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Monitoring Larval Populations of the Douglas-Fir Tussock Moth and the Western Spruce Budworm on Permanent Plots: Sampling Methods and Statistical Properties of Data

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Abstract

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Procedures for monitoring larval populations of the Douglas-fir tussock moth and the western spruce budworm are recommended based on many years experience in sampling these species in eastern Oregon and Washington. It is shown that statistically reliable estimates of larval density can be made for a population by sampling host trees in a series of permanent plots in a geographical monitoring unit. The most practical method is to estimate simultaneously densities on a plot of both insect species by the nondestructive sampling of foliage on lower crown branches of host trees. This can be done either by counting all larvae on sample branches or by estimating the frequency of occurrence of a selected threshold number of larvae in samples. Statistics are given on the expected within- and between-plot variances and the number of sample plots needed in different sized monitoring units. In large monitoring units, plot densities of tussock moth and budworm larvae usually are not normally distributed, but they can be normalized by logarithmic transformation to predict the probability of subpopulations of any given density occurring somewhere in the unit. It is urged that sampling methods be consistent and that monitoring be done annually to accumulate continuous databases that reflect the behavior of defoliator populations over a long period.

Keywords: Ecological monitoring, population monitoring, sampling insects, Douglas-fir tussock moth, *Orgyia pseudotsugata,* western spruce budworm, *Choristoneura occidentafis.*

Contents

Introduction

Monitoring is the systematic inventorying of insect populations over time. Its principal purpose is to track changes in the abundance of problem species to discover temporal and spatial patterns in population fluctuation. In the short term, monitoring information has immediate application for determining the present status of pest populations and planning pest management activities. Cumulative monitoring data also are needed for long-term research projects, such as building theoretical models to predict population trends, performing time-series analyses to identify the underlying causes of population change, and evaluating the long-term effects of pest management practices. Findings from these kinds of consistent efforts eventually will help in developing practical prescriptions needed in modern pest management.

The Douglas-fir tussock moth *(Orgyia pseudotsugata* (McDunnough)) and western spruce budworm *(Choristoneura occidentalis* Freeman) are the two most important defoliators of Douglas-fir *(pseudotsuga menziessi* (Mirb.) Franco) and true firs *(Abies* spp.) in the Western United States (Brookes and others 1978,1987). Various methods have been used to monitor their populations (Dahlsten and others 1992, Daterman and others 1979, Mason 1979, Shepherd and Otvos 1986, Srivastava and others 1984, Sweeney and others 1990). In recent years, sampling larvae by beating branches in the lower crown has become a popular technique. The success of this method is due primarily to the advantage of not having to clip branches higher in the tree and to the efficiency that comes with one person performing all phases of sampling on a tree. The procedure, therefore, is especially efficient and cost-effective. Although restricting sampling to only the lower crown foliage has sometimes been criticized, the method consistently has produced accurate estimates of tussock moth and budworm abundance and now has emerged as the method of choice for most larval sampling in the Pacific Northwest.

Because lower crown sampling is relatively inexpensive, monitoring studies employing this technique have been sustained for over 20 consecutive insect generations in some areas. Such long-term databases will be critical in the future for determining the overall response of defoliator populations to silvicultural treatments proposed as part of east-side forest restoration and ecosystem management. New programs concerned with managing the important pests affecting forest health should involve maintaining the continuity of these already existing data sets.

In this report, we review the techniques recommended for monitoring tussock moth and budworm larvae in the lower crown and summarize the statistical characteristics of data encountered over many seasons of monitoring natural populations of these insects.

Development of Sampling Methods and Data Sets

The sampling procedures reported evolved over a long period of development and have been field tested under many different forest conditions in the Western United States. Most of the methodologies are already published; appropriate literature citations are listed with their descriptions. The recommended techniques are efficient and deliberately simplified to ensure that monitoring remains practical and can be done at minimum expense. At the same time, they are statistically reliable and proven procedures for monitoring tussock moth and budworm populations.

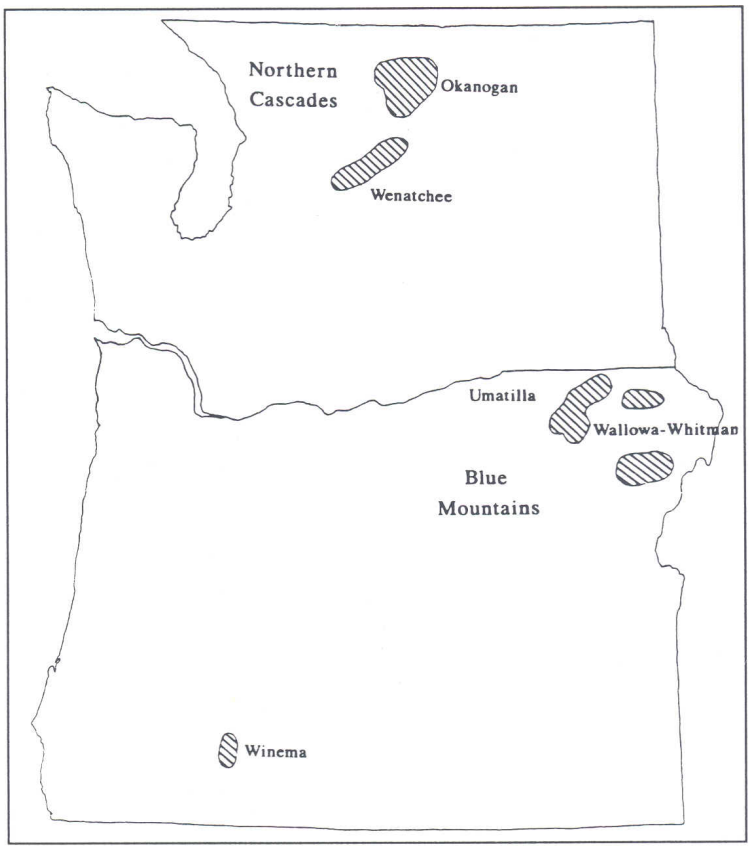


Figure 1-National Forests and approximate locations of monitored populations.

Monitoring began in 1971 with a larval inventory in six study areas in a rising population of the Douglas-fir tussock moth in the Blue Mountains of northeastern Oregon. As sampling techniques improved and monitoring became more practical, new study areas were established in other parts of the Northwest. Sampling was extended in 1984 to include larvae of the western spruce budworm so that both species could be monitored simultaneously on the same plots. As of 1992, annual monitoring studies included 48 permanent plots representing the behavior of tussock moth and budworm populations in parts of five National Forests in Oregon and Washington (fig. 1). Over the 22 years from 1971 to 1992, 1,028 plot-years of monitoring data were collected for the two species (table 1). This is one of the most extensive databases available on the variability and abundance of these two defoliators and contains invaluable information for planning new monitoring programs and interpreting their results.

