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DAMAGE PREDICTION FOR *CONTARINIA OREGONENSIS* FOOTE (DIPTERA: CECIDOMYIIDAE) IN DOUGLAS-FIR SEED ORCHARDS

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Abstract

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Damage at cone harvest by the Douglas-fir cone gall midge, *Contarinia oregonensis* Foote, was positively correlated with the number of egg-infested scales per conelet in the spring. Reducing the average number of galled seeds per cone by 1.5 increased the average number of filled seeds per cone by 1.0 in insecticide trials. Optimum sample sizes for estimating average densities of egg-infested scales were calculated to be one conelet per tree and 150 trees per orchard. The mean crowding variable was linearly related to average density so a sequential sampling technique relative to a critical density, using Iwao's procedure, was developed for determining the need of control actions.

Résumé

Une corrélation positive a été établie entre les dommages causés à la récolte de cônes par la cécidomyie des cônes du Douglas (*Contarinia oregonensis* Foote) et le nombre d'écailles infestées par cônelet au printemps. La réduction de 1,5 obtenue lors d'essais de répression avec des insecticides du nombre moyen des graines touchées par cône a entraîné une augmentation du nombre moyen de graines pleines par cône de 1,0. Les tailles optimales des échantillons pour l'estimation de la densité moyenne des écailles infestées d'oeufs ont été calculées comme étant d'un cônelet par arbre et de 150 arbres par verger. Un rapport linéaire existant entre la variable d'encombrement moyen et la densité moyenne, une technique d'échantillonnage progressif en fonction de la densité critique, selon la méthode d'Iwao, a été élaborée pour déterminer la nécessité de mesures de répression.

Introduction

The Douglas-fir cone gall midge (DFCGM), *Contarinia oregonensis* Foote (Diptera: Cecidomyiidae), is a serious pest of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, seed in coastal seed orchards in British Columbia (Miller 1980). DFCGM eggs are laid on scales near the axis of conelets (= immature cones) open to receive pollen (Hedlin 1961). The larvae mine into the scales where their feeding causes galls to form. Seed loss is caused by inhibition of ovule development or by fusion of seed wings to scales during gall formation which makes seed extraction impossible (Johnson and Heikkenen 1958).

Seed losses to DFCGM have been predicted in forest stands by determining both the number of overwintering larvae in the litter below trees and the size of the current cone crop (Johnson 1962). This technique has shortcomings for use in orchards, namely: (*i*) overwintering larvae are counted but the proportion of the population that emerges, which will vary among years and sites due to prolonged diapause, is not taken into account; (*ii*) rates of migration into orchards from nearby stands are not known; and (*iii*) DFCGM larvae do not overwinter in well-managed orchards because the larvae are removed during the annual cone harvest. Johnson and Hedlin (1967) proposed a method for determining the need for control actions based on egg counts on five randomly selected scales per conelet, but this method was not substantiated.

The optimum time for application of a systemic insecticide is after the conelets have closed following pollination but before they reach the pendant position, a period of 2–10 days depending on the weather. If damage prediction is to be a practical component in deciding whether or not to apply a systemic insecticide, it must be possible to complete damage prediction within a period of about 2 days.

Larval densities of DFCGM at cone harvest in seed orchards are determined by amounts of oviposition; natural mortality factors that occur during the egg and larval periods do not regulate DFCGM populations (Miller 1984). Therefore, damage prediction based on spring egg counts should be feasible. This study reports the relationship between damaged seeds per cone at harvest and number of egg-infested scales per conelet in the spring, and examines the distribution of egg-infested scales within orchards. A fixed sampling method for estimating average number of egg-infested scales per conelet is proposed, as is a sequential technique for classifying infestations with respect to whether or not a pest control treatment should be applied.

Materials and Methods

Egg-infested scales vs. damage. Conelets were collected after they had closed and approached the pendant position in early May at the following orchards: 10 trees at Saanich, 6 trees at Koksilah, 10 trees at Lake Cowichan, 9 trees at Pacific Forest Products (PFP), 10 trees at Quinsam, 10 trees at Snowdon, and 9 trees at Tahsis in 1979; 19 trees at Koksilah in 1980; 3 trees at Lake Cowichan, 4 trees at Quinsam, and 4 trees at Snowdon in 1981. Twenty randomly selected conelets were collected from each tree. These conelets were dissected and the egg-infested scales counted. Ten cones in 1979 and 20 cones in 1980 and 1981 were collected from the same trees at harvest. These cones were dissected and counts of filled and galled seeds were made. Tree averages of the numbers of galled seeds per cone were compared with numbers of egg-infested scales via regression analysis. Reductions in numbers of infested scales per cone at harvest and corresponding changes in numbers of filled seeds following insecticide treatments (Miller 1983*b*; D. Summers personal communication) were compared via regression analysis to quantify the relationship.

