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# Sampling Western Spruce Budworm Larvae by Frequency of Occurrence on Lower Crown Branches

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## Abstract

A sampling method was derived whereby budworm density can be estimated by the frequency of occurrence of larvae over a given threshold number instead of by direct counts on branch samples. The model used for converting frequencies to mean densities is appropriate for nonrandom as well as random distributions and, therefore, is applicable to all population densities of budworm. The method is suggested as a possible alternative to the direct counting of larvae in lower crown sampling.

Keywords: Sampling insects, insect defoliators, western spruce budworm, *Choristoneura occidentalis*, frequency sampling.

## Introduction

Estimates of larval abundance are critical to almost all phases of management of the western spruce budworm, *Choristoneura occidentalis* Freeman. The density of larvae in the middle crown of the host tree expressed as the number of individuals per square meter of branch area is a commonly used relative index of abundance. Density is estimated when most larvae are fourth instars and can be easily dislodged from the foliage for counting. Larvae are usually counted on 45-centimeter branch tips clipped from the midcrown with a pole pruner (Srivastava and others 1984). Mid-crown densities can also be estimated by the nondestructive beating of lower crown branches (Mason and others 1989).<sup>1</sup> Both methods require a complete count of all budworm larvae that drop off the sample branches. We have developed a new technique, recommended especially for lower crown sampling, by which budworm densities can be quickly estimated by counting only a fraction of the larvae on the sample.

In sparse populations, the density of insects can often be estimated simply by the frequency of occurrence of a single individual of the species on foliage samples. This is because at low densities insects are usually randomly distributed on samples and follow a Poisson series where the mean,  $y$ , is related to the proportion,  $p$ , of infested samples by

$$y = -\ln(1-p). \quad (1)$$

<sup>1</sup> Colbert, J.J.; Beckwith R.C. Sampling the western spruce budworm (Lepidoptera:Tortricidae): the relation between lower crown larval counts and midcrown density. Manuscript in review.

Techniques using this relation, or variations of it, are recommended for sampling sparse populations of at least two other forest defoliators, the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McD.) (Mason 1977, 1987), and the eastern spruce budworm, *Choristoneura fumiferana* (Clem.) (Lysyk and Sanders 1987). As sparse populations increase in density, the spatial distribution of individuals on samples unfortunately departs from randomness, and equation (1) tends to underestimate densities. The equation, therefore, is inappropriate for higher densities where individuals are usually aggregated.

To find a way to use frequency data to estimate means at all population densities, Gerrard and Chiang (1970) developed a new approach that is applicable to nonrandom as well as random distributions. The procedure first requires deriving a mathematical expression from conventional sample data that reflects the underlying spatial distribution of the insect. Density can then be estimated for any size population by knowing the proportion of sample units exceeding a given threshold of insects.

## Methods

### Data Set

To construct the appropriate model for the western spruce budworm, sample data were needed from a variety of natural budworm populations. The data used were direct counts of nominal fourth instars on samples collected from 1980 to 1982 in budworm outbreaks in north-central Washington and northeastern Oregon. Budworm populations were sampled at 15 sites, some in each of the 3 years and others only once. Sites were comprised of mixed conifer types dominated by budworm host species of grand fir, *Abies grandis* (Dougl.) Lindl., and Douglas-fir, *Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco. Sample plots differed in size and usually contained 25, but occasionally 20 or 100, selected trees representative of the local host type. The primary sample unit was three 45-centimeter branch tips on each of the sample trees on the plot. All larvae were counted on each three-branch sample unit, with plot density expressed as the mean number of larvae per sample. Separate samplings were made from the middle one-third of the crown and from the lower crown, usually 1-2 meters from the ground, and were summarized independently. Branch tips in the midcrown were clipped from the tree by using a pole pruner with basket (Paul 1979); the larvae were removed by beating the branches over a ground cloth where they were counted. Branch tips in the lower crown were rapped in place to dislodge larvae onto a handheld dropcloth (Mason and others 1989). The final data set contained 52 samplings, half from each of the two crown levels, for which means and proportions of counts exceeding selected threshold densities were calculated (table 1).

