INTERNAL REPORT 75

THE ANALYSIS OF THE ATTACK DISTRIBUTION OF AN ENDEMIC DOUGLAS-FIR BEETLE POPULATION

ABSTRACT

Felled second-growth Douglas-fir trees in western Washington were used to determine the attack distribution and develop a sampling technique for an endemic Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk. (Coleoptera:Scolytidae) population. The attack density varied by circumferential position. The lowest density was on the upper bole and the highest on one side with intermediate densities on the other side and the bottom. The sampling technique provides estimates of the number of trees and the number of samples within each tree needed to estimate the mean density of attack with a standard error of ten percent of the mean. The optimal quadrat size for the within-tree samples was shown to be between 182.9 and 365.8 square centimeters.

INTRODUCTION

The Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins is one of a few forest insects with the potential to kill healthy Douglas-fir, *Pseudotsugae menziesii* var. *menziesii* (Mirb.) Franco. In general, however, when suitable conditions for invasion of healthy trees do not exist, the beetle confines its attacks to weakened, injured or downed trees. In both situations this bark beetle is important in the consumer-decomposer interface by conditioning the host to invasion by decomposer organisms. The beetle also introduces host staining fungi. It is also possible that pathogenic fungi are directly dispersed by beetles emerging from diseased trees. In fact, special morphological features for the transport of fungal spores have been identified in a related bark beetle, *Scolytus ventralis* Leconte (Livingston and Berryman 1972), and in other *Dendroctonus* species (Barras and Perry 1971).

Since the emerging beetle population would be the critical stage in the dispersal of fungi, the density and distribution of new attacks would be directly related to the colonization of host material by the decomposer organisms. Thus the greater the density and uniformity of attack, the greater the probability of successful colonization by transported fungi.

Only a few studies have dealt with the attack distribution of the Douglas-fir beetle. Furniss (1962) studied the infestation patterns in standing and windthrown Douglas-fir trees in southern Idaho. He collected data on egg gallery density and resultant progeny, and he described a vertical attack gradient in standing trees. In windthrown trees the vertical stratification of galleries was absent, but variation did exist circumferentially. The density of egg galleries and progeny were greater on the bottom of trees than on the top; densities on the sides of the logs were intermediate between the top and bottom. Furniss' data are considered inapplicable to coastal Douglas-fir beetle populations because of differences in environmental conditions between southern Idaho and western Washington, i.e., because of differences in hosts, *Pseudotsugae menziesii* var. *glauca* versus *P. menziesii* var. *menziesii*, and because of differences in beetle populations (Atkins 1959).

The only study conducted in western Washington was by Johnson, Wright, and Orr (1961). They studied attack density and brood survival in windthrown, shaded and unshaded, old-growth and second-growth trees. They noted both circumferential and vertical stratification. Both attack and brood densities were found to be greater on the sides of the logs than on the tops. Greater densities of attack in the upper boles produced the height stratification. There have been no published reports on a sampling technique for estimating Douglas-fir beetle attack density in second-growth Douglas-fir trees in western Washington.

Thus recognizing the importance of the Douglas-fir beetle in the consumer-decomposer interface, a decision was made to investigate the attack distribution in felled, second-growth Douglas-fir trees. This decision also was based on the need for a sampling technique by coworkers.

MATERIALS AND METHODS

Site Preparation and Data Collection

To study *D. pseudotsugae* attack patterns, a stand of second-growth trees in an area with an endemic beetle population was located approximately four miles east of Cedar Falls, Washington, in the City of Seattle watershed. In mid-April twenty trees were randomly selected and felled. The trees were about fifty years old with an average DBH of 26.67 cm (10.5 in). A ring analysis indicated crown closure had taken place fifteen to twenty years earlier. Five of the test trees were cut into bolts for controlled experiments; the other fifteen trees were left in the field to be naturally infested by the emerging Douglas-fir beetle population.

