

Sampling scale dependence: Do Taylor's Power Law coefficients change significantly?

(Pergantungan pada skala pensampelan: Adakah pekali-pekali Hukum Kuasa Taylor berubah secara ketara?)

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Key words: pest, rice, sample plan, VIS, bootstrap, Taylor's coefficient, simulation, Malaysia

Abstrak

Hukum Kuasa Taylor banyak digunakan untuk menghurai corak taburan organisma, membentuk protokol pensampelan dan melaksanakan proses mengubah data numerik kepada data normal. Walaupun nilai pekali b Taylor dianggap khusus berasaskan spesies, kajian ini dan juga yang lain mendapati bahawa nilai b berubah-ubah. Skala pensampelan telah dibentuk dengan membesarkan saiz unit pensampelan (sampel) melalui penggabungan 2, 5, 10 dan 25 unit sampel (tambahan unit sampel). Bagi setiap unit sampel yang telah dibesarkan ini, sejumlah 10 sampel digunakan untuk mengira min dan varians semasa pelaksanaan simulasi. Justeru, setiap unit pensampelan mengandungi skala pensampelan didarabkan dengan 10. Apabila unit pensampelan dan skala pensampelan meningkat, nilai b yang melebihi 2 bertambah, tetapi peratusan yang berbeza secara ketara daripada 1 dan 2 menurun. Perubahan pada b agak kecil dengan peningkatan saiz sampel. Oleh yang demikian, kajian ini meramalkan lebih banyak nilai b yang melebihi 2 bagi populasi heterogenus yang tinggi kepadatannya. Kajian ini juga menyimpulkan bahawa nilai a dan b Taylor berbeza mengikut lokasi, masa dan skala unit pensampelan. Strategi pengawalan perosak bersepadu yang menggunakan Hukum Kuasa Taylor perlu mengambil kira penemuan-penemuan ini.

Abstract

Taylor's Power Law is a widely used variance-mean relationship in describing the dispersion patterns of organisms, in developing sampling protocols and in normalizing numerical data. However, although values of Taylor's b coefficient are regarded as species-specific, this study and others found b values to be variable. Sampling scale was developed by increasing the size of sampling unit (sample) with 2, 5, 10 and 25 unit samples (sample unit increment), from each of which a total of 10 samples were used to calculate its mean and variance during simulation. Consequently, sampling unit was adopted as unit samples chosen towards sampling scale enlargement multiplied by 10. As sampling unit and sampling scale increased, the percentage of b values larger than 2 increased but the percentage that was significantly different from 1 and 2 decreased. There is a relatively small change in b as sample size increased. It is inferred that there

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would be more b values larger than 2 in heterogeneous populations with high densities. This study concludes that Taylor's a and b values varied with locations, occasions and scales of sampling unit. Integrated pest management strategies which use Taylor's Power Law need to heed these findings.

Introduction

In the past decade, theoretical distributions such as Poisson and negative binomial were commonly used in describing the dispersion patterns of organisms. However, theoretical distributions are known to vary with both population density and sample unit size (Nyrop and Binns 1991), and k value of the negative binomial often varies with mean density (Buntin 1994). Consequently, models of relationship between population variance and mean were used to describe the dispersion patterns. One of these models is the Taylor's Power Law (Taylor 1961) which is based on logarithmic relationship between the sample mean (\bar{x}) and sample variance (s^2) of the biological populations. The coefficients obtained are widely used in estimating the dispersion of organisms (including mammals and invertebrates). These coefficients are also used in developing sampling protocols (Green 1970) and normalizing the data for further parametric statistical analysis (Healy and Taylor 1962).

In generating the coefficients, Taylor (1961, 1984) developed the variance-mean relationship as

$$\ln s^2 = \ln a + b \ln \bar{x} \quad (1)$$

where \ln is the natural log. The coefficient a is considered a scaling factor that varies with sample size selection (Taylor 1961) and locations (Trumble et al. 1989). The coefficient b is the index of dispersion patterns which, in contrast, is not affected by the environment, sampling scale and quadrat size, hence it is species-specific constant (Taylor et al. 1983; Taylor 1984). Uniform, random and clumped dispersion patterns are indicated when $b < 1$, $b = 1$, and $b > 1$ respectively. Several attempts have been made to clarify b values as species-specific. These studies found b to vary with location across a continent (Trumble et al. 1989),

pattern of pesticide use (Trumble 1985), sampling occasion (Sawyer 1989), and sampling scale, i.e. sampling unit size (Yamamura 1990).

Recently, using egg distribution of a chrysomelid, *Altica oleracea* (L.) (Coleoptera: Chrysomelidae), on the host plant *Oenothera biennis* (L.) and citrus red mite, *Panonychus citri* (L.) (Acarina: Tetranychidae), in the citrus ecosystem, Yamamura (1990) showed that b values became larger as the sampling scale increased. He developed the sampling scale through splitting colonies with increasing number of individuals in each colony along with enlargement size of quadrat. He found that with a smaller number of sampling units and larger sampling scale, b values increased. In the wet rice agroecosystem, the possibly changing values of Taylor's a and b coefficients have not been examined, despite their usage in parameterizing of arthropods populations (Hassan 1996, 1997) and formulation of prototype pest management protocols (Hassan and Rashid 1997a, b; Rashid et al. 1998a, b).

