MONITORING SPRUCE BUDWORM POPULATION DENSITY WITH SEX PHEROMONE TRAPS[1]

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Abstract

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Annual catches of male spruce budworm (*Choristoneura fumiferana* [Clem.]) in sex pheromone traps over a 21-year period in northwestern Ontario were well correlated with larval population densities in each subsequent year (r^2 = 81%). On the basis of the criterion of 3 successive years of increasing catches or a threshold of 50 moths per trap, warning of extensive defoliation could have been given 6 years in advance. In 18 plots in northwestern Ontario and 35 plots distributed throughout the province, coefficients of determination (r^2) between catch and population density in the same generation ranged from 40 to 74% in 1982 and 1983, but fell below 23% in 1984 when population densities in many plots were high. Coefficients of determination between catch and population densities in the following generation (eggs or larvae) ranged from 41 to 62%. On the basis of several years of cooperative research, sex pheromone traps are now in operational use in eastern North America for monitoring spruce budworm populations.

Résumé

Une bonne corrélation a été observée entre les prises annuelles de tordeuses des bourgeons de l'épinette mâles (*Choristoneura fumiferana* [Clem.]) dans les pièges à phéromone sexuelle et les densités des populations larvaires l'année suivante (r^2 = 81 %), au cours d'une période de 21 ans, dans le nord-ouest de l'Ontario. Selon le critère de 3 années successives d'augmentation des prises ou le critère de 50 adultes par piège, les fortes défoliations auraient pu être prévues 6 ans d'avance. Dans 18 placettes du nord-ouest de l'Ontario et 35 autres réparties dans toute la province, les coefficients de détermination (r^2) calculés entre les prises et la densité des populations pour la même génération varient entre 40 et 74 % en 1982 et 1983, mais ils chutent au-dessous de 23 % en 1984, année où la densité des populations était élevée dans de nombreuses placettes. Les coefficients de détermination entre les prises et les densités des populations de la génération suivante (oeufs ou larves) varient entre 41 et 62 %. À la suite de plusieurs années de recherches concertées, les pièges à phéromone sexuelle sont maintenant utilisés de façon opérationnelle dans l'est de l'Amérique du Nord pour la surveillance des populations de la tordeuse des bourgeons de l'épinette.

Introduction

The potential of sex pheromone traps for providing an index of long-term population changes is now well recognized, and an operational program to provide early warning of outbreaks of the spruce budworm (*Choristoneura fumiferana* [Clem.]) is being implemented in eastern North America (Allen *et al.* 1986).

In addition to providing indices of population trends, sex pheromone traps could be used to provide quantitative estimates of population density or to supplement or replace more costly and time-consuming sampling techniques currently in use, such as foliage collection to count egg masses, or extraction of larvae from their overwintering sites by using caustic solutions (Sanders 1985; Allen *et al.* 1986). To be of value for this purpose, trap catches must be closely correlated with population density.

Using virgin female moths as lures and sticky boards as traps, Miller and McDougall (1973) compared catches of male spruce budworm moths with larval population densities the following year over a 12-year period in one sample plot in northern New Brunswick.

[1]The use of trade names or products in this paper does not imply that they are specifically endorsed or recommended by the author or the Great Lakes Forestry Centre in preference to similar products not mentioned.

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The fact that they obtained a coefficient of determination (r^2) of 98% suggests that the technique has considerable merit. However, the use of live female moths and sticky boards is inconvenient, and attention has turned to use of the synthetic sex pheromone 95:5 (*E*:*Z*)-11-tetradecenal (Silk *et al.* 1980) in combination with various commercial trap designs.

For maximum usefulness, a trap must provide meaningful catches over a wide range of population densities. Sticky-bottomed traps such as the Pherocon 1C or 1CP (Zoëcon Corp., Palo Alto, CA, USA) are effective over a limited range of densities, because the sticky surface becomes saturated with moths and, as a result, catches at higher densities are unreliable (Houseweart *et al.* 1981). Therefore, interest has focussed on various designs of high-capacity bucket or funnel traps (Sanders 1986).