Table 1 - Number of plot-years of tussock moth and budworm monitoring data collected in Oregon and Washington between 1971 and 1992

National Forest	Douglas-fir tussock moth	Western spruce budworm[a]
	Plot-years	
Umatilla (OR)	246	154
Wallowa-Whtman (OR)	124	80
Winema (OR)	134	59
Okanogan (WA)	68	52
Wenatchee (WA)	63	48
Total	635	393

[a] Included in this group is the Modoc budworm, *Choristoneura viridis* Freeman, which was the principal budworm species monitored in the Winema National Forest.

The Sampling Approach

Terminology and Definitions

In explaining the approach recommended, some terms are used that have specific meanings in the sampling protocol. The following definitions of key terms are given to help in understanding how this nomenclature applies to the particular methods of monitoring that are described:

Branch area -Area of the plane occupied by a foliated branch when the branch is placed on a flat surface. A square meter of branch area is the standard unit of measure for expressing larval density. In lower crown sampling, a square meter of branch area is assumed to contain 9.3 45-cm branch tips, or 3.1 secondary sampling units.

Density index- Estimated middle crown density, assumed to be correlated with the true mean number of larvae at all crown levels.

Monitoring unit - A specific geographical or management area for which an estimate of population density is made.

Plot - An approximately 2-ha area occupied by host trees whose lower branches are accessible for sampling.

Plot density – Estimated mean number of larvae per square meter of branch area in the middle crown of trees in a plot.

Population -The collection of all larvae of the Douglas-fir tussock moth or western spruce budworm in the tree crowns of a defined monitoring unit.

Population density -Estimated mean number of larvae per square meter of branch area in the middle crown of trees in a monitoring unit.

Primary sampling unit-A predetermined number of sample trees drawn from a plot.

Sample mean -The mean number of larvae per three-branch sampling unit in a plot.

Secondary sampling unit -Three 45-cm branch tips in the lower crown of a sample tree in the primary sampling unit from which larvae are dislodged and counted.

Middle Crown Density as a Standard Index of Abundance

The year-to-year abundance of tussock moth and budworm larvae traditionally has been expressed by the number of individuals per standard unit of foliage or branch area (Carolin and Coulter 1972, Mason 1970, Morris 1957, Srivastava and others 1984). Because foliage is a variable quantity as opposed to a fixed unit of space like a hectare, such an expression of larval density is only an index of insect abundance in relation to available food or branch habitat. This can present problems in the analysis of long-term data sets, because changes in the quantity of foliage may alter the index value even though there has been no change in the absolute number of insects. Such relative indices of density, however, are more practical to estimate than absolute population density and have a long history of successful use in forest stands where the foliage base is relatively stable across years.

The random or systematic sampling of foliage throughout the whole tree crown is completely impractical operationally. Density indices for tussock moth or budworm, therefore, have traditionally been estimated for only the portion of the crown originating from the middle one-third of the bole on trees up to 15 m tall. This section of the crown, commonly called the middle crown, contains a majority of the tree's foliage and has been shown in numerous sampling studies to be a good indicator of average larval density over the whole crown (Campbell and others 1984, Mason 1970, Srivastava and others 1984). The density of larvae in the middle crown, therefore, is commonly used as the standard index of abundance for monitoring both the Douglas-fir tussock moth and the western spruce budworm. Middle crown density can be estimated either directly by drawing samples from the middle portion of the crown or indirectly by predicting from samples taken from the more accessible lower crown. Because the lower stratum of foliage within reach from the ground is easy to sample and the number of larvae found there is a good predictor of middle crown density, sampling lower branches is now the preferred technique for estimating the standard index of abundance (Mason 1977, 1987; Mason and others 1989; Torgersen and others 1993).

Permanent Sample Plots

The monitoring of larval abundance is a two-stage process involving the sampling of foliage in a small area to estimate a plot density and the sampling of a number of plots in a large area to estimate a population density. Each plot necessarily consists of a cluster of the principal host trees, Douglas-fir and true firs, with foliage low enough in the crown to be sampled from the ground. A plot is without explicit boundaries but, in practice, is about 2-ha, within which a fixed number of trees (primary sampling unit) are sampled. Trees sampled are selected indiscriminately in proportion to their occurrence in the plot so that results reflect the species composition of the area.

Resampling of the same plots annually is desirable to take advantage of previously located sites, forest types, and tree sizes already identified as meeting monitoring specifications. By using permanent plots, many of the same trees are sampled each year, thus reducing the effect of spatial variation and increasing sensitivity for detecting changes in insect density (Morris 1960). Analyses of overall population trends also are most sensitive when data from permanent plots in succcessive years can be treated as paired variates over a large monitored unit. Because the beating of lower branches is nondestructive, plots can be resampled year after year without damage to the trees.

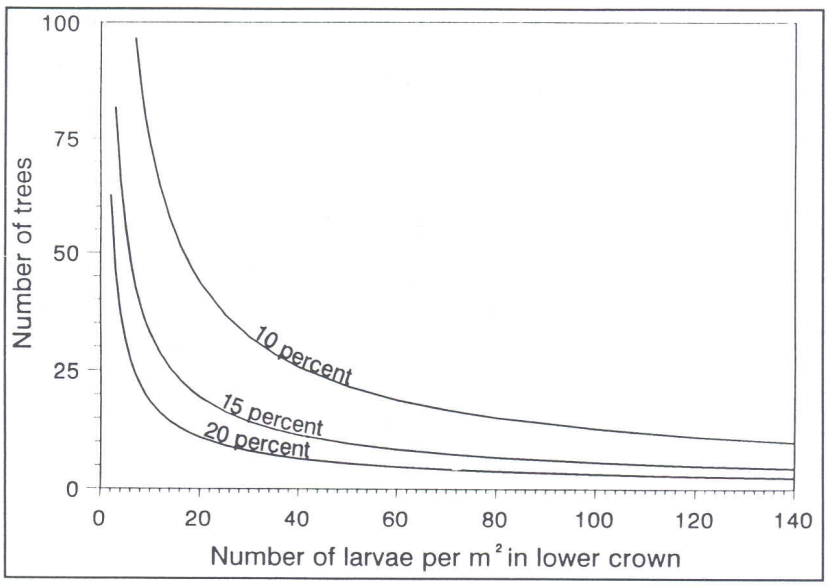


Figure 2-Number of trees required to estimate the density of tussock moth or budworm larvae on a plot with a standard error of 10, 15, or 20 percent of the mean at a 68-percent probability level.

Sample Branches

The sample on a host tree is three 45-cm branch tips (secondary sampling unit) within reach from the ground. On average, 3.1 sampling units or 9.3 45-cm branch tips of lower crown foliage comprise a square meter of branch area (Mason 1977, 1987). Depending on abundance of the two defoliators and the desired sampling precision, samples from 20 to 50 trees on a plot are needed each year. Normally, this sample size will give an estimate of plot density for either tussock moth or budworm with a standard error that is less than 20 percent of the mean at the 68 percent probability level (fig. 2). For the same relative precision, however, more samples are always needed at lower than at higher densities. The optimum combination of number of trees and permanent plots required in a particular situation can be calculated, if needed, by a multistage sampling program that takes costs as well as intraplot and interplot variances into consideration (Hazard and Stewart 1974).

