A METHOD FOR SAMPLING ENDEMIC POPULATIONS OF THE SPRUCE BUDWORM (LEPIDOPTERA: TORTRICIDAE) BASED ON PROPORTION OF EMPTY SAMPLE UNITS

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ABSTRACT

A method for sampling low-density populations of larvae of the spruce budworm *(Choristoneura fumiferana* [Clem.]), based on visual estimates of the proportion of empty branches in an area, is proposed. Analysis of counts of spruce budworm larvae on 45-cm branch tips shows that the proportion of branch tips containing no budworm ("zero budworm") (p_0) is inversely related to the mean number of budworm per branch tip ($\hat{u}$). The presence of other lepidoptera does not affect estimates of p_0 on balsam fir, but does on white spruce. However, densities on white spruce are related to densities on balsam fir. The relative variability of zero-group estimates is higher than that of conventional branch tip sampling, but more zero-group samples can be taken in a fixed unit of time. Simulations revealed that, provided that the cost of obtaining zero-group samples is 0.6 that of conventional sampling, zero-group sampling will be more efficient than conventional sampling at densities lower than three budworm per branch tip. Also, simulations indicate that, because of the high efficiency of zero-group sampling at low budworm densities, stochastic sampling biases are less likely to occur than for conventional sampling.

RÉSUMÉ

Les auteurs proposent une méthode d'échantillonnage des populations clairsemées de larves de tordeuse des bourgeons de l'épinette *(Choristoneura fumiferana* [Clem.]) basée sur des estimations visuelles du pourcentage de branches vides dans une région. Une analyse des larves de tordeuse des bourgeons de l'épinette dénombrées sur des extrémités de rameaux de 45 cm montre que le pourcentage d'extrémités de rameaux sans tordeuse ("zéro tordeuse") [p_0] est inversement proportionnel au nombre moyen de tordeuses par extrémité de rameau ($\hat{u}$). Chez le sapin baumier, la présence d'autres espèces de lépidoptères ne modifie pas les estimations de p_0, phénomène qui a été par contre observé chez l'épinette blanche. Les densités de ces populations d'insectes présentes chez l'épinette blanche sont toutefois corrélées à celles observées chez le sapin baumier. La variabilité relative des estimations des unités vides est supérieure à celle obtenue par la méthode d'échantillonnage conventionnelle, mais un plus grand nombre d'échantillons vides peuvent être prélevés pendant une période donnée. En admettant que le coût de prélèvement d'échantillons vides est de 0.6 fois celui de l'échantillonnage conventionnel, des simulations ont révélé que l'échantillonnage des unités vides sera plus efficace que l'échantillonnage conventionnel lorsque la densité de la population sera inférieure à trois insectes par extrémité de rameau. Les simulations révèlent également que l'échantillonnage stochastique devrait être moins biaisé que l'échantillonnage conventionnel en raison du degré de précision élevé de l'échantillonnage des unités vides, en présence de faibles densités de populations de tordeuses.

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INTRODUCTION

Existing methods for sampling spruce budworm (*Choristoneura fumiferana* [Clem.]) larvae have concentrated on high-density populations (Morris 1955, Sanders 1980, Régnière and Sanders 1983), and it is possible, with a reasonable amount of effort, to obtain abundance estimates for moderate-to-high populations that have an acceptable degree of precision. However, at low population levels, the proportion of branches with no budworm is high, and the zero counts result in excessive variance of the abundance estimates. Consequently, the number of samples that must be collected in an area in order to obtain statistically valid results is prohibitive[1]. The Morris (1955) sampling plan has been modified for endemic budworm populations (Miller 1964)[2], but this still yields imprecise estimates and requires excessive manpower because of the large sample sizes. The high cost of sampling an area also limits the number of plots that can be reliably sampled.

Sampling costs can be reduced by three methods:

1) using a sample unit that has a lower variance;
2) streamlining the sampling method so that little effort per sample is required;
3) accepting a lower degree of precision.

The most logical sample unit is the whole branch (Morris 1955) or 45-cm branch tip (Miller et al. 1972); consequently, there is litle room for improvement in this respect. Settling for a lower degree of precision is unacceptable; therefore, the best alternative is to streamline the sampling method.

In the case of the spruce budworm, the presence or absence of feeding larvae can be determined quickly and reliably by visual inspection with binoculars from the ground[3]; in this way, the need for costly collection and examination of foliage units can be eliminated. The objective of this report is to present the zero-group method as an alternative means of measuring the abundance of low-density spruce budworm populations.

Specifically, this report will:

1) briefly outline the operational aspects of the conventional and zero-group methods for estimating spruce budworm;
2) outline the theory of estimating abundance by using the zero-group method, and apply it to the spruce budworm;
3) compare the precision and accuracy of the two methods on the basis of an analysis of real and simulated data.

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[1] Miller, C.A. and McDougall, G.A. 1966. The endemic density of the spruce budworm in different forest types with particular reference to the Green River area. Dep. For. Rur. Devel., Fredericton, N.B. Intern. Rep. M-10.

[2] Miller, C.A. 1964. A sampling plan for endemic populations of the spruce budworm. Dep. For., Fredericton, N.B. Interim Res. Rep.

[3] Wypkema, R.C.P. 1982. The role of avian predators in the control of spruce budworm at endemic levels. Queen's University, Kingston, Ont. PhD thesis. 109 p.

OPERATIONAL ASPECTS OF SAMPLING ENDEMIC SPRUCE BUDWORM POPULATIONS

Conventional Sampling

To appreciate fully the usefulness of the zero-group method for sampling spruce budworm larvae, a brief description of conventional sampling methods is necessary.