This paper explores the possibility that Taylor's coefficients a and b vary with sampling location, occasion and scale (i.e. the size of sampling unit) through simulation of *Nephotettix* spp., *Nilaparvata lugens* and *Sogatella furcifera* populations in the rice ecosystem.

Materials and methods

Data collection

Direct visual counts on adults and nymphs of green leafhopper (GLH) (*Nephotettix* spp. – Homoptera: Cicadellidae), brown planthopper (BPH) (*Nilaparvata lugens* Stål – Homoptera: Delphacidae) and whitebacked planthopper (WBPH) (*Sogatella furcifera* Horvath – Homoptera: Delphacidae) were conducted at three paddy field locations. The

three locations were an experimental plot at Universiti Putra Malaysia (UPM), Serdang, Selangor (3° 2' N, 101° 42' E) (1991), a farmer's plots at Sawah Sempadan, Tanjung Karang, Selangor (SSTK) (3° 20' N, 101° 12' E) (1992) and a rice estate managed by the Federal Land Consolidation and Rehabilitation Authority (Felcra) at Seberang Perak, Perak (4° 7' N, 101° 4' E) (1997). At UPM, four adjacent plots (each measuring 30 m x 26 m) were transplanted with 21-day-old seedlings of MR 84 rice variety on 7th January 1991. No insecticides were sprayed during the entire 73-days sampling period. Weekly sampling commenced on 20th February through 2nd May 1991 using a single hill as the sampling unit. At SSTK, a transplanted and a direct-seeded plots were chosen. Weekly sampling commenced on 23rd April through 3rd June 1991 using one hill as the sampling unit. At Felcra, five direct-seeded plots were chosen randomly and biweekly sampling commenced on 7th October through 3rd December 1997. Sampling was made in a 10 cm x 10 cm quadrat sized (hereafter referred to as hill) sampling unit. Note that for the direct-seeded plot, a quadrat is equal to a hill in transplanted plot.

At each site, direct visual counting of individual arthropod was recorded into cassettes. Weekly examinations of 20 hills per plot at UPM and SSTK were conducted at 3-h intervals during each 24 h duration. For night sampling, waterproof torchlights, with 6V superheavy *Eveready*® battery, were used to examine the hills. The arthropods examined were easily recognized under this 6V-light. The sampling path was varied by walking through the field diagonally, followed by zig-zag and semi-circle patterns to ensure a good coverage of each sampling plot. Meanwhile, alternate weekly examinations of 70 hills per plot at Felcra were conducted during the day.

Simulation

Resampling methodology was used in selecting samples from the actual field data

with different sampling scales. A bootstrap simulation program was written in *Microsoft*® *QBasic*. The program format was screen-oriented and interactively operated through user input (*Figure 1*). Input parameters included the number of samples to compute each mean (\bar{x}) and variance (s^2) of a scale-based sampling, the number of unit samples used in sampling scale increment, the number of \bar{x} - s^2 pairs to execute the linear regression in generating the regression parameters, the *t*-tabulated value ($df = n - 2$, where *n* was the number of \bar{x} - s^2 pairs for regression) and finally the number of simulation replicates. The number of samples to compute the mean and variance for each unit-based sampling was automatically calculated by the program. During the simulation, a random number generator was used for each scale-based sampling run to select successive samples from a given data set. The linear regression runs of \bar{x} - s^2 pairs using unit or scale-based sampling were executed simultaneously at each simulation replicate thus enabling simultaneous counts of arthropod from the same selected sample. The readable simulation outputs were then saved for further simulation (data) analysis and presentation as described below.

Simulations were performed on four independent data sets of arthropods collected from the experimental plot at UPM (GLH and BPH), from transplanted (GLH) and (3) direct-seeded rice (GLH and WBPH) at SSTK, with four dates of sampling at each location, and 13 dates of sampling at Felcra (BPH and WBPH). The number of samples chosen for scale-based sampling were 2, 5, 10 and 25 sampling unit increments (SUI). To calculate each \bar{x} and s^2 for scale-based sampling, 10 samples were used. Therefore, the actual number of unit samples used to calculate each \bar{x} and s^2 for unit-based sampling depends on the SUI chosen for scale-based sampling, multiplied by 10. In this study, the number of \bar{x} - s^2 pairs for regression was set at $n = 32$ observations. Consequently, the *t*-tabulated value of 2.04

