossible in completely still air (Kirk 1985). It seems probable that thrips could use scent more effectively as an arrestant or to stimulate a visual response, because then the cue could also be used when the air is completely still. The commercial greenhouses had fans to promote air and carbon dioxide circulation in sections of the greenhouse causing wind patterns within rows above the crop, while the Harlow greenhouses had minimal air movement within the house. This could suggest that the host finding cues stimulated by anisaldehyde and ethyl nicotinate are different. If the host-finding response

mechanism were the same for both volatile chemicals, the results should be similar for both houses.

If the proximity of the scented traps in the research greenhouses resulted in mixing of the scents, perhaps a 'cocktail' of scents may be most effective in attracting thrips. Most polyphagous insects are attracted to a number of scents and colours or combination and chemical mediation of host finding is thought to occur with a mixture of chemicals involving synergism (Miller and Strickler 1984). A physiological 'green odour', in which there is a combination of two or more volatile chemicals exuding from the host, is frequently involved in host finding by leaf-feeding insects (Visser1986).

3.3.3 Correlation analysis: Correlation analysis between the means of both blue ($p=0.4865$) and yellow ($p=0.5940$) sticky trap captures and adults thrips counts on leaves were not significant. There was clearly no relationship between captures on coloured sticky traps and adult thrips counts on cucumber leaves. Steiner (1990) also found that there was no correlation between blue sticky trap captures and leaf counts for *F. occidentalis*. Sticky traps are designed to attract a high number of insects from a large area. This is done by capturing adult thrips in flight as they disperse above the crop canopy. Thrips numbers on traps are ultimately going to be much higher than the population indicated by leaf samples in the vicinity of the trap. This can be extrapolated to the general population in the greenhouse. The number of thrips caught on traps would reflect an overestimate of the infestation which is further complicated by the contagious distribution of thrips in the greenhouse. Traps placed within or near thrips' aggregations will capture more thrips than in sparsely populated areas.

There was a moderately significant correlation between the number of adult thrips captured on clear sticky traps and those adults counted on leaf samples (p=0.0318). This suggests that there is a relationship between aerial thrips populations and those found on leaves when there is no influence of colour (Fig. 1 and Fig. 2). This finding strengthens my earlier statement that colour distorts the number of thrips captures and cannot be a reliable indicator of the infestation level in the greenhouse. These coloured traps may still indicate the trend in the population, whether it is increasing, decreasing, or stable, or may be used in areas of high populations to assist other control measures in place.

3.3.4 Orius captures: The effect of scent (p=0.6287) and scent by colour interaction (p=0.9570) was not significant for *Orius* predators. The colour of the sticky trap was highly significant (p=0.0001) corresponding with the effects on *T. tabaci*. Blue sticky traps caught significantly more *Orius* than yellow, and yellow caught significantly more than clear traps (Table 5).

The behavioural mechanisms allowing predatory arthropods to detect their prey are largely unexplored (Sabelis and van Rijn 1997). Effective predators have a variety of characteristics that aid them in their detection of suitable prey. Domatia, areas known to be preferred by insects (insect-domatia association), may also be inhabited by their predators, *e.g. Amblyseius cucumeris* inhabiting cracks and crevices where onion thrips larvae are also known to reside. The evidence of anthocorids inhabiting domatia is scarce (Sabelis and van Rijn 1997); however, these predators have shown differential arrestment to host plants species without any association with the prey population on these plants (Beekman *et al.* 1991). Adult *Encarsia formosa* are known to be attracted to yellow traps when they are dispersing