Age of Sampled Larvae and Timing

Sampling comparable life stages each year is critical to the monitoring process. If there are large differences in the larval stages sampled from year to year, serious errors will be made in interpreting changes in population density. The larval stages preferred for monitoring are instars I and II of tussock moth, frequently called early larvae; and instars III, IV, and V of budworm, often called nominal fourth instars (color plates A and B, respectively). Early larvae of tussock moth are favored because they are more numerous than other instars and occur throughout the foliage, albeit in varying proportions. As a result, they have a relatively low intraplot variance and a higher probability of being found at low densities (Mason 1970). Nominal fourth-instar budworm also are well distributed and, after leaving the buds, are the youngest larvae to be dislodged easily from the foliage by beating (Srivastava and others 1984).

Early tussock moth larvae and nominal fourth instar budworm are found on the foliage about the same time of the year and can be sampled simultaneously. Both species normally reach these stages of development sometime after all buds have burst on host trees and when new shoots have elongated at least 4 to 6 cm (color plates C an D) (Wickman 1978). To assist in the correct timing of sampling, many studies have related insect development to measurable indices reflecting the onset of warm weather in the spring, such as the phenological status of host trees and degree-day accumulation over 5.5 °C (Kemp and others 1986; Shepherd 1983; Wickman 1976a, 1976b, 1977, 1988). Results show that well-timed sampling usually occurs in the range of 278-389 degree-days C accumulation.

In general, sampling properly timed for tussock moth larvae also will be synchronized for budworm larvae. The opposite is not always true, however, because budworm larvae that emerged early in the spring may be active weeks before tussock moth eggs hatch. An unseasonably cool spring can easily upset the normal synchrony between the species by delaying tussock moth egg hatch while budworm larvae continue to develop nearly on schedule. The timing of sampling, therefore, cannot depend on indices alone but also should be based on local temperatures and direct observation of insect development.

Beating Techniques and Equipment

Branches are easily sampled for larvae by holding a portable drop cloth under a 45-cm portion of a branch tip and rapping the branch sharply with a beating stick (color plates E and F). Free-living insect larvae and other arthropods on the branch are dislodged onto the cloth where they can easily be observed and counted (color plate G). In early summer after bud burst and when foliage is elongating, most tussock moth and budworm larvae will drop off the foliage readily when disturbed. Some budworm larvae, however, are more difficultto dislodge from webbed shoots than others and may require extra-vigorous beating for a complete count.

A hand-held drop cloth used successfully for many years is a 56- by 114-cm light-weight canvas supported underneath by a frame of aluminum crossmembers. The beating cloth can be unsnapped quickly from the frame for storage. Short lengths of wooden dowel or PVC pipe can be used for beating the foliage. A stick 56 cm long cut from 3/4-in PVC pipe is lightweight and will last for years. A complete description of materials, construction, and other suggestions are given by Paul (1979).

Estimating Plot Density

Complete Count of Larvae in Branch Samples

The most common method for estimating plot density is by simple random sampling of trees on the plot and counting all individuals in the three-branch sampling units. The mean number of larvae per sampling unit, $\bar{y}$, is then calculated for each insect species by,

$$\bar{y} = \frac{1}{m} \sum_{i=1}^{m} y_i , \qquad (1)$$

where Yi is the number of larvae in the sampling unit of the i'th tree and m is the number of trees sampled per plot (Mason and others 1989). Sample variance among three-branch sampling units, V(y), for the above cluster of trees assuming an infinite number of sampling units therefore is,

$$V(y) = \frac{1}{m-1} \sum_{i=1}^{m} (y_i - \bar{y})^2. \qquad (2)$$

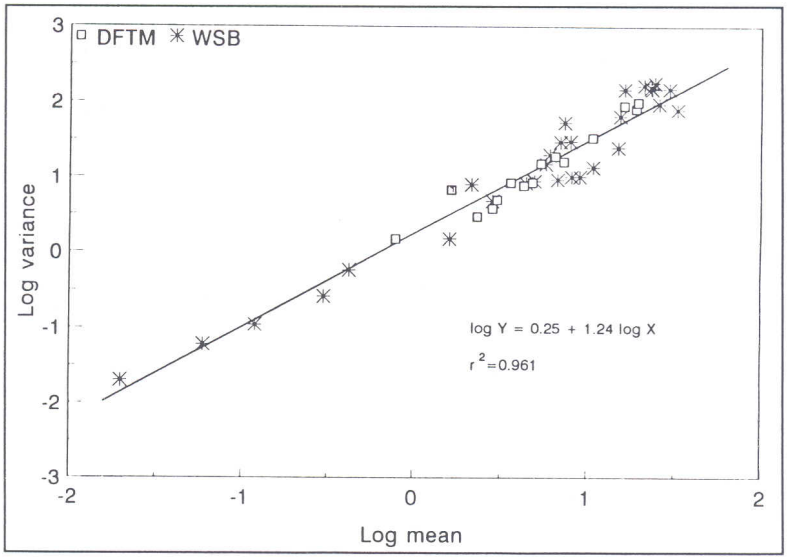


Figure 3-Relation between logarithmic-transformed values of intraplot variances and mean plot densities in lower crown samples for the Douglas-fir tussock moth and western spruce budworm.

In previous sampling operations, intraplot variances in the lower crown have been almost identical for tussock moth and budworm populations so that, for practical purposes, they can be considered to be the same (fig. 3).

Frequency of Occurrence of Larvae in Branch Samples

Population density also can be estimated on a plot without having to count all larvae in each sampling unit. The method was first developed for making quick estimates of density in sparse populations of tussock moth (Mason 1977, 1987), but it has been expanded to include the range of all natural densities of either the Douglas-fir tussock moth or the western spruce budworm [1] (Mason and Beckwith 1990). The technique is based on a statistical relation between the sample mean and the frequency of occurrence of different minimum numbers of larvae in the sampling units (Gerrard and Chiang 1970). The only measure required on a plot is a determination of the proportion of sampling units containing a specified threshold number of larvae. Depending on the threshold selected, this usually can be done by counting only a fraction of the total number of larvae on each sample. The mean number of larvae per sampling unit, $\bar{y}$, is then estimated by the equation,

$$\ln \bar{y} = \ln(1.603) + 1.08 \ln[-\ln(1-p)] + 0.937 \ln(t) - 0.246 \ln(t) \ln[-\ln(1-p)] , \quad (3)$$

where t is the selected threshold number and p is the proportion of sampling units containing t or more larvae (fig. 4). The threshold number always must be large enough so that $p < 1.0$ and can be chosen easily by using the average count of larvae in the first four sampling units. This method of estimating a sample mean has produced comparable results to that of making total counts and with less sampling time (fig. 5). The sampling error associated with $\bar{y}$ is more difficult to estimate, but it is similar in size to the error encountered in making complete counts for the same number of trees sampled (Mason and Beckwith 1990).