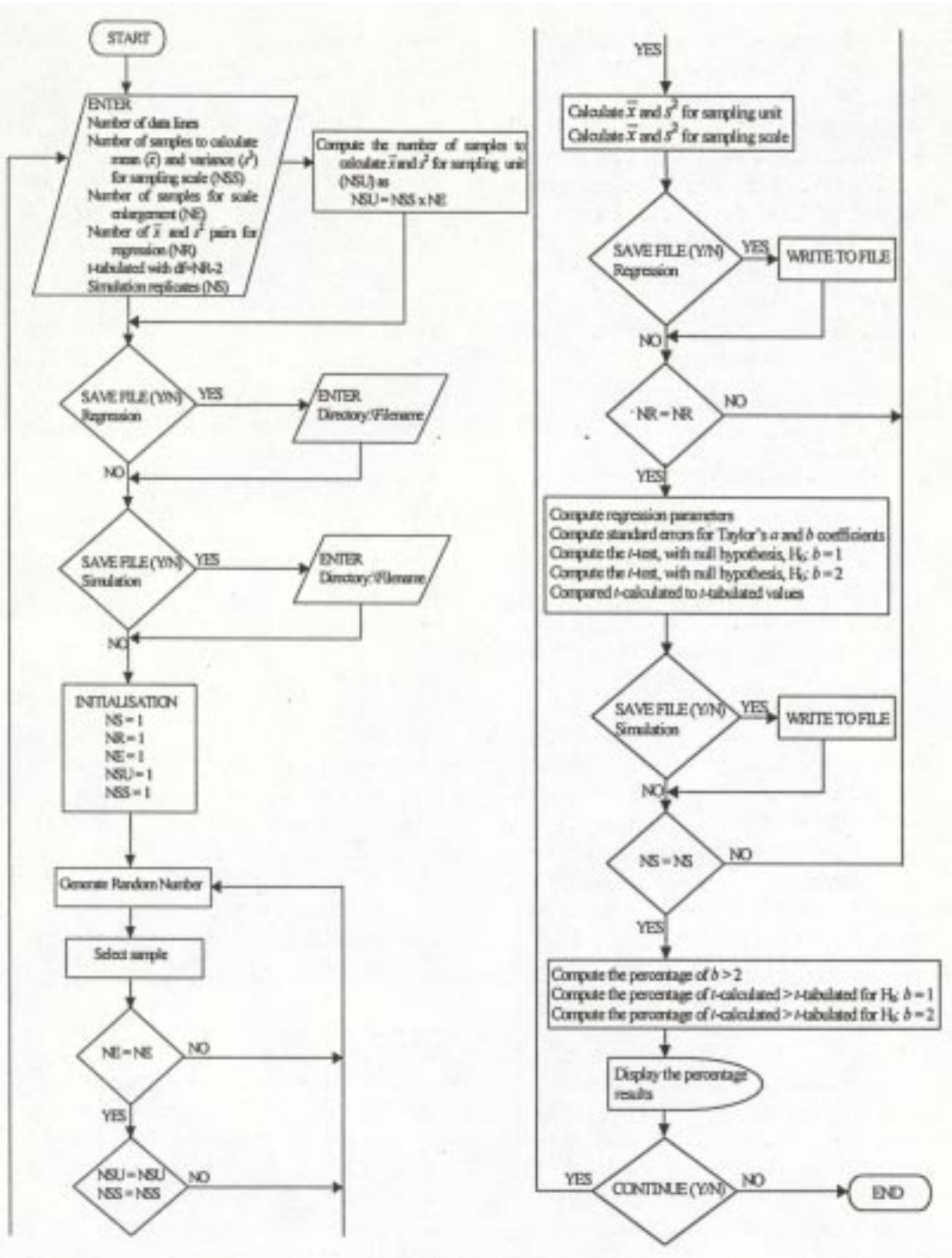


Figure 1. General flowchart showing algorithm of the simulation program in Microsoft® Qbasic

(df = 30 at $p < 0.05$) was used in testing whether the Taylor's coefficients obtained were significantly different from 1 and from 2. The former testing was carried out to indicate the dispersion pattern, whereas the latter to ensure that the b values were indeed larger than 2 for any $b > 2$. A set of 100 simulation replicates were generated for each data set. For true operating characteristics of the program during running of the simulation, only means and variances larger than 0 were allowed. Similarly, regression parameters larger than 0 were accepted to ensure that the model developed was representative of the actual system.

Simulation (data) analysis and presentation

Print file format of raw simulation data was transformed into a readable format which was organized into rows and columns using *Lotus® 1-2-3*. This package provides the capability of transporting a raw simulation output data file through "File/Import/Numbers" menu selection. The spreadsheet data were then transformed into *Lotus® 1-2-3* and *Microsoft® Excel* files for further data manipulations, analyses and presentations using other softwares. The effects of location (data source), SUI chosen and type of samples (sampling unit and sampling scale) on Taylor's coefficients computed from bootstrap simulation, were evaluated through an analysis of variance (ANOVA) with locations, unit samples used for sampling scale increment (SUI) and types of sampling (unit or scale-based) as the main effects, using *Statgraphics®* which can import *Lotus® 1-2-3* data files. The simulation results were graphically presented using *Kaleidagraph®* that can import *Microsoft® Excel* files.