In conventional sampling, units of foliage are removed from several trees in an area by using extension pole pruners operated from the ground. The branches are measured, bagged, and labeled in the field and returned to the laboratory where they are examined and the budworm are counted. Originally, a whole branch formed the basic unit, and a stratified sample from each sample tree in the ratio 1:1:0.5:0.5 was taken from four arbitrarily designated crown levels (top to bottom). This plan was developed for intensive studies of the population dynamics of the spruce budworm for moderate-to-high population levels. For more extensive surveys, a single branch or 45-cm branch tip per sample tree is used (Sanders 1980, Régnière and Sanders 1983).

At low population levels, the proportion of branches with zero insects increases to the point at which a larger than feasible number of branches must be collected to obtain valid estimates (Régnière and Sanders 1983). Miller[2] modified Morris' (1955) sampling plan in an attempt to overcome this problem. Sampling effort was reduced by sampling only feeding larvae, and only one branch per tree was taken. Stratified sampling was not used since within-tree variation is minor in comparison with between-tree variation. Dobesberger and Lim (1983) and Régnière and Sanders (1983) presented data for the calculated number of single 45-cm branch samples required for fixed levels of precision. At low densities, several hundred branches are required. Such large sample sizes and the need to examine branches in the laboratory to detect budworm larvae reduce the number of plots that can be sampled in a year.

A method for reducing examination time was developed by DeBoo et al. (1973). This involved beating the foliage in a drum to dislodge larvae, which were then collected in a small receptacle and counted. This method resulted in a reduction of the time required to process a 45-cm branch tip from 19.8 to 4.3 man-minutes with greater than 95% recovery of larvae. The cost of collecting the sample was unaffected. Although this represented a vast improvement over the examination method, the reduction in time was still insufficient as 14.3 man-hours were required to process a sample of 200 branch tips.

Zero-group Method

Rather than try to streamline existing survey methods, we decided to use a novel approach developed for estimating the abundance of organisms with highly clumped spatial distributions. The technique requires that the proportion of empty sample units, rather than the number of insects per sample unit, be determined in an area. This is called zero-group sampling (Gerrard and Chiang 1970, Nachman 1984).

Surveys with binoculars have been used to estimate defoliation without removing foliage from the trees (Sanders 1980), with the result that sampling time has been reduced. It is also possible to use binocular surveys to examine branches visually for spruce budworm[3]. The observer choses a tree to examine on the basis of good visibility from the ground. A branch is scanned with binoculars, and if a budworm is present, the branch is recorded as positive. At least 100 branches should be examined, and the proportion of branches from which budworm are absent (i.e., "zero budworm") is calculated and subjected to mathematical treatment to determine the density of budworm in the plot.

Sampling errors can be minimized by surveying in the morning or afternoon when side-lighting highlights the webs[3]. For the zero-group method, only the presence of budworm on a branch or their absence from it is determined, and if a careful search is made, the errors associated with detecting budworm larvae are small. This method is best suited to balsam fir *(Abies balsamea* [L.] Mill.) as it has very symmetrical branches. White spruce *(Picea glauca* [Moench] Voss) has bushier, more irregular branches that affect visibility; also, it is host to a greater variety of insects than is balsam fir. The presence of other insects on the branches may cause errors because of incorrect classification, but only if these are seen on branches that do not also contain budworm.

ESTIMATION OF POPULATION SIZE

Conventional Method

Estimation of population levels by means of the conventional sampling method is straightforward. Density can be expressed as the average number of insects per unit area of foliage (Morris 1955) or as the average number of insects per whole branch or per 45-cm branch tip (Miller et al. 1972). The average number of insects per 45-cm branch tip is the unit that will be used to indicate density throughout this report. The mean (m) is calculated as:

$$m = \frac{\Sigma X_i}{n} \qquad (1)$$

and the variance (V[m]) as:

$$V[m] = \frac{\Sigma X_i^2 - \frac{(\Sigma X_i)^2}{n}}{n - 1} \qquad (2)$$

where X_i = the number of insects on a single branch tip and n = the number of branch tips in the sample. The relationship between the sample mean and variance is often expressed as:

$$\ln V[m] = \ln a + b \ln m \qquad (3)$$

which is Taylor's power relationship (Taylor 1961). Equation 3 has been used previously to estimate sample sizes for low-level spruce budworm populations (Régnière and Sanders 1983).

The relative variability of the estimates, C[m], can be calculated as:

$$C[m] = \frac{(V[m]/n)^{1/2}}{m} \qquad (4)$$

(Karandinos 1976).

Zero-group Method

In order to use the zero-group method, it is first necessary to determine:

1) the relationship between the number of budworm per branch (m) and the proportion of branch tips with zero individuals (p_o);
2) the relationship between m and V[m] as determined according to Taylor's power relationship (Taylor 1961).

Once these relationships have been determined from a series of samples taken over a range of densities, equations to estimate the population mean density ($\hat{u}$) and its variance (V[$\hat{u}$]) from p_o can be developed (Gerrard and Chiang 1970, Nachman 1984). A brief summary of the estimation procedures is provided below.

The relationship between m and p_o from the *a priori* data set is determined by linear regression according to the model:

$$\ln m = a' + b' \ln(-\ln p_o) \qquad (5)$$

(Nachman 1984).