Distribution of egg-infested scales and fixed sample size requirements. In addition to the above egg samples, up to 120 conelets were collected from each of 43 trees, which had been divided into 12 sample cells (four aspects by three crown thirds), in 6 orchard-years from 1978 to 1981 (see Miller 1986 for details). In 1984, 10 conelets were collected from each of the upper, mid, and lower thirds of the crown on 10 trees in both Saanich and Snowdon seed orchards, and a further 10 conelets were collected from each of 10 trees that were bearing in the upper crown only at Snowdon. All conelets were dissected and the numbers of egg-infested scales were determined. In the 1978–1981 samples, the conelets on each sample branch were counted.

The data were compared with several frequency distributions, namely, normal, Poisson, negative binomial, binomial, Fisher's log, and Neyman A. Factors that affected the within-orchard distribution of egg-infested scales were determined by analysis of covariance using the number of conelets per branch as the covariate for the 1978–1981 data, and by analysis of variance for the 1984 data. These analyses and the procedures for estimation of fixed sample size requirements are the same as those used previously for egg densities (Miller 1986).

Sequential sampling plan. Iwao (1975) devised a method for sequential sampling plan development relative to a critical density based on the mean crowding parameter ($\overset{*}{m}$)[1]of Lloyd (1967) which is a measure of population dispersion. This procedure is valid if the linear relationship $\overset{*}{m} = \alpha + \beta m$ exists, where m is the mean density of the population and α and β are characteristics for the species concerned. This procedure has been used to evaluate infestations of other pests (Burts and Brunner 1981; Shaw *et al.* 1983; Shepherd *et al.* 1984), and was used for the development of this sequential sampling plan.

Results and Discussion

Egg-infested scales vs. damage. The number of galled seeds per cone was significantly related to the number of egg-infested scales per conelet (Fig. 1). Reducing the number of

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[1] $\overset{*}{m} = m + (s^2/m - 1)$.

galled seeds in cones through insecticide application resulted in an increase in the number of filled seeds, but the ratio of reduction to increase was not 1:1 (Fig. 2). Not all potential seeds develop into fertile seeds even in the fertile zone (middle two-thirds) of a cone due to factors other than insect damage, such as pollination and seed abortion. Also, some galls occur outside of the fertile zone of the cone and these have no bearing on the number of seeds produced by the cone. It is important to note that these data were gathered in seed orchards where supplemental pollination was practiced. As a result, changes in the number of filled seeds were probably less variable than in situations where supplemental pollination is not used or possible. In the regression in Figure 1, the intercept was set at 0 because calculated intercepts were not significantly different from 0 and because a 0 intercept is biologically logical.

The number of seeds that will be damaged by DFCGM can be predicted by estimating the number of egg-infested scales per conelet and using this number in the regression equation in Figure 1 to estimate the number of galled seeds that will subsequently develop if no control action is taken. This number would then be used as X in Figure 2 to estimate the potential number of additional filled seeds that should develop if all DFCGM larvae were controlled. To be realistic, few insecticide applications are 100% effective so this number should be adjusted by the efficacy rate expected, e.g. 85% is attainable operationally. A more direct relationship between egg-infested scales per conelet and gain in filled seeds per cone by insecticide application was not possible because of operational constraints in the orchards when the experiments were being conducted.

Distribution of egg-infested scales and fixed sample size requirements. Variance increased with average density (Fig. 3). Frequencies of egg-infested scales per conelet fitted the negative binomial distribution in about 80% (60/73) of the trees sampled. The data that did not fit the negative binomial distribution also did not fit any of the other frequency distributions. Attempts to estimate a common k failed. Calculating provisional k's (Waters 1955) showed that k increased from 0.8 to 26.9 as average density increased from <1.5 to >25 egg-infested scales per conelet. A similar situation has occurred in other insect populations (Iwao and Kuno 1971).

