

TRANSPORTABILITY OF FIXED-PRECISION LEVEL SAMPLING PLANS

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INTRODUCTION

Detailed knowledge of insect distributions and the primary factors affecting how insect populations utilize their available resources are critical to the development of accurate sampling plans in agroecosystems and integral to the study of population and community ecology of insects (TRUMBLE et al., 1987). Although few scientists question the value of sampling as a method for determining the need for control action, documenting the within-field and within-plant distributions of arthropod pests is often prohibitively expensive in both time and effort. This problem would be alleviated to a large extent if sampling plans created at one location could be utilized in other locations. In spite of the expense, and perhaps in response to a lack of success in transporting sampling programs between locations, a meaningful data base on insect distribution has appeared in the literature over the past 70 years.

TAYLOR's Power Law (TPL) (TAYLOR, 1961), a widely reported measure of dispersion, is often used to provide baseline information on insect distribution for sampling plans. According to TAYLOR (1984), the intercept of TPL is variable with sampling procedures, while the slope is characteristic of a species in a given environment. Regression coefficients from TPL are frequently used to generate fixed-precision level sequential sampling plans as developed by KUNO (1969) and extended using GREEN's (1970) formula. This formula is responsive to variation in the intercept of TPL, which could be expected to change with the sample unit or the sampler, and to the slope of TPL, which would fluctuate with any changes in within-field distribution. These effects were reported for fixed-precision level estimation plans for *Trichoplusia ni* (HÜBNER) on cabbage where the same cabbage cultivar, sampling, and cultural practices were used between widely separated geographic areas (TRUMBLE et al., 1987). TPL regression statistics for small and large larvae differed between location, with a trend for increasing aggregation from Louisiana to Texas to California. Consequently, more larvae needed to be counted in California before the population density could be estimated with a given precision.

To study the impact of variability in TPL regression coefficients on GREEN's for-

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mula, the effects of changing intercept and slope values were calculated using computer-generated data and observed for trends. The literature was then reviewed for examples which could document any such potential trends that might limit our ability to apply sampling programs developed at one location or time in other locations or times. In addition, some auxiliary sources of error which can occur during sampling or which are inherent in sequential estimation procedures were investigated.

MATERIALS AND METHODS

In the following sections on 1) statistical trends in fixed-precision level sampling and 2) the evaluation of data from the literature, intercept (α) and slope (b) from TPL,

$$\log s^2 = \log \alpha + b \log m, \quad (1)$$

were used to generate fixed-level sequential sampling plans (KUNO, 1969) using GREEN's (1970) formula, which is linearized by the logarithmic functions:

$$T_n^{b-2} = \frac{D_0^2}{\alpha} n^{b-1} \quad (2)$$

$$\log T_n = \frac{\log(D_0^2/\alpha)}{b-2} + \frac{b-1}{b-2} \log n \quad (3)$$

where $\log T_n$ = the cumulative number of arthropods sampled, α and b are the intercept and slope from equation 1, respectively, n is the sample size, and D_0 is the fixed level of precision. The precision level employed throughout this manuscript was standardized at 0.25 for comparative purposes. Log-log graphs, as justified by GREEN (1970), were used because these linearized data allowed straightforward comparisons between graphs.

Statistical trends in GREEN's formula

Fixed-precision level stop lines were generated for equation 2 with a Fortran 77 program for n of 1 to 100 using α of 0.5, 2.5, 5.0, 7.5, and 10, in combination with TPL b of -1 , -0.5 , 0.0 , 0.5 , 1.0 and 1.75 . Intercept values of $\alpha \leq 0$ were not tested because these values lead to a negative root ($\alpha < 0$) or an undefined solution ($\alpha = 0$) for T_n of equation (2). Slope values of greater than 2.0, which have been reported in the literature (KRING and GILSTRAP, 1983) and others, were not examined. GREEN (1970) noted that these result in stop lines with positive slopes.

Examples from the literature

The literature was examined for reports providing regression coefficients from TPL that allowed the generation of fixed-level sequential sampling plans using GREEN's (1970) formula. Although other approaches are available for generating fixed-precision level sequential estimation plans, (KUNO, 1969; RUDD, 1980, and others), TPL has been widely reported for a variety of arthropods in the literature and provided the

broadest range of potential comparisons. Thus, the statistical information presented in our manuscript should be used primarily to evaluate sampling plans based on TPL and GREEN's fixed-precision level sequential sampling formula, and may not provide comparable data for the other major approaches to developing sequential estimation plans. However, the concerns which focus on the biological differences between locations, over time, and with the sample units selected will be of interest for all available techniques.

The literature examined in our study was selected to allow comparisons of sampling programs between life stages, across seasonal or annual time, by sample unit, and between geographically separate locations. The species investigated included the Colorado potato beetle, *Leptinotarsa decemlineata* (SAY), the bird cherry-oat aphid, *Rhopalosiphum padi* (L.), the twospotted spider mite *Tetranychus urticae* (KOCH), and the cabbage looper, *Trichoplusia ni* (HÜBNER). Specifically, the Colorado potato beetle was chosen because a series of studies utilized equivalent sample units from two solanaceous hosts (tomato and potato); whole plant samples were used in all cases with the exceptions of HARCOURT (1963) and LATHEEF (1972). HARCOURT employed a 1/3 plant sample which was determined to provide distribution data that were not significantly different from whole plant samples. Similarly, LATHEEF used a 1/6 plant sample in which numbers of Colorado potato beetle in any stage of development reportedly did not vary significantly from whole plant counts. The distributional data for bird cherry-oat aphids and twospotted spider mites were included because sample sizes were variable and the reports spanned two continents.

Evaluation of errors in sampling and fixed-precision level population estimation

In order to determine how comparable two samplers were in assessing insect populations SHELTON (unpublished) produced a data set containing five weeks of larval counts of *Plutella xylostella* (L.) for a commercial cabbage field. Each sampler recorded numbers of large larvae from 122 randomly-selected plants on the same day and time each week during 1980. These data sets were used to generate TPL regression coefficients which then were used to calculate fixed-precision level stop lines with GREEN's formula.

To document if the variability in data points about the regression lines changed the precision from the intended level of 25%, Monte Carlo simulations were used. This was necessary because sequential estimation procedures that are based on empirical variance-mean relationships such as TPL, and designed to provide estimates with a specified coefficient of variation (CV), will not yield estimates with this CV each time they are used. This effect was illustrated by HUTCHINSON et al. (1988). While TPL generally provides excellent fits to data, there is still variability associated with the regression coefficients that is not considered in generating the stop lines. Therefore, the nominal CV will not be achieved during each sampling bout because the stop lines are based on average values for random observations. As a result, there

will be instances when a decision to stop sampling will be made before the required number of samples are collected to reach a specified degree of precision and there will be instances when more samples than required will be collected.