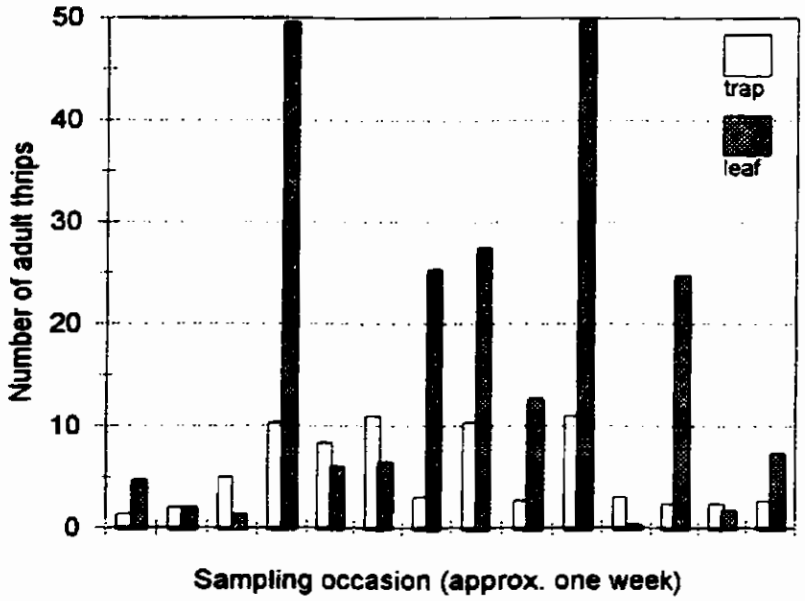

Fig. 1. Relationship between adults thrips captures on clear sticky traps and standard leaf samples in greenhouse cucumbers.

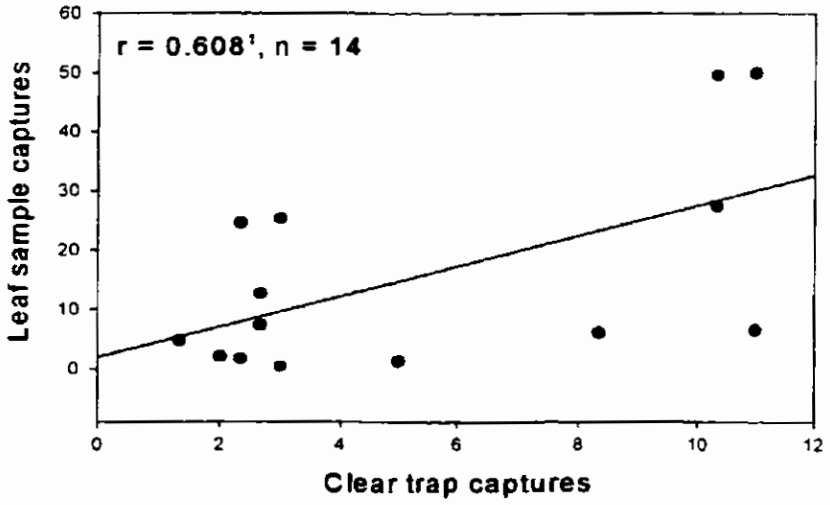

Fig. 2. Correlation between adults thrips captures on clear sticky traps and standard leaf samples in greenhouse cucumbers ([1]significant at $\alpha = 0.05$).

Table 5. The effect of trap colour on *Orius* captures on sticky traps in greenhouse cucumbers.

Trap colour	Mean captures
Blue	3.02[a]
Yellow	2.22[b]
Clear	0.23[c]

Values followed by the same letter are not significantly different (α=0.05), LSMeans, pdiff.

in search of whitefly hosts (van de Veire and Vacante 1984). It is probable that anthocorids may also have similar host finding cues, such as attraction to specific colour hues, as their thrips prey.

The alarm pheromone of thrips is present in their anal droplets and is believed to act as a prey finding kairomone for predators. It has been shown that *O. tristicolor* increased its rate of turning and spent 23 percent of its time within 5 mm of a pheromone source on bean leaf discs (Teerling *et al.* 1993). Traps that accumulate large numbers of thrips, such as blue traps, may have levels of this pheromone that are detectable by *Orius* predators in flight (Sabelis 1992).

3.4 Recommendations and Future Research

These results indicate that the volatile chemical attractants, anisaldehyde and ethyl nicotinate, do not enhance sticky trap captures sufficiently to control thrips by mass trapping in greenhouse cucumber crops. These results may indicate that volatile chemical attractants may enhance early detection of lower densities of thrips in the greenhouse to allow the expedient employment of other control measures. The observed variations in results from the

two locations strongly support the need for continued research in several areas of volatile chemical attractants. The behavioural mechanism involved in host-finding cues is the most important factor to be determined if this control tactic is to be exploited. The differential attractiveness of scents and their interaction with colour at the two locations imply that the two scents tested may induce different behavioural responses or may be influenced by air currents within the greenhouse.