[1] Unpublished data. On file with: Forestry and Range Sciences I_aboratory, 1401 Gekeler Lane, La Grande, OR 97850.

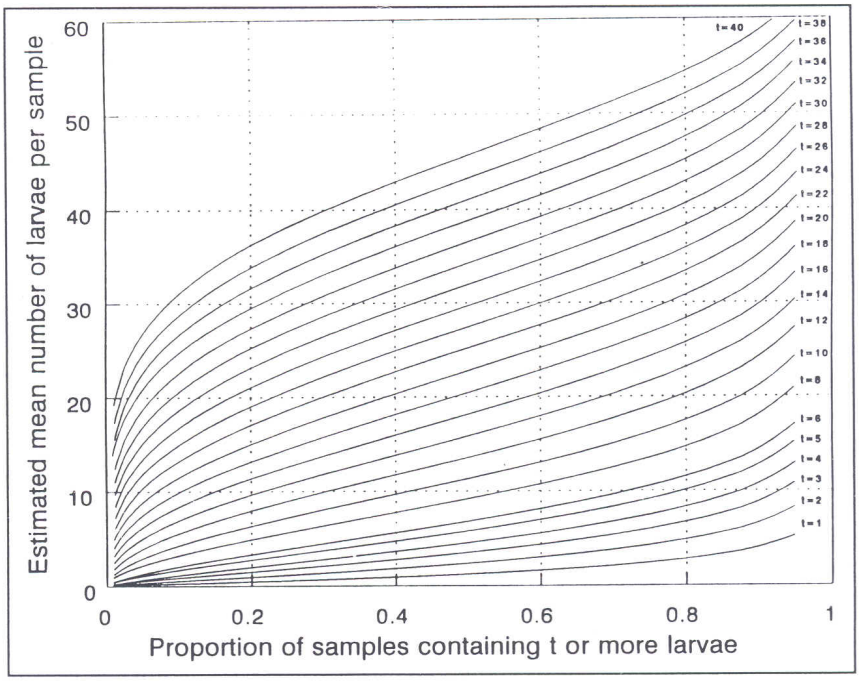


Figure 4- Estimated mean number of larvae per sampling unit in relation to the proportion of samples infested at different threshold densities (t). Lines were calculated by solutions of equation (3).

The example in table 2 uses actual counts of budworm larvae in a field plot and compares the total count method with the frequency of occurrence procedure for estimating density of larvae on the plot. Both methods gave similar estimates of density and sampling precision, but one-third fewer larvae had to be counted with the frequency of occurrence technique.

Converting Sample Mean to Middle Crown Density

To assure comparability of data in different projects, mean densities estimated for sampling units in the lower crown need to be converted to standard indices of abundance in the middle crown. This requires first expressing larval density in terms of a square meter of branch area and then applying a correction factor that reflects the vertical distribution of larvae of each species in the tree crown. The middle crown density per square meter, M, for the plot is,

$$M = (3.1\ \bar{y})\ R\ , \qquad (4)$$

where 3.1 is the average number of three-branch sampling units in a square meter, $\bar{y}$ is the mean density of larvae per sampling unit, and R is the simple ratio of expected middle crown to lower crown density. The distribution of tussock moth and budworm larvae in the crown is naturally variable and changes with larval age (Campbell and others 1984; Mason 1970, 1987). Annual monitoring, however, is recommended for early summer when the predominant larval stages are nearly the same each year. The correction factor, R, for these life stages has been examined in many sampling studies and been found to be relatively consistent; that is, 2.0 for tussock moth instars I and II and 2.23 for budworm instar IV (Mason 1970, 1987; Torgersen and others, in press). Estimates of lower crown density per sampling unit, therefore, can

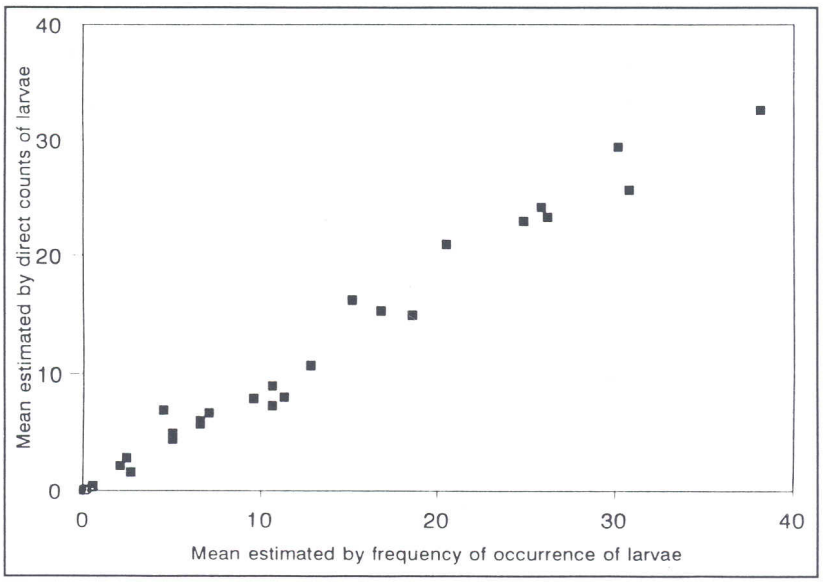


Figure 5-Comparison of mean number of western spruce budworm larvae per sampling unit estimated in the lower crown by direct counts and by frequency of occurrence (Mason and Beckwith 1990).

be converted to middle crown density per square meter by substituting one of these constants for R in equation (4). The crown level correction is useful only for converting to a standard index of abundance to compare with other populations. Because the same constants are used each year, the accuracy of the conversion has no influence on interpreting annual fluctuations in population density on the same monitoring plots.