If we assume that m is a valid estimate of $\hat{u}$, and if a measure of p_o is available for a particular area, equation 5 can be rearranged to calculate budworm density as:

$$\hat{u} = \exp(b' \ln(-\ln p_o) + a' + s^2/2) \qquad (6)$$

where a' and b' are the regression coefficients from equation 5 and s^2 is the error mean square from this regression. This correction ($s^2/2$) is necessary to eliminate bias resulting from regression of logarithmically transformed data (Nachman 1984).

The variance of ln $\hat{u}$ can be estimated, and has three additive components. The first results from use of the regression equation to estimate ln $\hat{u}$ from p_o, the second is due to estimation of p_o itself, and the third is from the spatial distribution of the insects on the branches. The formula used is:

$$V[\ln \hat{u}] = s^2 \left[\frac{1}{N} + \frac{(\ln(-\ln p_o) - \bar{X})^2}{SSDx} + \frac{(b')^2 (1-p_o)}{np_o (\ln p_o)^2} + \frac{a}{n} \hat{u}^{b-2} \right] \quad (7)$$

The terms of the equation are:

s^2 = error mean square from the regression of ln m on $\ln(-\ln p_o)$
N = number of observation pairs used in the regression
$\bar{X}$ = mean of $\ln(-\ln p_o)$
SSD_x = sum of squared deviations of $\ln(-\ln p_o)$
b' = slope of the regression in equation 5
p_o = proportion of empty sample units determined by taking n samples from an area
$\hat{u}$ = as described previously (equation 6)
a and b = regression parameters from the relationship between the mean and variance of a sample (equation 3).

Nachman (1984) showed:

$$V[\hat{u}] \simeq \hat{u}^2 V[\ln \hat{u}] \quad (8)$$

and following this, the relative variablity of $\hat{u}$, $C[\hat{u}]$, can be expressed as:

$$C[u] = \frac{V[\hat{u}]^{1/2}}{\hat{u}} = V[\ln \hat{u}]^{1/2} \quad (9)$$

This last result is very important for sample size considerations as it allows direct calculation of the precision of $\hat{u}$ from equation 7.

PARAMETER ESTIMATES

Source of Data

Data were collected from 1972 to 1982 in several plots near Black Sturgeon Lake in northwestern Ontario. Branches were collected in the conventional manner from white spruce and balsam fir, and consisted of at least twenty 45-cm mid-crown branch tips. Hence, 41 estimates of m, V[m], and p_o were available from white spruce, and 42 for balsam fir. Parameters for equations 3, 5 and 7were estimated by means of linear regression after the appropriate transformations were made.

The presence of other forest lepidoptera on each branch tip was recorded and the proportion of branches with no insects at all, p_ot, was calculated. The relationship between p_o and p_ot was determined by linear regression for both hosts, and t-tests were used to determine if the intercept and slope differed significantly from 0 and 1, respectively. A slope = 1 and intercept = 0 would indicate that the presence of other insects on the foliage does not affect estimates of the proportion of branches infested with spruce budworm. The relationship between ln (density on white spruce) and ln (density on codominant balsam fir) was also determined by means of linear regression. All analyses were conducted according to Statistical Analysis Systems (Anon. 1982).

Relationships Between m, V[m], and p_o

The relationship between m and V[m] for white spruce and balsam fir, respectively, was as follows (Fig. 1 and 2):

$$\ln V[m] = 0.709 + 1.291 \ln m, \quad r^2=0.97 \tag{10}$$

and

$$\ln V[m] = 0.769 + 1.240 \ln m, \quad r^2=0.97 \tag{11}$$

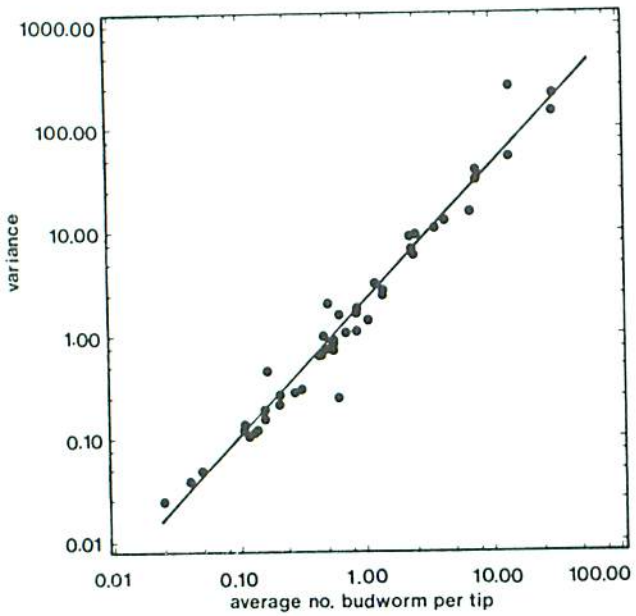

Figure 1. Relationship between the mean and variance of the number of spruce budworm per 45-cm branch tip on white spruce.

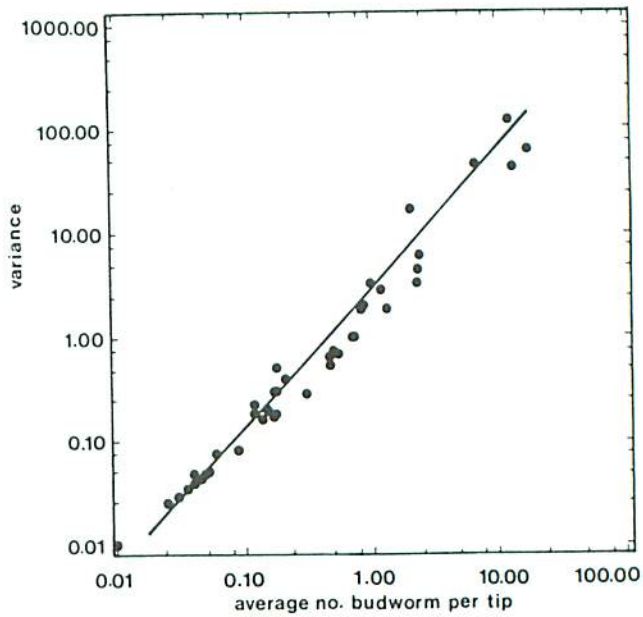

Figure 2. Relationship between the mean and variance of the number of spruce budworm per 45-cm branch tip on balsam fir.