The actual performance of a sequential estimation procedure based on TPL was ascertained using MONTE CARLO simulations with 500 iterations. In the simulations, data were generated to describe sample observations. During each simulated sampling bout the sample observations were compared to the stop lines and sampling continued until a stop sampling decision was reached. At this point the actual CV achieved was computed. Sampling was simulated for a group of true means and for each mean a set of CV's were determined. To carry out the simulations two assumptions were required. First, we assumed that sample observations of an arthropod population could be described by a negative binomial distribution with dispersion parameter k as a function of the mean and variance. For any given mean the variance was calculated using TPL, and k was computed as $m^2/(s^2 - m^2)$. Second, we assumed that the log of the variance for any given mean computed using TPL was normally distributed around the regression line with variance calculated after SNEDECOR and COCHRAN (1967) as:

$$mse/df + (\log(m) - \text{auglnm})^2 s_b^2 + mse. \quad (4)$$

In this equation mse is the mean square error from the regression relationship, df are the degrees of freedom associated with deviations from the regression, auglnm is the average of the natural log of the means used in the regression, m is the mean for which a variance is being predicted, and s_b^2 is the variance of the regression coefficient b from TPL.

Simulations then were conducted to test the effect of specified departures in the coefficients α and b from the values used to construct the stop lines.

RESULTS AND DISCUSSION

Several general trends are evident from the stop line calculations (Fig. 1). First, there is a point in each graph where the fixed-precision level stop lines intersect. As α from TPL increases, the intersection points are moved such that T_n and the number of samples required for a fixed-precision level estimate of the mean increase. At these points, regardless of the distribution (slope) of the population, an identical number of organisms (T_n) must be counted for a given number of samples to estimate population density; for $\alpha=0.5$ this intersect value is $T_n = 8.0$ at 7.5 samples. At fewer than 7.5 samples, larger b values (more aggregated populations) require that more organisms be counted to obtain the same precision of the estimate of the density. At more than 7.5 samples, larger b values require fewer organisms to be counted. Initially, this latter observation appears to run counter to the generally held concept that equivalent density estimates of more aggregated populations require more samples than less aggregated populations. However, given prior knowledge of the distribution of the

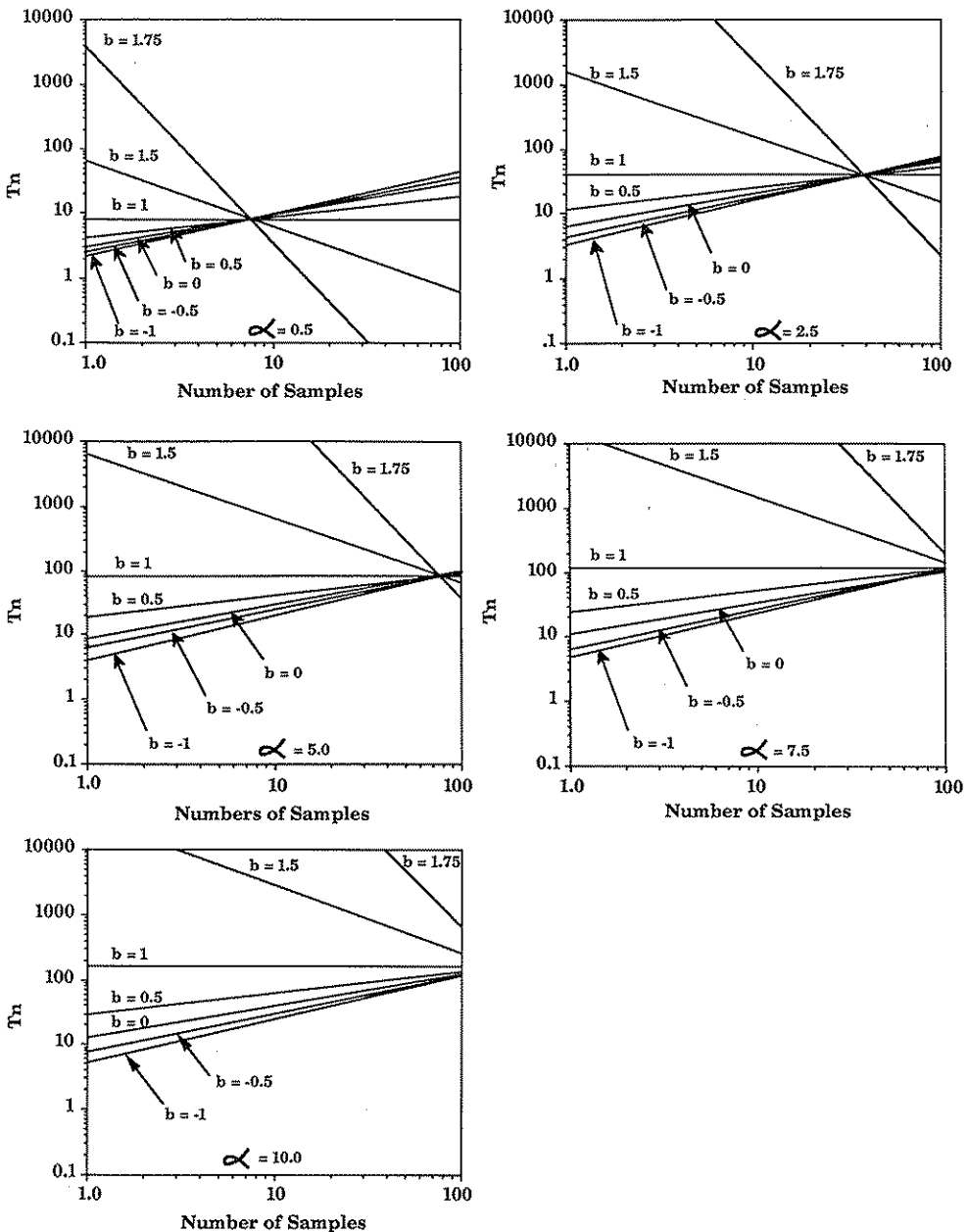


Fig. 1. GREEN's (1970) fixed-precision level stop lines generated for sample sizes of 1 to 100 using TAYLOR's Power Law alpha (α) values of 0.5, 2.5, 5.0, 7.5 and 10.0, in combination with TAYLOR's Power Law slope (b) values of -1.0 , -0.5 , 0.0 , 0.5 , 1.0 , and 1.75 . The precision level was standardized at 25% for all graphs.

organisms from the mean/variance relationship in TPL, it is apparent that the probability of encountering a cluster of organisms in an aggregated population increases as the number of samples increases; as this probability increases, cumulative number of

organisms needed to reach the stopline decreases.