Because of the dependence of variance on the mean, a transformation of the data was required prior to further analysis. The mean crowding – mean density relationship suggested an exponential transformation (Iwao and Kuno 1968) of $\chi^{0.446}$, which removed the dependence of variance on the mean (i.e. the relationship was not significant) and was used prior to analysis of the data.

The differences in average number of egg-infested scales per conelet among trees were significant in 7 of 8 orchard-years whereas crown level within tree was significant in only 5 orchard-years. Where crown level was a significant factor, numbers of egg-infested scales per conelet were higher in the upper crown than in the lower crown (Table 1). The effect of crown level appeared to be affected by density; differences among crown levels occurred at low densities but not at higher densities. Average number of egg-infested scales per conelet in the central portion of the cone-bearing part of a tree crown was the same as the overall tree average. Aspect within crown level and branch within aspect were not significant in any orchard-year. Numbers of egg-infested scales per conelet were not correlated with number of conelets per branch in 1978–1981 nor did densities of egg-infested scales vary significantly between heavily and lightly producing trees at Snowdon in 1984.

Using the procedures outlined in Miller (1986), the optimal numbers of conelets per tree (n_c) for estimating average numbers of egg-infested scales per conelet were calculated (Table 2). The time required for collecting and processing each conelet was estimated to be 7 min and the time required for tree selection was estimated to be 3 min; n_c ranged from 1 to 7. Multiplying the values of n_T by their respective n_c value and comparing the

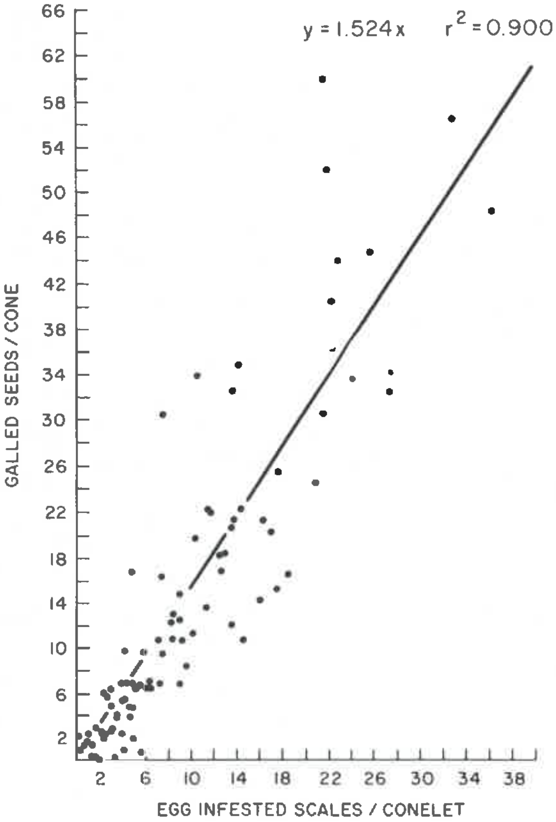

FIG. 1. Relationship between galled seeds per cone and egg-infested scales per conelet. The regression intercept was set at 0; the regression was highly significant, $P<0.001$.

products revealed that taking one conelet per tree required the fewest total sample conelets for all orchard-years. After recalculating the coefficients of variation, the number of sample trees required for estimating the average number of egg-infested scales per conelet in each orchard-year was determined from Stauffer (1983) (Table 2). For 90% confidence and 10%

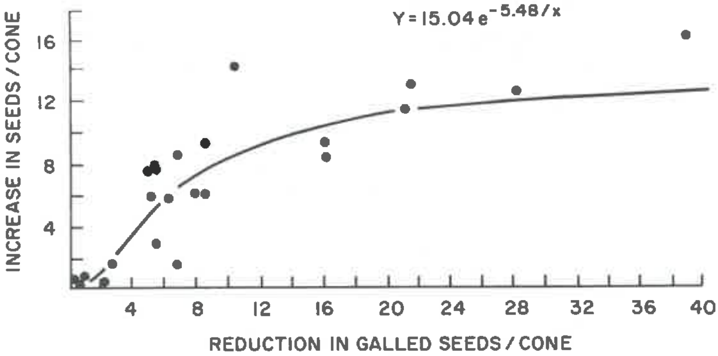

FIG. 2. Relationship between the increase in filled seeds per cone and the reduction in galled seeds per cone due to insecticide applications. The regression was highly significant, $P<0.001$; e = 2.71.

