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Spatial distribution of some major arthropods and sampling procedures for *Aphis gossypii* Glov. in polyculture system comprising chilli, brinjal and leucaena plants

(Taburan spatial beberapa artropod utama dan prosedur pensampelan bagi *Aphis gossypii* Glov. dalam sistem polikultur yang terdiri daripada tanaman cili, terung dan leucaena)

Key words: aphids, spatial distribution, Green's plan, Taylor's Power Law, Iwao's mean crowding, intercropping, polyculture, bootstrap

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Abstrak

Dalam usaha mengurangkan kehilangan hasil cili akibat virus rintik urat daun cili yang dibawa oleh *Aphis gossypii*, sistem polikultur telah diketahui dapat mengawal populasi perosak melalui pemangsaan oleh *Menochilus sexmaculatus*. Namun, maklumat yang ada tentang taburan spatial perosak dan pemangsa utama dalam sistem polikultur sangat sedikit. Maklumat sedemikian penting bagi membentuk pelan pensampelan untuk pengurusan perosak. Taburan spatial dua spesies perosak iaitu *A. gossypii* pada pokok cili dan terung serta *Heteropsylla cubana* pada pokok leucaena (petai belalang); dan satu spesies predator *M. sexmaculatus* telah dianalisis berdasarkan kaedah penanaman dan peringkat hidup yang berbeza, dengan menggunakan Hukum Kuasa Taylor (pekali *b*) dan indeks min kesesakan Iwao (pekali β). Seterusnya, pekali-pekali Taylor digunakan bagi membentuk pelan berjujukan Green untuk *A. gossypii* bagi setiap kaedah kultur. Kajian ini menunjukkan bahawa kesemua kategori artropod bertaburan secara berkelompok, dengan nilai *b* dan β melebihi 1 secara ketara. Apabila varians diregresi pada min densiti, Hukum Kuasa Taylor menunjukkan kepadanan tertinggi dengan nilai r^2 yang lebih tinggi dan ralat piawai yang lebih rendah dibandingkan dengan pengiraan secara min kesesakan Iwao. Ketidakupayaan terbang bagi nimfa afid dan afid tanpa sayap menghasilkan tahap perkelompokan yang tinggi. Dalam membentuk suatu pelan pensampelan, monokultur memerlukan saiz sampel yang kecil dibandingkan dengan penanaman dua dan tiga jenis. Densiti populasi spesies serangga dalam monokultur lebih tinggi berbanding dengan penanaman dua dan tiga jenis. Pelan Green memerlukan saiz sampel yang lebih kecil berbanding dengan pelan saiz sampel tetap. Saiz sampel juga berkurangan dengan penurunan tahap kepersisan daripada 0.20 kepada 0.30; pengurangan daripada 44 kepada 12 dalam monokultur, daripada 41 kepada 14 dalam penanaman dua jenis tanaman, dan daripada 51 kepada 17 dalam penanaman tiga jenis tanaman. Setiap jenis kultur juga menghasilkan peratusan yang tinggi bagi nilai kepersisan sebenar kurang daripada kepersisan optimal.

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Hasil yang diperoleh menunjukkan bahawa pelan Green dapat diamalkan dan digunakan dalam program pengurusan perosak bagi *A. gossypii*, dengan tahap kepersisan 0.30.

Abstract

In preventing crop losses due to chilli veinal mottle virus transmitted by *Aphis gossypii* on chilli plants, a polyculture system is known in many cases to suppress pests through predation by *Menochilus sexmaculatus*. However, information on spatial distribution of major pests and predators in polyculture crop system is little known. Yet such information is essential in developing sampling plans for pest management. The spatial distributions of two pest species, *A. gossypii* on chilli and brinjal plants and *Heteropsylla cubana* on leucaena plants; and one predator species, *M. sexmaculatus*, were analyzed with respect to different culture methods and life stages using Taylor's Power Law (*b* coefficient) and Iwao's mean crowding index (β coefficient). Subsequently, Taylor's coefficients were used in developing the Green's sequential plan for *A. gossypii* for each culture method. This study indicates that all arthropod categories were clumped, with β and *b* values significantly larger than 1. On regressing the variance on the mean density, Taylor's Power Law indicates the best fit with higher r^2 and lower standard errors compared with Iwao's mean crowding. The immobility of aphid nymphs and wingless aphids tends to result in high aggregations, whereas decreasing aggregations in winged aphids are due to the flight ability. In developing a sampling plan, monoculture requires a smaller sample size than that required by diculture and triculture. Population density of insect species in monoculture is higher than those in diculture and triculture. The Green's plan required smaller sample size than fixed-sample-size plan. As the precision level is decreased from 0.20 to 0.30, the sample size decreases from 44 to 12 in monoculture, from 41 to 14 in diculture, and from 51 to 17 in triculture. Each type of culture yielded a high percentage of actual precision level lower than the optimal precision level. The result obtained indicates that the Green's plan is feasible and applicable in pest management program for *A. gossypii* with a precision level of 0.30.

Introduction

In Malaysia, *Aphis gossypii* Glov. (Homoptera: Aphididae) has been recognized as a major pest of chilli (*Capsicum annuum* L.) that transmits the chilli veinal mottle virus (Abdul Samad 1984). This aphid vector extremely polyphagous and transmits over 50 plant viruses (Blackman and Eastop 1984). The various sources of infection would limit the effectiveness of chemical control on vectors (Maelzer 1986). Hussein and Abdul Samad (1993) studied the effectiveness of the cultural methods in controlling *A. gossypii* and the viruses through intercropping or polyculture and found that the vectors were abundant in monocropping (chilli only) than the dicrop combinations of either chilli and brinjal (*Solanum melongena* L.) or chilli and maize (*Zea mays* L.).