A second trend noted was that as the intercept values from TPL increase, the number of samples required to estimate the population density (T_n) increases for any given value of b . This effect is most noticeable for the higher values of b . For example, if five samples are collected for a data set with a b of 1.5, increasing α from 0.5 to 2.5 requires that 10–11 and over 300 organisms, respectively, be counted to estimate the population density. At lower b values, the differences are not as dramatic; increasing α values from 0.5 to 2.5 increases the numbers of samples required at a slope of 0.5 from approximately 6 to 11, respectively, yet the slopes of the stop lines do not change. Therefore, α behaves as a location parameter as seen by inspection of equation (3) and has its greatest effect at high b values. Since most arthropod populations exhibit aggregated distributions (TAYLOR, 1984), even relatively small changes in α will have a substantial effect on the sample sizes required for population estimates using fixed-precision level sampling plans.

A third obvious trend, also seen by GREEN (1970), is that the slopes of fixed-precision stop lines are positive for b values less than one. Although b values of less than one rarely have been reported, these stop lines should be useful as long as the mean density per sample is not too low. For example, given $\alpha=7.5$ and $b=-1$ (Fig. 1), sampling from a nearly uniform population with a density of one per sample would not be likely to produce T_n values above the stop line and sampling could continue ad infinitum. Finally, when $b=1$ the slope of the stop line is horizontal for any value of α . Therefore, the stop line is independent of the number of samples taken and simply changes in location as a function of α .

Examples from the Literature

Fixed-precision-level estimation plans generated from data presented in the literature provide practical examples of the variability in monitoring programs induced by differences in TPL intercept and slope values resulting from dissimilar regressions; 1) between life stages, 2) between crops, 3) among geographic regions, 4) among variable sample sizes and units, and 5) across annual time. In addition, several of the trends seen in the prior section were evident in the literature.

Colorado potato beetle on tomato and potato. Sampling variability induced by life stages assessed, by host crop, and by geographic location were evident for the Colorado potato beetle. Fixed-precision level stop lines generated by GREEN's formula generally were similar for large larvae between Virginia, Maryland (ZEHNDER and LINDUSKA, 1988), and Ontario, Canada (LATHEEF, 1972) for the range of samples reported in Fig 2. The stop line from New York (NYROP and WRIGHT, 1985) was substantially higher. For the adult beetles, the stop lines for Virginia, New York and Maryland were broadly similar in the range of samples presented in Fig. 2, but the stop line for adults in Ontario was substantially lower. At all locations more large larvae than

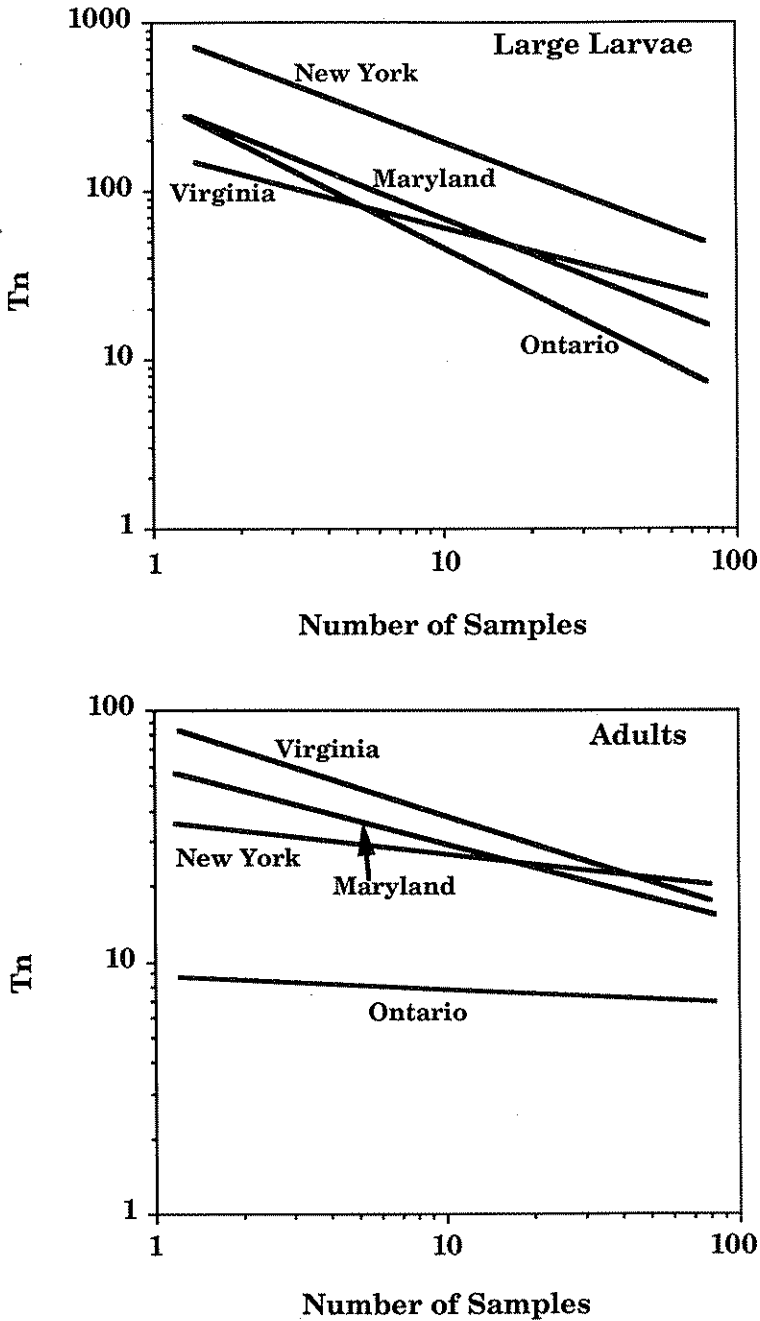


Fig. 2. Fixed-precision level stop lines for large larvae (3rd to 4th instars) and adults of the Colorado potato beetle for eastern North America based on TAYLOR'S Power Law coefficients presented in literature cited in Table 1. Averaged values from Table 1 were used to generate the stop lines.

adults needed to be counted from 1 to 10 plants to estimate the population density at the same precision level (Fig. 2). However, TPL values for the more aggregated large larvae generated stop lines with a more negative slope, which would ultimately require a lower T_n than the adults. Not surprisingly, intercept values, which TAYLOR suggested were related to sampling procedures, varied by over 100% between some location (Table 1).