Table 1—Data set of mean number of budworm larvae per sample unit in relation to the proportion of samples with larval numbers equal to or more than specified threshold densities ( $t$ )

**Table 1—Data set of mean number of budworm larvae per sample unit in relation to the proportion of samples with larval numbers equal to or more than specified threshold densities ( $t$ )**

| Trees per plot | Mean per sample | Proportion of samples containing at least $t$ larvae <sup>a</sup> |         |         |         |         |          |          |          |
|----------------|-----------------|-------------------------------------------------------------------|---------|---------|---------|---------|----------|----------|----------|
|                |                 | $t = 1$                                                           | $t = 2$ | $t = 3$ | $t = 5$ | $t = 8$ | $t = 13$ | $t = 21$ | $t = 34$ |
| 20             | 37.40           | 1.00                                                              | 1.00    | 1.00    | 1.00    | 1.00    | 1.00     | 0.90     | 0.45     |
| 20             | 2.35            | .85                                                               | .65     | .40     | .10     | 0       | 0        | 0        | 0        |
| 20             | 2.35            | .90                                                               | .60     | .45     | .10     | 0       | 0        | 0        | 0        |
| 20             | 3.20            | .95                                                               | .65     | .50     | .30     | .05     | 0        | 0        | 0        |
| 25             | 36.52           | 1.00                                                              | 1.00    | 1.00    | 1.00    | 1.00    | 1.00     | .96      | .56      |
| 25             | 40.96           | 1.00                                                              | 1.00    | 1.00    | 1.00    | 1.00    | 1.00     | .84      | .68      |
| 25             | 15.64           | 1.00                                                              | 1.00    | .96     | .84     | .68     | .52      | .32      | .04      |

See footnote on next page.

Table 1—continued

| Trees<br>per<br>plot | Mean<br>per<br>sample | Proportion of samples containing at least <i>t</i> larvae <sup>a</sup> |              |              |              |              |               |               |               |
|----------------------|-----------------------|------------------------------------------------------------------------|--------------|--------------|--------------|--------------|---------------|---------------|---------------|
|                      |                       | <i>t</i> = 1                                                           | <i>t</i> = 2 | <i>t</i> = 3 | <i>t</i> = 5 | <i>t</i> = 8 | <i>t</i> = 13 | <i>t</i> = 21 | <i>t</i> = 34 |
| 25                   | 10.45                 | 1.00                                                                   | .95          | .95          | .70          | .65          | .45           | .05           | 0             |
| 25                   | 3.52                  | .92                                                                    | .76          | .56          | .28          | .08          | .04           | 0             | 0             |
| 25                   | .68                   | .44                                                                    | .20          | .04          | 0            | 0            | 0             | 0             | 0             |
| 25                   | 37.88                 | 1.00                                                                   | 1.00         | 1.00         | 1.00         | 1.00         | 1.00          | .96           | .44           |
| 25                   | .20                   | .20                                                                    | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 0                     | 0                                                                      | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 0                     | 0                                                                      | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 7.96                  | 1.00                                                                   | .88          | .80          | .68          | .44          | .20           | .08           | 0             |
| 25                   | 4.32                  | .84                                                                    | .68          | .48          | .44          | .16          | .04           | 0             | 0             |
| 20                   | 2.04                  | .88                                                                    | .60          | .28          | .08          | 0            | 0             | 0             | 0             |
| 25                   | 1.56                  | .76                                                                    | .52          | .24          | 0            | 0            | 0             | 0             | 0             |
| 25                   | 1.40                  | .72                                                                    | .40          | .12          | .04          | 0            | 0             | 0             | 0             |
| 25                   | 6.36                  | .96                                                                    | .84          | .76          | .52          | .24          | .12           | .08           | 0             |
| 25                   | 4.48                  | .88                                                                    | .80          | .80          | .44          | .12          | 0             | 0             | 0             |
| 25                   | 12.44                 | 1.00                                                                   | 1.00         | 1.00         | .88          | .80          | .52           | .12           | 0             |
| 25                   | .08                   | .08                                                                    | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | .04                   | .04                                                                    | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 0                     | 0                                                                      | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 12.88                 | .92                                                                    | .92          | .92          | .80          | .64          | .48           | .24           | 0             |
| 100                  | 17.10                 | 1.00                                                                   | 1.00         | 1.00         | .95          | .85          | .67           | .36           | .04           |
| 100                  | 1.84                  | .86                                                                    | .56          | .27          | .05          | 0            | 0             | 0             | 0             |
| 100                  | 2.09                  | .83                                                                    | .51          | .34          | .10          | .03          | 0             | 0             | 0             |
| 100                  | 1.91                  | .80                                                                    | .49          | .28          | .07          | .02          | 0             | 0             | 0             |
| 25                   | 20.52                 | 1.00                                                                   | 1.00         | 1.00         | 1.00         | .92          | .88           | .48           | 0             |
| 25                   | 22.64                 | 1.00                                                                   | 1.00         | 1.00         | .96          | .96          | .76           | .48           | .16           |
| 25                   | 8.84                  | 1.00                                                                   | .84          | .80          | .68          | .44          | .20           | .10           | 0             |
| 25                   | 7.35                  | 1.00                                                                   | .95          | .85          | .70          | .35          | .15           | .05           | 0             |
| 25                   | 4.00                  | .92                                                                    | .72          | .60          | .40          | .12          | .04           | 0             | 0             |
| 25                   | .24                   | .20                                                                    | .04          | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 17.76                 | 1.00                                                                   | 1.00         | 1.00         | 1.00         | .92          | .76           | .32           | .04           |
| 25                   | 0                     | 0                                                                      | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | .04                   | .04                                                                    | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | .08                   | .08                                                                    | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 11.44                 | 1.00                                                                   | .92          | .88          | .80          | .64          | .40           | .12           | 0             |
| 25                   | 4.28                  | .68                                                                    | .52          | .44          | .40          | .20          | .08           | 0             | 0             |
| 25                   | 1.20                  | .40                                                                    | .28          | .16          | .08          | .04          | 0             | 0             | 0             |
| 25                   | 1.20                  | .64                                                                    | .48          | .08          | 0            | 0            | 0             | 0             | 0             |
| 25                   | .52                   | .32                                                                    | .12          | .04          | 0            | 0            | 0             | 0             | 0             |
| 25                   | 3.24                  | .76                                                                    | .52          | .48          | .28          | .04          | .04           | 0             | 0             |
| 25                   | 3.00                  | .88                                                                    | .80          | .44          | .20          | .08          | 0             | 0             | 0             |
| 25                   | 4.48                  | .88                                                                    | .72          | .60          | .40          | .16          | .04           | 0             | 0             |
| 25                   | 0                     | 0                                                                      | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | .04                   | .04                                                                    | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 0                     | 0                                                                      | 0            | 0            | 0            | 0            | 0             | 0             | 0             |
| 25                   | 7.28                  | 1.00                                                                   | .92          | .84          | .60          | .36          | .12           | .08           | 0             |