The relationship between m and p_o for white spruce and balsam fir, respectively, was (Fig. 3 and 4):

$$\ln m = 0.358 + 1.128 \ln (-\ln p_o), \quad r^2=0.98 \tag{12}$$

and

$$\ln m = 0.427 + 1.120 \ln (-\ln p_o), \quad r^2=0.97 \tag{13}$$

Hence, for both white spruce and balsam fir, ln V[m] can be accurately predicted from ln m. As the density in an area increases, the proportion of empty sample units decreases. Values of the regression parameters used in estimating V[ln u] (equation 7) strictly from estimates of p_o are given in Table 1.

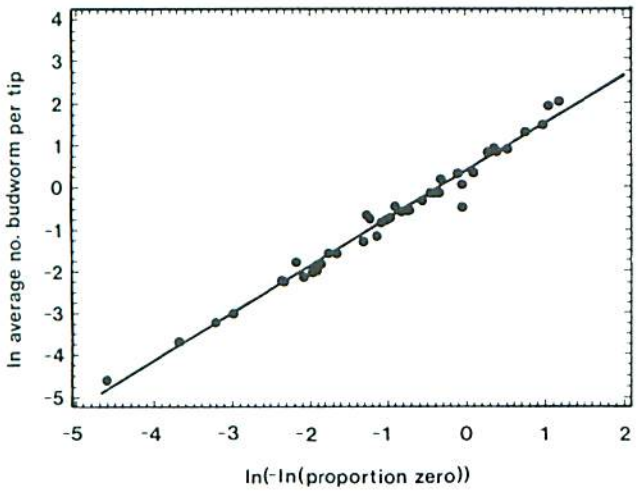

Figure 3. Relationship between the mean number of spruce budworm per 45-cm branch tip and the proportion of empty sample units on white spruce.

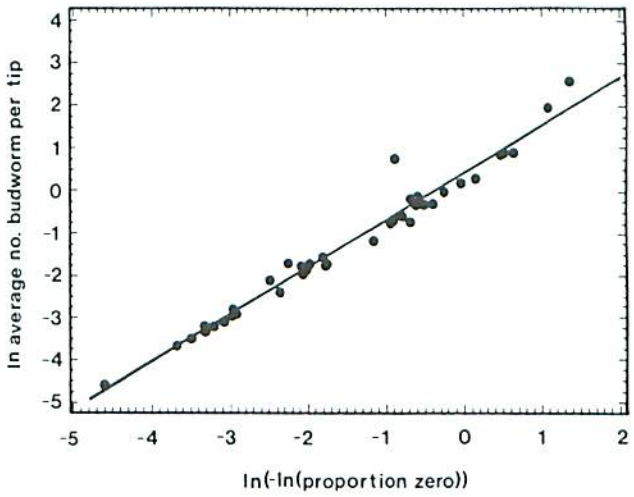

Figure 4. Relationship between the mean number of spruce budworm per 45-cm branch tip and the proportion of empty sample units on balsam fir.

Table 1. List of parameters used to estimate the number of spruce budworm larvae per branch tip from the proportion of empty branch tips.

Parameter	White spruce	Balsam fir
a	2.0318	2.1576
b	1.2907	1.2397
a'	0.3578	0.4269
b'	1.1275	1.1204
s^2	0.0437	0.0840
N	43	42
SSD_x	69.3173	85.1066
$\bar{X}$	-0.9800	-1.5703

Effect of Other Insects on Estimation of p_o

The relationship between the proportion of branches without spruce budworm (p_o) and the proportion of branches without any insects (p_ot) was, for white spruce, as follows (Fig. 5):

$$p_o = 0.42 + 0.57\ p_ot,\ se(b_o) = 0.07,\ se(b_1) = 0.16,\ r^2 = 0.27 \qquad (14)$$

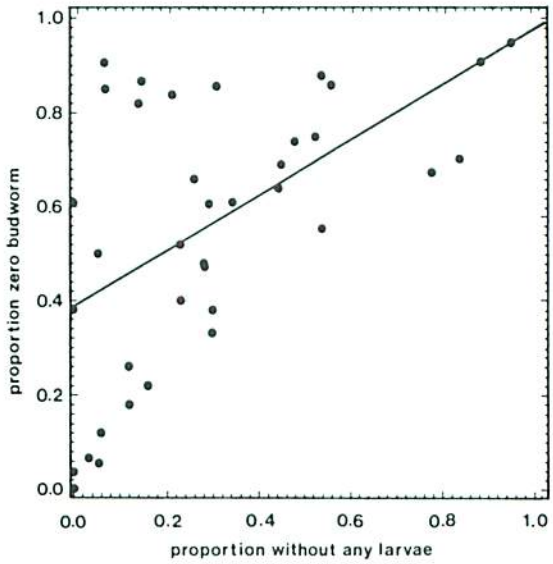

Figure 5. Relationship between the proportion of sample units without spruce budworm and the proportion without any lepidoptera on white spruce.