Such observations point out the complex interaction of the α and b in GREEN'S formula. For example, the population in Ontario had a higher α than Virginia or Maryland, and quite similar b . Therefore, one would anticipate that the Ontario population would require a higher T_n for any given sample number than the other locations to estimate the density at a fixed precision. However, Ontario population required fewer cumulative larvae per sample for any number of samples above five. Thus, even the relatively small differences in regression coefficients seen in Table 1 can result in substantial differences in fixed-precision level estimation plans.

Bird cherry-oat aphid on cereals. Stop lines generated for *R. padi* in cereals among various geographic locations provide additional insight into the effects of variation of TPL regression coefficients. A series of different sample units ranging from 1 tiller to 0.3 m produced quite similar TPL b values for South Dakota (ELLIOT and KIECKHEFER, 1986), and two studies in Sweden (EKBOM, 1985; EKBOM, 1987), but much higher b values in Quebec, Canada (BA-ANGOOD and STEWART, 1980) and Texas (KRING and GILSTRAP, 1983) (Table 2). The TPL slope from Texas was over 2.0, and fixed-precision level stop lines were not calculated. In spite of the similar b values, the stop lines for the fixed-precision level sampling plans required that T_n values of 161 to

Table 1. Intercept (α) and slope (b) values from TAYLOR'S Power Law for Colorado potato beetles in eastern North America

Stage	VA ¹		MD ¹		NY ²		Ottowa ³	Ontario ⁴	
	α	b	α	b	α	b	b	α	b
Eggs	0.06-0.20	1.07-1.15	0.08	1.23	0.15-0.18	1.12	1.08-1.11	0.05	1.13
Small larvae	0.51-0.62	1.47-1.52	0.50	1.58	1.00-1.03	1.22	1.54-1.60	—	1.07-1.38
Large larvae	0.32	1.28-1.51	0.23	1.41	0.55-0.58	1.17-1.22	1.35-1.43	1.39	1.47
Adults	0.17-0.21	1.23-1.33	0.15	1.26	0.18	1.53	1.11	0.49	1.05
Sample Unit	plant		plant		plant		1/3 plant	1/6 plant	

¹ Data from ZEHNDER and LINDUSKA (1988); multiple years samples produced a range of values in some years; data from tomatoes.

² Data from NYROP and WRIGHT (1985); data from potatoes.

³ Data from HARCOURT (1963); no intercept values were available; the 1/3 plant sample was reported not to be significantly different from a whole plant sample; data from tomatoes.

⁴ Data from LATHEEF (1972); egg, large larvae (third instars only), and adult values calculated from data in Tables 10, 11 and 9, respectively; data were not available to allow calculation of intercept values for first, second or 4th instar larvae; the 1/6 plant sample was reported to be insignificantly different from a whole plant sample; data from tomatoes.

Table 2. Intercepts (α) and slopes (b) from TAYLOR's Power Law for the bird cherry-oat aphid, *Rhopalosiphum padi* (L.) in cereals

Value	South Dakota ¹ USA	Texas ² USA	Quebec ³ Canada	Sweden ⁴ A	Sweden ⁵ B
α	5.00	-0.56-1.80	0.94	2.88	6.40
b	1.43	2.19-2.32	1.87	1.45	1.35
Sample Unit	0.3 m	0.1 m	20 tillers	10 tillers	1 tiller

¹ Data from ELLIOTT and KIECKHEFER (1986).

² Data from KRING and GILSTRAP (1983).

³ Data from BA-ANGOOD and STEWART (1980).

⁴ Data from EKBOM (1985); most fields near Uppsala.

⁵ Data from EKBOM (1987); from fields in southern and central Sweden.

384 aphids be accumulated in South Dakota and Sweden, respectively, before the populations could be accurately estimated by 10 samples (Fig. 3). T_n at Quebec was intermediate at 226 cumulative aphids. Thus, even if the TPL b coefficients between locations are similar, variation in sample units producing differential TPL α will result in fixed-precision level stop lines which are not transferable between locations. For 15 samples, T_n values for South Dakota and both studies in Sweden still varied by over 100% (range=115 to 288); the more aggregated populations in Quebec now required that only 15 aphids be counted.

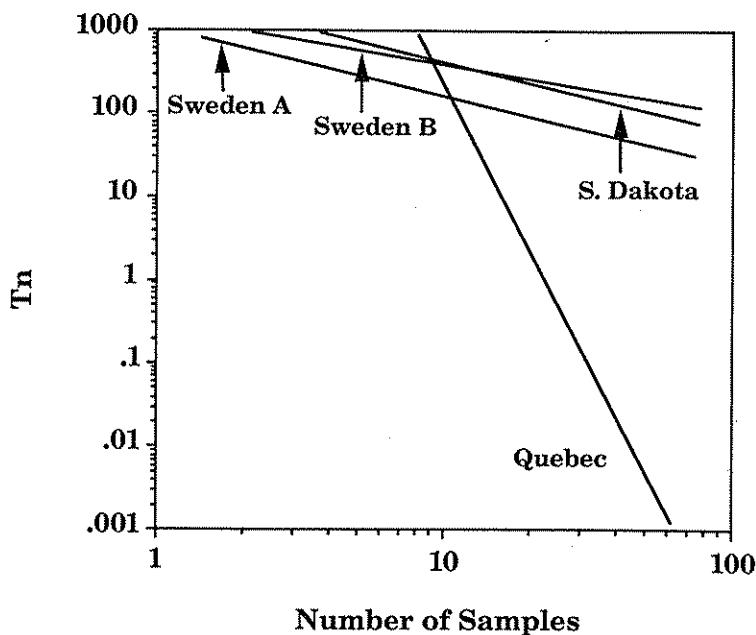


Fig. 3. Fixed-precision level stop lines for *Rhopalosiphum padi* (L.) in cereal crops in Europe and North America based on TAYLOR's Power Law coefficients presented in literature cited in Table 2.

Table 3. Intercepts (α) and slopes (b) from TAYLOR's Power Law for an aphid complex in soybeans and for the two-spotted spider mite, *Tetranychus urticae* (KOCH), in strawberry

Value	Aphids in soybeans ¹				<i>T. urticae</i> in strawberry ²		
	1976	1977	1978	Average	1983	1984	Average
α	0.623	1.147	0.748	0.836	2.20	2.61	2.405
b	1.613	1.024	1.311	1.305	1.60	1.82	1.71
Sample Unit	horizontal ermine lime trap				trifoliolate leaf		

¹ Data from IRWIN (1980).

² Data from TRUMBLE (1985).