<sup>a</sup> A sample unit was three 45-cm branch tips from a tree.

## Analysis

All analyses of data followed the method described by Gerrard and Chiang (1970). Using their procedure, we developed a new equation for estimating mean larval density per sample,  $y$ . Independent variables are the selected threshold density,  $t$ , and the proportion,  $p$ , of primary sample units on the plot containing at least  $t$  larvae. In its logarithmic form, the final Gerrard and Chiang model is

$$\ln(y) = \ln(a) + b \ln[-\ln(1 - p)] + c \ln(t) + d \ln(t) \ln[-\ln(1 - p)] . \quad (2)$$

Parameters in the equation were estimated by substituting values of  $p$  for a range of threshold densities and solving by least squares.

Two sources of error are associated with the above model in estimating  $\ln y$ : (1) variability in the estimate of the parameters, and (2) sampling errors in estimating frequency (Gerrard and Chiang 1970). Parameter errors were estimated from the variance,  $V_1(\ln y)$ , of a linear regression by,

$$V_1(\ln y) = s^2 x_0'(X'X)^{-1} x_0 , \quad (3)$$

where  $s^2$  is the residual mean square,  $x_0$  is the row vector of terms in the prediction equation, and  $(X'X)^{-1}$  is the inverse of the normal matrix. Sampling errors of estimates of  $p$  were calculated from the sample variance,  $V_2(\ln y)$ , according to the method given by Gerrard and Chiang in which,

$$V_2(\ln y) = \left( \frac{b + d \ln(t)_j}{(1 - p) \ln(1 - p)} \right)^2 \left( \frac{p(1 - p)}{m} \right) , \quad (4)$$

where  $b$  and  $d$  are parameters from equation (2),  $p$  is the proportion of insects exceeding the  $j$ 'th threshold density, and  $m$  is the number of sample trees in a plot. The sum of the above two variances is the total variance,  $V(\ln y)$ , which is related to  $V(y)$  by,

$$V(\ln y) = \left( \frac{1}{y} \right)^2 V(y) , \quad (5)$$

$$\text{or} \quad V(y) = V(\ln y) y^2 . \quad (6)$$

Examples of expected errors are illustrated by determining the sampling error as a percentage of the mean, PE, for a range of means at different threshold densities and tree sample sizes by,

$$PE = \frac{100 \sqrt{V(y)}}{y} . \quad (7)$$

$V(y)$  in equation (7) was estimated from the sum of  $V_1(\ln y)$  and  $V_2(\ln y)$  after substituting respective values of  $m$  and  $t$  in equation (4).