The infestation period was closely monitored, and in mid-June after the initial flight, data were collected on attack density and location of individual attacks. This information was obtained in each tree by collecting data from four, 0.372 m^2 (4 ft^2) sampling areas. Samples 1, 2 and 3 were located in the lower, middle and upper bole respectively, and were spaced equidistant from each other. Sample 4 was located midway between 1 and 2. The quadrats were situated on the upper side of the log in such a manner that each quadrat extended one foot on either side of a center line bisecting the log. A 360° protractor was then placed in the center of a quadrat, with zero degrees oriented towards the crown on the center line. The angle of each attack from zero degrees and its distance from the center of the quadrat were then recorded. Thus the exact position of each attack within each sample was determined.

This type of analysis enabled the construction of "attack maps" by plotting the position of attacks within a quadrat on paper. Each "map" was then divided circumferentially into four 15.24 X 60.96 cm (6 X 24 in) subsamples with the long axis of each oriented along the bole. Thus the samples for each tree consisted of four height samples, each containing four circumferential samples.

Preliminary Analysis

The raw data from the 128 samples were initially grouped in a frequency diagram and tested for goodness of fit with various known distributions. The Poisson distribution was tested for fit using a Chi-square test (Sokal and Rohlf 1969). The normal distribution was tested using third and fourth moment (g1 and g2) statistics, and the Kolmogorov-Smirnov (K-S) D-max statistic. Although the K-S D-max statistic is only properly used with continuous functions, it has been shown that with a large sample size, the type I error for discrete data is no greater than that for continuous distributions (Sokal and Rohlf 1969).

The correlation of means and variances was tested using the correlation coefficient r. Estimates of the mean density of attack and variance from each tree were the variables used to calculate r.

This preliminary analysis indicated that the data were nonnormal and that the means and variances correlated.

The Analysis of Variance and Data Transformation

Since the analysis of variance (ANOVA) was proposed as a technique for testing various hypotheses, its applicability to the collected data was investigated. The assumptions the data must fulfill for the ANOVA to be valid are (Eisenhart 1947): (a) that the variances be unaffected by changes in the mean level of the measurements; (b) that the variances are normally distributed; (c) that the treatment and environmental effects are additive; and (d) that the variances are homogeneous. The most critical assumption is (a), and when it is fulfilled, (c) and (d) are usually also valid. Nonnormality (b), unless skewness is gross, has little effect on the results of the ANOVA (Cochran 1947).

Since preliminary analysis indicated that at least two of the above assumptions, (a) and (b), were not fulfilled, the need for a data transformation was implied. The purpose of a transformation is to change the scale of measurement so that the ANOVA becomes more valid (Bartlett 1947).

Thus the efficiency of two common transformations, the $\sqrt{x + .5}$ and the $\log(x + 1)$, in stabilizing the data was investigated. The reduction in correlation between the variances and the means was tested using the product moment correlation coefficient, and the degree of normalization of the data was tested using the third and fourth moment statistics and the K-S D-max statistic.

Analysis of the Distribution of Attacks

A mixed model, nested factorial design for the ANOVA of the transformed data was used to test the effects and interactions of individual trees, heights, and circumferential position on the distribution of attack. Trees and heights were treated as random effects, with heights nested in trees, while circumferential positions were considered fixed. It was necessary to use the nested factorial design in this model because height levels varied from tree to tree in this experiment, i.e., the location of samples with respect to height were not the same in any two trees (Figure 1). The expected mean squares (EMS), sums of squares (SS) and degrees of freedom (df) for the ANOVA model are given in Table 1. The component EMS's and SS's were derived by methods suggested by Scheffé (1959).

The effects of circumferential position were further tested for significance using a separate mixed model factorial treatment design for the ANOVA. The data were collected from six trees independent of the samples previously collected. Four, 6 X 24 in samples were taken from each tree; one from the top of the log, one from the bottom, and one from each side. The trees were considered random effects and the circumferential samples fixed. The degrees of freedom and expected mean squares for this model are given in Table 2. Student-Newman-Keuls test (Sokal and Rohlf 1969) was used to detect differences in mean level of attack between circumferential positions.