Knowledge dispersion patterns aids in understanding the dynamics of the distribution of an arthropod in its ecosystem (Sevacherian and Stern 1972) because of the interactions between the insect and its habitat which may reflect behavioural characteristics of the species (Taylor 1961). The distribution of any arthropod can be described by a theoretical probability distribution models such as Poisson, negative binomial, positive binomial, or by

empirical relationships between parameters fitted by linear regressions. The empirical relationships for direct-counts are determined by regressing Lloyd's mean crowding (Lloyd 1967) against the corresponding sample mean parameters (Iwao 1968) and the logarithmic linear regression of the variances and means (Taylor 1961, 1984). On the other hand, the empirical relationships of presence-absence counts are determined by the logarithm regression of mean density on the proportion of empty sampling units (Kono and Sugino 1958), the proportion of infestation [P(I)] calculated based on four distribution models against the actual P(I) (Wilson and Room 1983; Hassan 1996), and the numerical density functions of optimum sample size curves (Hassan and Rashid 1997). Distribution information is essential in developing sampling plan either for density estimation or for classification to aid decision making in integrated pest management (IPM).

The objective of this paper is to describe the spatial distribution of major arthropods in an experimental polyculture system. Subsequently, a set of fixed-precision sequential sampling plans based on the empirical model of Taylor's Power Law as proposed by Green (1970) is developed for *A. gossypii* and presented here.

Materials and methods

Crop establishment

The MC4 chilli and Mte brinjal variety were direct seeded in polybags (15 cm x 8 cm) containing 3:2:1 soil mixtures of top soil, organic matter and sand. Two-and-a-half month old leucaena [*Leucaena leucocephala* (Lam.) de Wit (Mimosoidae: Leguminosae)] seedlings were transplanted to develop tricrop plots according to a Latin square design at Universiti Putra Malaysia in 1991. Each plot measured 9 m x 12 m and was separated from other plots by a 2 m alley of bare ground *(Figure 1)*. Three plots were allocated for each culture method and a total of nine plots were prepared. All nine plots were planted with chilli, three of which as monocrop, three in combination with brinjal and the rest in combination with brinjal and leucaena. The densities of chilli plants in the monocrop, dicrop and tricrop were 135, 75 and 45/plot, respectively. The densities of brinjal plants in the dicrop and tricrop were 60 and 45/plot respectively. Leucaena plants in the tricrop plots consisted of only 45 plants/plot. Weeding within plots and between plots was manually carried out everyday. The entire cropping season was from early July to October 1991.

Data sampling

Direct counts of major pests and predators were made from 19th July through 8th October 1991. At the first sampling date, the chilli and brinjal plants were 1.5 months old while the leucaena plants were 4 months old. On the average, at this stage, each crop produced 5–6 mainstem nodes (MSN). Five plants from each species in each plot were randomly selected and the number of arthropods present were counted with the mainstem node and its subtended structures as a sampling unit. The mainstem nodes were numbered from the top of the plant starting with number 1 (mainstem terminal bud), the next mainstem node below as number 2 and so on *(Figure 2)*. A total of eight mainstem nodes on each plant were recorded. For each sampling date, the total numbers of aphids (*A. gossypii*), psyllids [*Heteropsylla cubana* Crawford (Homoptera: Psyllidae)] and lady beetle coccinellid [*Menochilus sexmaculatus* Fabricius (Coleoptera: Coccinellidae)] at each mainstem node were recorded.

Statistical analysis

The degree of aggregation of insect counts was evaluated based on two simple empirical relationships of Taylor's Power Law (Taylor 1961, 1984) and Iwao's mean crowding regression (Iwao 1968). In each arthropod category, for each cultural method and for each sampling date, the data on counts per mainstem node were analyzed to