Aphids on soybeans and twospotted spider mites on strawberries. The effects of seasonal variation in TPL regression coefficients are evident from data collected for an aphid complex on soybeans (IRWIN, 1980) and for *T. urticae* on strawberries (TRUMBLE, 1985) (Table 3). According to TAYLOR (1984), the TPL b values presented by IRWIN (1980) are not significantly different between years. On this basis the use of pooled data to create an "averaged" TPL regression could be justified for use in a sequential sampling plan as was presented by IRWIN (1980). Yet, when these coefficients are incorporated in GREEN's formula, the stop lines are grossly different between years, leading to substantial differences in the cumulative numbers of aphids which need to be counted in order to compute a fixed-precision level estimate of population densities (Fig. 4A). Although the fit of TPL was robust for the aphid complex on soybeans, as well as for insect complexes on other crops (TRUMBLE and OATMAN, 1984), the observed variation between years for insect complexes could reasonably be expected as the composition of the species changed. Species composition changes can affect the sampling counts through changes in population distribution or utilization of the habitat of the sample unit by each species. Even when only a single species is evaluated, fixed-precision level stop lines may be substantially different between years (Fig. 4B). Thus, the pooling of several years of data to produce a single stop line with GREEN's formula for an organism or a complex of organisms, even if the slopes of TPL are not significantly different, may not always be valid.

These examples clearly demonstrate potential sources of error in pooling data or averaging TPL values for use in formula (2). Monte Carlo simulations of the soybean data (Table 4) and strawberry data (Table 5) demonstrated that the amount of deviation from the expected CV of 25% was variable with the mean population density. For example, simulations for aphid populations (Table 4) using TPL coefficients from the pooled aphid data as the anticipated population distribution of the model and the 1976 TPL coefficients for the input values demonstrated that the deviation from the expected CV generally increased with increasing mean density; a mean density of one showed less than 1% of the samples would have a CV of 32.6% or greater, while a population with a mean density of 16 showed 29.8% of the samples with a CV in excess of 32.6%. Nearly 17% of the samples had a CV in excess of 42.5%. Interest-

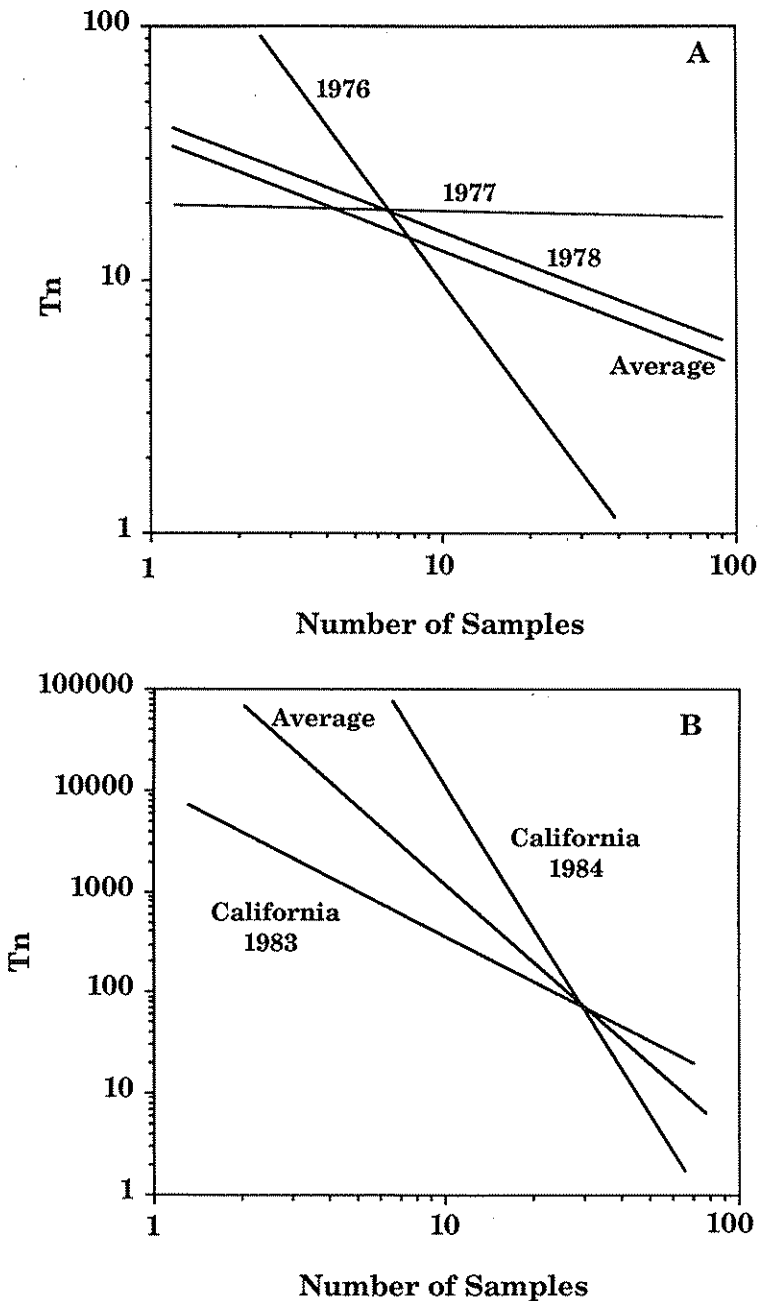


Fig. 4. Annual variation in fixed-precision level stop lines for an aphid complex in soybeans and for *Tetranychus urticae* (Koch) in strawberries. TAYLOR's Power Law coefficients and associated literature are cited in Table 3.

ingly, even though the average CV was reduced by increasing density for 1977 and 1988 data, the proportion of samples exceeding 32.6% was relatively small for all means except a mean of 1 in 1977. In general, these proportions were similar or lower

Table 4. MONTE CARLO simulations providing average coefficient of variation (CV), average number of samples, and proportion of samples falling within selected CV ranges for aphid populations in soybeans with varying mean density¹.