Results and discussion

The percentage of Taylor's b values larger than 2 increased with increasing sampling unit in unit-based sampling and with increasing SUI in scale-based sampling (*Table 1*). However, the percentage of b

values that were significantly different from 1 and 2 decreased with increasing SUI when tested with a t -test. This occurred because as the sampling scale becomes larger, any aggregated dispersion pattern would change to random and finally assume a uniform pattern (Elliot 1977; Campbell and Madden 1990). In contrast, for unit-based sampling, inconsistent patterns emerged in decreasing and increasing of percentage of b significantly larger than 1 and 2 with different SUI chosen (*Table 1*). Thus there is a relatively small change in Taylor's b as sample size increased. Although the percentage of b larger than 2 increased in both unit and scale-based sampling, their values did not differ from 2 when tested with a t -test. For example, *Nephotettix* spp. (UPM 1991) with 25 sampling units for increment (SUI), 54% of unit-based sampling and 61% of scale-based sampling yielded b values larger than 2 but only 4% significantly differed from 2 (*Table 1*). This non-significant effect is probably due to the increase in standard errors of the regression parameters as SUI increased (*Figure 2*).

The study also indicates that populations with high density and variability would yield more b values higher than 2, as shown by *Nilaparvata lugens* and *Sogatella furcifera* at Felcra in 1997 (*Table 1* and *Figure 3*). However, in populations with low density and variability (lower standard errors), the probability of b significantly higher than 2 increased with increasing SUI for both unit and scale-based sampling, as shown in *Nephotettix* spp. at UPM (1991), transplanted plot at SSTK (1992), *Nilaparvata lugens* at UPM (1991) and *Sogatella furcifera* at SSTK (1992) (*Table 1*). This result is obtained because values of b increased as a decreased (*Figure 4*) and the relevant species show aggregated dispersion with b significantly larger than 1 (*Table 1*). At a low population density, Taylor's regression coefficients satisfactorily described the dispersion parameters of insects (Taylor 1984; Cho et al. 1995). This may not be entirely true for a high density

Table 1. Percentage of Taylor's b larger than 2 and of t -test of b larger than 1 and 2 out of 100 simulation runs on three insect pest species sampled from transplanted or direct-seeded rice in three areas

| Species | Data source | $\bar{x} \pm SE$ (no. samples) | Sampling unit increment | Percentage of $b > 2$ out of simulation no. | | Percentage t -test of $b > 1$ | | Percentage t -test of $b > 2$ | |
|--------------------------------|--------------------------------|-----------------------------------|-------------------------------|--|-------|------------------------------------|-------|------------------------------------|-------|
| | | | | SU | SCALE | SU | SCALE | SU | SCALE |
| <i>Nephotettix</i> spp. | UPM 1991 (Transplanted) | 2.19 ± 0.09 (639) | 2 | 25 | 20 | 68 | 52 | 0 | 1 |
| | | | 5 | 37 | 46 | 68 | 34 | 1 | 3 |
| | | | 10 | 40 | 46 | 65 | 17 | 1 | 2 |
| | SSTK 1992 (Transplanted) | 0.83 ± 0.05 (636) | 25 | 54 | 61 | 74 | 13 | 4 | 4 |
| | | | 2 | 0 | 4 | 77 | 56 | 0 | 0 |
| | | | 5 | 1 | 17 | 77 | 35 | 0 | 0 |
| SSTK 1992 (Direct-seeded) | 0.79 ± 0.05 (640) | 10 | 3 | 20 | 56 | 13 | 0 | 1 | |
| | | 25 | 3 | 36 | 71 | 12 | 0 | 2 | |
| | | 2 | 0 | 1 | 44 | 24 | 0 | 0 | |
| <i>Nilaparvata lugens</i> | UPM 1991 (Transplanted) | 1.45 ± 0.07 (635) | 5 | 0 | 3 | 40 | 7 | 0 | 0 |
| | | | 10 | 0 | 15 | 28 | 11 | 0 | 0 |
| | | | 25 | 0 | 24 | 34 | 5 | 0 | 0 |
| | Felcra 1997 (Direct-seeded) | 5.91 ± 0.36 (780) | 2 | 5 | 11 | 62 | 44 | 0 | 0 |
| | | | 5 | 18 | 37 | 71 | 34 | 0 | 1 |
| | | | 10 | 18 | 40 | 59 | 21 | 0 | 0 |
| <i>Sogatella furcifera</i> | SSTK 1992 (Direct-seeded) | 1.80 ± 0.08 (640) | 25 | 26 | 45 | 54 | 13 | 1 | 5 |
| | | | 2 | 0 | 1 | 13 | 14 | 0 | 0 |
| | | | 5 | 0 | 9 | 14 | 4 | 0 | 0 |
| Felcra 1997 (Direct-seeded) | 5.40 ± 0.29 (700) | 10 | 0 | 17 | 8 | 3 | 0 | 0 | |
| | | 25 | 0 | 41 | 8 | 8 | 0 | 3 | |
| | | 2 | 91 | 89 | 100 | 99 | 23 | 17 | |
| | | | 5 | 90 | 84 | 96 | 81 | 27 | 23 |
| | | | 10 | 95 | 87 | 97 | 65 | 21 | 7 |
| | | | 25 | 93 | 69 | 95 | 26 | 30 | 6 |