The slope was significantly different from 1 ($t = 2.62$; $df = 34$; $p = 0.013$) and the intercept was significantly different from 0 ($t = 6.22$; $df = 34$; $p = 0.0001$). Hence, it can be seen that the presence of other insects on white spruce branches will complicate estimation of p_o.

The relationship between p_o and p_ot for balsam fir was as follows Fig. 6):

$$p_o = 0.04 + 0.98\ p_ot,\ se(b_o) = 0.03,\ se(b_1) = 0.04,\ r^2 = 0.95 \qquad (15)$$

The slope was not significantly different from 1 ($t = 0.51$; $df = 37$; $p = 0.617$) and the intercept was not significantly different from 0 ($t = 1.53$; $df = 37$; $p = 0.1341$); hence, other insects are not sufficiently common on balsam fir to affect estimates of p_o. However, since densities of spruce budworm on codominant balsam fir and white spruce are related (Fig. 7, $r^2 = 0.80$), estimation of p_o on balsam fir is sufficient to estimate spruce budworm density in mixed stands.

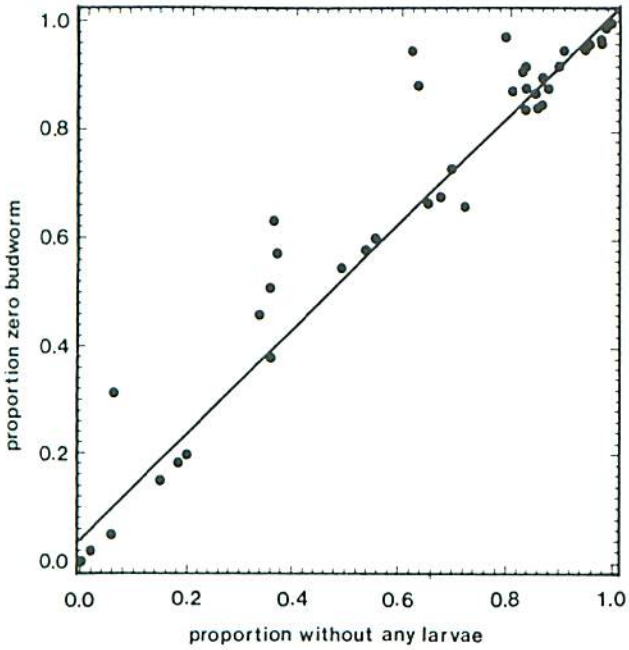

Figure 6. Relationship between the proportion of sample units without spruce budworm and the proportion without any lepidoptera on balsam fir.

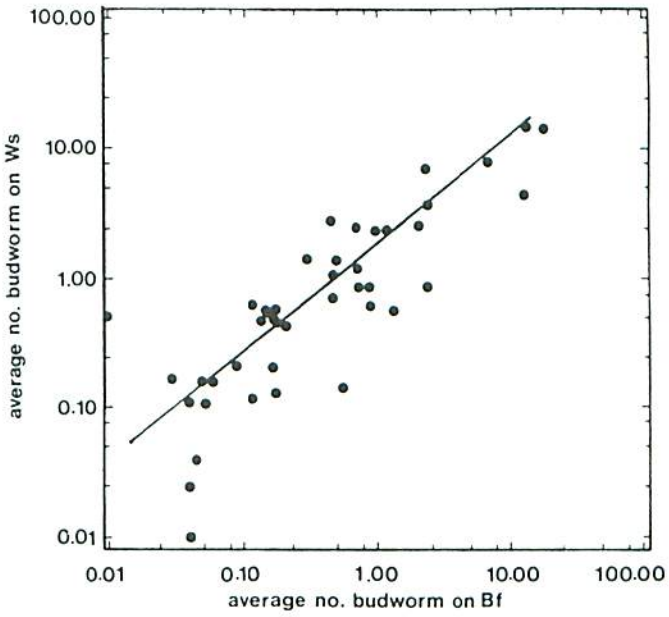

Figure 7. Relationship between the density of spruce budworm on white spruce and on balsam fir.

COMPARISON OF METHODS

Relative Variability

Because white spruce is unsuitable for visual surveys, because of the difficulty involved in seeing feeding larvae on trees of this species, and because of the presence of other insects, the zero-group method is applicable only to balsam fir. Therefore, comparisons between the two methods will be made for this host only. For comparisons between the conventional and zero-group methods, sample sizes were fixed at 50, 100, 250 and 500 branches since, in practice, sample sizes are generally predetermined on the basis of available manpower.

The relative variablity of conventional abundance estimates was calculated from equation 4 by using the level of abundance to estimate its variance (equation 3). The results are shown in Figure 8. For all sample sizes of 50 branches or more, the relative variability of the estimates is less than 1 (SE = $\bar{X}$), and variability decreases with increasing levels of abundance.

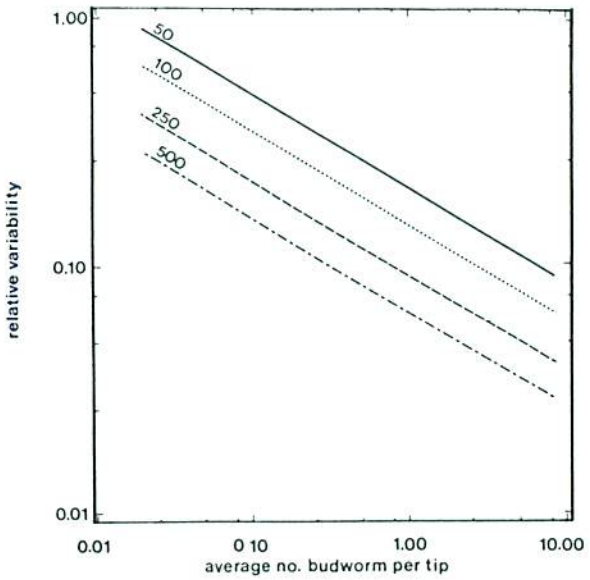

Figure 8. Relative variability of conventional estimates of spruce budworm density at various densities for n = 50, 100, 250, and 500 branches.