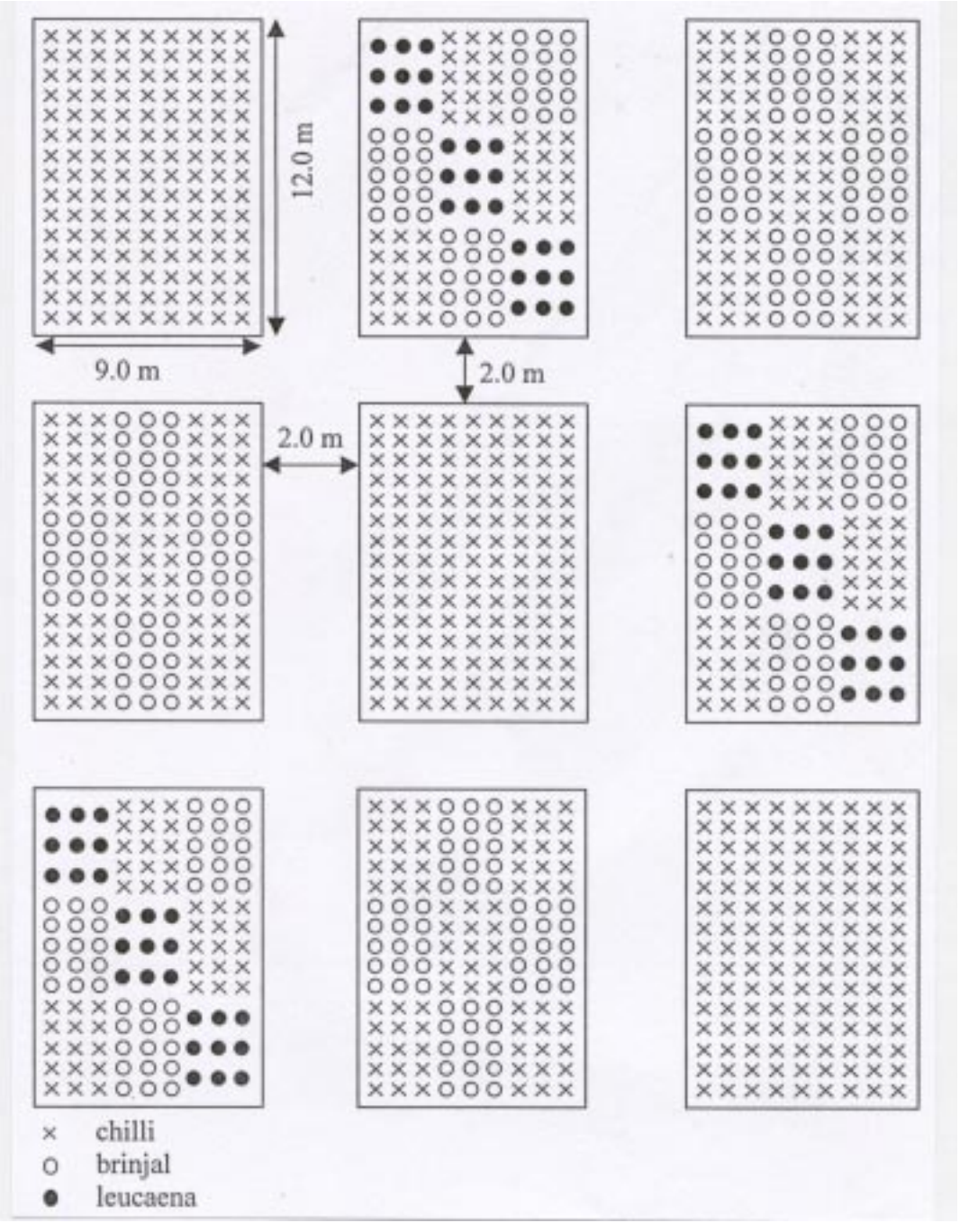

Figure 1. Diagram showing the separation of monocrop (chilli only), dicrop (chilli and brinjal), and tricrop (chilli, brinjal and leucaena) plots using Latin square design at Universiti Putra Malaysia (1991)

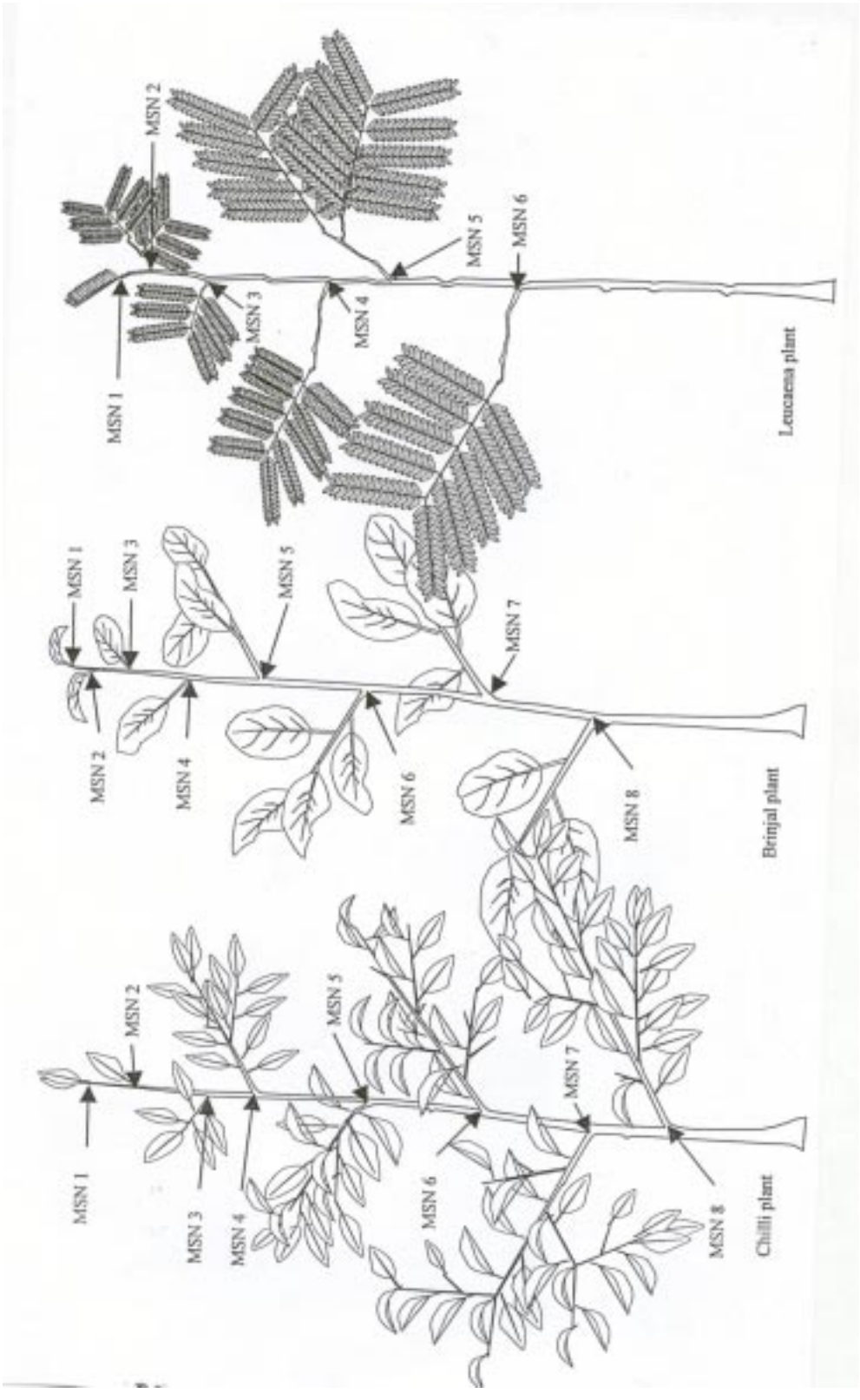

Figure 2. Numbering the mainstem nodes of chilli, brinjal and leucaena

obtain sample variance (s^2) and sample mean ($\bar{x}$), where the sample mean was estimated as

$$\bar{x} = \frac{\text{Total insect counts}}{\text{No. of MSN observed}} \quad (1)$$

Subsequently, Lloyd's (1967) mean crowding statistic ($\overset{*}{x}$) was estimated from each sample mean ($\bar{x}$) and variance (s^2) as

$$\overset{*}{x} = \bar{x} + [(s^2/\bar{x}) - 1] \quad (2)$$

Estimated $\overset{*}{x}$ were then regressed against the corresponding sample means (Iwao 1968). The slope (β) of the regression is a measure of aggregation and the *y* intercept (α) provides an indication of whether the basic unit of the population is an individual ($\alpha = 0$) or a group ($\alpha > 0$).