Estimating and Interpreting Population Densities

Population Mean of Monitoring Unit

Permanent plots are monitored to estimate the population density of a larger geographical unit. To ensure that plots adequately represent the unit, it is important that they be selected objectively. The monitoring units might be relatively small, such as a Ranger District or a silvicultural treatment area, or larger, such as a National Forest or a geographical province; for example, a portion of the Blue Mountains or the northern Cascade Range. Data from the successive monitoring of populations on permanent plots are usually summarized in terms of these specific monitoring units. The mean population density for a monitoring unit is simply the mean of the individual plot densities defined by,

$$\overline{M} = \frac{1}{n} \sum_{i=1}^{n} M_i \, . \qquad (5)$$

where M is the population mean of the monitoring unit, Mi is larval density on the i'th plot of the unit, and n is the number of sample plots in the unit. The variability among plots measured by interplot sampling variance therefore is,

$$V(M) = \frac{1}{n-1} \sum_{i=1}^{n} (M_i - \overline{M})^2 \, . \qquad (6)$$

Table 2-Comparison of plot densities of western spruce budworm estimated by total count of larvae on sampling units (equation 1 in text) and by frequency of occurrence of 13 or more larvae on sampling units (equation 3 in text)

Counts of budworm larvae on sampling units in order of sampling[a]	11	20	7	14	20
	19	14	10	20	3
	14	5	41	22	19
	11	11	21	34	34
	25	19	20	20	19

Statistical parameter	Estimated by total count of larvae	Estimated by frequency of occurrence of larvae> 13
Number of larvae counted	453	292
Proportion of samples with 13 or more larvae	NA	0.72
Mean number of larvae per sample (sample mean)	18.12	19.76
Standard error	1.79	2.24[b]
Percent precision of estimate	9.85	11.34
Mean number of larvae per square meter in lower crown[c]	56.17	61.26
Mean number of larvae per square meter in middle crown (plot density)[d]	125.26	136.61

[a] Data collected from a plot of 25 trees near Fish Lake, Wallowa-Whitman National Forest, June 1987.
[b] Calculated by method in Mason and Beckwith (1990).
[c] Number of larvae per sampling unit converted to number per square meter by multiplying by 3.1.
[d] Lower crown density corrected to middle crown density by multiplying by 2.23.

The population mean and interplot variance also are related by a simple power law,

$$V(M) = a\,\overline{M}^{\,b}, \qquad (7)$$

where a and b are parameters reflecting the spatial variation of larval populations over the monitoring unit (Taylor 1961). This relation is especially useful because once the parameters have been determined, variance can be predicted for any expected population mean.

Previous monitoring has generated a large database of tussock moth and budworm densities from which the mean-variance relation using equation (7) has been determined for three different sized monitoring units (figs. 6, 7, and 8). Not surprisingly, interplot variation increases for both species as the size of the area monitored increases (table 3, page 16). Larger areas always introduce the possibility for more variability as new habitats and environments are included. A case in point is the unusually large parameter a in equation (7) for predicting budworm variance in geographical provinces. This large value was the result of high variability of budworm populations in the northern Cascade Range province where outbreak densities persisted in the Okanogan National Forest but were absent from the nearby Wenatchee National Forest.

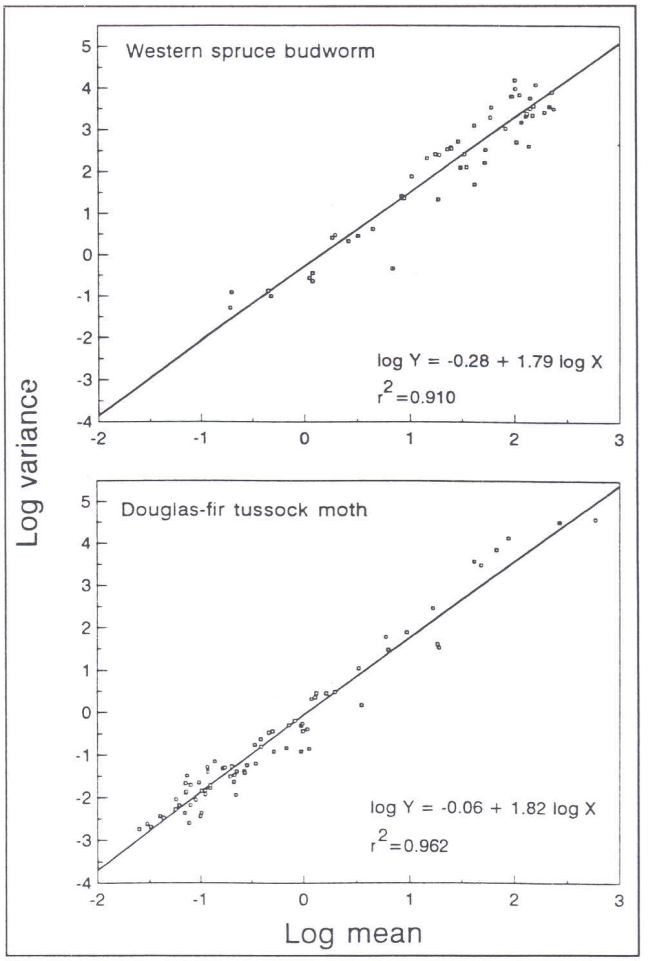


Figure 6---Relation between logarithmic-transformed values of interplot variances and mean population densities in District-sized monitoring units.

Number of Sample Plots

The interplot variation in a monitoring unit is important because it influences the sample size needed for an estimate of population density at the desired level of precision. Assuming infinite plots are available for sampling and a normal distribution of densities in the monitoring unit, the approximate number of plots, n, required is,

$$n = \frac{t^2 V(M)}{E^2}, \qquad (8)$$

where *t* is Student's *t* for a specified confidence probability, and E is the desired standard error of estimate (Cochran 1977). By solving equation (7) for variance and substituting in equation (8), the appropriate number of permanent plots in a monitoring unit can be estimated for any specified sampling error.

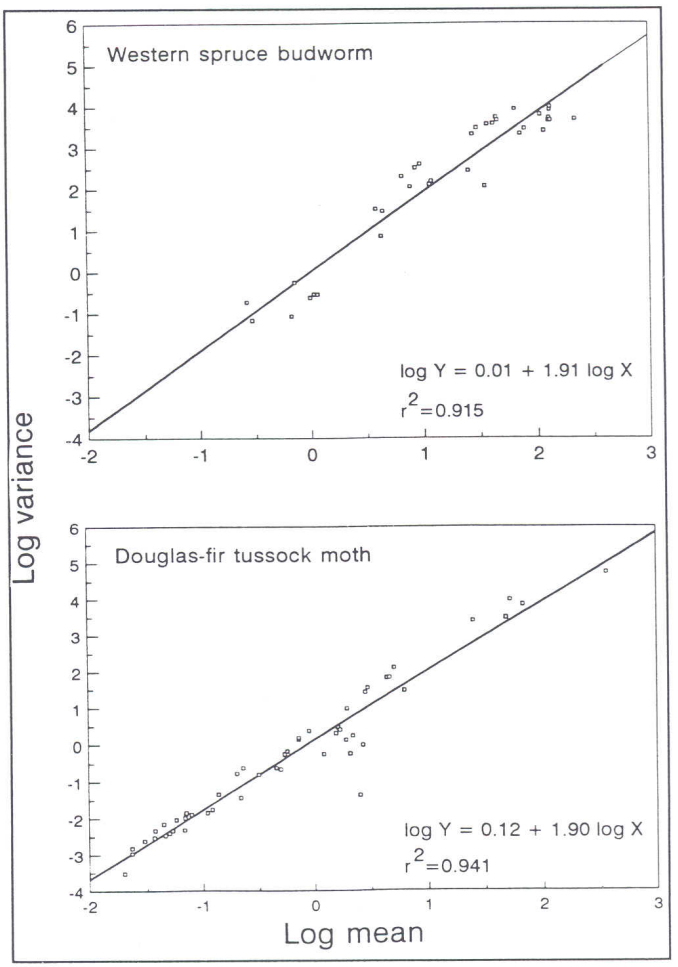


Figure 7-Relation between logarithmic-transformed values of interplot variances and mean population densities in Forest-sized monitoring units.