Development of the Sampling Technique

A procedure developed by Morris (1955) for spruce budworm populations and modified by Berryman (1968) for scolytids was used to calculate the number of samples needed to sample with a specified standard error of the mean. Using the relationship:

$$S\bar{y} = \sqrt{Ns\ Vb + Vw/Ns\ Nt}$$

where $S\bar{y}$ is the standard error of the mean, Ns is the number of samples per tree, Nt is the number of trees sampled, Vb is the between-tree variance, and Vw is the within-tree variance; the number of trees and samples within trees can be calculated.

Estimates of Vb and Vw are obtained in the following manner: $Vw =$ (SSt - SSb)/df$t$ - df$b$ and Vb = (MSb - Vw)/N, where SSt is the uncorrected total sum of squares from the ANOVA, SSb is the uncorrected between-tree sum of squares, df$t$ and df$b$ are their respective degrees of freedom, MSb is the between-tree mean square, and N is the number of sample units used to estimate within-tree variation.

Snedecor's (1956) formula for the calculation of sample size was also used for comparison with the above method:

$$n = t^2\ S^2/D^2\ \bar{x}^2$$

where n is the number of samples, t is Student's t, s^2 is the variance, and D is the desired level of precision and x is the mean.

Since it is desirable to use the arithmetic means in the previous calculations, and since the component variances are expressed in terms of the transformed scale, adjustments must be made to make the two comparable. This is most easily done by expressing the arithmetic means on the transformed scale.

The effect of quadrat size was also tested, using a simple treatment design for the ANOVA. The quadrat sizes tested were 1463.04, 731.52, 365,76, 182.88 and 91.44 cm^2 (576, 288, 144, 72, and 36 in^2) respectively, with the smaller quadrats nested in the largest. The means were tested for significance of difference using the Student-Newman-Keuls test. The optimal quadrat size was selected on the basis of the smallest quadrat which possessed a mean that was not significantly different from the mean for 1463.04 cm^2 (576 in^2) quadrat.

RESULTS

Frequency Distribution

The raw data from the 128 samples were grouped in frequency classes. The mean number of attacks per sample was 1.76 with a variance of 1.52. The ratio of the variance to the mean was equal to 0.86, indicating that the grouped data followed a Poisson series. A chi-square goodness of fit test of the observed data to the expected frequency for the Poisson series provided a chi-square value of 0.304. The critical chi-square value, alpha (α) equal to 0.05, with two degrees of freedom is 7.879; thus the null hypothesis that the sample data followed a Poisson series was not rejected.

The goodness of fit of the observed data to the expected normal distribution was also tested, using the Kolmogorov-Smirnov D-max statistic. The value of K-S D-max calculated from the observed frequency was 0.191. The critical value for D-max, α equal to 0.05 was 0.120, thus the null hypothesis that the observed data followed a normal distribution was rejected. The third and fourth moment statistics for the observed frequency distribution were 0.4483 and -0.4029 respectively. These values indicated that the data was skewed to the right and was platykutosic with reference to the expected normal frequency distribution (the value of both moments is zero in a normal distribution). Both the observed frequency and expected normal frequency distributions are shown in Figure 1.

Data Transformation

Since the raw data appeared to follow the Poisson distribution, further violations of the assumptions for the analysis (ANOVA) were expected. In the Poisson series the mean equals the variance, therefore the variance varies directly with changes in the mean. Thus the correlation coefficient r was used to test for correlation between the means and the variances. The mean and variance were calculated for each tree and were used as the variables to calculate r. The value for this sample was 0.66, which represented a significant level of correlation (t-test, α equal to 0.05).

Since the distribution derived from the observed data violated at least two of the assumptions for use of the ANOVA, nonnormality and independence, the need for a data transformation was indicated. The two transformations that were tested for their efficiency in normalizing the data and reducing the mean variance correlation were the $\sqrt{x + .5}$ and the log $(x + 1)$.

The efficiency of the transformations in normalizing the data was tested using the third and fourth moment statistics (g1 and g2) and the K-S D-max statistic. The values of g1 and g2 for $\sqrt{x + .5}$ were -0.1557 and -0.6432 respectively; for $\log(x + 1)$, -0.4993 and -0.5317 respectively. The K-S D-max values were 0.1596 for the $\sqrt{x + .95}$ and 0.1848 for the $\log(x + 1)$. Neither of the transformations were effective in normalizing the data (critical value for D-max, α equal to 0.01, is 0.144).