SE = standard error, SU = unit-based sampling, SCALE = scale-based sampling

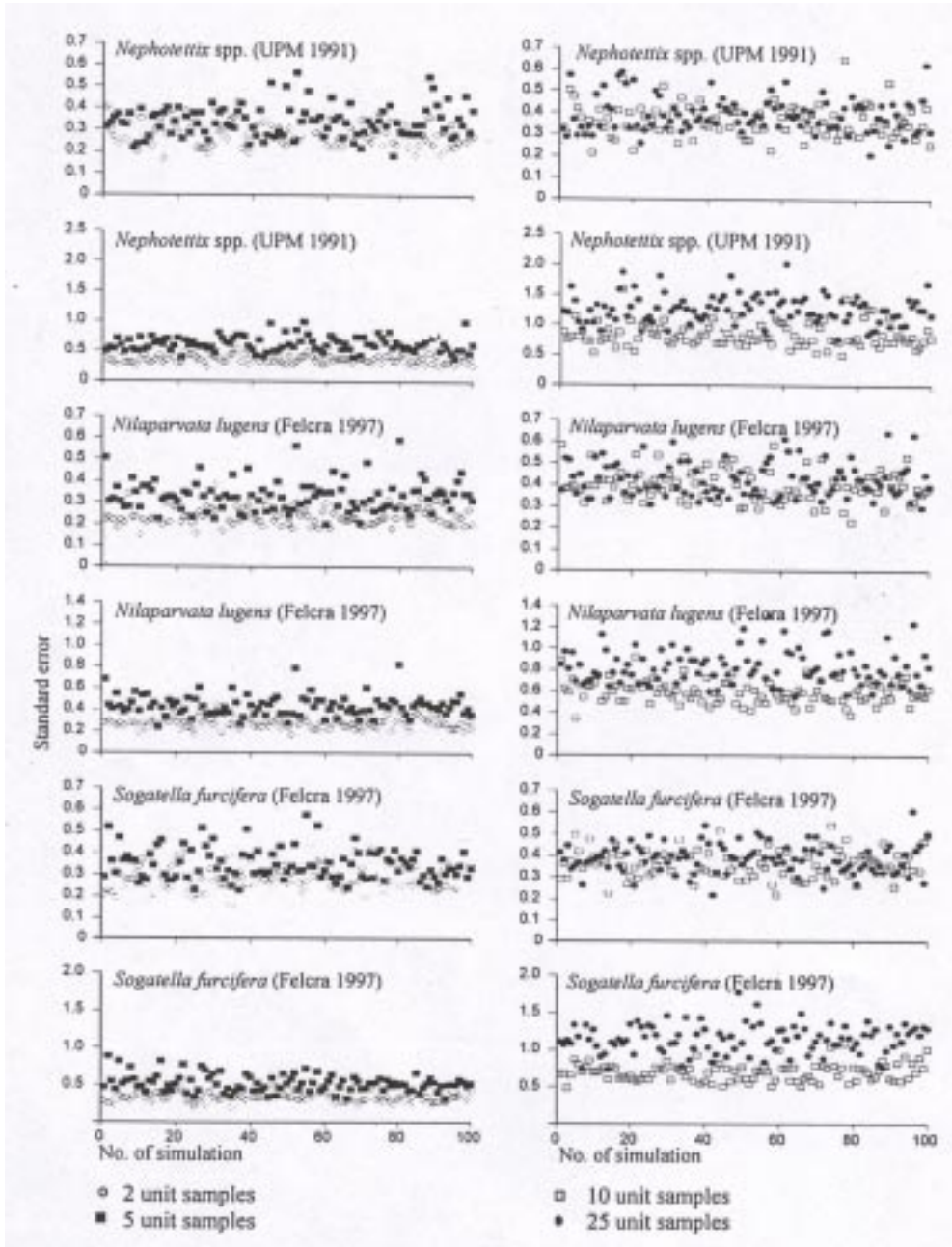


Figure 2. Distribution of standard error of Taylor's b at different number of unit samples used as sampling unit increment (SUI) for scale-based sampling on three insect pests. For each species, the first row represents unit-based sampling and the second row represents scale-based sampling. SUI of 2 and 5-unit samples are used in the left column, whereas 10 and 25-unit samples are used in the right column

