Forecasting defoliation by the jack pine budworm

V.G. Nealis, P.V. Lomic, and J.H. Meating

Abstract: A method for forecasting current-year defoliation by the jack pine budworm, *Choristoneura pinus pinus* Free. (Lepidoptera: Tortricidae), at the stand level is described. The method is based on empirically derived relationships between defoliation and the densities of jack pine budworm egg masses, overwintering larvae, early-larval feeding stages, and pollen cones (micro-sporangiate strobili) of the host trees. Parameters for the forecast model were developed and tested with independent sets of survey data from Ontario combined with more precisely estimated relationships between jack pine budworm survival and the abundance of pollen cones. The method forecasts defoliation categories of light, moderate, or severe with greater than 75% accuracy, with the highest accuracy associated with the most severe defoliation category. Areas for further improvement in the model are identified and discussed in the context of integrating known population ecology of the jack pine budworm with realistic operational requirements of pest managers.

Résumé : Une méthode permettant de prédire, à l'échelle du peuplement, le niveau de défoliation de l'année courante causée par la tordeuse du pin gris, *Choristoneura pinus pinus* Free. (Lepidoptera : Tortricidae), est présentée. Cette méthode est basée sur une série de relations empiriques entre la défoliation et la densité des masses d'œufs, des larves en dormance hivernale, des jeunes larves de printemps de tordeuse du pin gris et des cônes mâles (strobiles portant les microsporanges) présents sur l'essence hôte. Les paramètres du modèle de prédiction ont été développés et testés à l'aide d'un ensemble de données indépendantes provenant d'inventaires réalisés en Ontario et de relations plus précises entre la survie larvaire de la tordeuse du pin gris et l'abondance de cônes mâles. Le modèle prédit les niveaux de défoliation léger, modéré et sévère avec une précision dépassant 75%, la plus grande précision étant associée à la catégorie de défoliation sévère. Les avenues pouvant être exploitées dans le but de bonifier le modèle sont identifiées et discutées dans un cadre d'intégration des connaissances sur la biologie de la tordeuse du pin gris et des exigences opérationnelles réalistes des gestionnaires oeuvrant dans le secteur de la gestion des ravageurs.
[Traduit par la Rédaction]

Introduction

The jack pine budworm, *Choristoneura pinus pinus* Free. (Lepidoptera: Tortricidae), is a native defoliator of jack pine, *Pinus banksiana* Lamb., in North America. Its biology and ecology have been reviewed recently (Nealis 1995). Outbreaks of the jack pine budworm can cause significant defoliation of jack pine. Severe defoliation causes measurable growth loss in the year immediately following infestation. Repeated defoliation can cause mortality in suppressed and understory trees as well as top kill and whole-tree mortality in dominant and co-dominant trees (Kulman et al. 1963; Gross 1992). In Canada, historical records show that both the frequency and extent of outbreaks of the jack pine budworm have increased over the past 30 years in the Prairie provinces (Volney 1988) and in Ontario (Howse and Meating 1995). Average losses in growth and mortality of jack pine caused by jack pine budworm in Ontario forests were estimated at nearly 2 $\times 10^6 \mathrm{m}^3$ per year between 1982 and 1987 (Gross et al. 1992).

The aerial application of insecticides to suppress outbreak populations of the jack pine budworm and protect foliage has been utilized in Ontario repeatedly since 1985 (Meating et al. 1995). These control operations depend on forecasting where intolerable defoliation is likely to occur and targetting these areas for treatment. Historically, the methods used for forecasting defoliation by the jack pine budworm have been adopted from the methods developed for the closely related spruce budworm, *Choristoneura fumiferana* (Clem.), i.e., estimating the population levels of egg masses and (or) overwintering larvae by sampling and inspecting branches and subsequently relating these population levels to degree of defoliation. When applied to the jack pine budworm, however, these methods have proved to be inadequate because the simple relationships between the estimated densities of egg masses or overwintering budworms and subsequent defoliation are neither consistent nor sufficient to predict defoliation (Lavigne and Carter 1986; Meating 1986). Meating (1986) suggested that better predictions of defoliation might be made by incorporating information on pollen-cone (microsporangiate strobili) abundance into the forecasts, since jack pine budworm is well known to be associated with pollen cones of the tree. Subsequently, Nealis and Lomic (1994) demonstrated a functional relationship between survival of early-instar jack pine budworms and pollen-cone abundance at the stand level that could be used to predict survival of spring-emerging jack pine budworm from the estimated density of pollen cones.

Received June 14, 1996. Accepted February 28, 1997.