## Results

### Empirical Observations

A simple illustration of the relation between the mean and frequency is the comparison of mean budworm density relative to the proportion of sample units with at least one larva ( $t=1$ ). As plotted in figure 1, mean density is a positive function of the frequency of infested samples on a plot. When  $p < 1.0$  the relation is adequately described by a form of equation (1) with the curve modified to account for the departure from randomness at higher densities. On plots where  $p = 1.0$ , larger thresholds and new equations obviously must be fitted to describe the mean frequency relation.

The series of linear regression lines in figure 2 were calculated to illustrate the regular progression of lines from a low to a high threshold density. As the threshold increases, the intercept also rises and the slope declines. The regression statistics in table 2 confirm that the equations fit the data set remarkably well. The approach of Gerrard and Chiang, therefore, also seems to be applicable to budworm data.

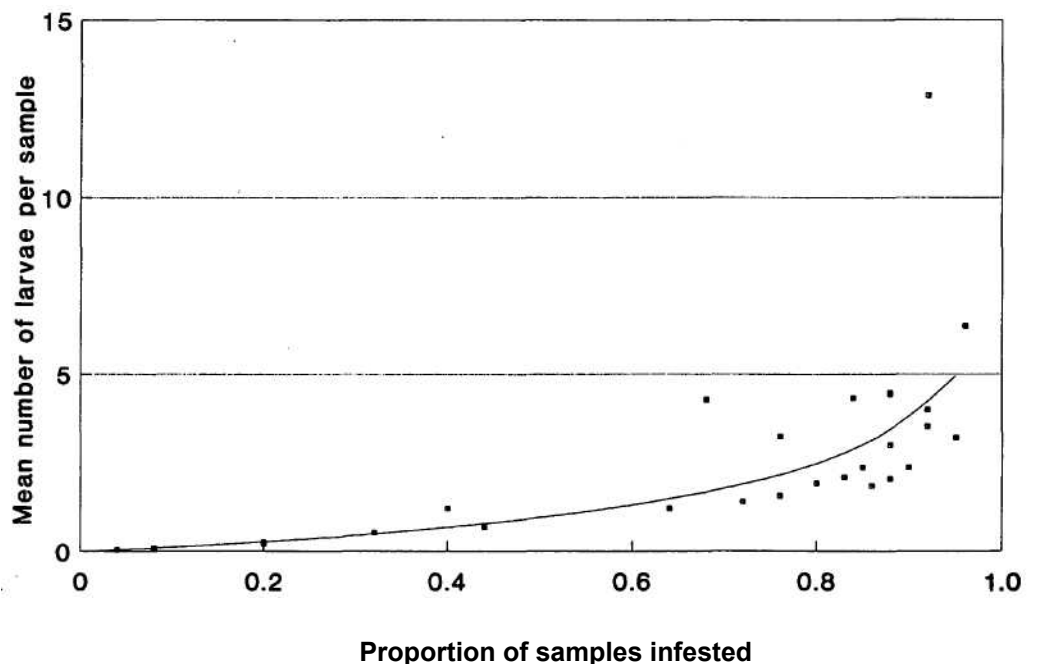


Figure 1 – Relation between mean number of larvae per sample unit and proportion ( $p$ ) of samples occupied when  $p < 1.0$ . Calculated from data in table 1 for  $t=1$ .