The correlation of the transformed means and variances was tested using the correlation coefficient r. The value of r for $\sqrt{x + .5}$ transformation was 0.42; for the $\log(x + 1)$ was 0.32. Neither of these values indicated any significant (t-test, α equal to 0.05) correlation between the transformed means and variances.

It was previously stated that the most critical assumption for the use of the ANOVA is that the variances be unaffected by changes with the mean level of measurements. It also was stated that nonnormality had little effect on the results of the ANOVA. Therefore, the $\log(x + 1)$ was selected for use as a data transformation with the ANOVA since it was most efficient in reducing the mean-variance correlation.

Distribution of Attacks

The results of the ANOVA to detect the effects of trees, heights and circumferential position on the mean levels of attack are given in Table 4. None of the single effects nor their interactions were found to be significant. The high F ratio for circumferential position, however, indicated that if the total circumference were included, then the potential effect might be significant.

The effect of total circumference was tested using data collected from six independent samples previously described above. The $\log(x + 1)$ data transformation was used with the ANOVA; the results are given in Table 5.

Since circumferential position was found to be significant, Student-Newman-Keuls test was used to determine which positions possessed mean levels of attack different from the others. The results are given in Table 6. The top was significantly different from all other positions. Side 2 also was different from all others. The mean levels of attack between side 1 and the bottom were not significantly different. These results indicate that the distribution of attacks varies with circumferential position but not with height or between trees.

Sampling Technique

The number of samples needed to obtain an estimate of the mean density of attach with a ten percent standard error of the mean was based on estimates of the within- and between-tree variances, 0.0452 and 0.00083 respectively. These estimates were obtained in part from the ANOVA and were expressed on the transformed scale. Thus in order to obtain a meaningful estimate of the standard error on the transformed scale, a correction factor had to be applied to the arithmetic mean ($\bar{x}$). This was necessary because the antilog of the transformed mean minus one (geometric mean) was not symmetric with respect to the arithmetic mean. The ratio of the geometric mean $\bar{y}$ to the arithmetic mean was 1.467/1.759 and equal to 0.834, and by applying this correction factor to $\bar{x}$ we obtained antilog $\bar{y}$ - 1 equal to 1.466. Applying the correction factor to the standard error of the arithmetic mean $S\bar{x}$, we obtained antilog ($\bar{y}$ + $S\bar{y}$) - 1 equal to 1.613 and antilog ($\bar{y}$ - $S\bar{y}$) - 1 equal to 1.319. Thus the transformed estimates were $\bar{y}$ equal to 0.39199, $\bar{y}$ - $S\bar{y}$ equal to 0.32613 and $\bar{y}$ + $S\bar{y}$ equal to 0.41714. This provided two values for the transformed standard error of the mean, 0.02515 and 0.6586; again this was due to the assymmetry of the arithmetic and transformed scales with respect to each other.

The smaller of the two estimates, $S\bar{y}$ equal to 0.02515, was used in calculating sample size because it provided the larger and possibly safer estimate of the number of samples needed to estimate the mean density of attack. Estimates of the number of within-tree samples (Ns) and number of trees (Nt) needed to sample with the specific precision $S\bar{y}$, are given in Table 7.

For contrast with the Morris method of estimating sample size, Snedecor's formula was used to calculate the total number of samples (Nt X Ns) needed to estimate mean density with a standard error of ten percent at a 95 percent confidence level. The results obtained using this formula indicated that 198.28 (199) total samples were needed when estimates of the untransformed mean and variance were used, and 120.26 (121) samples when the transformed parameters were used.

The effect of quadrat size in estimating the mean density of attack was tested using the ANOVA (Table 8). Student-Newman-Keuls test was used to determine which quadrat sizes possessed mean densities different from the largest, 1463.04 cm^2 (576 in^2). The results for both transformed and untransformed data are given in Table 9. For the transformed means, the 91.44 cm^2(36 in^2) quadrat was the only one different from the 1463.04 cm^2 quadrat. For the untransformed data, the 91.44 and 182.88 cm^2 (72 in^2) quadrats were both significantly different from the 1463.04 cm^2 quadrat. The difference in the results from the two scales is again due to their assymmetry with respect to each other.