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This study investigates the possibility of improving forecasts of jack pine budworm defoliation by using relationships between conventional population measurements of various stages of the budworm and pollen-cone abundance in the stand. We develop regression models based on survey data that describe the relationships among jack pine budworms, pollen cones, and defoliation. The ability of these models to forecast defoliation was tested on a second, independent set of survey data. Our study proposes that improvements in our capability of forecasting defoliation by the jack pine budworm can be made with few basic changes to the current system of monitoring. We also identify areas where monitoring methods can be refined further to increase the efficacy of the forecast model.

Methods

Data sources and analysis

Data utilized in this study were collected by the *Forest Insect and Disease Survey* (Canadian Forest Service) in Ontario, supplemented by data from more intensively studied research plots. Two independent sources of survey data were used: one for model development and a second for testing the model. Data used for model development were extracted from more than 100 plots surveyed throughout northern Ontario as part of an operational protection program in 1985 and 1986. Thus sites were selected because of known or suspected infestations and the data were drawn from an extensive geographical area. In such operational programs, surveyors are faced with the need to rapidly assess a large number of plots on a once-only basis, so no formal plot descriptions were made. All plots, however, were in forest stands dominated by mature jack pine, as this was a criterion of the protection program. Branch samples were selected from the midcrowns of a cluster of codominant trees at least 50 m from the stand edge (Morris 1955). Survey data for testing the model were obtained from permanent sample plots established in 1992 in northeastern Ontario. All stands were dominated by jack pine between 37 and 96 years of age and stocking densities ranging between 525 and 2314 stems/ha. Mean (standard deviation) DBH and tree height were 18.0 (3.3) cm and 15.4 (0.84) m, respectively. Plots were 4×25 m and were laid out at least 50 m from the stand edge. Fifty trees within the plot were labelled as permanent sample points. Branch samples were removed from every fifth tree. For estimation of the relationship between pollen-cone abundance and jack pine budworm survival, 2-ha plots located in northeastern Ontario and northern Michigan were used. Within these plots five 0.01-ha subplots were located at least 50 m apart. Branch samples were removed from two trees selected from among the cluster of trees within these subplots (Nealis and Lomic 1994).

Survey estimates of the density of egg masses, feeding larvae, pollen cones, and of defoliation were composed of six 60-cm branch tips from the midcrowns of six codominant trees (one branch per tree) per plot (Meating 1986). Estimates of the density of overwintering larvae and pollen cones were based on 10, and in some cases 20, 1-m branch tips per plot (Nealis and Lysyk 1988; Nealis and Lomic 1994). Analysis of the distribution of egg masses showed that a 1-m branch tip was also the preferred sample unit length for estimating egg mass density (Lomic 1995). Paired comparisons of egg masses on the 60-cm tip and 40-cm basal sections of 1-m branch tips collected in research plots allowed calculation of a conversion factor. Egg mass density was approximately 2.25 times greater on the basal section than on the distal section of the branch, so the egg mass density reported from 60-cm branch tips in surveys was multiplied by 2.25 to obtain an estimate of egg mass density for a 1-m branch unit. Similarly, pollen cones were more abundant on basal portions of the branch so, where necessary, estimates based on 60-cm branch tips were multiplied by 1.1 to convert to an estimate of pollen-cone density for a 1-m branch. Comparison of the distribution of early-stage feeding larvae on 1-m branches showed no difference in the density of basal and distal portions, so no conversion was applied for this stage. Thus, the 1-m branch tip was the common unit for expressing density of independent elements in the model. Densities of overwintering and feeding larvae were expressed as number of budworms per 100 shoots (Nealis 1991). Defoliation was estimated by experienced observers who classified defoliation either by assigning a percent defoliation to the whole branch or by randomly selecting a subset of shoots on which to base the estimate.

Data from survey plots were considered point samples, so estimates of egg mass and larval densities were based on the total number of egg masses or larvae on all branches divided by the total number of branches or shoots, respectively. Mean percent defoliation was the arithmetic mean of all observations for each point sample. Population counts of jack pine budworm were converted to a log scale, and the arcsine transformation was applied to estimates of percent defoliation. These elements were combined in a series of regression models using the MGLH module of SYSTAT (Wilkinson 1992).

Model development

Model development utilized various independent data sets. The relationship between the density of egg masses and overwintering budworm was obtained from 17 sites surveyed near Sudbury, Ontario, in 1993. The relationship between survival of jack pine budworm from the overwintering to the early-stage feeding larvae (instars 3 to 5) and the abundance of pollen cones used data described by Nealis and Lomic (1994) and Nealis (1995). Briefly, the densities of overwintering jack pine budworm budworm and pollen cones were measured first on 20 branches per plot. Then, densities of established, feeding jack pine budworm and of pollen cones were estimated again on the same trees following emergence and dispersal of the budworm in the spring. The rate of change in budworm abundance between the overwintering and feeding larval stages was expressed as the difference in log mean densities of the two stages. This value was regressed against the density of pollen cones on the branch to estimate the parameters of the relationship.