Many researchers state that volatile chemical attractants naturally occur in combination rather than singly. In this context, if a mixture is to be tested, the appropriate concentrations of each volatile must be determined. High concentrations of some attractants may be necessary to induce a response, while others may require minute amounts. The hypothesis is that ethyl nicotinate exists in small quantities in nature but induces a strong result (Teulon *et al.* 1993). Anisaldehyde may not induce the same response. The use of a slow release dispenser reduced, if not eliminated, the problem of blending and carryover of scents in the greenhouse for these trials. The slow release dispensers may have adversely affected the trials by not allowing sufficient release of the chemical necessary to induce the expected response.

The relationship between trap catches and infestation levels is complex and the evidence for trap catches being reliable indicators of the size of the crop infestation or the amount of damage is mixed (Lewis 1997c). This study indicated that clear trap captures were correlated with adult thrips populations on nearby leaves while coloured traps distorted this relationship. If traps are to be used to estimate the thrips population in the greenhouse, a reliable relationship model needs to be developed. Non-baited bi-colour traps have had

variable results in attracting western flower thrips. Le Blanc (1993) tested a number of colours with contrasting background combinations, none of which attracted significantly more WFT than single colour traps. Vernon and Gillespie (1995) found that sticky traps with contrasting background colours increased thrips captures. These traps could be tested in combination with volatile chemical attractants.

Finally, with the pressure to adopt environmentally sound control measures, it is important to assess the effects of the various control measures on each other. Insect responses to scents and colours are known to occur in flight (Lewis 1997b). If an appropriate scent and trap colour combination is found, it will be necessary to determine its effect on aerially mobile predators, such as *Orius* spp.

It is recommended that sticky traps remain in use for selective trapping in highly populated areas to determine the initial occurrence of thrips in the greenhouse or to monitor the population trends thereafter. If mass trapping by sticky traps baited with volatile chemical attractants is to be recommended as a control measure, insect captures need to be increased dramatically to justify the expense and extra caution required to work with these devices.

4. Sequential Sampling

Abstract

The spatial distribution of *Thrips tabaci* Lindeman [Thysanoptera: Thripidae] larvae and adults and the predatory mite, *Amblyseius cucumeris* (Oudemans) [Acari: Phytoseiidae], on greenhouse cucumbers was calculated using two variance-mean models: Iwao's patchiness regression (IPR) and Taylor's power Law (TPL). Both models determined thrips larvae and adults to be contagiously distributed in greenhouse cucumbers with a density contagious coefficient, b_p, (IPR) and index of aggregation, b, (TPL) significantly greater than 1. These values for the predatory mites resulted in ambiguities, *e.g.* the IPR determined that these predators were not contagiously distributed while the TPL revealed they were. The index of basic contagion, a_p, (IPR) indicted that aggregates were the basic component of thrips larvae population.

Based on these parameters, Iwao and binomial sequential sampling plans were developed for thrips larvae and adults on greenhouse cucumbers. The economic threshold used was estimated at 75 percent of a working economic injury level of 9.5 larvae and 1.7 adults and calculated to be 7.1 and 1.3, respectively. The maximum sample number to be taken were calculated to be 66 for larvae and 46 for adults for Iwao's plan. The maximum sample number for the binomial sequential sampling plan was 39 for larvae and 67 for adults.

4.1 Background

Sampling populations to determine diversity and estimated numbers of living species are the most fundamental research activities in ecology because ecological questions focus on distribution and abundance of organisms as influenced by biological and physical aspects of the environment. Sampling provides a foundation for research programmes generating information on density, dispersion, age structure, reproduction, and migration. A synthesis of the data ultimately yields an understanding of the population dynamics of the species (Pedigo 1994). The synchrony between injurious life stages of the pest and susceptible stages of the host is important (Higley and Peterson 1994). The development of sampling programmes is based upon clear understanding of insect bionomics, host interaction, and management goals (Hutchinson 1994) and these sampling plans serve as the basis of integrated pest management (Pedigo and Bentin 1994).