DISCUSSION

Frequency Distribution

The result of the goodness of fit test on the raw data indicated that the observed frequency followed the Poisson distribution. In order for the Poisson distribution to be an acceptable model for an insect population three assumptions must be fulfilled (Waters and Henson 1959): (a) the probability of any individual occupying a quadrat is constant; (b) the probability of any quadrat being occupied is constant; and (c) the presence of an individual in a quadrat does not change the probability of another individual occupying the same quadrat. These assumptions rarely, if ever, hold for natural insect populations.

It is apparent that if density gradients exist within a population then either assumption (a) or (b) or both, are violated. The existence of density gradients in Douglas-fir beetle populations is clearly demonstrated since attack density varies significantly with circumferential position. Thus the fit of the raw data to the Poisson series must be due to a sampling artifact. The artifact in this study was due to the use of samples from only the upper area of the infested bole. If the sampling universe had been expanded to include the whole bole, laterally and circumferentially, then the data generated would not have followed the Poisson. In this case the mean density of attack probably would have been lower and the variance higher, resulting in a variance to mean ratio greater than one. This high ratio would imply that the frequency distribution generated by the data would be best described by the negative binomial distribution. Thus, in this study the fit to the Poisson series is artificial, and has little biological significance.

Data Transformation

Since the goodness of fit test indicated that the Poisson model best described the frequency generated by the raw data, the appropriate transformation to normalize the data for the ANOVA was thought to be the $\sqrt{x + .5}$ (Scheffe 1956). We noted that this transformation was not effective in normalizing the data; although it did significantly reduce the variance-mean correlation. The other transformation tested, the $\log(x + 1)$, was not effective in normalizing the data either, but it was finally selected for use with the ANOVA because it reduced the variance-mean correlation to a greater degree than the $\sqrt{x + .5}$ transformation. In fact, the $\log(x + 1)$ transformation is usually used when the variance exceeds the mean for a set of data, thus it is appropriate for use with data that follow a negative binomial distribution. Therefore, considering that the fit to the expected Poisson distribution was probably an artifact, this transformation may, in reality, have been more appropriate.

Distribution of Attacks

The mixed model nested factorial design used for the ANOVA has been used by other workers for the analysis of distribution effects on scolytid populations (Berryman 1968, DeMars 1970). This model is appropriate only if there exists no significant interaction between the simple effects. If significant interaction did exist, then calculation of meaningful F-ratios would not be possible. Fortunately there was no reason to assume that interaction would exist, especially with the use of a restricted sampling universe.

Although the initial ANOVA did not indicate the presence of any significant effects, the F-ratio for circumferential position was high (significant at α equal to 0.10), therefore this effect was further investigated using data collected from the total circumference. Results of this investigation showed that differences in mean attack density varied significantly by circumferential position. The top position possessed a level of mean density different from all others. This low density is consistent with the results from other studies (Furniss 1962, Johnson et al. 1961) on the attack distribution of Douglas-fir beetle populations. The reason beetles avoid the tops of logs is unknown, but it has been suggested that this is due to the fact that the beetles tend to be negatively phototactic (Furniss 1962), or that they avoid the upper surfaces due to higher bark temperatures (Johnson et al. 1961). Neither of these explanations satisfactorily accounts for the results in these experiments since all of the study trees were in the shade.

One side position possessed a mean attack density much greater than levels at other positions. The reason for this high attack density is unknown, but it may be due to some unique environmental conditions that resulted in a statistical artifact. The reason the attack density on the bottom of the log was not greater may be due to the fact that the lower boles of some trees were inaccessible to the beetles.

Sampling Technique

The effect of quadrat size on the estimation of the mean density of attack was significant. It was further shown that a quadrat with an area between 72 and 144 square inches is optimal in estimating mean density, i.e., it provides the same result as the 576 square inch quadrat. Since the safest estimate of mean density would come from a larger quadrat, and also considering that it is not much more difficult to collect a 144 square inch sample than a 72 square inch sample, the 144 square inch quadrat should be used.