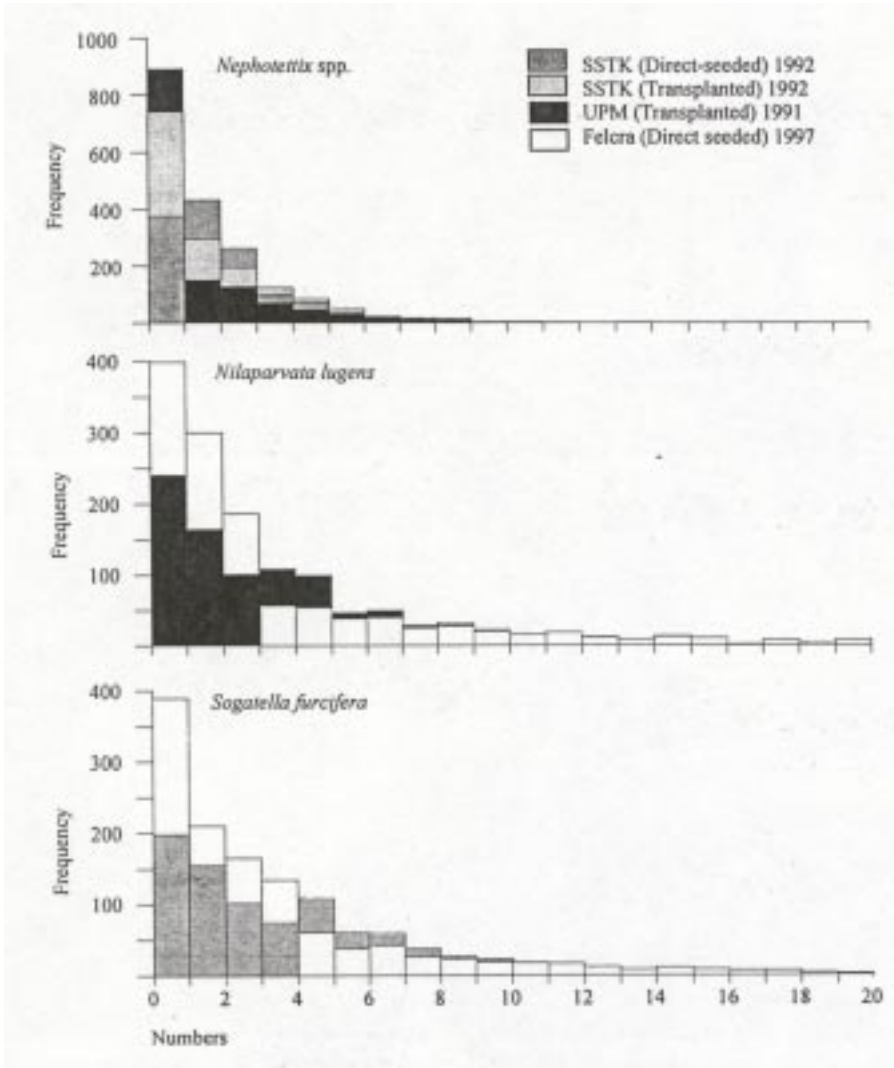


Figure 3. The frequency distribution of spatial variation in numbers of occurrence for three insect pests sampled from transplanted and direct-seeded rice in three locations

population. Here, we propose that b values larger than 2 will be obtained in most cases of heterogeneous populations with high densities.

The ANOVA result indicates that the values of a obtained from different locations, SUI and different types of sampling (unit or scale-based) were significantly different ($p < 0.01$), except for *Sogatella furcifera* and SUI of *Nephotettix* spp. (Table 2). In contrast, there are significant effects ($p < 0.01$) of each main

effect with respect to b values. This indicates that Taylor's b would change even for the same species but with different areas or locations, unit samples used for scale increment (SUI) and with different types of sampling used (unit or scale-based sampling). There are also indications of changing b with occasion since the data sources used in the simulation were from different years or seasons.