For the same error, more plots will usually be needed for large monitoring units and at low larval densities. Examples are given in figures 9,10, and 11 (pages 16-17) where sample sizes generated from the previously derived equations for expected variance (table 3) are plotted over a range of tussock moth and budworm densities. Except for low larval densities in the province-sized monitoring unit, these calculations show that budworm populations usually can be monitored with fewer plots than are needed for tussock moth populations. In general, the maximum number of permanent plots needed for monitoring both species together are 15 to 20 for District-sized units, 25 to 30 for the average Forest, and 50 to 60 for a larger province. These sample sizes assume a precision of estimate of 20 percent of the mean and a confidence level of 68 percent, which probably are adequate for the purposes of most larval monitoring. Improving the levels of precision and confidence always requires more plots to monitor, which would increase cost and possibly jeopardize continuity of the program. It also should be remembered that a precise estimate usually is not as

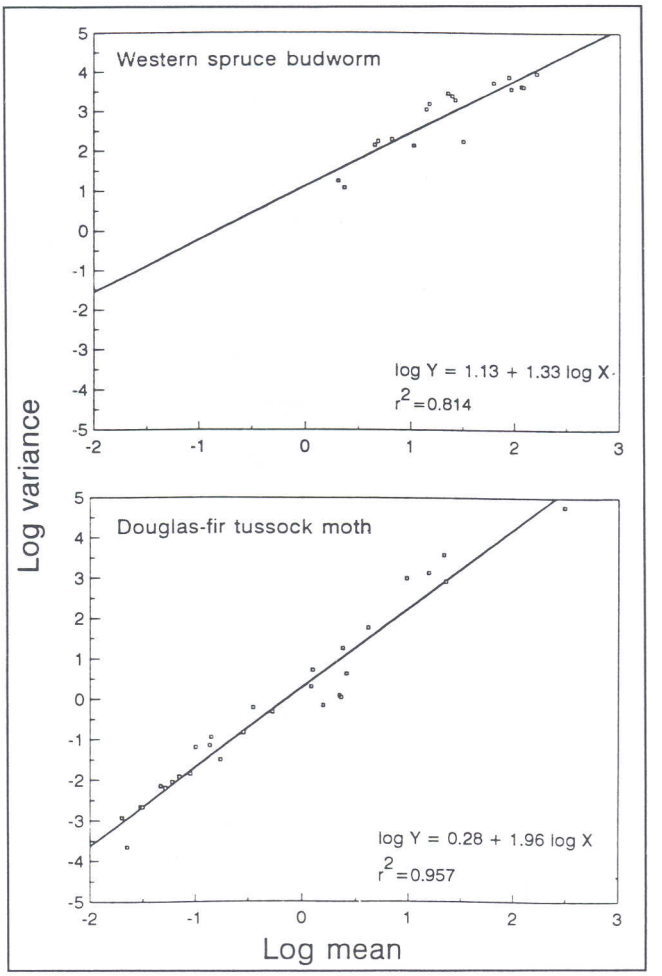
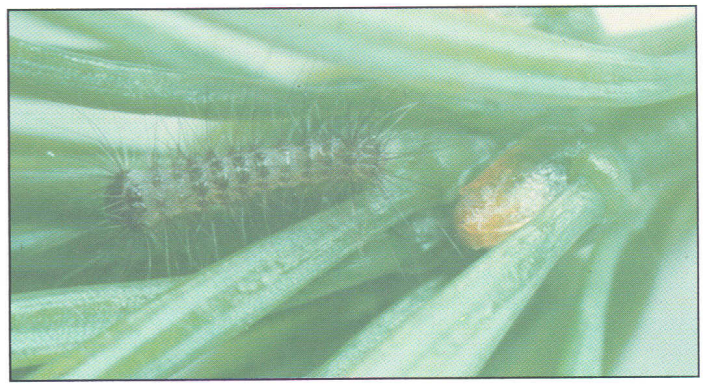


Figure 8-Relation between logarithmic-transformed values of interplot variances and mean population densities in province-sized monitoring units.

necessary at low densities, because the magnitude of the error on a numerical scale is also small. Decisions on sample size will depend on many factors, not the least of which are available resources, practicality, and the ultimate uses for the monitoring data.

Population Normality and Predicting Defoliation

When populations are normally distributed, inferences can be made about the frequency of different larval densities in the monitoring unit even though they may not be represented in the plot samples. The shape of the normal distribution curve, as determined by the estimated population mean and variance, gives the probability of a subpopulation of another density occurring somewhere in the monitoring unit. This is measured by the distance of that density value from the population mean expressed in terms of the number of standard deviations, called the standard normal deviate. The probability, P, for any specified standard deviate, Z, under the normal curve can be read from a table of cumulative standard normal distribution (table 4). The percentile under the curve where values exceed the standard deviate, therefore, is 1-P.



Color Plate A-First instar of the Douglas-fir tussock moth.

Color Plate B-Fourth instar of the western spruce budworm.

Color Plate C-New foliage development on grand fir *(Abies grandis* (Dougl. ex D. Don) Lindl.) at the proper time for sampling first instar tussock moths or nominal fourth instar budworms.

Color Plate D-New foliage development on Douglas-fir at the proper time for sampling first instar tussock moths or nominal fourth instar budworms.

E

F

Color Plates E and F-Sampling lower crown branches with a drop-cloth and beating stick.

G

Color Plates G and H-Drop-cloth with larvae and dried needles from a sample branch.

H

Table 3-Statistics for the relation between population mean and interplot variance for 3 sizes of monitoring units as expressed by the power curve, $V(M) = aM^{b}$ [a]

Monitoring unit	Douglas-fir tussock moth			Western spruce budworm		
	Number of observations	Parameters		Number of observations	Parameters	
		a	b		a	b
District	91	0.87	1.82	53	0.52	1.79
National Forest (Wallowa-Whitman, Umatilla, Okanogan, and Wenatchee)	51	1.32	1.90	35	1.02	1.91
Geographical province (northern Blue Mountains and northern Cascades)	29	1.91	1.96	18	13.49	1.33

[a] Parameters a and b were calculated by linear regression after expressing the power curve logarithmically as $\log V(M) = \log a + b \log M$.