The variance-mean relationship of Taylor's (1961, 1984) Power Law was used as a second empirical model. A linear regression of $\ln s^2$ versus $\ln \bar{x}$ of each sample was used to describe the variance-mean relationship as

$$\ln s^2 = \ln a + b \ln \bar{x} \quad (3)$$

The slope (*b*) of this regression is also a measure of aggregation and the *y* intercept (*a*) is simply a sampling factor.

The *t*-statistic was subsequently used to test the significance of the differences of the estimated β and *b* (denoted as $\hat{\beta}$ and $\hat{b}$) from 1 (unity) to describe the dispersion pattern. Generally, values of $\hat{\beta}$ and $\hat{b}$ that are significantly larger than 1 would indicate aggregation, and values significantly less than 1 would indicate uniform dispersion, while values of $\hat{\beta}$ and $\hat{b}$ which are not significantly different from 1 would indicate a random distribution.

Sampling plan for A. gossypii

A suitable sampling plan for *A. gossypii* was designed based on the spatial distribution information of the insect. Coefficients from Taylor's Power Law regression were used to develop fixed-precision-level sequential sampling plans for assessing actual number of *A. gossypii*. The sampling stop lines are calculated using the following formula of Green (1970)

$$\ln(Tn) = \frac{1n(D_0^2/a)}{b-2} + \frac{b-1}{b-2}\ln(n) \quad (4)$$

where *a* and *b* are Taylor's coefficients

Tn = cumulative number of individuals

n = the total number of samples

D_0 = the fixed level of precision in terms of the standard error divided by $\bar{x}$

The levels of precision used in estimating stop lines were 0.20, 0.25, and 0.30, which represent a reasonable range for pest management purposes (Southwood 1978).

Validation of sequential sampling

A bootstrap simulation program developed by Naranjo and Hutchison (1997) was used to evaluate the fixed-precision stop-line plan in a simulation analysis for validation of Green's plan for *A. gossypii*. The degree to which actual precision levels obtained agreed with desired precision levels was evaluated using bootstrap simulation (Efron and Tibshirani 1986), performed on independently collected data sets not used in developing the sampling plan. For this purpose, one field of the same intercrops at Field 2 of Universiti Putra Malaysia was sampled in 1991 on 16 dates. In the field, *A. gossypii* were directly counted on a leaf located at the middle of the chilli plant. In each plot and for each sampling date, a total of 30 chilli plants were randomly selected for recording (Hussein, M. Y., 1991 unpublished data). Therefore, a total of 90 chilli plants were sampled from each culture method for each sampling date. Data sets were classified into monocrop (chilli only), dicrop (chilli and brinjal), and tricrop (chilli, brinjal and leucaena).

During simulation, a random number generator was used to select successive samples from a given data set until the cumulative number of individuals (*Tn*) equalled or exceeded the stop line for the Green's plan. Population densities, total

Table 1. Dispersion parameters obtained using Iwao's mean crowding and Taylor's Power Law regression models on two major pests of intercropping culture method, *Aphis gossypii* and *Heteropsylla cubana*. Both models yielded aggregation coefficients which were significantly >1 at p <0.01, indicating that *A. gossypii*, *H. cubana* and *M. sexmaculatus* (predator) were clumped

Crop	Culture method	Species	Iwao's mean crowding							Taylor's Power Law						Probability level
			n	$\hat{\alpha}$	SE	$\hat{\beta}$	SE	r^2	t	$\hat{a}$	SE	$\hat{b}$	SE	r^2	t	
		A. gossypii														
Chilli	Monocrop	Winged	82	0.03	0.48	3.06	0.16	81.75	12.88	3.35	0.05	1.62	0.03	96.58	20.67	p <0.01
		Wingless	116	9.22	3.18	2.01	0.08	84.63	12.63	3.42	0.08	1.70	0.03	95.50	23.33	p <0.01
		Nymphs	140	1.95	3.37	2.50	0.08	87.96	18.75	3.10	0.08	1.73	0.03	95.28	24.33	p <0.01
	Dicrop	Winged	53	–0.15	0.63	3.41	0.15	90.68	16.07	3.39	0.08	1.70	0.05	95.40	14.00	p <0.01
		Wingless	102	–5.39	2.92	3.70	0.11	91.67	24.52	1.15	0.09	1.76	0.04	94.18	19.00	p <0.01
		Nymphs	127	–1.35	2.47	2.97	0.10	87.27	19.70	3.03	0.09	1.75	0.04	93.95	18.75	p <0.01
	Tricrop	Winged	74	0.81	0.53	2.75	0.10	91.80	18.23	3.31	0.06	1.71	0.04	96.16	17.75	p <0.01
		Wingless	134	–0.15	2.81	2.95	0.08	90.86	24.38	3.22	0.08	1.79	0.03	95.90	26.33	p <0.01
		Nymphs	145	1.62	3.56	2.73	0.06	92.27	28.83	2.66	0.09	1.83	0.03	95.85	27.67	p <0.01
			Life stages													
		Winged	211	0.25	0.31	2.98	0.07	88.76	28.29	3.35	0.04	1.67	0.02	96.30	33.50	p <0.01
		Wingless	354	3.77	2.08	2.63	0.06	84.27	27.17	3.25	0.05	1.75	0.02	95.35	37.50	p <0.01
		Nymphs	414	1.28	1.85	2.68	0.04	90.28	42.00	2.94	0.05	1.78	0.02	95.22	39.00	p <0.01
			Combined all life stages with respect to culture methods													
	Monocrop		340	4.38	1.77	2.30	0.05	86.64	26.00	3.42	0.04	1.69	0.02	96.70	34.50	p <0.01
	Dicrop		284	–3.09	1.58	3.32	0.07	89.12	33.14	3.22	0.05	1.73	0.02	95.55	36.50	p <0.01
	Tricrop		355	1.25	1.74	2.79	0.04	92.29	44.75	3.13	0.04	1.79	0.02	96.59	39.50	p <0.01
			Combined all life stages and culture methods													
			981	2.02	1.06	2.66	0.03	88.66	55.33	3.29	0.02	1.74	0.01	96.38	74.00	p <0.01
		A. gossypii														
Brinjal	Dicrop	Winged	53	–0.43	0.23	3.44	0.21	83.25	11.62	2.77	0.08	1.53	0.05	94.68	10.60	p <0.01
		Wingless	103	2.32	0.53	1.80	0.07	88.01	11.43	2.97	0.06	1.61	0.04	93.54	15.25	p <0.01
		Nymphs	132	–3.37	2.44	3.81	0.25	64.14	11.24	3.22	0.07	1.69	0.04	93.25	17.25	p <0.01