Estimates of within- and between-tree attack density variance indicated that variance within trees was greater than variance between trees. This was not totally unexpected since the sampling universe was restricted and only successfully attacked trees were included. Therefore estimates of the number of samples required to sample with a standard error of ten percent of the mean indicate that sampling more intensively within trees significantly reduces the number of trees needed to be sampled.

Recognizing that the high variance within trees was due to the circumferential attack density gradient, a sampling formula can be recommended. If only the infested portion of trees with an attack density greater than one attack per square foot is to be sampled, then five or six trees should probably be selected. Within each tree, four or five height levels should be sampled, and within each sample data from all four circumferential positions should be collected. To insure that all four positions are equally sampled, 6 X 24 inch (144 square inch) quadrats should be used. The fewest number of trees considered reasonable should be sampled, since the time required to collect samples within a tree is less than the time required to locate new trees with the desired parameters. In natural field populations of the Douglas-fir beetle in coastal second-growth Douglas-fir trees, a minimum of six trees would be considered reasonable. This sampling formula will probably provide meaningful estimates of mean density; in no case will use of this system underestimate mean density.

If this sampling technique is applied to naturally windthrown trees in a number of different locations, then collection of additional samples may be required. The reason that additional effort may be necessary is due to the fact that data from only freshly felled, second-growth trees were used in this study to derive the number of samples needed to estimate the mean density. Thus the number of additional samples needed to obtain the desired precision can be determined using the appropriate formulae (see Materials and Methods) in conjunction with new variance estimates.

SUMMARY

1. The distribution of *D. pseudotsugae* attack did not vary significantly with tree height, but did vary significantly by stem circumferential position. The lowest attack density was on the upper bole, and the highest on one side, with intermediate densities on the opposite side and the bottom of the log.

2. A sampling technique for estimating the mean density of attack within the infested portion of trees was developed. The number of trees and the number of samples within each tree needed to estimate the mean density of attack with a standard error of ten percent of the mean were calculated. The optimal quadrat size for the within-tree samples was shown to be between 182.88 and 365.76 cm^2 (72 and 144 in^2).

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Table 1. Degrees of freedom (df), sums of squares (SS) and expected mean squares (EMS) for the ANOVA model to test the effect of trees, heights and circumferential position on attack density.

Source of variation	df	SS	EMS		Denominator for F-ratio
Trees	$I - 1$	$JK \sum_i (y_i - y.)^2$	$\sigma_e^2 + JK\sigma_T^2 + K\sigma_H^2$	(1)	(2)
Heights	$I(J - 1)$	$K\sum_i \sum_j (y_{ij} - y_{i}.)^2$	$\sigma_e^2 + K\sigma_H^2$	(2)	(5)
Circumferential position (A)	$K - 1$	$IJ \sum_k (y_k - y.)^2$	$\sigma_e^2 + IJ\sigma_A^2 + J\sigma_{TA}^2$	(3)	(4)
T · A	$(I - 1)(K - 1)$	$J \sum_i \sum_k (y_{ik} - y.k - y_{i}. + y \cdots)^2$	$\sigma^2 + J\sigma_{TA}^2$	(4)	(5)
H · A (error)	$I(J - 1)(K - 1)$	$\sum_i \sum_j \sum_k (y_{ijk} - y_{i.k} - y_{ij.} + y_{i}..)^2$	σ_e^2	(5)	
Total	$IJK - 1$	$\sum_i \sum_j \sum_k (y_{ijk} - y \cdots)^2$			

Table 2. Degrees of freedom (df) and expected mean squares (EMS) for the ANOVA model to test the effect of circumferential position on attack density.