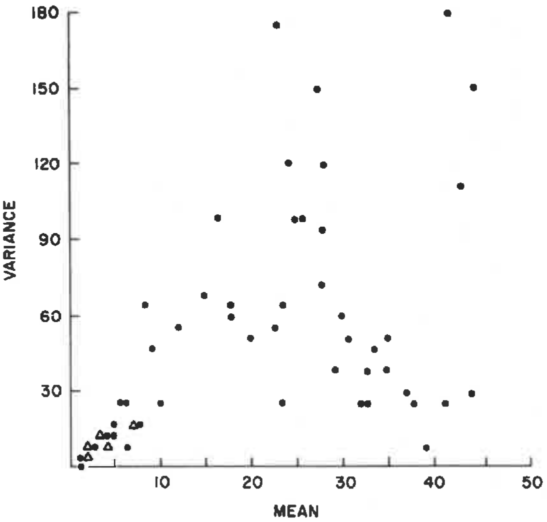

FIG. 3. Variance vs. mean for DFCGM egg-infested scales per cone on individual trees.

sampling error, one conelet should be sampled from each of 150 trees. At 7 min per conelet, processing 150 conelets would take 17.5 person-hours.

The proportions of infested scales (p) were used to estimate the number of scales that should be sampled in a simple random sampling design (Cochran 1977):

$$n = \frac{t^2pq}{d^2}$$

where $q = 1-p$, t = Student's t, and d = desired sampling error. In 5 of 8 orchard-years, the sample size requirement was equal to or greater than the number of scales in most conelets. Therefore, the whole conelet should be dissected in sample processing instead of randomly selecting five scales per conelet, as suggested by Johnson and Hedlin (1967).

Sequential sampling plan. The values of the negative binomial distribution for densities of 2.6 and 5.2 infested scales per cone (representing 10 and 20% seed loss) were 0.8 and 1.4, respectively, which were significantly different. Thus, it was not possible to estimate a common k for critical densities of practical significance so use of the Wald method (the

Table 1. Average densities of egg-infested scales in crown thirds of Douglas-fir trees in 8 orchard-years

		Crown level*				
Year	Orchard	Upper	Mid	Lower	Overall average	Range of tree means
1978	Koksilah	31.0a	29.7a	28.4a	29.7	14.0–42.2
	Quinsam	17.1a	14.7ab	10.4b	13.5	3.7–29.3
1980	Koksilah	2.3a	1.9a	0.7b	1.7	0.6– 3.5
1981	Lake Cowichan	18.8a	16.0a	11.0b	15.3	11.6–17.4
	Quinsam	3.0a	2.5a	1.7b	2.4	1.5– 4.2
	Snowdon	6.1a	5.6ab	3.2b	5.0	1.3– 9.6
1984	Dewdney	10.5a	10.8a	10.5a	10.6	3.1–28.7
	Snowdon	32.5a	33.8a	28.8a	31.9	15.6–48.1

*Averages for each orchard-year followed by the same letter are not significantly different, Duncan's new multiple range test, $P<0.05$.

Table 2. Components of total variance contributed by among- and within-tree variances, optimum number of conelets per tree (n_c), and, when estimating average number of egg-infested scales per conelet and $n_c = 1$, coefficients of variation (cv) and numbers of trees per orchard required to obtain two levels of confidence and precision

					$n_c = 1$				
						Confidence			
						90%		80%	
		Source of variation*			cv†	% sampling error		% sampling error	
Year	Orchard	Among	Within	n_c	(%)	10	20	10	20
1978	Koksilah	0.0072	0.0064	0.6	24	19	6	11	4
	Quinsam	0.0093	0.0066	0.6	50	70	19	43	12
1980	Koksilah	0.0012	0.0033	1.1	55	84	23	52	14
1981	Lake Cowichan	0.0001	0.0049	6.6	3	3	2	2	2
1981	Quinsam	0.0057	0.0047	0.6	59	97	26	59	16
	Snowdon	0.0021	0.0048	1.0	67	124	33	76	20
1984	Dewdney	0.0149	0.0035	0.3	63	110	29	67	18
	Snowdon	0.0033	0.0027	0.3	15	9	4	6	3
	$\bar{x}$‡	0.0055	0.0046	1.4	42	50	14	31	9

*Data transformed by $x^{0.446}$ prior to analyses.