(cont.)

Table 1. *(cont.)*

Crop	Culture method	Species	Iwao's mean crowding							Taylor's Power Law						Probability level
			n	$\hat{\alpha}$	SE	$\hat{\beta}$	SE	r^2	t	$\hat{a}$	SE	$\hat{b}$	SE	r^2	t	
Brinjal	Tricrop	Winged	54	–0.41	0.20	3.39	0.27	75.44	8.85	2.20	0.12	1.42	0.08	86.75	5.25	p <0.01
		Wingless	117	0.24	0.78	2.51	0.08	89.97	18.88	3.06	0.06	1.61	0.04	94.58	15.25	p <0.01
		Nymphs	146	0.00	1.72	2.54	0.10	81.99	15.71	3.10	0.07	1.67	0.04	93.70	16.70	p <0.01
			Life stages													
		Winged	108	–0.42	0.15	3.42	0.16	80.83	15.13	2.51	0.07	1.49	0.04	91.23	12.15	p <0.01
		Wingless	221	1.26	0.52	2.24	0.06	87.54	20.67	3.02	0.04	1.62	0.03	94.27	20.67	p <0.01
		Nymphs	279	–0.18	1.52	2.79	0.11	71.19	16.25	3.16	0.05	1.68	0.03	93.69	22.67	p <0.01
			Combined all life stages with respect to culture methods													
	Dicrop		290	–0.28	1.15	3.05	0.14	62.04	14.64	3.16	0.04	1.65	0.02	94.83	32.50	p <0.01
	Tricrop		319	0.07	0.79	2.53	0.06	85.04	25.50	3.10	0.04	1.64	0.02	95.53	32.00	p <0.01
			Combined all life stages and culture methods													
			610	0.21	0.69	2.66	0.06	75.03	27.67	3.13	0.03	1.65	0.02	95.30	32.50	p <0.01
		H. cubana	Life stages													
Leucaena	Tricrop	Adults	135	0.93	1.23	1.88	0.12	64.78	7.33	2.20	0.09	1.44	0.05	84.96	8.80	p <0.01
		Nymphs	127	220.28	63.80	1.99	0.07	88.10	14.14	6.49	0.10	1.77	0.02	98.65	38.50	p <0.01
		Eggs	112	276.44	77.13	1.97	0.07	86.82	13.86	6.42	0.17	1.77	0.03	97.26	25.67	p <0.01
			Combined all life stages within tricropping culture method													
			376	110.23	27.14	2.08	0.03	91.19	36.00	2.48	0.08	1.89	0.02	97.28	44.50	p <0.01
		M. sexmaculatus														
			Combined all life stages, culture methods and crops													
			167	–1.28	0.17	6.60	0.24	82.02	23.33	2.53	0.08	1.50	0.05	85.81	10.00	p <0.01

SE = standard error

samples taken and actual precision levels obtained were calculated based on 500 simulation runs.

Results and discussion

Dispersion parameters

Distribution parameters using Iwao's mean crowding and Taylor's Power Law regression models on two pests, *A. gossypii* (on chilli and brinjal plants) and *H. cubana* (on leucaena plants) with respect to the different categories are shown in *Table 1*. However, the predator *(M. sexmaculatus*) data were pooled by all categories including life stages, culture methods and crops for regression analysis because of low population densities *(Table 1)*. Taylor's Power Law coefficients provided the best fit (r^2) to all stages of arthropod categories and cultural methods *(Table 1)*. The coefficients of determination (r^2) of Taylor's regression ranged from 84.96 to 98.65 while for the Iwao's regression model the values ranged from 62.04 to 92.29. The standard errors of the regression coefficients were smaller in Taylor's regression model (0.01–0.08), compared with Iwao's regression model (0.03–0.27), similarly showing that the Taylor's Power Law approach yielded the better fit to the distribution of the data. Aggregation coefficients ($\hat{\beta}$ and $\hat{b}$) by both models were significantly larger than 1 (p <0.01), indicating that each species conformed well to the aggregative pattern of distribution. However, it should be noted that for each species, for different populations and in different agroecosystems, arthropods could exhibit different patterns of spatial distribution (Hassan 1996), because of different behavioural characteristics resulting from interactions between the arthropod and its habitat (Taylor 1961).

Taylor's $\hat{b}$ coefficients of aphid nymphs and wingless adults are slightly larger than those for winged aphid, with aphid nymphs showing higher aggregation level in all types of culture method and for both chilli and brinjal plants *(Table 1)*. The higher aggregation of wingless (apterous) adults is due to their immobility, whereas that of the nymphs is due to higher concentration in the same area (Reilly and Sterling 1983). In contrast, the flight ability of the winged (alate) adults leads to dispersal, hence decreasing the aggregation. The leucaena pest, *H. cubana*, also showed similar patterns of aggregation with respect to eggs and nymphs (higher degree of aggregation), in comparison with the psyllid adults.