Using a covered funnel trap of their own design (Ramaswamy and Cardé 1982), Ramaswamy *et al.* (1983) obtained an r^2 of 93% for the relationship between spruce budworm larval density and moth catch over a narrow range of densities in six plots in northern Michigan. Allen *et al.* (1986) carried out a 3-year field assessment of various types of high-capacity, nonsaturating traps for monitoring low- to medium-density spruce budworm populations. Values of r^2 for regressions of population density on trap catch rarely exceeded 50% when all the data were pooled, but in many instances stratification of the data by region yielded closer correlations and the authors concluded that pheromone trapping showed considerable promise as a tool for estimating local population density.

At the same time as the studies of Allen *et al.* (1986), similar studies were being carried out in Ontario. This paper reports the results of these studies, together with the results of 21 years of sex pheromone trapping in one location in northwestern Ontario.

Methods

Long-term Monitoring of Population Trends. Each year from 1966 to 1986 (except for 1969), pheromone traps were deployed in the same plot in an extensive area of maturing mixed-wood forest near Black Sturgeon Lake in northwestern Ontario. Traps were set out about 1 week before the moth flight period, as determined by branch sampling for pupae, and were collected after the flight, to provide a count of moths caught throughout the flight period. Because the technique was evolving over the years, different lures and traps were used at different times. From 1966 to 1971, before the identification of the sex pheromone, virgin female moths in screen-covered vials were used to lure the males to vertical plywood boards, each 30 cm^2, coated with Tanglefoot (The Tanglefoot Co., Grand Rapids, MI). From 1972 to 1976, Sectar 1 traps (3-M Co., St. Paul, MN) were used. These were baited with polyethylene caps containing 4.5 mg of the synthetic pheromone, Δ-11-tetradecenal, containing predominantly the *E*-isomer but with unknown small amounts of the *Z*-isomer. From 1977 to 1986, polyvinyl chloride lures (Sanders 1981) containing 0.03% (w/w) of Δ-11-tetradecenal (95–97% *E*-isomer) were used. Pherocon 1CP traps were used from 1977 to 1980. From 1981 to 1986, high-capacity nonsaturating traps were used (Sanders 1986); homemade double-funnel traps (Sanders 1986) were used from 1981 to 1983, and International Pheromone System "Uni-traps" were used from 1984 to 1986. In all years the traps were deployed at a height of 2 m, and were spaced 20 m apart. Between 5 and 10 traps per plot were used each year in this study.

Estimates of larval population densities, based on 45-cm branch tips collected from the midcrown of balsam fir (*Abies balsamea* [L.] Mill.) and white spruce (*Picea glauca* [Moench] Voss), were also available each season. Numbers of branches sampled ranged from a low of 60 (1970–1974) to over 500 (1967–1969). In all other years, 100 or more branches were sampled.

Estimating Population Density. The relationship between trap catch and population density was also investigated in two studies in which traps were deployed in a number of plots of different population density, as indicated by larval sampling the previous year. From 1982 to 1984, traps were deployed in 18 plots in north central Ontario, located along Highway 17 between White River and Nipigon, along Highway 11 between Nipigon and Hornepayne, and along Highway 631 between Hornepayne and White River, a distance of 850 km. The plots were in mixed-wood stands that contained at least 50% balsam fir and/or white spruce (by basal area), were homogeneous for at least 1 km along the road, and had trees that were $\geqslant$ 15 m tall. Sampling to determine larval population densities was carried out each year during the fourth and fifth larval instars. Sample trees were codominant balsam fir, selected every 10–20 m on a traverse through each plot. A single 45-cm branch tip was taken from the midcrown of each sample tree and the larvae were counted on the site. A modified form of sequential sampling was used. Sampling was terminated if, on average, 10 or more larvae per branch were found on the first 10 branches, or 1 or more larvae on the first 25 branches. If no larvae were found on the first 25 branches, then sampling continued until one larva was found. Numbers were then expressed as larvae per branch tip. Mensurational data were collected at each sampling location as follows. In three subplots within each plot, counts of trees by species and size class were made on a variable-radius plot with a prism wedge (basal area factor of 10). From these data the number of trees per hectare, by size and species, and the basal area of each species were calculated.