When a population is sampled, three basic pieces of information are calculated: (i) the estimate ($\bar{x}$) of the true mean (m); (ii) the estimate (s^2)of the true variance (σ^2); and (iii) the size (unit). The indices used for the description of animal populations are derived from various arrangements of these pieces of information (Southwood 1978). Ideally, sequential sampling plans should be calculated for those stages for which there is spatial dispersion data (Boivin *et al.* 1991). The mean-variance relationships of Taylor (1961) and Iwao (1968) have been used effectively as foundations for many protocols (Binns and Nyrop 1992). These relationships are extremely important because they permit the prediction of variances for estimated mean, which in turn allows for the development of sequential sampling procedures. Both models describe this relationship well, although the Taylor's power law (TPL) seems

to be more common (Binns and Nyrop 1992).

Taylor (1961) showed the mean-variance relationship to follow a power law which approximates an index of aggregation, b, describing an intrinsic property of the organism under study. This index of aggregation is a true population statistic, with a continuous graduation from near uniform ($b \rightarrow 1$; variance < mean) through random, ($b = 1$; variance = mean) to highly aggregated ($b \rightarrow \infty$; variance > mean) distribution (Taylor 1961).

Lloyd (1967) determined the mean crowding index, $\mathring{x}$, which approximates the intensity of interaction between individuals as they express a level of crowding in a given unit of habitat. Iwao (1968) demonstrated that the mathematical relationship between mean density and mean crowding describes certain characteristics of the spatial distribution that are inherent to each species in a given habitat and can be described by simple linear regression, called Iwao's patchiness regression (IPR). The y-intercept of the regression line is termed the 'index of basic contagion' (Iwao 1970) and indicates the insect's tendency to crowding (positive) or repulsion (negative) and is a property of the species. The slope of the regression line is the 'density contagious coefficient' and is related to the pattern in which the organism utilizes its habitat and parallels that of the index of aggregation of the TPL. Both models have received critical attention and both remain important for the development of sampling procedures (Binns and Nyrop 1992).

The simplest way to avoid pest populations reaching unacceptable levels involves taking samples from an ongoing process, infer from them what the process is doing, and make a decision either to not take action or reset the process (Binns 1994). It is essential to know how to gather sufficient information about pest abundance to be able to make correct

decisions without incurring expensive costs (Binns and Nyrop 1992). Only the degree of effort necessary to start sampling before pest injury becomes unacceptable should be employed (Higley and Peterson 1994). Enumerative counts of a pest is the most accurate method to assess the pest population (Binns and Bostonian 1990); however, when the pest is small or abundant, collecting and processing a large number of samples is very time consuming. In sequential sampling, the total number of samples taken is variable and depends on whether or not the results so far obtained give a definite answer to the question posed about the frequency of occurrence of an event, *i.e.* abundance of an insect (Southwood 1978). Pests for which a certain level of infestation can be tolerated and that can change in numbers rapidly are suited for sequential sampling (Fournier *et al.* 1995). In addition to being faster and therefore less costly per sample unit basis, it is also the most feasible field sampling method for many organisms (Binns and Nyrop 1992).

When time constraints are important, a binomial, or presence-absence, sampling plan in which decision making is based on intensity, or proportion of plants infested, is preferred (Shipp and Zariffa 1991). Decision-making based on intensity often reduces sampling time because the sample size necessary to make a decision is based in part on the information gathered as sample units are inspected and the practitioner terminates inspection once an infestation is found (Brewer *et al.* 1994). There are only two possible outcomes in binomial sampling - the organism is either present or absent.

The compromise with binomial sampling is the increased uncertainty with respect to estimated densities or sample classification decisions (Binns and Nyrop 1992). Estimates of a mean using binomial sampling have considerably more variation associated with them than

one based on complete enumeration methods. In agricultural systems, the increased variation and subsequent increase in sample size needed to predict the population mean can be offset by the ease with which the sample units are classified as infested or not infested. As the degree of clumping increases, this advantage becomes more apparent. An advantage of binomial sampling that is seldom mentioned is that these methods are impervious to the effects of one to a few unusual observations in a sample. This is important because the goal of a sampling plan is to estimate the population density and use the resulting value as an estimate of the 'typical' damage that a 'typical' plant experiences. A given level of pests is required before damage occurs, therefore the estimate of the typical damage is critical. The use of different tally thresholds, the minimum number of organisms present to categorize the plant as infested, can extend and improve binomial sampling plans (Jones 1994). This does not significantly compromise the advantage of binomial sampling of not requiring actual counts of the pest. The use of a tally threshold with a specific sequential sampling approach may allow decisions based on the proportion of leaves having damaging population levels present rather than a mean population density level. This would eliminate the variance associated with the required conversion of the proportion of plants infested to the mean, and result in fewer samples being required (Jones 1994).