Mean density	average CV	average no. sample	Proportion of Samples in CV ranges				
			<7.5	7.6-17.5	17.6-32.5	32.6-42.5	>42.5
Average (pooled)Data							
1.00	0.241	14.330	0.000	0.102	0.796	0.094	0.008
6.00	0.213	4.494	0.026	0.362	0.508	0.064	0.040
11.00	0.206	3.062	0.104	0.370	0.392	0.080	0.054
16.00	0.192	2.472	0.190	0.360	0.300	0.064	0.086
21.00	0.170	2.090	0.270	0.334	0.268	0.076	0.052
1976 Data							
1.00	0.210	14.130	0.000	0.182	0.812	0.006	0.000
6.00	0.243	4.404	0.028	0.292	0.484	0.124	0.072
11.00	0.248	3.088	0.070	0.290	0.422	0.096	0.122
16.00	0.260	2.482	0.122	0.272	0.308	0.130	0.168
21.00	0.232	2.168	0.198	0.248	0.292	0.124	0.138
1977 Data							
1.00	0.283	14.478	0.000	0.058	0.680	0.210	0.052
6.00	0.201	4.442	0.042	0.394	0.460	0.092	0.012
11.00	0.170	3.076	0.130	0.468	0.340	0.046	0.016
16.00	0.154	2.458	0.224	0.402	0.310	0.044	0.020
21.00	0.135	2.076	0.354	0.362	0.234	0.036	0.014
1978 Data							
1.00	0.230	14.236	0.000	0.130	0.808	0.060	0.002
6.00	0.209	4.384	0.034	0.390	0.462	0.088	0.026
11.00	0.191	3.102	0.100	0.374	0.446	0.060	0.020
16.00	0.190	2.466	0.200	0.326	0.326	0.080	0.068
21.00	0.170	2.074	0.296	0.306	0.262	0.088	0.048

¹ Intercept and slope values for TPL from IRWIN (1980), Table 3.

than those produced when the simulation was run using pooled aphid data for both the anticipated population and for the input values. Thus, for 1977 and 1978, the use of the average stop line would be feasible. If highly aggregated populations are suspected as in 1976 ($b=1.613$, Table 3), this sample plan would be inappropriate.

In spite of the significant differences between slopes of the 1983 and 1984 regression lines for *T. urticae* in strawberry (TRUMBLE, 1985), the use of an average fixed-precision level stop line would not seriously affect the operating characteristics of the estimation program at the California Strawberry Advisory Board's (1989) current economic threshold of 15 spider mites per trifoliolate for years like 1983, with lower than the average aggregation (Table 5). For 1984, with higher than average b , the use of pooled data results in about 27% of the samples exceeding a CV of 32.6%, with 9 to 10% of the samples exceeding a CV of 42.5% for a mean density of 15. Even for simulations where the population was run using the averaged TPL values for both the model and the input parameters, nearly 10% of the samples at a mean of 15

Table 5. MONTE CARLO simulations providing average coefficient of variation (CV), average number of samples, and proportion of samples falling within selected CV ranges for spider mite populations in strawberry with varying mean density¹.

Mean density	average CV	average no. samples	Proportion of Samples in CV ranges				
			<7.5	7.6-17.5	17.6-32.5	32.6-42.5	>42.5
Average (pooled) Data							
1.00	0.236	39.566	0.000	0.164	0.744	0.090	0.002
6.00	0.231	23.684	0.000	0.226	0.680	0.088	0.006
11.00	0.227	20.138	0.000	0.254	0.640	0.100	0.006
16.00	0.233	17.906	0.000	0.216	0.690	0.080	0.014
21.00	0.231	16.590	0.000	0.210	0.688	0.100	0.002
26.00	0.227	15.672	0.000	0.256	0.638	0.096	0.010
31.00	0.226	14.964	0.002	0.300	0.576	0.112	0.010
1983 Data							
1.00	0.231	39.338	0.000	0.148	0.802	0.050	0.000
6.00	0.204	23.610	0.000	0.338	0.642	0.020	0.000
11.00	0.196	19.860	0.000	0.384	0.606	0.010	0.000
16.00	0.193	17.864	0.000	0.414	0.576	0.010	0.000
21.00	0.187	16.584	0.004	0.448	0.536	0.012	0.000
26.00	0.189	15.510	0.002	0.456	0.532	0.010	0.000
31.00	0.184	14.814	0.002	0.470	0.518	0.010	0.000
1984 Data							
1.00	0.248	39.456	0.000	0.126	0.742	0.124	0.008
6.00	0.262	23.742	0.000	0.146	0.640	0.166	0.048
11.00	0.272	20.176	0.002	0.136	0.578	0.212	0.072
16.00	0.279	18.008	0.000	0.166	0.558	0.184	0.092
21.00	0.285	16.604	0.000	0.130	0.552	0.216	0.102
26.00	0.286	15.678	0.002	0.120	0.564	0.212	0.102
31.00	0.285	15.024	0.000	0.148	0.532	0.216	0.104

¹ Intercept and slope values for TPL from TRUMBLE (1985), Table 3.

mites/leaflet would exceed a CV of 32.6%.

Evaluation of errors in sampling and fixed-precision level population estimation

Analysis of the data (from SHELTON, unpublished) showed TPL coefficients of $\alpha = 1.312$, $b = 1.346$ ($r^2 = 0.970$) and $\alpha = 0.877$, $b = 1.257$ ($r^2 = 0.984$) for sampler 1 and 2, respectively. When these regression values are incorporated in GREEN's formula, T_n values are divergent at low sample numbers (range for 5 samples = 20.1 to 35.7), but converge as sample sizes approach 100 (range for sample size of 90 = 7.39 to 7.75) (Fig. 5). The observed variability between samples could be due to real differences between populations on the groups of plants examined in the field, to differences in monitoring abilities between samples, or simply due to inherent variation in estimation of the TPL coefficients. These data suggest variation in estimates of TPL coefficients used in the stop line formula could affect the ultimate accuracy of the sampling plan.

The variability in the mean-variance relationship had a substantial impact on the

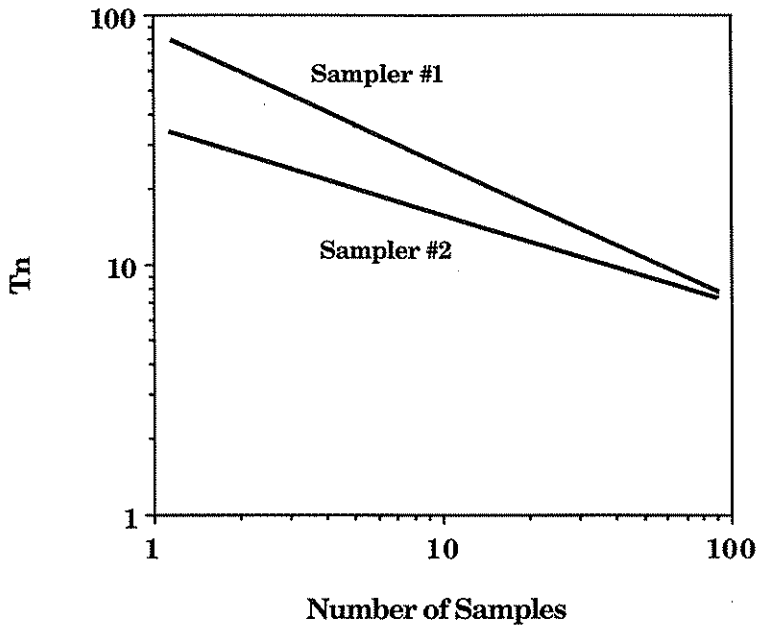


Fig. 5. Variation in fixed-precision level stop lines for large larvae (3rd to 4th instars) of *Plutella xylostella* (L.) in commercial cabbage for two samplers monitoring the same fields on the same dates. TAYLOR's Power Law coefficients are listed in the text.

precision of the sequential estimation plans (Table 6). In spite of the exceptionally good fit of the regression line ($r^2=0.98$), when regression variability was considered, approximately 10% of the time the actual CV was greater than 42.5% when the 'fixed'

Table 6. Distribution of coefficient of variation (CV) determined via MONTE CARLO simulation when variability in the variance-mean relationship was and was not considered¹.