In a second study, traps were systematically deployed in 1983 and 1984 throughout the range of the spruce budworm in Ontario by Forest Insect and Disease Survey (FIDS) staff from the Great Lakes Forestry Centre. The plots were laid out in representative stands susceptible to attack by the budworm, i.e. mature stands containing a high proportion of host trees (balsam fir and/or white spruce). In all, 48 plots were involved, but because not all plots were completely sampled each year, the number of data points available for the analyses differed between the 2 years.

In these plots, third and fourth larval instars and egg masses were sampled. In all, ten 45-cm branch tips were taken from the midcrown of codominant balsam fir and were shipped to the laboratory for examination, and the numbers of larvae per branch were recorded. Egg sampling was conducted by a modified sequential sampling system based on that of Morris (1954). Results were expressed as the number of egg masses per 10 m^2 of branch surface. Estimates of defoliation were made at the same time by assessing visually the percentage of the current year's foliage removed by the insects.

The two studies were part of a broader program that was also aimed at determining the most appropriate type of trap; consequently, different trap designs were used at different times. Included were Pherocon 1CP traps (the only sticky traps used), covered funnel traps (CFT) (Ramaswamy and Cardé 1982), double-funnel traps (DFT) (Sanders 1986), and Uni-traps. Traps in these two studies were deployed in clusters of either three or five at least 40 m in from the edge of the stand according to the same protocols described by Allen *et al.* (1986). When in clusters of three, traps were positioned in an equilateral triangle with 40 m between traps. In clusters of five, four of the traps were positioned in a square, 40 m on a side, and the fifth was placed in the center. Traps were hung ca. 2 m from the ground on branches of the host trees, well removed from living foliage.

Polyvinyl chloride pellets, 4 mm in diameter and 10 mm long, were used as lures in these two studies. In the CFT, DFT, and Uni-traps lures contained 0.03% synthetic pheromone (w/w). This concentration was chosen because the release rate of pheromone is close to that of a calling female (Sanders 1981). Because sticky-bottomed Pherocon 1CP traps quickly become saturated with moths when a lure of this potency is used, even in moderately dense populations (Houseweart *et al.* 1981), lures containing 0.003% and 0.0003% synthetic pheromone by weight were used as well in these traps. Fresh lures were manufactured each year by the New Brunswick Research and Productivity Council, and were kept refrigerated until used. The traps were placed out in mid-June, which is 1–2 weeks

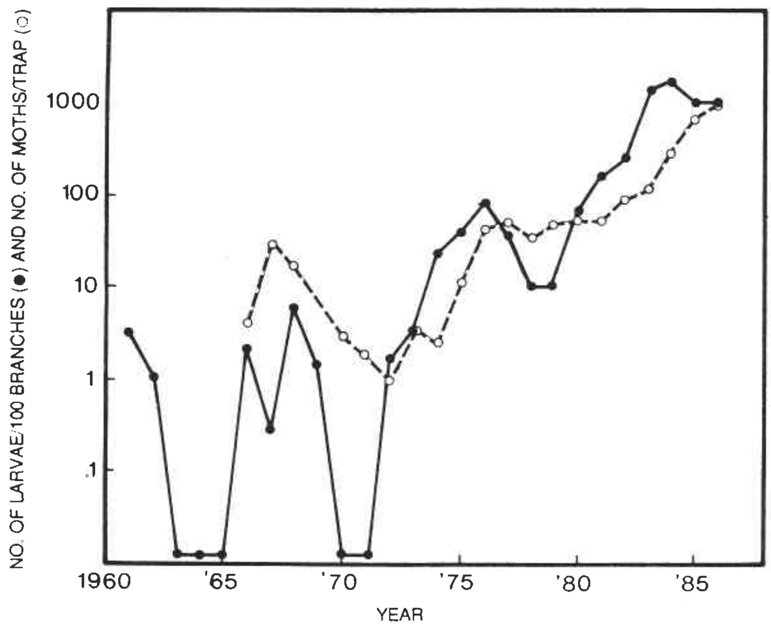

FIG. 1. Numbers of spruce budworm male moths captured in pheromone-baited traps (broken line), and densities of late-instar larvae (solid line) at Black Sturgeon Lake, northwestern Ontario, 1966–1986.

before the normal start of moth flight. This was to provide time for the release rate of the pheromone to stabilize before the start of moth flight. Lures were pinned to the inside top of the traps.