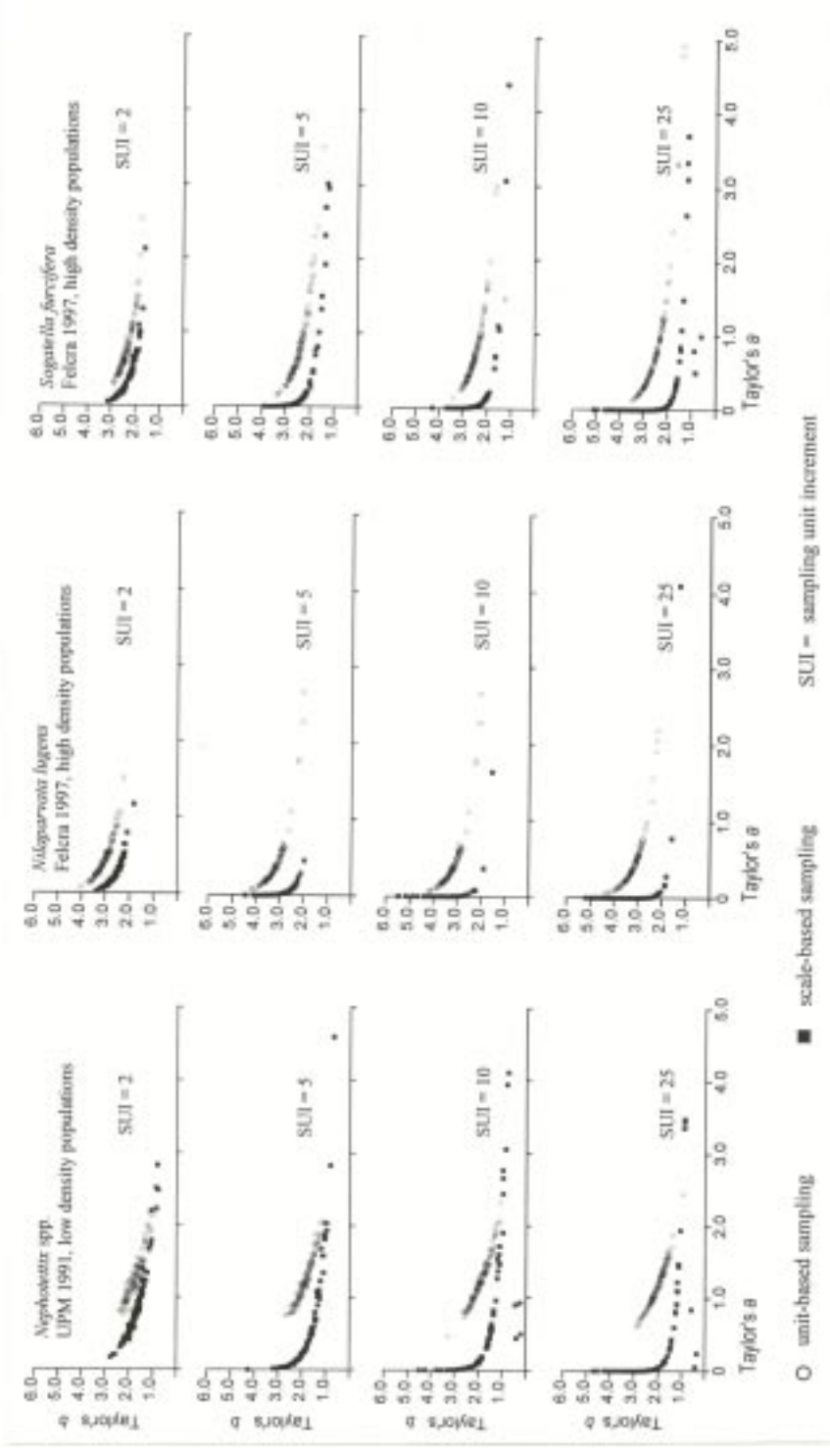


Figure 4. The relationship of Taylor's b and a coefficients with four sampling scales on three insect pests

Table 2. Results of ANOVA on Taylor's *a* and *b* coefficients for three insect pests with location, unit sample used for scale increment (SUI) and sampling type (unit or scale-based sampling) as main effects using 100 replicates of bootstrap simulation data

| Species | Source of variation | Mean square | df | F-ratio | Significant level |
|----------------------------|---------------------|-------------|----|----------|-------------------|
| Taylor's <i>a</i> | | | | | |
| <i>Nephotettix</i> spp. | Location | 128.91 | 2 | 120.49 | 0.0000 |
| | SUI | 1.68 | 3 | 1.58 | 0.1935 |
| | Sampling type | 239.34 | 1 | 223.71 | 0.0000 |
| <i>Nilaparvata lugens</i> | Location | 320.39 | 1 | 803.11 | 0.0000 |
| | SUI | 3.07 | 3 | 7.70 | 0.0000 |
| | Sampling type | 150.93 | 1 | 378.33 | 0.0000 |
| <i>Sogatella furcifera</i> | Location | 1.29 | 1 | 0.01 | 0.9403 |
| | SUI | 284.94 | 3 | 1.27 | 0.2835 |
| | Sampling type | 88.39 | 1 | 0.39 | 0.5372 |
| Taylor's <i>b</i> | | | | | |
| <i>Nephotettix</i> spp. | Location | 75.87 | 2 | 302.47 | 0.0000 |
| | SUI | 1.95 | 3 | 7.77 | 0.0000 |
| | Sampling type | 3.59 | 1 | 14.31 | 0.0002 |
| <i>Nilaparvata lugens</i> | Location | 708.18 | 1 | 2 530.22 | 0.0000 |
| | SUI | 16.31 | 3 | 58.28 | 0.0000 |
| | Sampling type | 2.20 | 1 | 7.86 | 0.0051 |
| <i>Sogatella furcifera</i> | Location | 565.12 | 1 | 1 493.05 | 0.0000 |
| | SUI | 7.89 | 3 | 20.84 | 0.0000 |
| | Sampling type | 9.05 | 1 | 23.90 | 0.0000 |