Such plans have been developed for minute and abundant pests such as aphids on brussel sprouts (Wilson *et al.* 1983), mites in garden seed beans (Bechinski and Stoltz 1985), and onion thrips on field onions (Fournier *et al.* 1995). The objective of this study was to adapt existing sequential sampling plans, Iwao and binomial, developed for onion thrips on field onions to this pest in greenhouse cucumber production.

4.2 Materials and Methods

4.2.1 Greenhouse facilities: The same crops used in the volatile chemical attractant trials were used in the development of sequential sampling programmes. In the research greenhouses 1996 fall crop, 18 samples were taken from each house. In the second crop of 1997, 15 samples were also taken. Lastly, in the commercial greenhouses, 9 samples were taken from the designated sections of each crop.

4.2.2 Sample preparation: The sampling unit was a mature, middle leaf (Steiner 1990) collected by cutting the leaf, including its petiole, over a large container which was sealed immediately. Samples were obtained from each location on a weekly basis. Samples were not taken from the outside rows or from the first or the last plants in a plot to avoid edge effects. Sampling from the same plant was also avoided to prevent weakening the plant.

In the laboratory, the leaf sample was held over a large funnel and washed twice under a strong water stream (Steiner 1990). The insects and mites were caught in a nitex nylon mesh screen (mesh size = 188 μm) attached at the base of the funnel with an elastic. The container, leaf and funnel were rinsed with 70 percent ethanol to dislodge any remaining thrips and anaesthetize the entire catch to facilitate counting. Counting was performed under a stereomicroscope[29] with fibre optics illumination usually at 40x magnification. The number of first and second larval instar thrips, adult thrips, and predators (commercial greenhouse data) were recorded. The data from Harlow research greenhouses and Stokdijk greenhouses were pooled to give one data set for the development of the sequential sampling plans.

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[29]Wild Heerbrugg stereomicroscope: Wild Leitz Canada Ltd., Willowdale, Ontario.

4.2.3 Iwao sequential sampling plan: For each sampling period, the mean and variance of larval and adult thrips were determined and used to calculate the mean crowding index according to the equation by Lloyd (1967):

$$\mathring{x} = \bar{x} + (s^2/\bar{x} - 1)$$

in which $\mathring{x}$ is the mean crowding of the sample, $\bar{x}$ is the mean density of thrips of each age class per leaf and s^2 is the variance of the number of thrips of each age class per leaf. The mean crowding indices describes the intensity of interactions between individuals as they express a level of crowding in a given unit of habitat.

The aggregation of the individuals was quantified by the patchiness regression (IPR) represented by the linear regression of $\mathring{x}$ on $\bar{x}$ in the equation:

$$\mathring{x} = b_r\bar{x} + a_r$$

in which the intercept (a_r) is the index of basic contagion and the slope (b_r) is the density contagious coefficient (Iwao 1968). When $a_r = 0$, a single individual is the basic component of the population. When $a_r > 0$ or $a_r < 0$, there is a positive (clumping) or negative (repulsion) association between individuals, respectively. When $b_r = 1$, the basic components of the population are randomly distributed in space, and when $b_r > 1$, the distribution is contagious. The patchiness regressions were determined for thrips larvae and adults for all locations and for the predatory mites, *A. cucumeris*, at the commercial site. The resulting values for a_r and b_r were tested for significant departure from 0 and 1 respectively, using *t*-tests.

The sequential sampling procedure proposed by Iwao (1975) proposes the curves for the upper and lower acceptance limits using the following equation:

$$T_{upper} = n \cdot ET + t\,[n((a_r + 1)\,ET + (b_r - 1)\,ET^2)]^{1/2}$$

$$T_{lower} = n \cdot ET - t\,[n((a_r + 1)\,ET + (b_r - 1)\,ET^2)]^{1/2}$$

where T is the total number of thrips captures (larvae or adults), n is the number of samples taken, ET is the economic threshold, t is the student's value of t at 0.1 significance level for a two-sided t-test, a_r is the index of basic contagion, and b_r is the density-contagious coefficient. The economic thresholds were based on 75 percent of the preliminary economic injury level (EIL) estimates of Steiner (1990) for larval and adults thrips.