Results

Long-term Monitoring of Population Trends. The results of 21 years of pheromone trapping and larval population monitoring at Black Sturgeon Lake are shown in Figure 1. Even though different lures and traps were used over the 21-year period, the changes in pheromone trap catches show the same trend as larval density. During the early 1960s and early 1970s, population densities were very low; in several years no larvae were found. Moth catches were also low, but catches never fell to zero. A significant increase in larval density in the late 1960s was mirrored by the trap catches. During the 1970s, both larval density and trap catch showed steady increases up to 1976. Both data sets showed a check in population growth from 1977 through 1979. From 1980 onward both larval counts and trap catches climbed steadily, and populations reached outbreak status in 1983 and caused extensive defoliation.

Regression analyses were carried out on the data, transformed to log x in the case of the trap catches, and to log $(x+1)$ in the case of the larval density estimates where there were several zeros. The r^2 for the regression of larval density on trap catch in the same year is 66%, but for larval density on trap catch the previous year it increases to 81%.

Estimating Population Density. (A) Northwestern Ontario. *Relationship between moth catch and larval density within the same generation.* Ten data sets from northwestern Ontario are available for analyzing the relationship between moth catch and larval density within the same generation (i.e. within the same year). The coefficients of determination (r^2) from regression analyses on the data transformed to logarithms are shown in Table 1, and three of the data sets, those with the highest r^2 each year, are shown graphically in Figure 2.

Table 1. Relationship betwen logarithm of spruce budworm larval counts per 45-cm branch tip and logarithm of spruce budworm male moth catches in various trap designs within the same generation in 18 plots in north central Ontario

Year	Type of trap	Concentration of lure	Number of traps per plot	Coefficient of determination (r^2) (%)
1982	DFT	0.03	5	74
	CFT	0.03	5	58
	Pherocon 1CP*	0.03	3	21
	Pherocon 1CP*	0.003	3	5
	Pherocon 1CP*	0.0003	3	65
1983	DFT	0.03	5	50
	DFT	0.03	3	49
1984	DFT	0.03	5	22
	Uni-trap	0.03	5	14
	Uni-trap	0.03	3	4

*Only those plots are included in which larval densities were below 2.5 per branch tip ($n = 12$).

In 1982 the DFT gave an r^2 of 74.4%, the CFT 58%. In the same year the Pherocon 1CP traps evidently became saturated with moths at the higher population densities with all three concentrations of pheromone lure. Traps baited with the 0.0003% concentration were saturated at a larval density of 2.5 per branch tip. Therefore, analysis of the data for the 1CP traps was restricted to those plots in which larval densities were lower than 2.5 per branch tip ($n = 12$). This gave an r^2 of 65% for traps baited with 0.0003% lures. With the higher concentrations, saturation occurred even at low population densities, and poor correlations resulted even though the analyses were restricted to the 12 lower-density plots.

In 1983 only the DFT were used, in clusters of either three or five. In both instances the r^2 was close to 50%. When the average catch for the three-trap cluster was plotted against the average catch for the five-trap cluster in the same plot, an r^2 of 93% was obtained, an indication that the more economical three-trap cluster can be used in place of a five-trap cluster.

In 1984, when DFT were used, the correlation was much lower than in the previous years ($r^2 = 22\%$), principally because in several plots the moth catches were higher than anticipated from the larval densities. Coefficients of determination for IPS Uni-traps in three- or five-trap clusters were even lower ($r^2 = 4$ and 14%, respectively). Here again, as in 1983, the correlation between average catches in the three-trap and five-trap clusters was high ($r^2 = 79\%$).

Relationship between moth catch and larval population in subsequent generations. The regressions of larval density on moth catch the previous year are shown in Figure 3. In the first year, when 1983 larval densities were regressed on 1982 moth catch, the r^2 was 62%. In the second year the value fell to 21%, again because in some plots the larval densities were higher than predicted from the moth catches of the previous year.