The relative variability of abundance estimates with the zero-group method was estimated from equations 6, 7 and 9. The change in relative variabilty of the estimates with density is shown in Figure 9. For sample sizes of 100 or more, the standard error is less than or equal to the mean at densities of less than one larva per branch tip. At densities of more than one larva per branch tip, variability increases because of increasing uncertainty associated with the estimation of p_o, an inherent property of the binomial distribution. The variance of p_o is greatest when very few or very many sample units are occupied.

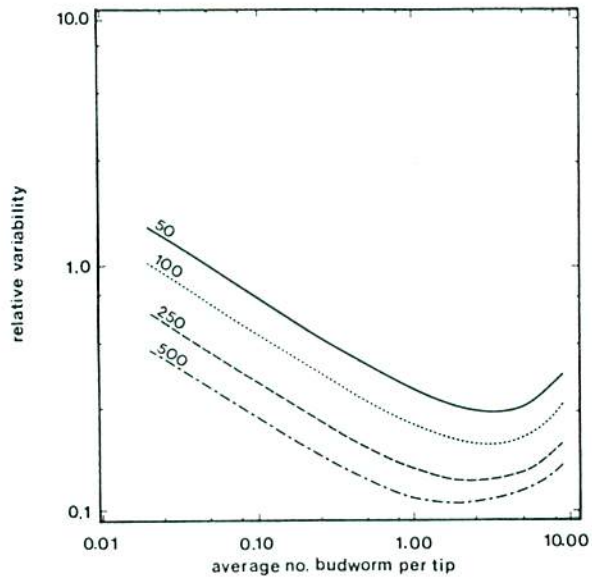

Figure 9. Relative variability of zero-group estimates of spruce budworm density at various densities for n = 50, 100, 250, and 500 branches.

The ratio of the relative variability of the zero-group estimates to conventional estimates for a given density and sample size was calculated as $C[\hat{u}]/C[m]$ and is shown in Figure 10. The relative variability of the two methods will be equal when this ratio equals 1; that of the zero-group method will be more variable if this ratio is greater than 1 and less variable if the ratio is less than 1. At low budworm densities (< 1.0 larvae per branch tip), variability associated with the zero-group estimates is ca 1.6 times that of the conventional estimates for a fixed sample size. Above this density, $C[\hat{u}]$ increases at a greater rate than $C[m]$.

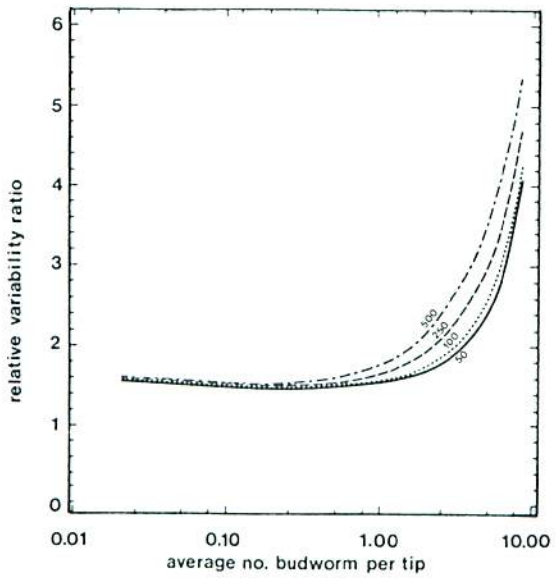

Figure 10. Ratio of the relative variability of zero-group to conventional estimates of spruce budworm abundance for n = 50, 100, 250 and 500 branches.

Relative Efficiency

Any comparison between conventional and zero-group sampling should also take into consideration the cost of sampling (Nachman 1984). For the conventional method, the cost per sample equals the time required to collect a branch, ca 3 man-minutes, plus the time required to move the sampling equipment from tree to tree, ca 1 man-minute (Morris 1955), plus the time required to examine the sample, ca 4.3 man-minute with the drum-beating technique of DeBoo et al. (1973), for a total cost per sample unit of 8.3 man-minutes. The zero-group method will require slightly less time for the move from tree to tree since transporting cumbersome equipment is not required: i.e., ca 0.75 man-minute, plus 1 man-minute to examine a branch tip from the ground, for a total of 1.75 man-minutes per sample unit.

If we assume that the time required for a two-man crew to sample a site is 7 hours, 840 man-minutes would be available to collect and process the sample. It requires 8.3 man-minutes to collect and process each sample unit by the conventional method, as opposed to 1.75 man-minutes per sample unit by the zero-

group method. If the zero-group method is used, ca 480 trees can be sampled; if the conventional method is used, only 100 can be sampled. Abundance estimates in the range of 0.01 to 10 larvae per branch tip would have relative variabilities of 0.55 to 0.10 with 500 zero-group samples in comparison with 0.77 to 0.10 with 100 conventional samples. Although estimates obtained by the zero-group method have higher variation than do estimates obtained with the same sample size by the conventional method, the zero-group method is less expensive per sample. More samples can be taken in an area if the zero-group method is used, and estimates with higher overall precision may result.