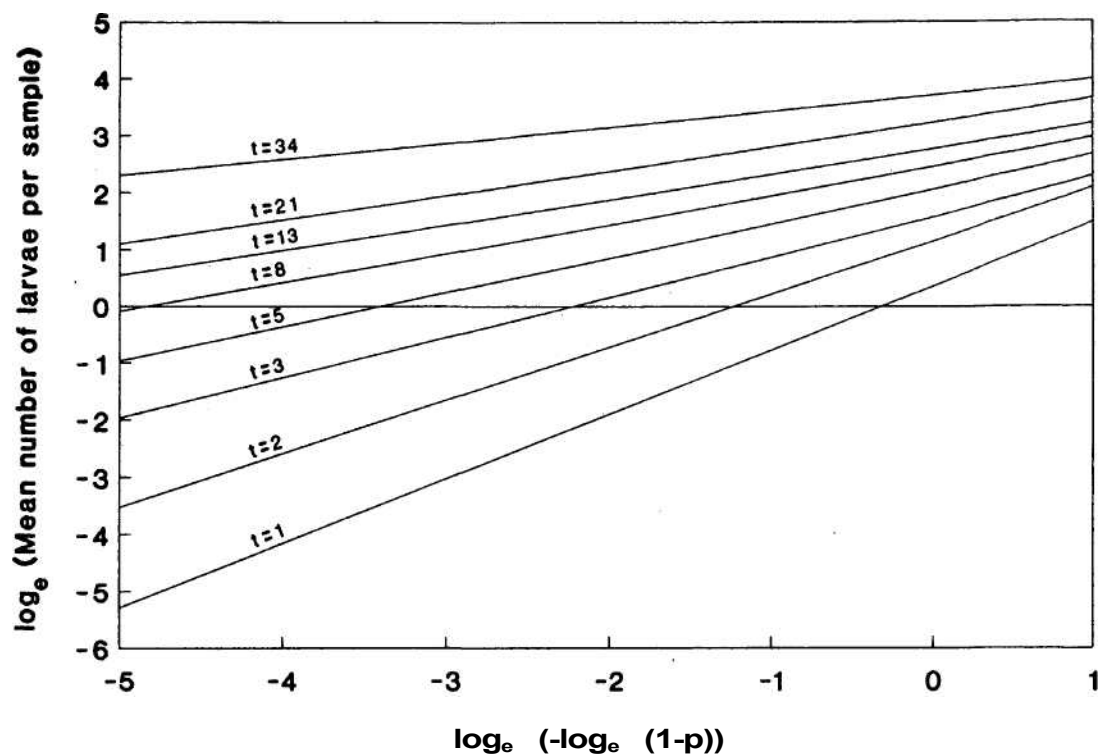


Figure 2—Regression lines showing logarithmic relation between mean number of larvae per sample unit and  $-\ln(1 - p)$  for specified threshold densities ( $t$ ). Calculated from data in table 1.

Table 2—Statistics for regressions in Figure 2 of  $\ln(Mn)$  on  $\ln[-\ln(1 - p)]$

| Threshold density | Number of observations | Equation                                  | $r^2$ |
|-------------------|------------------------|-------------------------------------------|-------|
| 1                 | 30                     | $\ln(Mn) = 0.36 + 1.130 \ln(-\ln(1 - p))$ | 0.942 |
| 2                 | 30                     | $\ln(Mn) = 1.15 + 0.939 \ln(-\ln(1 - p))$ | .891  |
| 3                 | 30                     | $\ln(Mn) = 1.58 + 0.709 \ln(-\ln(1 - p))$ | .934  |
| 5                 | 29                     | $\ln(Mn) = 2.06 + 0.605 \ln(-\ln(1 - p))$ | .935  |
| 8                 | 26                     | $\ln(Mn) = 2.45 + 0.507 \ln(-\ln(1 - p))$ | .945  |
| 13                | 20                     | $\ln(Mn) = 2.76 + 0.443 \ln(-\ln(1 - p))$ | .965  |
| 21                | 18                     | $\ln(Mn) = 3.22 + 0.423 \ln(-\ln(1 - p))$ | .927  |
| 34                | 8                      | $\ln(Mn) = 3.70 + 0.279 \ln(-\ln(1 - p))$ | .969  |

**Model Parameterization** Calculated parameters for the Gerrard and Chiang model from the budworm data are:

$$\begin{aligned}
 a &= 1.649 \\
 b &= 1.030 \\
 c &= 0.920 \\
 d &= -0.223
 \end{aligned}$$

After substitution into equation (2), the new parameterized model becomes,

$$\begin{aligned}
 \ln(y) &= \ln(1.649) + 1.030 \ln[-\ln(1 - p)] \\
 &\quad + 0.920 \ln(f) - 0.223 \ln(t) \ln[-\ln(1 - p)]
 \end{aligned} \tag{8}$$