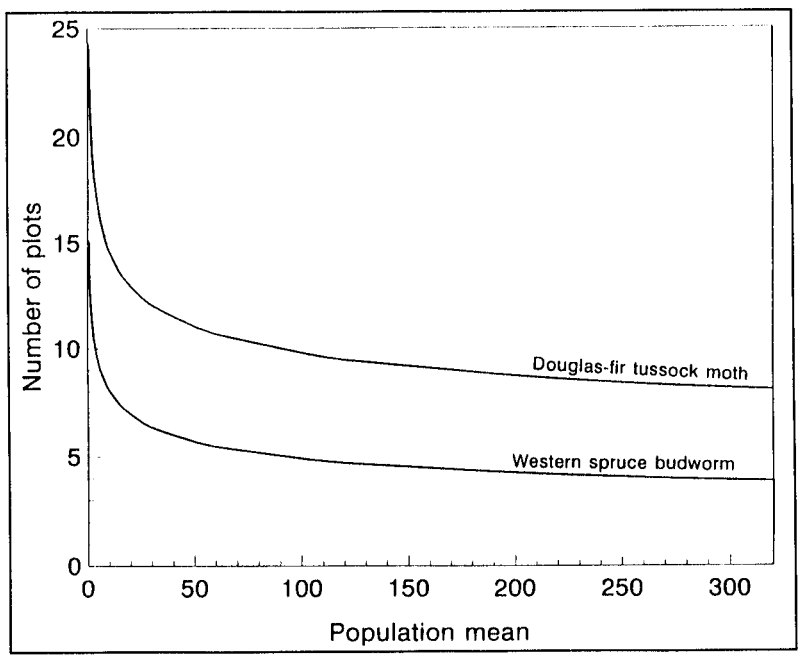


Figure 9-Number of plots required to estimate population density for a District-sized monitoring unit with a standard error of 20 percent of the mean and a 68-percent probability level.

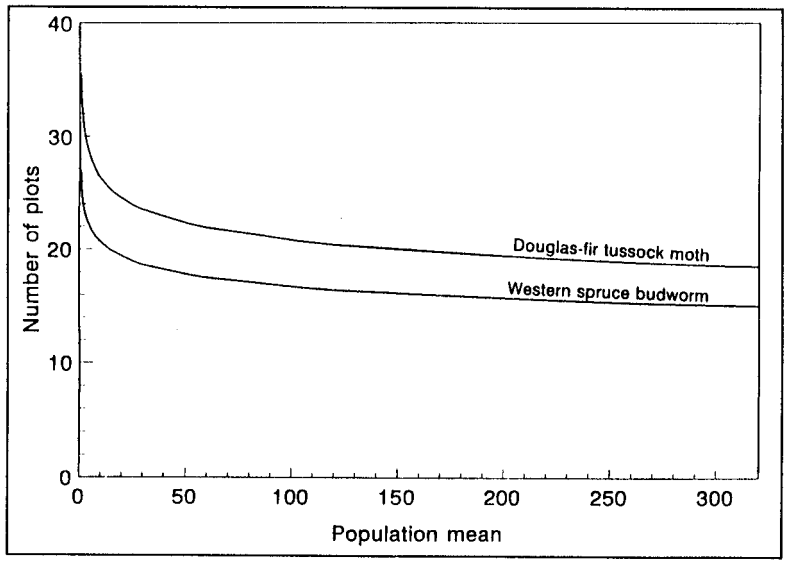


Figure 10-Number of plots required to estimate population density for a Forest-sized monitoring unit with a standard error of 20 percent of the mean and a 68-percent probability level.

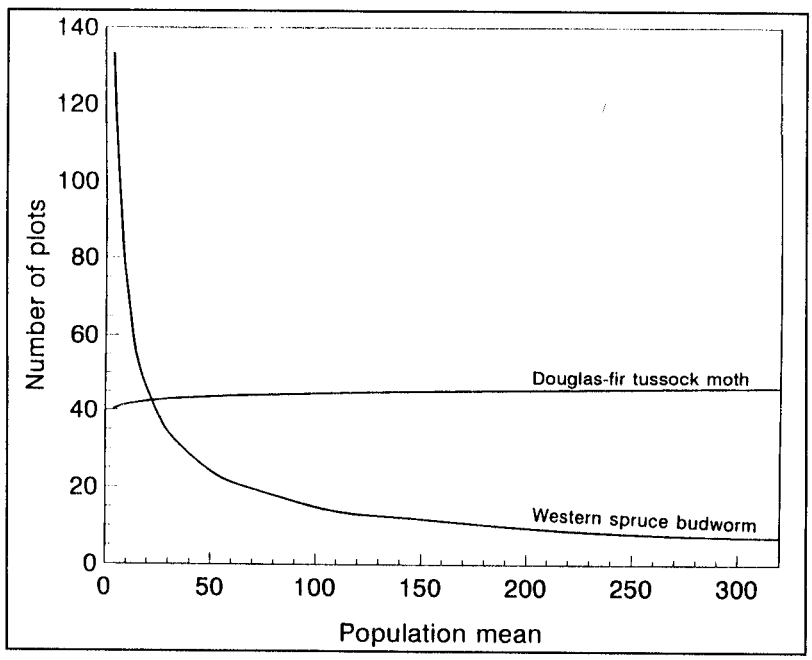


Figure 11-Number of plots required to estimate population density for a province-sized monitoring unit with a standard error of 20 percent of the mean and a 68-percent probability level.

Table 4--Cumulative probability, P, in normal distribution for different standard normal deviates, Z

Z	p	Z	P	Z	P
0.0	0.5000	1.0	0.8413	2.0	0.9772
.1	.5398	1.1	.8643	2.1	.9821
.2	.5793	1.2	.8849	2.2	.9861
.3	.6179	1.3	.9032	2.3	.9893
.4	.6554	1.4	.9192	2.4	.9918
.5	.6915	1.5	.9332	2.5	.9938
.6	.7257	1.6	.9452	2.6	.9953
.7	.7580	1.7	.9554	2.7	.9965
.8	.7881	1.8	.9641	2.8	.9974
.9	.8159	1.9	.9713	2.9	.9981

Source: Abbreviated from Gilbert (1987).

As an example, if 30 is the threshold number of larvae per square meter at which visible defoliation appears and $\sqrt{V(M)}$ is the standard deviation of the plot densities, the likelihood of defoliation somewhere in the monitoring unit for any population mean and variance can be estimated by solving,

$$Z_P = \frac{30 - \overline{M}}{\sqrt{V(M)}} \qquad (9)$$

and then calculating the percentile (1-P) where density exceeds 30 larvae per square meter. Because of the importance of the estimated mean and standard deviation in defining the probabilities for a monitoring unit, the procedure will produce the most reliable results from sample sizes of at least 30 plots that give good estimates of these parameters.