†cv(%) = $\left(\frac{\sqrt{s_T^2}}{\bar{x}}\right)$ 100.

‡Arithmetic average.

most commonly used method) for development of a sequential sampling plan (Onsager 1976) was not possible.

Mean crowding ($\overset{*}{m}$) was strongly and linearly related to mean (m) for egg-infested scales per conelet ($P<0.01$). Iwao (1968) states that the value of α may change with the size of quadrat whereas the value of β should remain constant. My data followed this pattern (Table 3); α increased with the size of the quadrat whereas β, which tended to decrease with increased quadrat size, was not significantly different among quadrats. Taylor (1984), in his review of methods for describing spatial distributions of populations, was critical of the $m/\overset{*}{m}$ method because its assumption of a linear relationship was often violated with changes in density. Comparison of regression lines for different ranges of densities showed that the regression lines were not significantly different and therefore population density was not significant in the $m/\overset{*}{m}$ relationship for number of egg-infested scales. Also, attempts to fit curves to the data showed that correlations between $\overset{*}{m}$ and m were not improved, and often reduced, relative to linear correlation so the linear relationship was assumed to be valid.

The level of insect infestation that can be tolerated is a function of the value of each particular seed crop and the size of the seed crop (Miller 1983*a*). In most British Columbia seed orchards, 10% seed loss to insects is tolerable. The number of damaged seeds per cone that could be tolerated (assuming 10%) has ranged at individual orchards from 1.6 in poor seed years to 4.7 in good seed years, averaging 2.9, based on the numbers of filled seeds per cone that have occurred in the orchards from 1978 to 1984. The average number of egg-infested scales per conelet that will result in 10% seed loss was calculated to be 2.6, using Figures 1 and 2, and 85% insecticide efficacy. This average critical density is probably the best value to use because the proportion of seeds that will develop into healthy filled seeds cannot be predicted at the time of sampling for DFCGM damage prediction (late April to early May).

Individual trees may be classified using the following expression ($\alpha = 1.548$, $\beta = 0.989$, and critical density $= 2.6$ in Iwao's (1975) procedure):

$$T_{0(n)} = 2.6\,n + t\sqrt{6.6\,n}$$

where $T_{0(n)}$ is the stop line points for n samples. The stop lines derived from this equation using t values associated with a sampling error of 10% are shown in Figure 4. Average infestation can be accurately estimated by sampling halfway up the cone-bearing region of a crown and this is where samples should be collected. When using this plan, one should stop when the cumulative total of egg-infested scales exceeds the upper stop line, indicating that midge control may be desirable, or when the cumulative total drops below the lower stop line, indicating that midge control is not needed. If the cumulative total remains between the stop lines sampling should continue. The maximum number of cones that should be sampled (see Iwao 1975 for formulae) was calculated to be 97, based on a sampling error of 10% and a 90% confidence interval.

For classifying seed orchards, the following equation was derived for the sequential sampling stop lines based on one conelet per tree and substituting 3.3 for α, 0.9 for β, and 2.6 for critical density into Iwao's formulae:

$$T_{0(n)} = 2.6\,n + t\sqrt{10.5\,n}.$$

The stop lines for this equation with a sampling error of 10% and a 90% confidence interval are shown in Figure 5. The maximum number of trees that should be sampled (see Iwao 1975 for formulae) was calculated to be 154, which is similar to the number (150) needed for 90% confidence and 10% sampling error using a fixed sample size.

The sequential sampling plan outlined above has been used operationally for Douglas-fir seed orchards in British Columbia since 1981. During the period 1981–1985, 31 orchard-years have been sampled and decisions were usually made by the time 100 conelets had

Table 3. Parameters ($\bar{x} \pm$ SE) of the mean crowding – mean density relationship for DFCGM egg-infested scales as affected by quadrat size

Quadrat	α*	β*	n	r^2
Branch	1.548a	0.989±0.016a	389	0.904
Crown third	2.666b	0.935±0.009a	204	0.987
Tree	3.269b	0.903±0.011a	72	0.992

*Values within the column followed by the same letter are not significantly different, $P<0.05$.

been processed. The time required by one person to process the samples was 4–16 h, averaging about 7–8 h. Thus, use of the sequential technique around a critical density can reduce by about one-half the time required for making a decision compared with that required for determining the average density of egg-infested scales. This reduction, although not great, can be important in warm, dry years when the period between sampling and optimum time for application of a systematic insecticide can be only 2 or 3 days or if samples from several orchards are processed at about the same time by one or two people at a site away from the orchards (as currently done in British Columbia). If time is not limiting, dissection of 150 conelets is preferable.