The relative efficiency of a sample method is defined as:

$$RE = \frac{\bar{X}}{(SE)(Cs)} = \frac{1}{C[\bar{X}]}\,\frac{1}{Cs} \qquad (16)$$

This is also termed relative net precision (Ruesink 1980). $\bar{X}$ is the sample mean, SE is the standard error, $C[\bar{X}]$ is the relative variability of the estimate, and Cs is the total cost of obtaining the sample (the cost required to collect a single sample unit, c, multiplied by the sample size, n).

The relative efficiency of the sample methods was evaluated at different densities for sample sizes of 50, 100, 250, and 500 branch tips and is recorded in Figures 11 and 12. For any fixed sample size, the zero-group method had a much higher relative efficiency than the conventional method at densities up to 10 larvae per branch tip. Hence, the lower cost of obtaining samples by the zero-group method more than compensates for the lower degree of precision of the method.

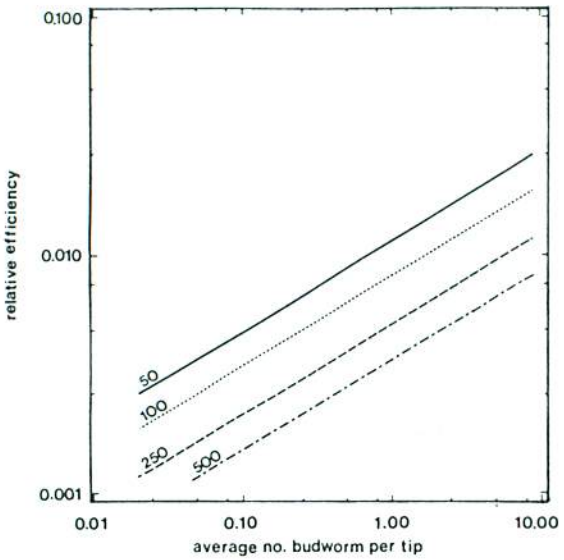

Figure 11. Relative efficiency of conventional estimates of spruce budworm density at various densities for n = 50, 100, 250, and 500 branches.

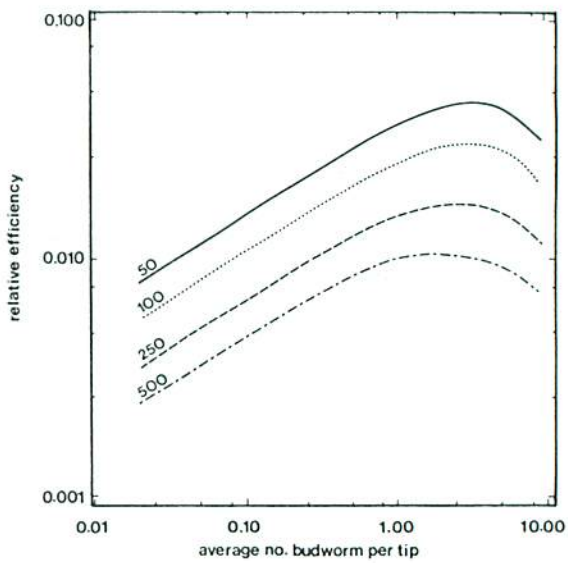

Figure 12. Relative efficiency of zero-group estimates of spruce budworm density at various densities for n = 50, 100, 250, and 500 branches.

The two methods can also be compared on the basis of equal sampling cost rather than equal sample size. Since the cost per sample unit with the conventional method is nearly five times that of the zero-group method, 50 and 100 conventional samples cost the same as 250 and 500 zero-group samples, respectively. The comparison is easily made by superimposing Figures 11 and 12, and determining the points of intersection of the two sets of lines (Fig. 13). This occurs at ca two larvae per branch tip; therefore, for a fixed amount of effort, the zero-group method is more efficient at densities of two larvae per branch tip or fewer, while above this level, the conventional method is more efficient on the basis of equal sample cost.

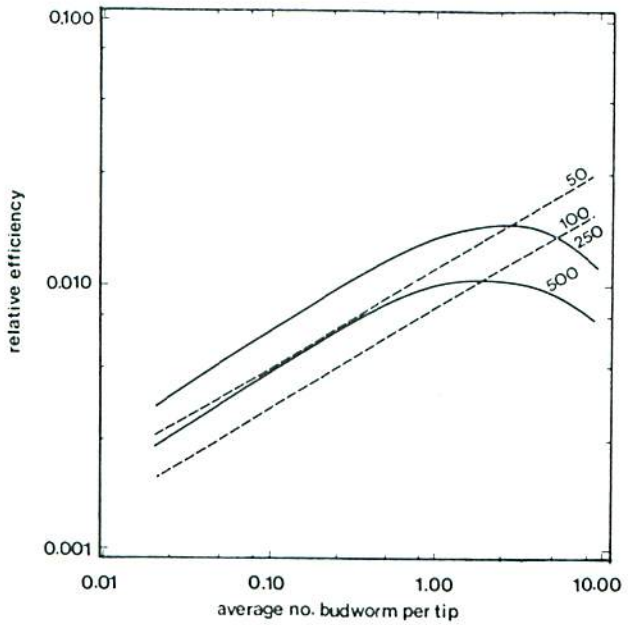

Figure 13. Relative efficiency of estimates of spruce budworm density at various densities for a fixed amount of effort. Dashed lines are conventional estimates with n = 50 and 100; solid lines are zero-group estimates with n = 250 and 500. Collection of 50 conventional sample units requires the same effort as 250 zero-group sample units.