Unfortunately, larval densities often are not distributed normally over the monitoring unit but may be asymmetrical because of aggregations of larvae that skew the data to the right. In these cases a lognormal distribution, which is usually achievable by transforming the original data to logarithms, better describes the probability of different densities. The standard normal deviate for the defoliation threshold density is estimated the same as in equation (9), except that 30 is transformed to its natural logarithm, and $\overline{M}$ and V(M) are calculated from transformed plot densities.

A useful guide for deciding when transformation is needed is the ratio of the standard deviation to the population mean (coefficient of variation). As long as the ratio is less than 1.2, even though data are not necessarily distributed normally, the original data are preferred for analysis; otherwise a logarithmic transformation should be used (Gilbert 1987).

In a test of 42 data sets of tussock moth and budworm densities in the Blue Mountains and northern Cascades provinces, we found that only 14 (one-third) initially met the criteria for normality. After employing the rule of a 1.2 coefficient of variation, however, and transforming skewed data to natural logarithms, 39 data sets met the condition of normality (table 5).

Table 5-Frequency distribution of larval densities of Douglas-fir tussock moth and western spruce budworm in province-sized monitoring units[a]

Insect species and geographical province	Distribution			
	Normal	Lognormal[b]	Other	Total
	Number of data sets			
Douglas-fir tussock moth in the northern Blue Mountains	5	10		15
Douglas-fir tussock moth in the northern Cascade Range	4	5		9
Western spruce budworm in the northern Blue Mountains	5	3	1	9
Western spruce budworm in the northern Cascade Range	0	7	2	9
Total	14	25	3	42

[a] Tests for normality were performed by computer analysis of normal probability plots using the statistical package MINITAB, Release 8.0 (Ryan and Joiner 1976).
[b] Data transformed to natural logarithms before testing for normality.

An example of the usefulness of this statistical technique can be seen in its application to a set of tussock moth densities collected from the Umatilla National Forest in 1992 (table 6). Because of high variability among plot densities, the coefficient of variation exceeded 1.2, thus requiring normalization of the data by a logarithmic transformation. The results show that although the mean population density of 4.63 larvae per square meter was far below the threshold for defoliation, after transformation 5.4 percent of the area under the normal curve exceeded a density of 30 larvae at which some visible defoliation would be likely. This prediction was confirmed later in the summer by patchy tussock moth defoliation in a part of the monitored area despite overall low densities in the Forest.

Conclusions

Monitoring is most valuable when it is used for building continuous databases that record the behavior of defoliator populations over an extended period. Although this often means sampling in years when population densities are low, these periods of low numbers can be as important as outbreaks in analyzing the long-term behavior of populations. Analyses of time-series data may be the only way to recognize important mechanisms embedded in the population's history that are essential for building the predictive models needed in pest management (Berryman and Millstein 1990). Accumulating continuous databases requires a financial commitment to monitoring every year that, realistically, may be difficult to maintain. Nonetheless, this approach is still the most practical, if not the only, way of diagnosing key processes underlying the dynamics of defoliator populations (Berryman, in press). Long-term databases also will be valuable for recording the possible effects of new silvicultural approaches or changes in global climate on insect pests. There is no better way of answering questions on these subjects than to document the actual response of the populations over a long period.

Table 6-Plot densities of Douglas-fir tussock moth larvae with statistical calculations for a monitoring unit of 18 plots in the northern half of the Umatilla National Forest in June 1992[a]

Arithmetic plot densities (mean number of larvae per square meter plus 0.01)	0.54	0.01	0.29	0.48	0.87
	1.02	.38	.38	2.30	.08
	.01	.01	19.06	22.23	11.03
	24.07	.22	.42		
Natural logarithms of plot densities	-.62	-4.61	-1.24	-0.73	-.14
	.02	-.97	-.97	.83	-2.53
	-4.61	-4.61	2.95	3.10	2.40
	3.18	-1.51	-.87		
Statistical parameter					
Mean of arithmetic plot densities (population density):		4.63			
Standard deviation		8.33			
Coefficient of variation		1.80			
Mean of logarithmic plot densities:		-.61			
Standard deviation		2.49			
Number of normal deviates to defoliation density (In 30)		1.61			
Visible defoliation percentile (from table 4)		.054			

[a] Logarithmic transformations are for normalizing data to estimate percentile of population with densities capable of causing visible defoliation of trees.

Regardless of how strong a case can be made for defoliator monitoring, it is doubtful that any program can survive for long unless the sampling system is relatively simple and inexpensive to use. The methods we have described are a most efficient and cost-effective way of monitoring tussock moth and budworm populations. Not only can larval populations be censused over large units with statistically measured confidence limits, but their numbers can be interpreted directly in terms of the critical threshold densities affecting trees and stands. The only requirement is having representative stands with a stratum of lower crown host foliage accessible for sampling from the ground. Dense even-aged stands where all the crowns are out of reach, obviously, are not suited for monitoring by these methods. When acceptable conditions are available, however, the regular monitoring of defoliator larvae should be made a routine part of ecosystem management.

Acknowledgments

The idea that defoliator larvae might be monitored by beating lower crown foliage over a portable drop cloth was first given to us 25 years ago by Dan Dotta and Dick Hunt of the California Division of Forestry, who used a similar technique for quickly evaluating tussock moth populations. In the intervening years, many colleagues and assistants helped us to formalize and test procedures leading to the standard methodologies that we now recommend. We thank all those who have participated with this development through the years. Technical reviews of an early draft of this paper were made by John W. Hazard, Statistical Consulting Service, Bend, OR; Boyd E. Wickman and Torolf R. Torgersen, Pacific Northwest Research Station, La Grande, OR; Donald W. Scott, Wallowa-Whitman National Forest, La Grande, OR; Katharine A. Sheehan, Forest Pest Management, Pacific Northwest Region, Portland, OR; and Julie C. Weatherby, Forest Pest Management, Intermountian Region, Boise, ID. Their help in improving the final paper is much appreciated.

English Equivalents

1 centimeter (cm) = 2.54 inches
1 degree-day C = 1.8 degree-days F
1 °C = [5(°F - 32)]+9
1 meter (m) = 39.7 inches
1 hectare (ha) = 2.47 acres
1 square meter (m^2) = 1550 square inches

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Procedures for monitoring larval populations of the Douglas-fir tussock moth and the western spruce budworm are recommended based on many years experience in sampling these species in eastern Oregon and Washington. It is shown that statistically reliable estimates of larval density can be made for a population by sampling host trees in a series of permanent plots in a geographical monitoring unit. The most practical method is to estimate simultaneously densities on a plot of both insect species by the nondestructive sampling of foliage on lower crown branches of host trees. For best results, sampling methods need to be consistent with monitoring done annually to accumulate continuous databases that reflect the behavior of defoliator populations over a long period.

Keywords: Ecological monitoring, population monitoring, sampling insects, Douglas-fir tussock moth, *Orgyia pseudotsugata,* western spruce budworm, *Choristoneura occidentalis.*

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