Mean/ sample	Average CV	Average <i>n</i>	Distribution of CV			
			.075-.175	.175-.325	.325-.425	> .425
With regression variability						
2.0	.269	47.8	.260	.536	.112	.092
4.0	.264	32.3	.258	.540	.102	.100
6.0	.249	25.6	.296	.508	.110	.086
8.0	.256	21.8	.306	.520	.092	.082
10.0	.245	19.3	.326	.486	.100	.088
Regression variability removed						
2.0	.263	47.8	.202	.626	.126	.046
4.0	.244	32.5	.202	.644	.106	.048
6.0	.246	25.5	.210	.606	.142	.042
8.0	.246	21.7	.220	.648	.078	.054
10.0	.240	19.2	.260	.574	.118	.048

¹ The variance-mean relationship was based on data for European red mite with $\alpha=4.32$, $b=1.42$, $mse=0.278$, $df=145$, $avglnm=0.728$, and $s_b^2=0.004$, $r^2=0.98$ (see NYROP 1989 for sampling details). The nominal coefficient of variation (CV) was 0.25; based on 500 iterations.

or nominal value was 25% for means of 2.0 to 10.0 per sample. With regression variability removed this dropped to ca 5%. If mse is larger the spread in distribution of the CV will increase. In this specific case the mse is quite small ($mse=0.278$). As expected, average CVs were very close to nominal values and did not vary much with and without regression variability. This also was true for average sample sizes. From these observations it is clear that, at times, 1) the precision of a density estimate will be higher than specified, which means that more samples than required will be taken, and 2) at times precision of a density estimate will be less than specified, and too few samples will be taken. This effect is inherent in using regression estimates in a deterministic equation such as GREEN's (1970) formula. At high values of b in particular, the variability of these estimates may substantially affect the sampling effort associated with the fixed-precision level estimates of the mean. Depending on the distribution of CVs attained, performance of the sampling procedure may or may not have any significance in terms of management decisions.

Researchers running simulations with their data would be able to determine if too many or too few samples deviated from the nominal CV selected, and could adjust the CV value in GREEN's (1970) formula to allow for the most efficient sampling program. Such a program would have the bulk of the samples falling within the desired range of CVs, with a minimum number of samples with CVs above 32.5%.

It is evident that the transportability of sampling plans between locations or over time will be influenced by variation about the regression lines as well as any factors that influence the intercept and slope values from TPL. Geographic and temporal variation in such factors as biological control agents (HARCOURT, 1965; TRUMBLE and OATMAN, 1984), pesticide applications (TAYLOR, 1987; TRUMBLE, 1985), edge effects (LEWIS, 1965), arthropod behavioral patterns (CAFFERY and WORTHLEY, 1927; SHOWERS et al., 1980), biotype formation, host quality etc. and a wide range of environmental differences (temperature, frost, rain, etc.) could impact sampling efficiency and population distribution. Given the variability in sampling techniques and the potential deviation from stop line precision estimates suggested by the MONTE CARLO simulations, as well as the incomplete list of factors just noted, the lack of similarity in fixed-precision level stop lines is not surprising. In fact, it is surprising that pest management programs utilizing fixed-precision level estimation plans have proven useful for many years in many different cropping systems. One potential explanation for this success is that the estimates of economic injury levels generally are conservative. A second possible explanation is that values are often so low that small changes in b do not affect the sampling plan greatly.

Nonetheless, variation in TPL regression statistics can have a large effect on sampling plans. Some of the potential sources of variation in developing fixed-precision level stop lines for agroecosystems can be minimized by collecting distribution data from either commercial fields or from research plots with realistic cultural practices, pest control procedures, and of a size adequate to minimize edge effects. Some addi-

tional information would be valuable. If possible, the major biological control agents should be listed. Information on surrounding crops and significant environmental factors (frost, rain, etc.) would be useful. Presentation of all key regression information (intercept and slope values of TPL, standard error of these estimates, mean square errors, etc.) is strongly recommended. This information would provide for the establishment of a more complete data base in the literature which might permit scientists to determine how a sequential sampling plan would perform in any given area or time. Such data are necessary for the use of MONTE CARLO simulations that determine to what degree fixed-precision level estimation plans deviate from the fixed or expected level of the coefficient of variation at specific mean densities.

SUMMARY

Several general trends were evident when TAYLOR's Power Law intercept and slope values were varied in GREEN's (1970) formula for fixed-precision level sequential sampling (KUNO, 1969). First, there is a point in each graph where the fixed-precision level stop lines intersect. As the α values from TPL increase, the intersection points are moved such that T_n and the number of required samples increase. To the left of this intersection point, more aggregated populations require that more cumulative organisms be counted for an estimate of the mean. To the right of the intersection point, the more aggregated a population the fewer cumulative organisms need to be counted. The α value of TPL generally acts as a "location" factor, moving fixed-precision level stop lines without changing their slopes. This effect of α on the stop lines increases with increasing b values. However, the b value from TPL affects both the location and the slope of the stop lines. The impact of b on stop lines increases with larger values of b .

A review of the literature, as well as the results of a few studies designed to examine geographic variation in arthropod dispersion, indicate that the distribution of a given species, as well as fixed-precision level sampling programs based on GREEN's (1970) formula, can vary significantly between geographic locations and over time within a given location. There are many factors affecting the transportability of fixed-precision level sampling programs for specific arthropods between geographic locations, between years, and among crops. Some of the key factors are examined, including between-sampler variation and variation inherent in the regression statistics used in the sequential estimation procedure of GREEN (1970). Some considerations for the development of future sampling programs are discussed.

REFERENCES

- BA-ANGOOD, S. A. and R. K. STEWART (1980) Sequential sampling for cereal aphids on barley in southwestern Quebec. *J. Econ. Entomol.* 73: 679-691.