Nyrop and Simmons (1984) warn that sampling error may in fact be larger than expected using Iwao's technique, a problem common with other procedures for sequential plan development (Folwer 1983). Supplementary sampling to determine the accuracy of

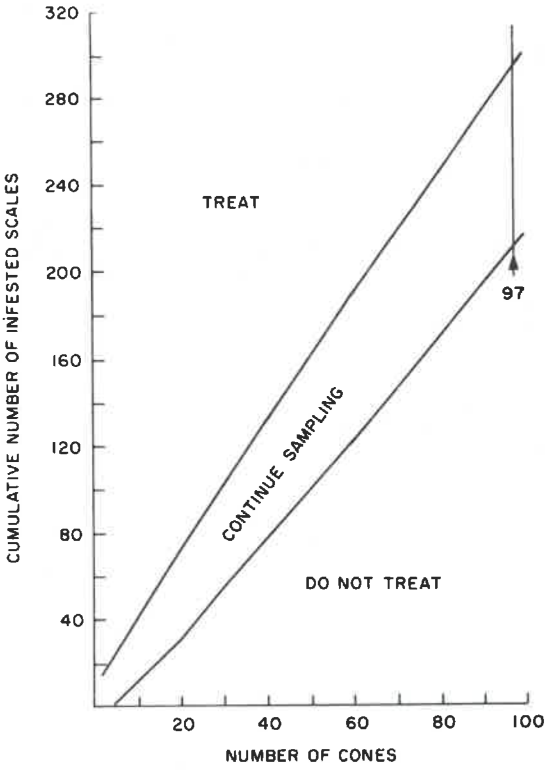

FIG. 4. Sequential sampling graph for individual trees with 10% sampling error and 90% confidence using a critical density equivalent to 10% seed loss. Conelets should be collected from the midpoint of the conelet-bearing region.

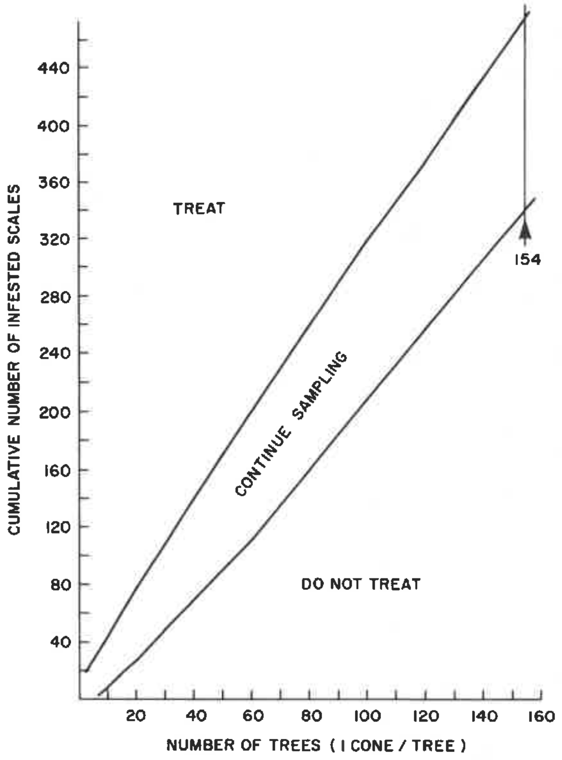

FIG. 5. Sequential sampling graphs for an orchard taking one conelet per tree, at the midpoint of the conelet-bearing region, with 10% sampling error and 90% confidence using a critical density equivalent to 10% seed loss (2.6 egg-infested scales per conelet).

the sequential sampling plan in the operational use of the technique, i.e. 31 orchard-years, has indicated that the technique has not yet resulted in a wrong decision. Fortunately, the decision has usually been clear cut, i.e. either heavy or light infestations occurred. Only in 3 orchard-years was the decision based on a "borderline" infestation. Detailed examination of actual vs. predicted damage at three orchards showed that actual damage was within 10% of the predicted damage. However, the possibility of larger than expected sampling error should be remembered when using the technique. The technique reported herein was developed in seedling orchards and may require some modification for use in clonal seed orchards, especially if variation among clones in susceptibility to DFCGM is important.

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