The relationship between the density of early-instar feeding budworms and subsequent defoliation was quantified using survey data from plots assessed during spray programs in northern Ontario in 1985 and 1986. Only data from unsprayed plots were used. A graphical method of inverse regression (Draper and Smith 1981) was applied to these data to estimate the density of feeding jack pine budworm necessary for defoliation to exceed threshold values of 30%, 50%, and 75%. These values correspond roughly to operational categories of light, moderate, and severe defoliation. An independent data set from survey plots assessing jack pine budworm defoliation between 1992 and 1994 was used to test the adequacy of these threshold values. Observed budworm densities in this test data set were first categorized as above or below each of the three estimated threshold values and an expected level of defoliation obtained. Observed defoliation was then compared with the expected value and the number of correct and incorrect predictions scored.

The final forecast model predicts defoliation from the number of egg masses and pollen cones in the stand. Thirty-five of the 71 data points described above had all of this necessary information. This subset of data was used to evaluate the operational forecast model. Once again, defoliation forecast by the model was compared with that actually observed in the stand, and the number of correct and incorrect predictions was scored.

Results

Density of jack pine budworm and defoliation thresholds

As expected, the density of egg masses was not correlated with defoliation by the jack pine budworm at the stand level in the test survey data set ($r = 0.10$, $p > 0.20$, $n = 108$). The density of early-stage feeding jack pine budworms, however, was

Fig. 1. Relationship between percent defoliation and the density of early-stage feeding jack pine budworm based on survey data collected in Ontario from 1992 to 1994. Regression analysis used the arcsine transformation of percent defoliation, but untransformed values are plotted here. These were the data used in testing both the defoliation thresholds and the full forecast model.

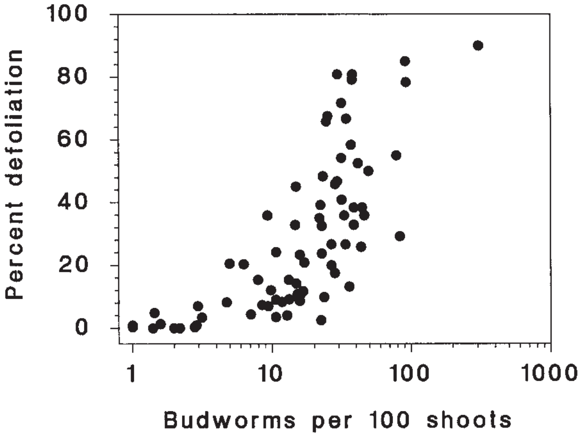
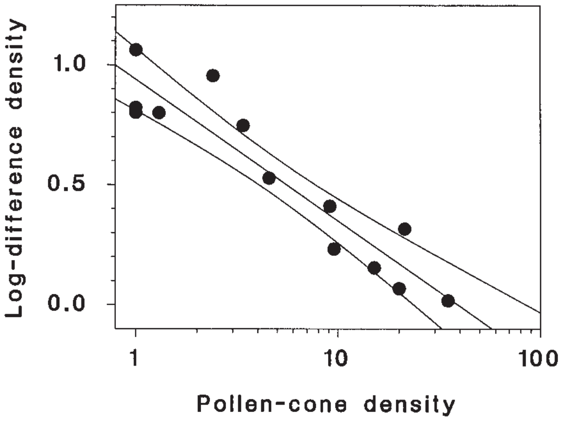
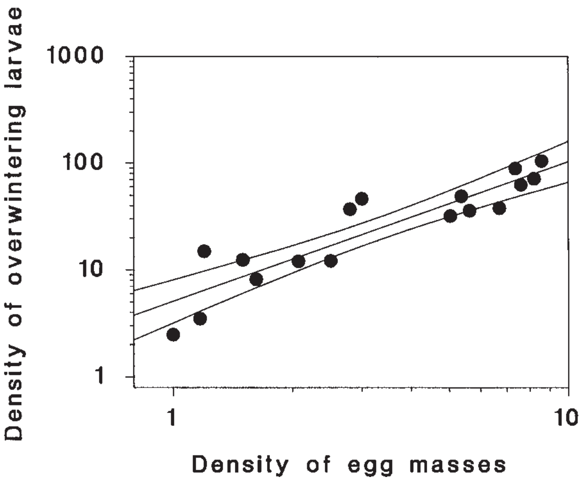