Adjustments by stand types. Population densities are expressed as numbers of insects per branch tip, but moth catches are presumed to represent an area covering several hundred square metres. Therefore, some method should be incorporated into the calculations to express the population densities based on area. This is done most conveniently by multiplying density estimates by the basal area of the host tree species in the plot (white spruce and balsam fir), because basal area is correlated with quantity of foliage. However, regression analyses on the converted data did not improve the variability explained by the regression. Various other weighting factors were tried in an effort to improve the correlations; these were basal area of white spruce or balsam fir alone, number of stems of host plants

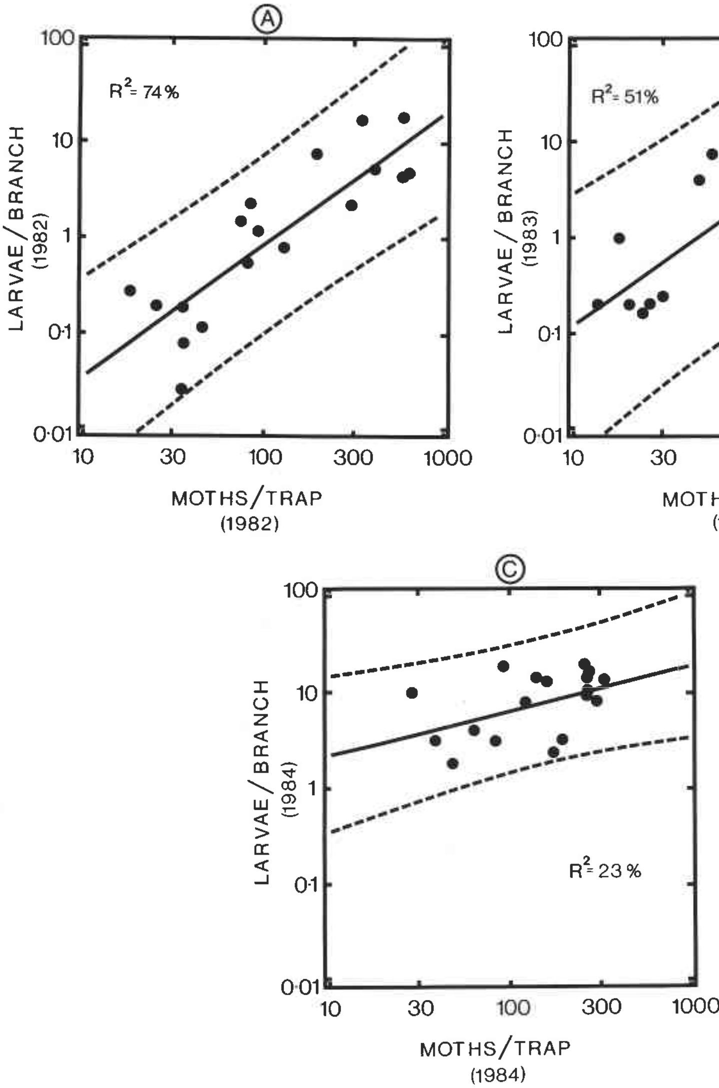

FIG. 2. Relationships between average moth catch in five double-funnel traps and densities of late-instar larvae per 45-cm branch tip in same generations. A, 1982; B, 1983; C, 1984. Dotted lines indicate 95% confidence limits.

7.5 cm DBH and larger, and proportion of total basal area in host plant species. In all cases there were no major changes in the r^2 values.

(B) FIDS plots. Values of r^2 for the correlations between moth catch and various parameters of population density in the FIDS plots within the same and subsequent generations are shown in Table 2. In 1983 average trap catches ranged from 9 to 545, with larval densities between 0.3 and 93.2 per branch tip. In 1984 trap catches averaged from 3 to 835, with larval densities between 1.0 and 97.6 per branch tip. In spite of these wide ranges, values of r^2 for the relationship between catch and larval density, either within the same generation or within the subsequent generation, were no greater than 41%. Relationships between trap catch and egg densities or defoliation were little better; r^2 values ranged from 29 to 46%.