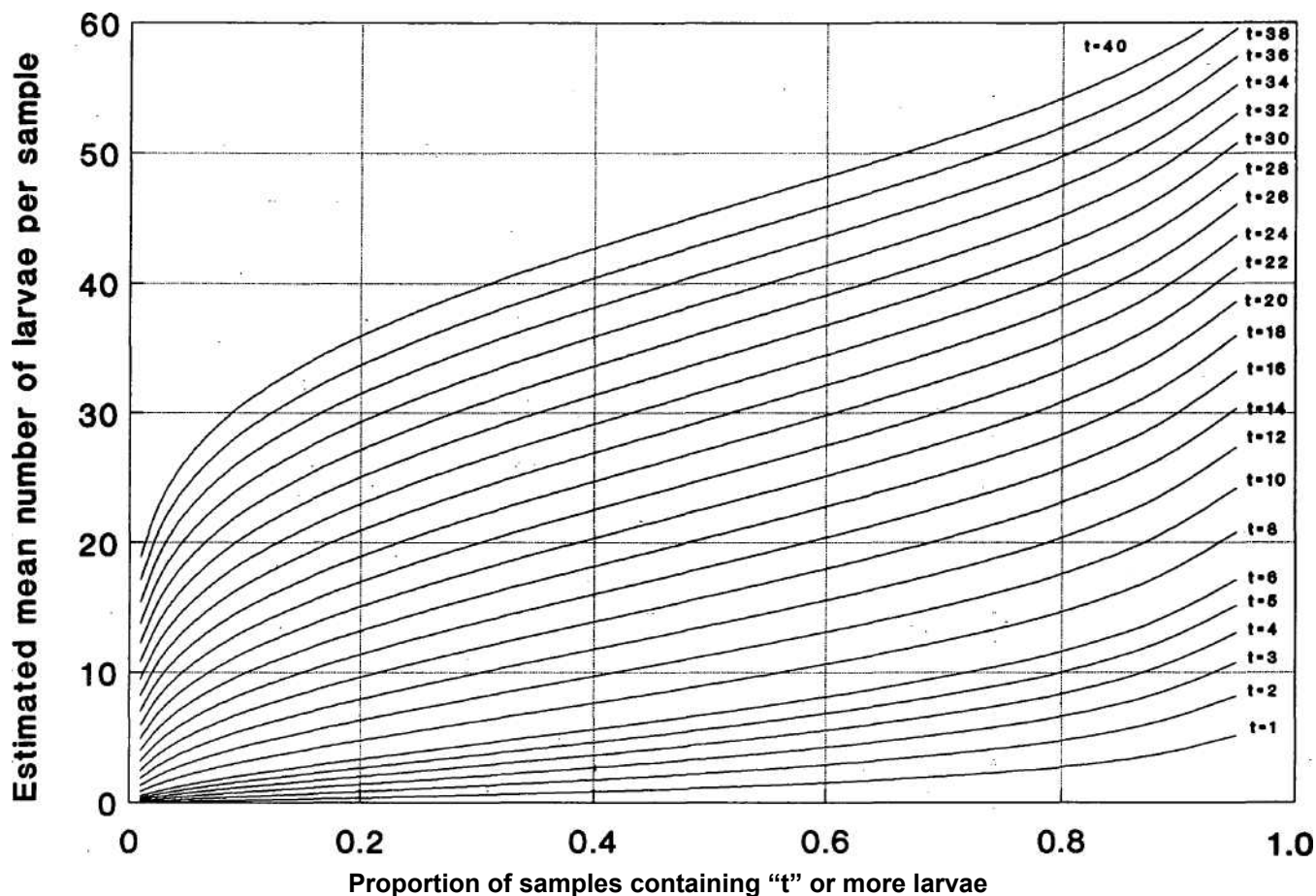


Figure 3—Estimated mean number of larvae per sample unit in relation to proportion of samples infested at different threshold densities ( $t$ ). Lines were calculated by solutions of equation (8)

This single model accounted for 94.8 percent of the variation among individual logarithmic means of budworm larval densities. The equation can be used to estimate mean budworm density on a plot for any determined  $p$  and specified  $t$ . Curves of mean densities per sample unit generated for a range of selected thresholds are plotted on an arithmetic scale in figure 3.

#### Sampling Error

Examples of the sampling precision that can be expected at three threshold densities and sample sizes of 12, 25, 50, and 100 trees are given in figure 4. The trends of the curves show that for the same precision, more trees must be sampled at the lower than at the higher thresholds. For outbreak populations (that is, mean densities  $>10$  larvae per three-branch sample), a sample size of only 25 trees will usually give a precision greater than 20 percent. More trees, however, may be needed at lower densities depending on the precision required of the sample.