Taylor's parameter estimates of the combined all-stages (winged, wingless and nymphs) data of *A. gossypii (Figure 3)* for different culture methods were used in subsequent simulation runs to evaluate and develop the sampling plan using Green's (1970) algorithm. In a sampling plan using the stop line, samples are to be taken sequentially until the cumulative number of aphids exceeds the stop line values for a given number of samples taken. The required sample size (n) increases as the desired level of precision increases from D_0 = 0.3 to 0.2. *Figure 4* shows the Green's sequential stop lines for *A. gossypii* at different densities and culture methods used in this study. It can be seen that at a certain precision for a similar population density and comparing the three cropping cultures, the monoculture demands the least sample size while the triculture requires the largest. These results were probably affected by the use of different Taylor's coefficients during constructing the plans.

Validation of the sampling plan

Data sets with the mean number of aphids <1 per plant were excluded from the simulation to attain a 20% precision level. Only the earlier sampling dates in each sampling month (from July to November 1991) were selected for simulation analysis to ensure that the pest management program for *A. gossypii* is carried out monthly and during the first week of each month. Therefore, five samples (sampling dates) out of 16 samples (sampling dates) with n = 60 and 90 samples for each date were simulated and their summary statistics for each culture

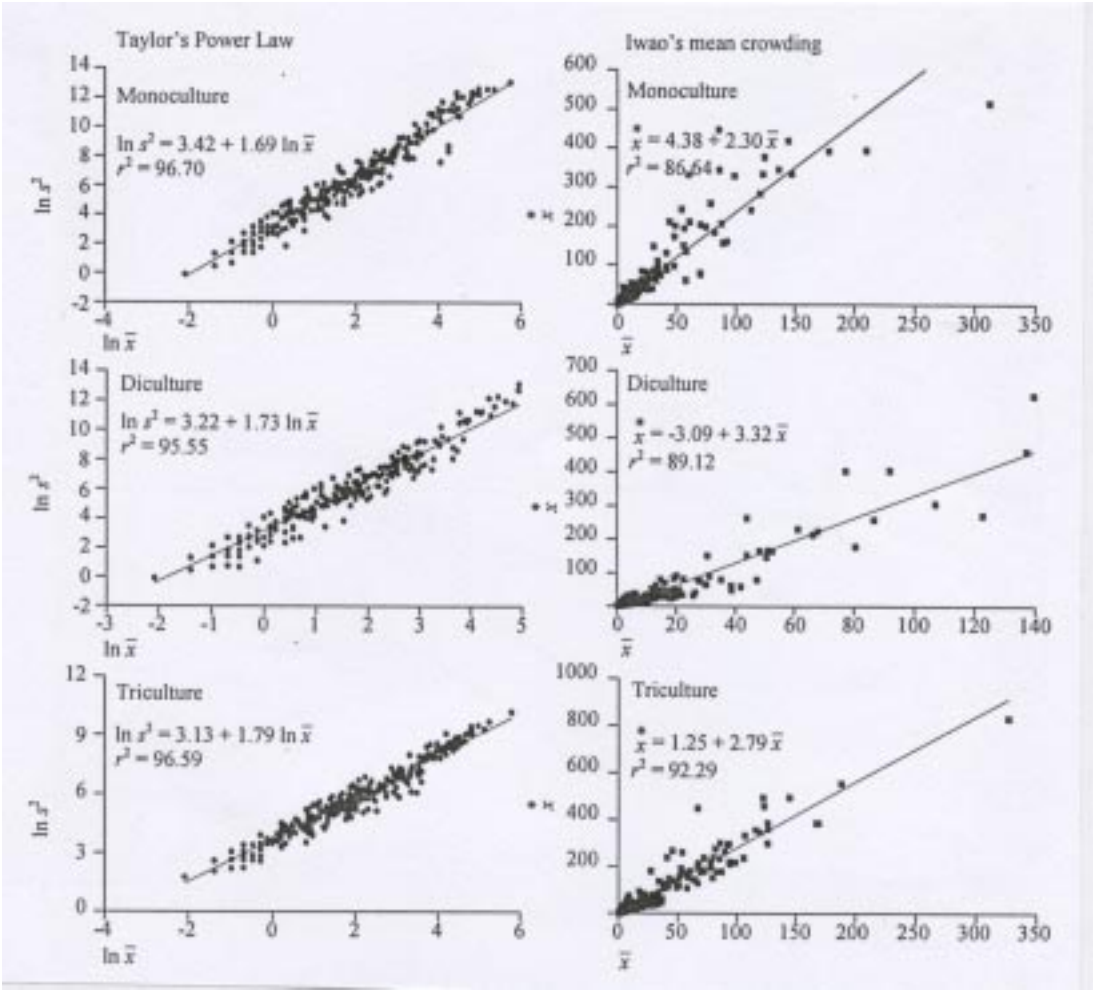

Figure 3. The linear relationships s^2 vs $\bar{x}$ of Taylor's Power Law and $\overset{*}{x}$ vs $\bar{x}$ of Iwao's mean crowding of ***Aphis gossypii*** *(combination of all stages) for three culture methods. Observations were done on 8 mainstem nodes of 5 plants (= each data point in the graph) at different sampling dates at Universiti Putra Malaysia (1991)*

method are shown in *Table 2* to *Table 4*. The monoculture (chilli) crop showed aphid population densities ranging from 9.17 to 51.48 per plant *(Table 2)*. The aphid population densities ranged from 7.54 to 44.27 per plant *(Table 3)* for diculture plots (chilli and brinjal) and from 7.93 to 34.82 per plant in the triculture (chilli, brinjal and Leucaena) *(Table 4)*. These results showed that the density of aphids were higher in the monoculture than in diculture and triculture plots. Hussein and Abdul Samad (1993) reported a similar finding in numbers of *A. gossypii* in monoculture relative to those in diculture planting.