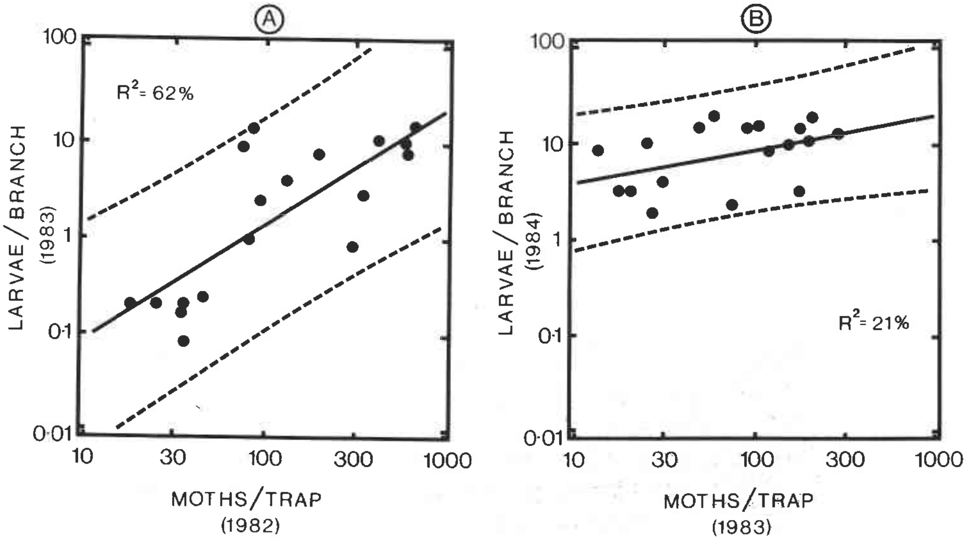

FIG. 3. Relationships between average moth catch in five double-funnel traps and densities of late-instar larvae per 45-cm branch tip in following generations. A, 1982 moth catch in comparison with 1983 larval density; B, 1983 moth catch in comparison with 1984 larval density. Dotted lines indicate 95% confidence limits.

Discussion

The superiority of high-capacity nonsaturating traps to sticky-bottomed traps for monitoring populations over a wide range of population densities is apparent in Table 1. Even when regression analyses were restricted to plots with densities of fewer than 2.5 larvae per branch tip, the higher-potency lures still resulted in trap saturation. With very low-potency lures (0.0003% [w/w]), a good correlation was obtained in the low-density plots. At low densities, therefore, these traps can be used to monitor populations, but over wider ranges of densities, nonsaturating traps are required.

Table 1 also shows that slightly better correlations are obtained with clusters of five traps rather than three. However, the improvements are not great, and because of the close correlation between average catches in five traps compared with three traps in the 2 years in which comparisons were made (r^2 = 93 and 79%), the savings in cost realized by using three traps instead of five may be justified.

Table 2. Relationship between catches of male spruce budworm moths in sex pheromone traps and various estimates of spruce budworm population density in Forest Insect and Disease Survey permanent sample plots in Ontario. Double-funnel traps were used in 1983, International Pheromone Systems Uni-traps in 1984

Correlation		Number of plots	Coefficient of determination (r^2) (%)
Moth catch in 1983 versus:			
Larvae per branch tip	1983	33	40
Defoliation (%)	1983	35	29
Egg masses per 10 m²	1983	35	41
Larvae per branch tip	1984	16	41
Moth catch in 1984 versus:			
Larvae per branch tip	1984	17	23
Defoliation (%)	1984	26	46
Egg masses per 10 m²	1984	28	37

The effectiveness of sex pheromone traps for indicating population trends is demonstrated clearly in Figure 1. By using the criterion of 3 successive years of increasing moth catch or a threshold of 50 moths per trap (see Fig. 1), it would have been possible in 1977 to predict the onset of the outbreak, which first caused extensive defoliation in the vicinity of Black Sturgeon Lake in 1983, 6 years in advance. If this relationship is subsequently borne out in other areas, we will have a tool capable of providing forest managers with a 6-year warning of extensive defoliation or a 10- to 11-year warning of tree mortality.