The costs per sample unit used are best estimates based on available information and experience. These costs can vary depending on the skill and experience of the observer. The effect of altering the cost per sample unit on the relative efficiency of the zero-group method in relation to the conventional method was examined by increasing this cost two and three times. The results are shown in Figure 14. If c is set at 1.75, the zero-group method is much more efficient than the conventional method as has already been demonstrated. This is true for densities of fewer than three budworm per branch tip even if the cost per sample unit for the zero-group method is doubled. Only if 5 man-minutes per zero-group sample unit were required would the relative efficiency of the zero-group method be consistently equal to or less than that of the conventional method.

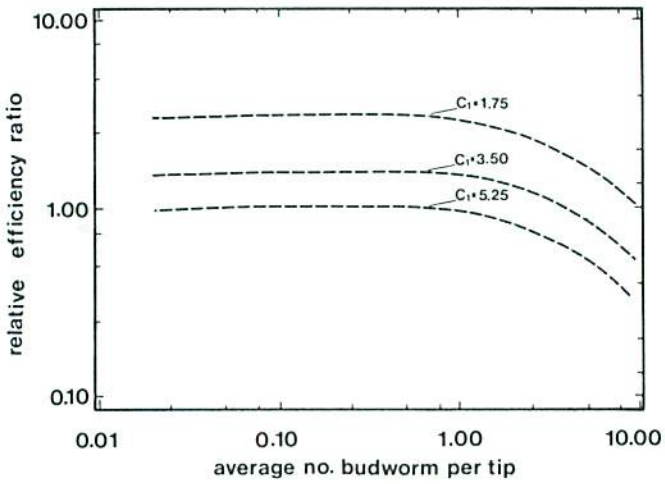

Figure 14. Effect of altering the cost per zero-group sample unit on the ratio of the relative efficiency of zero-group estimates to conventional spruce budworm density estimates.

Stochastic Sampling Bias

So far, comparisons have been made between the two methods in terms of variability, cost and efficiency. Accuracy is also an important criterion when one is evaluating sampling methods Inaccuracies may be attributable to many factors, such as the experience, interest and competence of the workers, but can be minimized or reduced by means of adequate supervision and training. Sampling error can arise when one is sampling populations in which a large proportion of the sampling units contain zero individuals. It is quite possible that if the sample consists of fewer than 100 branches, few insects or none at all will be found. As a result, the sample mean will be less than the population mean. This is termed stochastic sampling bias and arises as a result of sampling a particular distribution.

This source of bias was estimated by means of simple computer simulations. The datasets with $\bar{x} \leqslant 0.05$ budworm per branch tip were pooled and used to construct a frequency distribution of spruce budworm counts (Table 2). A negative binomial distribution with parameters $\bar{x}$ = 0.0375 and k = 3.2173 described this distribution well (χ^2 = 0.023; df = 1; p 0.90) and was used with a random number generator to draw samples of n = 50, 100, 250 and 500 "branches" from 100 simulated populations. The results are shown in Table 3. Even with a sample size of n = 50 branches per site, the true population mean was underestimated by almost 50% in over half of the simulations. Twenty percent of the simulations had a mean of 0. Thirty-seven percent of the simulated means were underestimates when n equalled 100 and 3% equalled 0. When n equalled 250 or 500, no estimates of 0 were obtained, fewer underestimates occurred, and the extreme values were closer to the theoretical mean. Since the zero-group method allows sample sizes of 250 and 500 with the equivalent effort of obtaining only 50 or 100 conventional samples, the problem of stochastic sampling bias is greatly reduced when the zero-group method is employed.

Table 2. Frequency distribution of the number of spruce budworm per branch tip on balsam fir for datasets with mean density = 0.05 budworm per branch tip.

Larvae per branch tip	Observed frequency	Expected frequency[a]	Expected proportion[a]
0	1055	1054.986	0.9635
1	39	39.047	0.0356
2	1	0.947	0.0009
3	0	0.019	0.0001

[a] Expected frequency and proportion based on a negative binomial with parameters $\bar{x} = 0.0375$ and $\hat{k} = 3.2173$.

Table 3. Results of sampling n branches from 100 simulated spruce budworm populations with a negative binomial distribution and parameters $\bar{x}$ = 0.0375 and $\hat{k}$ = 3.2173

Branches/sample	Mean of 100 samples	Range of sample means	% means = 0.02	% means = 0
50 (conventional)	0.031	0.100	53	20
100 (conventional)	0.036	0.100	37	3
250 (conventional)	0.036	0.052	8	0
500 (conventional)	0.037	0.034	1	0
250 (zero-group)	0.038	0.064	8	0
500 (zero-group)	0.039	0.040	1	0

SUMMARY

At densities of fewer than two larvae per branch tip, the zero-group method is more efficient than conventional sampling because of lower sampling costs. Higher relative variability of the estimates is offset by the increased number of samples that can be taken on a site, and estimates with higher overall precision per unit cost result. There are no data for comparing zero-group estimates with conventional estimates. More work needs to be done in this area. Simulations show that, since for the same cost much larger samples sizes can be obtained by the zero-group method than by conventional sampling, stochastic sampling biases are much less likely to occur with zero-group sampling than with conventional sampling at the same cost.

The zero-group method is applied by examining one branch tip from each of 200 or more balsam fir trees in an area. The proportion of branch tips with 0 individuals is calculated and used with equation 6 to calculate $\hat{u}$, mean density. The variance of $\ln \hat{u}$ is calculated by using equation 7, and is converted to the variance of $\hat{u}$ by using equation 8.

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