- California Strawberry Advisory Board (1989) 1989 update on two spotted spider mite management. April 9 Strawberry News Bulletin, Watsonville, CA.
- CAFFERY, D. J. and L. H. WORTHLEY (1927) A program report on investigations of the European corn borer. USDA Dept. Agric Bull. 1476: 1-155.
- EKBOM, B. S. (1985) Spatial distribution of *Rhopalosiphum padi* (L.) (Homoptera: Aphididae) in spring cereals in Sweden and its importance for sampling. *Environ. Entomol.* 14: 312-316.
- EKBOM, B. S. (1987) Incidence counts for estimating densities of *Rhopalosiphum padi* (Homoptera: Aphididae). *J. Econ. Entomol.* 80: 933-935.
- ELLIOTT, N. C. and R. W. KIECKHEFER (1986) Cereal aphid populations in winter wheat: spatial distributions and sampling with fixed levels of precision. *Environ. Entomol.* 15: 954-958.
- GREEN, R. H. (1970) On fixed precision level sequential sampling. *Res. Pop. Ecol.* 12: 249-251.
- HARCOURT, D. G. (1963) Population dynamics of *Leptinotarsa decimlineata* (SAY) in eastern Ontario. I. Spatial pattern and transformation of field counts. *Can. Entomol.* 95: 813-820.
- HARCOURT, D. G. (1965) Spatial pattern of the cabbage looper, *Trichoplusia ni*, on crucifers. *J. Econ. Entomol.* 59: 1190-1192.
- HUTCHINSON, W. D., D. B. HOGG, M. A. POSWAL, R. C. BERBERET, and G. W. CUPERUS (1988) Implications of the stochastic nature of KUNO's and GREEN's fixed-precision stop lines: sampling plans for the pea aphid (Homoptera: Aphididae) in alfalfa as an example. *J. Econ. Entomol.* 81: 749-758.
- IRWIN, M. E. (1980) Sampling aphids in soybean fields. 239-259. In M. KOGAN and D. HERZOG (eds) *Sampling methods in soybean entomology*. Springer-Verlag, New York.
- KRING, T. J. and F. E. GILSTRAP (1983) Within-field distribution of greenbug (Homoptera: Aphididae) and its parasitoids in Texas winter wheat. *J. Econ. Entomol.* 76: 57-62.
- KUNO, E. (1966) A new method of sequential sampling to obtain the population estimates with a fixed level of precision. *Res. Pop. Ecol.* 11: 127-136.
- LATHEEF, M. A. (1972) Population dynamics of the Colorado potato beetle, *Leptinotarsa decemlineata* (SAY) on tomato in eastern Ontario. *Ph. D. Dissertation*, Carleton University, Ottawa.
- LEWIS, T. (1965) The effects of an artificial windbreak on the aerial distribution of flying insects. *Ann. appl. Biol.* 55: 503-512.
- NYROP, J. P. and R. J. WRIGHT (1985) Use of double sampling with reference to the Colorado potato beetle, *Leptinotarsa decemlineata* (Coleoptera: Chrysomelidae). *Environ. Entomol.* 14: 644-649.
- NYROP, J. P., A. M. AGNELLO, J. KOVACH and W. H. REISSIG (1989) Binomial sequential classification sampling plans for European red mite (Acari: Tetranychidae) with special reference to performance criteria. *J. Econ. Entomol.* 82: 482-490.
- RUDD, W. G. (1980) Sequential estimation of soybean arthropod population densities. 94-104. In M. KOGAN and D. HERZOG (eds) *Sampling methods in soybean entomology*. Springer-Verlag, New York.
- SHOWERS, W. B., E. C. BERRY and L. VON CASTER. (1980) Management of second generation European corn borer by controlling moths outside the cornfield. *J. Econ. Entomol.* 73: 88-91.
- SNEDECOR, G. W. and W. G. COCHRAN (1967) *Statistical methods*. 6th ed. Iowa State Univ. Press, Ames.
- TAYLOR, L. R. (1961) Aggregation, variance and the mean. *Nature (London)* 189: 732-735.
- TAYLOR, L. R. (1984) Assessing and interpreting the spatial distributions of insect populations. *Ann. Rev. Ehtomol.* 29: 321-357.
- TAYLOR, R. A. J. (1987) On the accuracy of insecticide efficacy reports. *Environ. Entomol.* 16: 1-8.
- TRUMBLE, J. T. (1985) Implications of changes in arthropod distribution following chemical application. *Res. Popul. Ecol.* 27: 277-285.
- TRUMBLE, J. T., J. V. EDELSON and R. N. STORY (1987) Conformity and incongruity of selected dispersion

- indicies in describing the spatial distribution of *Trichoplusia ni* (HÜBNER) in geographically separate cabbage plantings. *Res. Popul. Ecol.* 29: 155-166.
- TRUMBLE, J. T. and E. R. OATMAN (1984) Dispersion analysis and resource utilization of aphid parasitoids in a non-depletable environment. *Res. Popul. Ecol.* 26: 124-133.
- ZEHNDER, G. W. and J. J. LINDUKA (1988) Within-field distribution patterns and fixed-precision-level sampling plans for Colorado potato beetle (Coleoptera: Chrysomelidae) in tomatoes. *J. Econ. Entomol.* 81: 692-696.

精度固定逐次抽出計画の汎用性

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精度固定方式による逐次推定法 (KUNO, 1969) で分散-平均値関係に TAYLOR のべき乗則 (TPL) を用いた GREEN (1970) の逐次抽出計画について、TPL のパラメータ (α と b) の値の変化が調査停止線をどのように変化させるかを詳しく検討し、この抽出計画の、異なる場所・年次間での汎用性について考察した。

α を固定して b を大きくしていくと、停止線はある点を中心に回転する形で勾配を低下させていく。すなわち、密度がその中心点より低い範囲では b が増すほど調整終了に必要な観測個体数は増すが、その点以上の密度範囲では逆に b が増すほど必要観測個体数が減少することになる。他方、 b を固定して α を増していくと、停止線の勾配は変化しないが、その位置が上方に移行する。いずれにせよ、これらのパラメータ値の変化が抽出計画の実際に大きく影響することは明らかである。

一方、昆虫類やハダニ類の実際の分布データから、これらのパラメータ値や得られた調査停止線の地域間、あるいは年次間の変異性を調べたところ、同種内でも有意に変動しうることを、したがって、逐次推定計画の別地域や別年次への転用に際してはその汎用性についての検討が必要であることがわかった。そこでこのような地域・年次間変異をもたらす主要要因について考察し、あわせてサンプリング計画の発展に向けての問題点を指摘した。