On each sampling date and at each precision level, the Green's sequential plan requires less samples than fixed-sample-size sampling (FSS). The number of samples decreased as precision level decreased, but the standard error of the estimated mean increased in proportion with the decreasing precision level *(Table 2* to *Table 4)*. Numbers of samples required by the Green's plan to stop sampling reduced from 44 to 12 in monoculture, from 41 to 14 in diculture

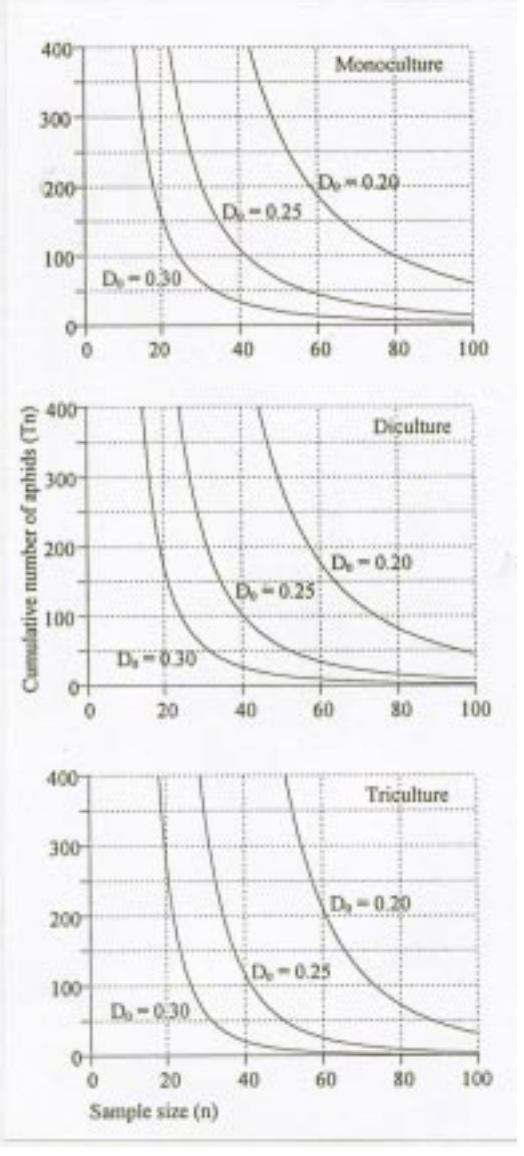

Figure 4. Green's sequential stop lines for three fixed-precision levels (D_o) for various aphid densities and culture methods

and from 51 to 17 in triculture, as the precision levels decreased from 0.2 to 0.3.

The simulated populations' mean densities based on Green's algorithm were within 95% range of actual population mean densities (original data sets using FSS plan) even though precision levels differed *(Table 2* to *Table 4)*. However, the standard errors of the mean estimates are mostly larger than those of fixed-sample-size plan, especially at higher mean densities, probably due to the small sample size required by Green's sequential plan *(Table 2* to *Table 4)*. Therefore, the values of the actual precision levels (D) yielded from the higher mean densities plots are larger than the desired precision levels (D_0) as shown for the first sampling date (11 July 1991) in all culture methods *(Table 2* to *Table 4)*. For the first sampling date, D is lower than D_0 by less than 20% at almost all precision levels and for all culture methods. Nonetheless, as the precision level decreased, the percentages of D lower than D_0 increased as shown by the second sampling date of monoculture, from 27.2 to 51.0 *(Table 2)* and from 28.6 to 50.0 for the third sampling date of diculture plots *(Table 3)*. For other sampling dates, this sampling plan is applicable since a higher percentage of D lower than D_0 is indicated even at a high precision level (D = 0.2). In monoculture, the actual precision level ranged from 55.8% to 100%, from 64.6% to 100% in diculture and from 82.2% to 100% in triculture. The highly aggregated distribution pattern shown by aphids was probably the cause of high variability in the data sets. At high densities, as the variances of the density estimates increased, the cumulative number of aphids *(Tn)* rapidly increased, thus making possible a quick stop in the sequential sampling operation. Consequently, smaller sample sizes were obtained through the sequential sampling plan. Therefore, the high standard errors would lead to lower precision since the precision level is defined as standard error divided by the mean. However, sample size should be minimized at higher densities to reduce sampling cost and sampling time for counting the large numbers of aphids. Hence, it becomes obvious that some management actions (e.g. spray the crops with insecticide) may be necessary even if the estimates of high population density is made at lower precision levels (Cuperus et al. 1982; Shelton et al. 1994).

Table 2. Statistics of Green's sequential sampling for 500 simulation runs for each of five *A. gossypii* population densities observed on chilli plants in monoculture plots (UPM 1991) at three desired precision levels

Date	Statistics	Statistics from all samples (FSS)	Av. statistics for 500 simulations at 3 desired precision levels		
			$D_0 = 0.20$	$D_0 = 0.25$	$D_0 = 0.30$
11 July 1991	Mean density	47.25	49.04	49.46	51.65
	SE	8.84	13.58	16.74	20.54
	D	0.19	0.28	0.34	0.40
	n	60.00	26.00	17.00	12.00
	T_n		1 275.04	840.82	618.72
	% $D \leq D_0$	–	1.20	5.60	12.80
7 Aug. 1991	Mean density	51.48	53.09	52.98	54.06
	SE	7.93	12.23	14.61	17.06
	D	0.15	0.23	0.28	0.32
	n	60.00	26.00	17.00	12.00
	T_n		1 380.34	900.66	648.72
	% $D \leq D_0$	–	27.20	41.60	51.00
4 Sept. 1991	Mean density	17.58	17.87	18.14	18.29
	SE	2.75	3.59	4.44	5.25
	D	0.16	0.20	0.24	0.29
	n	60.00	36.00	23.00	16.00
	T_n		643.32	417.22	292.64
	% $D \leq D_0$	–	55.80	60.80	59.40
2 Oct. 1991	Mean density	24.78	24.90	24.67	24.86
	SE	3.32	4.57	5.62	6.78
	D	0.13	0.18	0.23	0.27
	n	60.00	32.00	21.00	15.00
	T_n		796.80	518.07	372.90
	% $D \leq D_0$	–	96.40	87.80	82.20
6 Nov. 1991	Mean density	9.17	9.17	9.20	9.22
	SE	0.91	1.30	1.63	1.93
	D	0.10	0.14	0.18	0.21
	n	90.00	44.00	28.00	20.00
	T_n		403.48	257.60	184.40
	% $D \leq D_0$	–	100.00	100.00	100.00