The maximum number of samples to be taken in order to determine if the population level is equal to the economic threshold was determined by the following formula:

$$n_{max} = t^2/d^2 \cdot [(a_r + 1)\,ET + (b_r - 1)ET^2]$$

where d is the confidence interval of the estimated mean density.

4.2.4 Binomial sequential sampling plan: In binomial sequential sampling, the relationship between the proportion of plants infested and the mean number of thrips per sample is estimated by the formula of Wilson and Room (1983):

$$P = 1 - e\,[(-\bar{x}\ln(a\bar{x}^{(b-1)})/(a\bar{x}^{(b-1)} - 1)]^{-1}$$

where P is the proportion of plants infested, and $\bar{x}$ is the mean density of thrips per plant. Parameters a and b are estimated from (TPL) (Taylor 1961):

$$s^2 = a\,\bar{x}^b$$

where a is a scaling factor related to sample size and b is an index of aggregation characteristic of the species. To determine the value for a, the values of $\bar{x}$ and s^2 were

plotted on a $\log_{10}/\log_{10}$ scale. From the regression equation, the value of a was calculated at the point where $\bar{x} = 1$. The value of b was then determined from the equation:

$$\log_{10} s^2 = \log_{10} a + b \log_{10} \bar{x}$$

The index of aggregation, b, can be used to classify dispersion patterns. If $b = 1$, thrips are evenly distributed in space (variance < mean). If $b < 1$, then thrips exhibit random distribution (variance = mean). If $b > 1$, then thrips exhibit contagious distribution (variance > mean). The value of b was tested for significance greater than 1 using t-tests.

Acceptance limits were estimated by calculating a confidence interval for the proportion of plants infested corresponding to the economic threshold multiplied by the number of plants inspected (Bechinski and Stoltz 1985):

$$P_s n \pm t_{(0.1,\infty)} n [((P_s(1-P_s))/n)]^{1/2}$$

where P_s is the economic threshold (expressed as a proportion of plants infested), n is the number of plants inspected, t is the student value of t for two sided test at α level of 0.1 with infinite degrees of freedom.

The maximum sample number to check in the eventuality of a density equal to the economic threshold is determined by the equation of Karandinos (1976):

$$n_{max} = (t^2_{(0.05,\infty)} P_s(1-P_s))/h^2$$

where h is the precision desired.

4.3 Results and Discussion

The mean captures of thrips life stages are shown in Fig. A.1, A.2, and predatory mites in the Appendix, Fig. A.3 of the Appendix. Populations of thrips were established in the greenhouses prior to sampling. In the commercial greenhouse, thrips were controlled with predatory mites.

4.3.1 Iwao sequential sampling plan: Iwao's patchiness regressions of the mean crowding ($\mathring{x}$) on mean density ($\bar{x}$) obtained for the pooled results were significantly linear for both onion thrips larvae and adults, as well as the predatory mites, *A. cucumeris* (Table 6 and Fig. 3).

Table 6. Statistics of the regression of mean crowding ($\mathring{x}$) on mean density ($\bar{x}$) for captures of *T. tabaci* larvae and adults, and the predatory mite, *A. cucumeris*, in greenhouse cucumbers.

Life Stages	Intercept a_r	Slope b_r	Adjusted-R^2	Correlation coefficient[1]	n
T. tabaci: Larvae	1.761	1.314	96.3	0.982**	43
Adults	0.291	1.415	90.3	0.951**	43
A. cucumeris	1.770	1.279	96.9	0.985**	20

[1] Correlation coefficient, all of these were significant at $\alpha = 0.01$.

The values for the index of basic contagion (a_r) are listed in Table 7. The index of basic contagion for thrips larvae was significantly greater than 0 indicating that the basic components of these populations were aggregates. For thrips adults and the predatory mites, the index of basic contagion was not significantly greater than 0 indicating that the basic component of the population was an individual.