For the long-term study at Black Sturgeon Lake correlations between trap catch and larval density in the same year (r^2 = 66%) or in the subsequent year (81%) were high. For the 1982–1984 data from north central Ontario and the FIDS plots, values of r^2 for the relationships between larval densities and moth catches in the same year ranged from 23% (1982) to 74% (1984). In the north central Ontario plots (Table 1), the reduced correlation may be due to the increasing budworm densities. In 1981 the infestation in north central Ontario occurred west of the study area and covered 660 000 ha, but by 1985 it had expanded into a single outbreak covering 12 million ha that engulfed the study area. In 1982 larval densities in the study plots ranged from 0.02 to 19.4 larvae per branch tip, whereas in 1983 only in one plot was density below 0.1 larva per branch, and by 1984, in no plot was density below 1.0 larva per branch. In both 1983 and 1984 some of the plots with relatively high population densities had unexpectedly low moth catches. The reasons are unknown, but moth dispersal may be one of them.

Of greater interest are the relationships between densities of eggs or larvae and trap catch in the previous generation. For the 1982–1984 data, r^2 values were all significant, but relatively low. The confidence intervals shown in Figures 3*a* and 3*b* indicate that the predictive power of the traps as indicators of populations of late-instar larvae in the following generation was not high. With a moth catch of 100, densities of late-instar larvae can be predicted to fall between 0.1 and 10 larvae per branch 19 times out of 20. The highest r^2 (62%, Fig. 3A) was still well below those obtained in the long-term study of a single-plot—81% for the Black Sturgeon Lake data in this study, and 89% obtained by Miller and McDougall (1973) in New Brunswick.

There are several reasons that the correlations obtained from multiple plots in a single year are poorer than those from the long-term data for single plots. First, variability in trap catch among different plots will be affected by local climate, topography, and stand composition. Second, spruce budworm populations in the different plots are not independent. Moth movement can occur over many tens of kilometres and, as a result, high moth populations in one area can affect trap catch in another without necessarily causing a corresponding change in population density the following year. An attempt was made in the present study to compensate for plot-to-plot variation by multiplying larval density by various measures of host-plant foliage. However, r^2 values were not improved. Nevertheless, because trap catches are estimates of area-wide densities it is logical that some weighting factor for the amount of foliage should be included, and this should be a consideration in future development of a monitoring system that uses sex pheromone traps. Lack of predictability can also be attributed to the fact that the methods of estimating egg and larval densities are inherently very inaccurate, particularly at low population densities.

Allen *et al.* (1986) attempted to identify threshold catches that could be used to alert the forest manager to incipient outbreaks, so that more intensive quantitative sampling could be carried out. A value of one late-instar larva per branch was used as a convenient density because it is at this point that intensive larval sampling becomes practicable. The data of Allen *et al.* (1986) indicated a threshold of 40 moths per trap for populations of one or more larvae per branch in the same generation, and 10 moths per trap for one or more larvae in the following generation. The Black Sturgeon Lake data from the present study indicate a threshold between 50 and 100 for one or more late-instar larvae per branch

(Fig. 1). The north central Ontario data for 1982 and 1983 suggest that 100 moths per trap could be used as an indicator of one or more larvae per branch in both the same and the subsequent generation (Figs. 2 and 3). However, the association broke down in 1984 when larval densities in all plots exceeded one per branch. Clearly the relationship will be affected by trap design and lure potency, and will vary with different stand conditions. Nevertheless, the use of pheromone traps as an "early warning" system for the forest manager has considerable merit, and the establishment of threshold values is of high priority for the future.

As a result of these studies and those reported by Allen *et al.* (1986), together with references therein, a coordinated program has been started in eastern North America for the annual deployment of sex pheromone traps to monitor spruce budworm populations. In 1986 this included approximately 550 locations spread over seven Canadian provinces and six states in the United States. The primary objective is to monitor changes in low-density populations to provide early warning of incipient outbreaks, from which threshold values for catches will be determined for advising pest control specialists of the need for further assessment. It is hoped that the data will also establish useful correlations between trap catch and population density, so that the traps may also be used to replace or supplement existing quantitative sampling techniques.

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