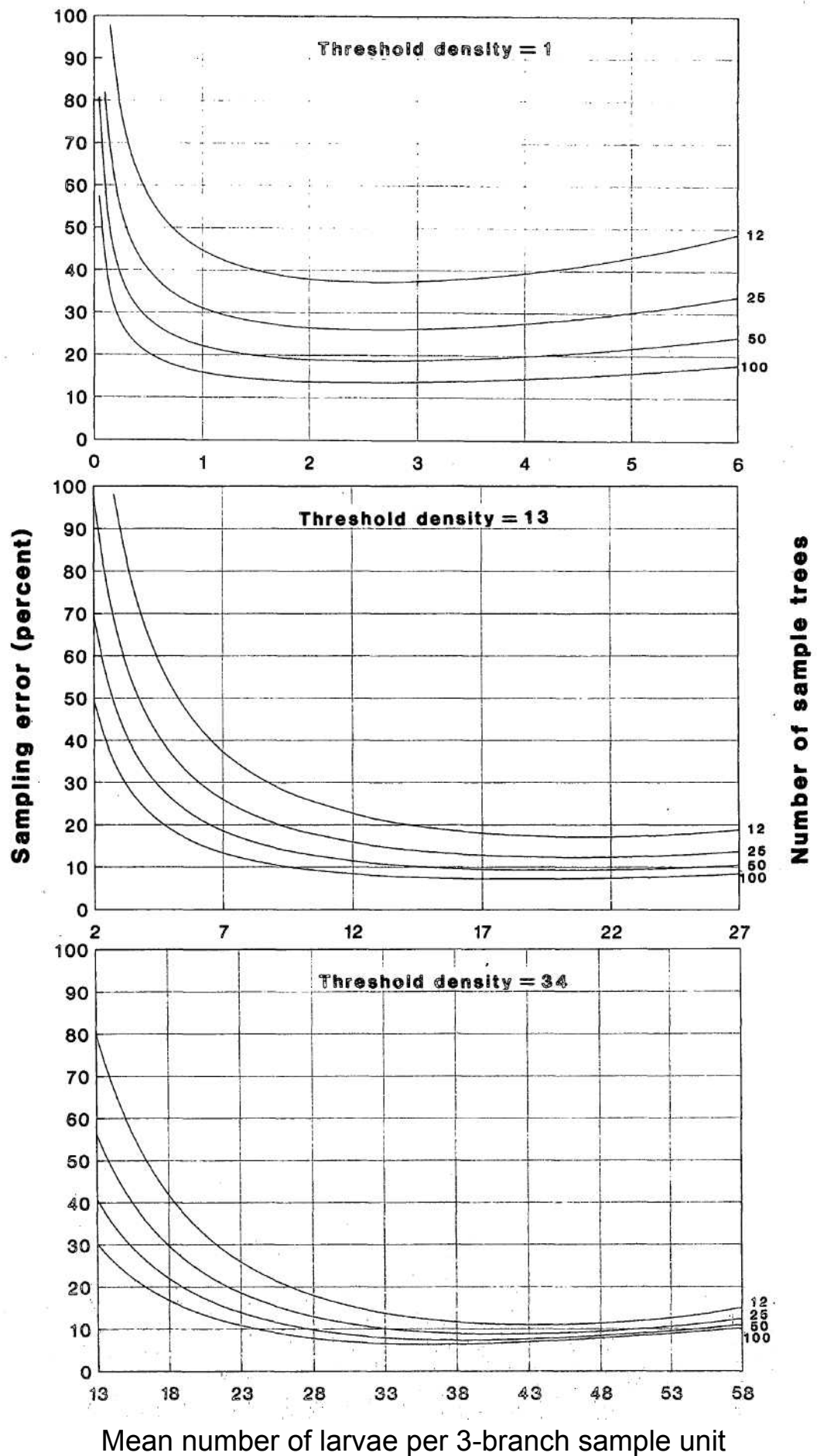


Figure 4—Relation of sampling error percentage to mean number of larvae per sample unit at four different sample sizes and three threshold densities.