We conclude that Taylor's *a* and *b* values differ with different locations, sampling occasions and sampling scales. Moreover, the percentage of *b* values significantly larger than 1 and 2 decreased as sampling scale increased. Our findings in the wet rice ecosystem validate observations recorded in other ecosystems (Sawyer 1989; Trumble et al. 1989; Yamamura 1990). Consequently, any sampling system which demand reasonably constant species-specific parameters and attributes, need to address the issue of sampling scale dependence. Proper sampling technologies are imperative, since it is universally accepted now that sampling is an integral component of successful integrated pest management systems (Pedigo and Buntin 1994).

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References

- Buntin, G. D. (1994). Developing a primary sampling program. In *Handbook of sampling methods for arthropods in agriculture* (Pedigo, L. P. and Buntin, G. D., ed.) p. 137–74. Boca Raton, FL: CRC Press
- Campbell, C. L. and Madden, L. V. (1990). *Introduction to plant disease epidemiology* 532 p. New York: John Wiley & Sons
- Cho, K., Eckel, C. S., Walgenbach, J. F. and Kennedy, G. G. (1995). Spatial distribution and sampling procedures for *Frankliniella* spp. (Thysanoptera: Thripidae) in staked tomato. *J. Econ. Entomol.* **88**: 1658–65

- Elliot, J. M. (1977). *Some methods for the statistical analysis of samples of benthic invertebrates* 2nd ed., 160 p. (Sci. Publ. No. 25). Ambleside, Cumbria, UK: Freshwater Biol. Assoc.
- Green, R. H. (1970). On fixed precision level sequential sampling. *Res. Popul. Ecol.* **12**: 249–51
- Hassan, S. T. S. (1996). Population and distribution parameters of arthropods of wet paddy ecosystem, and their fits to distribution models. *Malays. Appl. Biol.* **25**: 61–8
- (1997). Action thresholds of wet rice arthropods for pest management decision-making in Malaysia. *Pertanika J. Trop. Agric. Sci.* **20**: 65–74
- Hassan, S. T. S. and Rashid, M. M. (1997a). Presence/absence sequential plans for pest management decision making, for arthropods of wet rice ecosystem in Malaysia. *Pertanika J. Trop. Agric. Sci.* **20**: 51–63
- (1997b). Numerical and binomial optimal samplings of arthropods of wet paddy ecosystem in Malaysia. *J. Trop. Agric. and Fd. Sc.* **25**: 55–63
- Healy, M. J. R. and Taylor, L. R. (1962). Tables for power-law transformation. *Biometrika* **49**: 557–9
- Nyrop, J. P. and Binns, M. R. (1991). Quantitative methods for designing and analyzing sampling programs for use in pest management. In *Handbook of pest management in agriculture* Vol. 2 (Pimentel, D., ed.) p. 67–132. Boca Raton, FL: CRC Press
- Pedigo, L. P. and Buntin, G. D., ed. (1994). *Handbook of sampling methods for arthropods in agriculture* 714 p. Boca Raton, FL: CRC Press
- Rashid, M. M., Hassan, S. T. S., Azhar, I., Alwi, A. and Hussein, M. Y. (1998a). Variable intensity sampling: Developing operational plans for the green rice leafhopper in wet paddy ecosystem in Malaysia. *J. Trop. Agric. and Fd. Sc.* **26**: 41–50
- (1998b). Variable intensity and fixed-size sampling plans: Comparative analysis using simulated *Nephotettix* spp. (Homoptera: Cicadellidae) populations in wet paddy ecosystem in Malaysia. *J. Trop. Agric. and Fd. Sc.* **26**: 51–63
- Sawyer, A. J. (1989). Inconsistency of Taylor's *b*: simulated sampling with different quadrat sizes and spatial distributions. *Res. Popul. Ecol.* **31**: 11–24
- Taylor, L. R. (1961). Aggregation, variance and the mean. *Nature* **189**: 732–5
- (1984). Assessing and interpreting the spatial distributions of the insect populations. *Ann. Rev. Entomol.* **29**: 321–57
- Taylor, L. R., Taylor, R. A. J., Woiwood, I. P. and Perry, J. N. (1983). Behavioural dynamics. *Nature* **303**: 801–4
- Trumble, J. T. (1985). Implications of changes in arthropod distribution following chemical application. *Res. Popul. Ecol.* **27**: 277–85
- Trumble, J. T., Brewer, M. J., Shelton, A. M. and Nyrop, J. P. (1989). Transportability of fixed precision level sampling plans. *Res. Popul. Ecol.* **31**: 325–42
- Yamamura, K. (1990). Sampling scale dependence of Taylor's power law. *Oikos* **59**: 121–5