Source of variation	df	EMS		Denominator for F-ratio
Bolts	$I - 1$	$\sigma_e^2 + J\sigma_B^2$	(1)	(3)
Circumferential position (A)	$J1- 1$	$\sigma_e^2 + I\sigma_A^2$	(2)	(3)
B · A (error)	$(I - 1)(J - 1)$	σ_e^2	(3)	
Total	$IJ - 1$			

Table 3. Results of the ANOVA to test the effects of trees, heights, circumferential position and their interaction on the attack density. of *D. Pseudotsugae*.

Source	Degrees of freedom	Corrected sum of squares	Mean squares	*F*-ratio
Trees	7	0.40938	0.05848	1.185 (1)
Heights	24	1.18473	0.04936	1.384 (2)
Circumferential position	3	0.51758	0.17253	3.032 (3)
CP · T	21	1.19487	0.05690	1.596 (4)
CP · H(T)	72	2.56754	0.03566	
Total	128			

Critical values of *F*:

(1) $F_{.05}$ (7,24) = 2.43 (not significant)

(2) $F_{.05}$ (24,74) = 1.67 (not significant)

(3) $F_{.05}$ (3,21) = 3.07 (not significant)

(4) $F_{.05}$ (21,72) = 1.72 (not significant)

Table 4. Results of the ANOVA to test the effects of circumferential position on attack density of *D. pseudotsugae*

Source	Degrees of freedom	Corrected sum of squares	Mean squares	*F*-ratio	
Bolts	5	0.30	0.06	2.86	(1)
Circumferential position	3	0.23	0.08	3.81	(2)
B · CP (errors)	15	0.32	0.021		
Total	24	0.85			

Critical values of *F*:

(1) $F_{.05}$ (5,15) = 2.90 (not significant)

(2) $F_{.05}$ (3,15) = 3.29 (significant)

Table 5. S-N-K test for differences between the mean level of *D. pseudotsugae* attack density by circumferential position.

$$S\bar{y} = \sqrt{\frac{\text{Error MS}}{n}} = \sqrt{\frac{0.209}{6}} = 0.19$$

$$LSR = Q\alpha\ (K,v) \cdot S\bar{y} = Q.05\ (K,15) \cdot 0.19$$

If the difference between the means exceeds *LSR* for the given *K*, then the difference is significant.

K	2	3	4
Q	3.01	3.67	4.08
LSR	0.572	0.697	0.775

Value of	Differences between position	Value of the differences
4	S2 - T	1.83 (sig)
3	S2 - B	1.17 (sig)
	B - T	1.00 (sig)
2	B - S1	0.34 (not sig)
	S1 - T	0.86 (sig)

Position

Top (T)
Side 1 (S1) } no significant
Bottom (B) } difference
Side 2 (S2)

Table 6. The number of samples needed to obtain an estimate of the mean density of *D. pseudotsugae* attack with a ten percent standard error of the mean based on estimates of within- and between-tree variance.

Number of within-tree samples (*Ns*)	Number of trees (*Nt*)	Total number of samples (*Ns* X *Nt*)
32	4	128
20	5	100
16	6	96
12	8	96
8	11	88
4	20	80

Table 7. The results of the ANOVA to test the effect of quadrat size on *D. pseudotsugae* attack density.

Source	Degrees of freedom	Corrected sum of squares	Mean square	*F*-ratio
Quadrats	4	0.5957	0.1489	6.803
Error	35	0.7662	0.0219	
Total	40			

Critical value of F: $F_{.01}$ (4,35) = 3.91

Table 8. S-N-K test for the difference between the mean level of attack density by quadrat size based on transformed and untransformed data.

Untransformed data

$$S\bar{y} = 0.1812$$

$$LSR = Q\alpha\ (K,v) \cdot S\bar{y} = Q.05\ (K,15) \cdot 0.1812$$

Quadrat size (cm^2)	91.44	182.88	365.76	731.52	1463.04
Mean density (per 0.092 m^2)	0.25	1.06	1.29	1.52	1.78

The underlined means are not significantly different from each other.

Transformed data

$$S\bar{y} = 0.0523$$

$$LSR = Q\alpha\ (K,v) \cdot S\bar{y} = Q.05\ (K,15) \cdot 0.0523$$

Quadrat size (cm^2)	91.44	182.88	365.76	731.52	1463.04

The underlined quadrat sizes are not significantly different from each other.