SE = standard error of mean
D = actual precision level
n = number of samples
T_n = cumulative number of individuals
FSS = fixed-sample-size sampling
Precision level refers to SE/ $\bar{x}$

Generally, the number of samples required by the Green's plan was less than that of fixed-sample-size plan. At a higher population density, the plan required less number of samples compared with populations at lower densities, which led to a smaller probability of achieving the required precision level. It is clearly shown that decreasing the precision level from 0.2 to 0.3 reduces the sample size and increases the percentage of precision level, even at a high population density *(Table 2* to *Table 4)*. Therefore, the precision level at 0.3 is recommended for management applications for *A. gossypii* at different culture methods, especially when cost and time are limiting.

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Table 3. Statistics of Green's sequential sampling for 500 simulation runs for each of five *A. gossypii* population densities observed on chilli plants in diculture plots (UPM 1991) at three desired precision levels

Date	Statistics	Statistics from all samples (FSS)	Av. statistics for 500 simulations at 3 desired precision levels		
			$D_0 = 0.20$	$D_0 = 0.25$	$D_0 = 0.30$
11 July 1991	Mean density	44.27	45.54	45.89	46.62
	SE	8.45	12.15	15.27	18.11
	D	0.19	0.27	0.33	0.39
	n	60.00	30.00	19.00	14.00
	T_n		1 366.20	871.91	652.68
	% $D \leq D_0$	–	0.20	2.40	9.40
7 Aug. 1991	Mean density	29.42	29.55	29.57	29.24
	SE	4.43	5.83	7.24	8.48
	D	0.15	0.20	0.25	0.29
	n	60.00	33.00	21.00	15.00
	T_n		975.15	620.97	438.60
	% $D \leq D_0$	–	69.60	64.60	66.00
4 Sept. 1991	Mean density	12.72	12.85	12.99	13.34
	SE	2.26	2.76	3.43	4.11
	D	0.18	0.21	0.26	0.31
	n	60.00	41.00	27.00	19.00
	T_n		526.85	350.73	253.46
	% $D \leq D_0$	–	28.60	44.60	50.00
2 Oct. 1991	Mean density	17.33	17.80	17.94	17.86
	SE	2.61	3.34	4.04	4.65
	D	0.15	0.19	0.23	0.26
	n	60.00	38.00	24.00	17.00
	T_n		676.40	430.56	303.62
	% $D \leq D_0$	–	79.80	71.60	71.20
6 Nov. 1991	Mean density	7.54	7.61	7.60	7.64
	SE	0.83	1.16	1.41	1.70
	D	0.11	0.15	0.19	0.22
	n	90.00	47.00	30.00	21.00
	T_n		357.67	228.00	160.44
	% $D \leq D_0$	–	100.00	100.00	100.00

SE = standard error of mean
D = actual precision level
n = number of samples
T_n = cumulative number of individuals
FSS = Fixed-sample-size sampling
Precision level refers to SE/ $\bar{x}$

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Table 4. Statistics of Green's sequential sampling for 500 simulation runs for each of five *A. gossypii* population densities observed on chilli plants in triculture plots (UPM 1991) at three desired precision levels

Date	Statistics	Statistics from all samples (FSS)	Av. statistics for 500 simulations at 3 desired precision levels		
			$D_0 = 0.20$	$D_0 = 0.25$	$D_0 = 0.30$
11 July 1991	Mean density	29.48	30.06	30.36	30.60
	SE	5.51	6.94	8.69	10.27
	D	0.19	0.23	0.29	0.34
	n	60.00	39.00	25.00	18.00
	T_n		1 172.34	759.00	550.80
	% $D \leq D_0$	–	4.00	18.00	29.80
7 Aug. 1991	Mean density	34.82	34.93	34.98	35.58
	SE	5.06	6.40	7.93	9.60
	D	0.15	0.18	0.23	0.27
	n	60.00	38.00	24.00	17.00
	T_n		1 327.34	839.52	604.86
	% $D \leq D_0$	–	96.00	89.20	82.20
4 Sept. 1991	Mean density	13.13	13.22	13.22	13.34
	SE	1.46	1.68	2.09	2.51
	D	0.11	0.13	0.16	0.19
	n	60.00	46.00	30.00	21.00
	T_n		608.12	396.60	280.14
	% $D \leq D_0$	–	100.00	100.00	100.00
2 Oct. 1991	Mean density	18.83	18.88	19.22	19.13
	SE	2.34	2.77	3.49	4.16
	D	0.12	0.15	0.18	0.22
	n	60.00	43.00	28.00	19.00
	T_n		811.84	538.16	363.47
	% $D \leq D_0$	–	100.00	100.00	100.00
6 Nov. 1991	Mean density	7.93	7.99	7.94	7.93
	SE	0.78	1.03	1.25	1.49
	D	0.10	0.13	0.16	0.19
	n	90.00	51.00	33.00	23.00
	T_n		407.49	262.02	182.39
	% $D \leq D_0$	–	100.00	100.00	100.00

SE = standard error
D = actual precision level
n = number of samples
Tn = cumulative number of individuals
FSS = Fixed-sample-size sampling
Precision level refers to SE/ $\bar{x}$

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