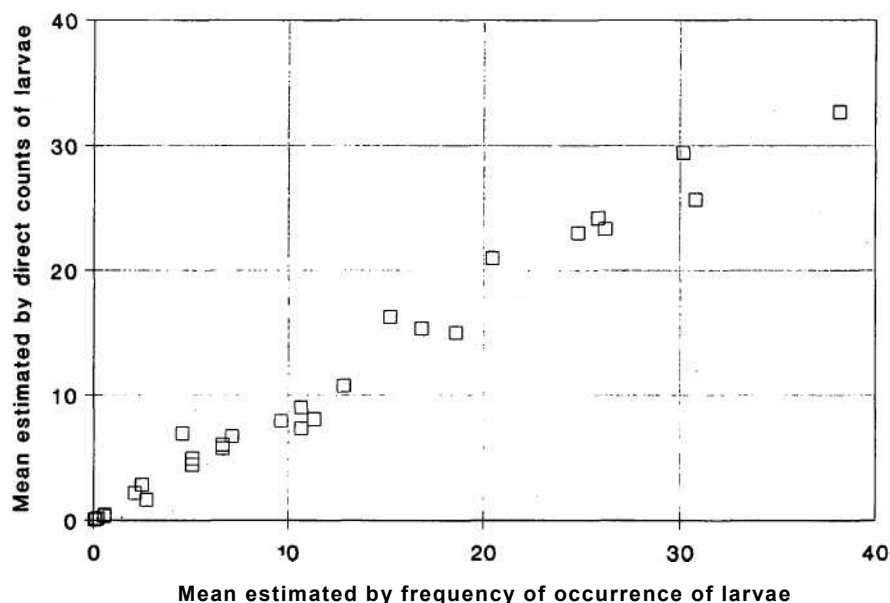


Figure 5—Comparison of mean number of larvae per sample unit estimated in the lower crown by direct counts and by frequency of occurrence.

## Comparison of Methods

The new model was field tested on 26 plots in 1987 by comparing budworm densities estimated by frequency with those by direct counts. Densities were first estimated on the plot by counting all larvae on the three-branch sample unit on each of 25-50 trees (Mason and others 1989). From the data for each plot, a threshold density was then selected, a  $p$  calculated, and a mean density estimated by solving the frequency equation. The plotted densities from counts relative to those estimated by frequency closely followed a 45-degree slope expected in a 1 to 1 relation (fig. 5). A correlation analysis also showed that larval densities estimated by frequency of occurrence accounted for over 98 percent of the variation in estimates by direct counts.

## Discussion

Frequency sampling is an efficient alternative to making direct counts of budworm larvae on lower crown branches. Mean density is estimated simply by determining the proportion of samples on the plot with a number of larvae equal to or greater than a selected threshold number. The determined proportion is easily converted into mean density by reading the proper curve in a graph (fig. 3) or by solving the frequency equation (equation 8) after substituting appropriate values for  $t$  and  $p$ . Equation (8) can be programmed into a handheld calculator so that a precise solution is immediately available in the field after sampling the plot.

Selecting a threshold density is an important decision that needs to be made at each sample location. The threshold must be large enough that  $p < 1.0$ . In a Poisson series, the most efficient estimates of density are made when  $p$  is about 0.8 (Fisher 1970). For most reliable results, Gerrard and Chiang (1970) also recommend choosing a threshold for their model that will give a  $p$  between 0.5 and 0.8. We have found that the average count of larvae on the first four samples gives a satisfactory threshold density and guarantees a  $p < 1.0$ .

To avoid confusion, care must be taken to ensure consistency in the units of measurement. Mean density calculated from the frequency model is always in terms of the number of larvae per three-branch sample unit. This value may need to be corrected to reflect the preferred units of measure. For example, the mean number of larvae per sample can be converted to the number of individuals per 45-centimeter branch tip by dividing by 3.0, or to the number of larvae per square meter by multiplying by 3.1, which is the assumed number of three-branch samples in a square meter of grand fir or Douglas-fir branch area (Mason 1987). Because budworm densities have traditionally been expressed for the middle crown, estimates of density made in the lower crown may also need correction for differences in larval distribution in the tree crown. Midcrown densities of nominal fourth instars can be estimated by multiplying lower crown densities by a factor of 2.41 (Mason and others 1989).

For the same precision of estimate, more trees may need to be sampled by the frequency method than are required by directly counting all larvae (see fig. 4) (Mason and others 1989). In practice, however, the time saved on a plot by not always having to beat all three branches on a sample tree makes the two methods competitive, even if more trees have to be frequency sampled for equivalent precision. When a fixed sample like 50 trees is monitored annually on a plot, frequency sampling is quicker than counting and provides a precision (<20 percent) that is adequate for most operational or monitoring purposes.

## Acknowledgments

Many assisted in the collection of field data, but we especially acknowledge Paul E. Joseph, Oregon Department of Forestry, La Grande, Oregon, for providing data collected by our format from three plots in 1981 and Ronald E. Wiggins, formerly of the Pacific Northwest Research Station, La Grande, who oversaw the collection of the remaining data. We also thank H. Gene Paul of the La Grande laboratory for preparing all the graphs. We are particularly indebted to David B. Marx, Department of Biometry, University of Nebraska, Lincoln, for his statistical review and for providing the proper equation to use in calculating the variance associated with the estimated parameters. Valuable review comments were also given by C.J. Sanders, Forestry Canada, Sault Ste. Marie, Ontario; R.F. Shepherd, Forestry Canada, Victoria, British Columbia; and T.R. Torgersen and B.E. Wickman, Pacific Northwest Research Station, La Grande. We thank them all for their assistance.

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