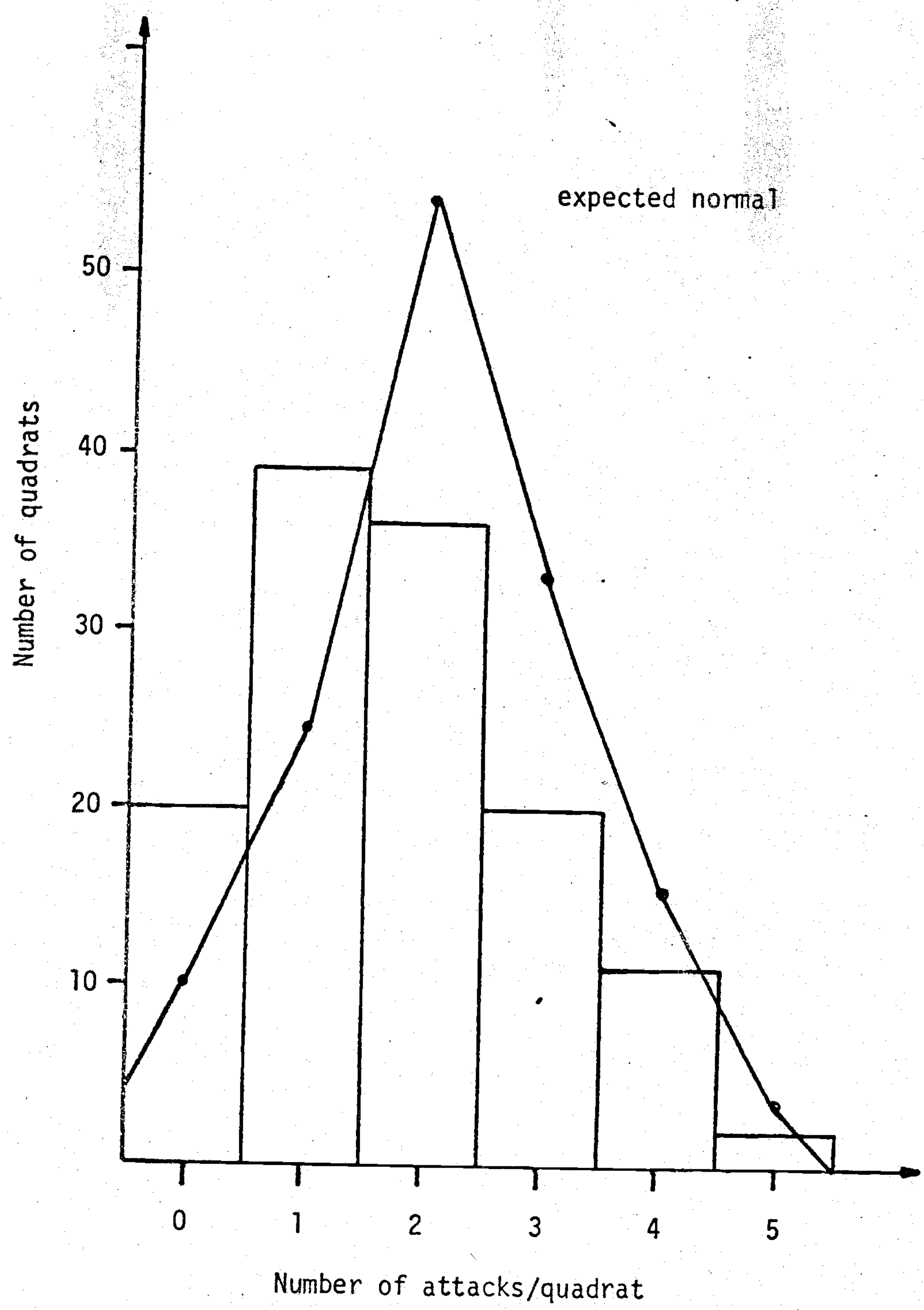

Figure 1. The observed and expected normal frequency of *D. pseudostugae* based on 0.092 m^2 (128 sq ft) quadrats.