Fig. 2. Relationship between mortality of newly emerged jack pine budworm expressed as the difference in log mean densities of overwintering and early-larval budworms and the abundance of pollen cones in the stand: $Y = 0.94 - 0.59X$, $R^2 = 0.88$. Curves are 95% confidence intervals on mean predicted values.



correlated closely with eventual defoliation in the stand ($r = 0.79, p < 0.01, n = 108$). Model development, therefore, began with quantifying the relationship between the density of these feeding budworms and defoliation in the data from the surveys conducted in Ontario in 1985 and 1986. By inverse regression (Draper and Smith 1982) the density of feeding jack pine budworm required to cause more than 30%, 50%, and 75% defoliation was estimated to be 6.1, 16.8, and 55.2 budworms per 100 shoots, respectively. When tested with the independent data set (Fig. 1), these estimated thresholds correctly identified the 30%, 50%, and 75% defoliation categories 65%, 75%, and 96% of the time, respectively. We conclude that the estimated thresholds were adequate for further model development, particularly for the most severe defoliation categories.

Fig. 3. Relationship between densities of egg masses and overwintering budworms: $Y = 0.71 + 1.31X$, $R^2 = 0.83$. Curves are 95% confidence intervals on mean predicted values.



Development of the forecast model

Estimates of feeding budworm density occur too late in the season to have value as a forecast tool, so model development proceeded by working backwards from the feeding larval stages and relating density estimates of earlier occurring life stages, such as eggs or overwintering larvae, to the density of feeding larvae and hence defoliation. The relationship between the abundance of successive life stages of insects is determined by the survival rate between those two stages. Survival between the overwintering and early-instar stages of the jack pine budworm is a direct function of the abundance of pollen cones in the stand (Nealis and Lomic 1994). This relationship is shown in Fig. 2. Assessment of both overwintering budworm density and the density of pollen cones on trees can be made in the previous winter or autumn (Moore and Nozzolillo 1991; Nealis and Lomic 1994). Consequently the forecasts of defoliation can be made available as soon as early winter of the year preceding the expected defoliation. The time frame to plan intervention can be further increased because the density of overwintering jack pine budworm can be predicted from an estimate of egg-mass density (Fig. 3).

The model predicting the expected density of feeding jack pine budworm from the densities of egg masses and pollen cones is summarized as

$$[1] \quad N_{\mathrm{L4}} = -0.24 + 1.31\mathrm{EGG} + 0.66\mathrm{CONE}$$

where N_{L4} is the predicted $\log_{10}$ number of feeding jack pine budworms per 100 shoots, EGG is the $\log_{10}$ density of egg masses per 1-m branch, and CONE is the $\log_{10}$ number of pollen cones per 1-m branch. Once the expected density of feeding jack pine budworm is determined, the category of defoliation, as defined above, can be forecast. A schematic diagram of the entire sequence of forecasting defoliation from egg-mass density and estimates of predictability for each step (as expressed by the coefficient of determination, R^2) is given in Fig 4.

Testing the forecast model

The parameters in eq. 1 are the result of a synthetic approach to model building, and an estimate of a standard error for prediction is not straightforward. The standard error of estimate for the multiple regression of the density of feeding budworm

Fig. 4. Algorithm for forecasting defoliation by the jack pine budworm from population parameters. Precision of each step in algorithm is expressed as the coefficient of determination (R^2) from regressions described in the text.

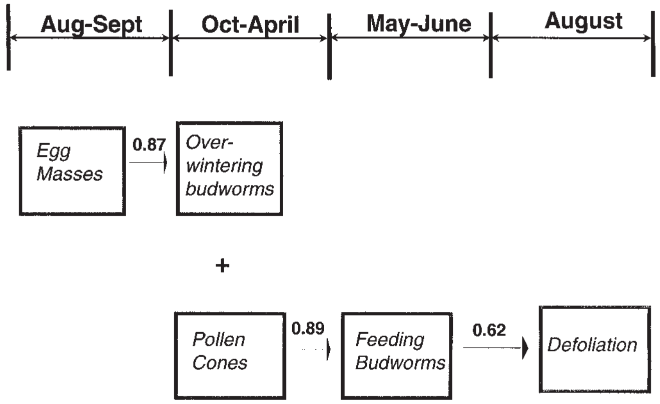


Table 1. Matrix of forecast and observed defoliation in test data set.

Moderate to severe defoliation (>50%)			Severe defoliation (>75%)		
	Observed			Observed	
Forecast	<50%	>50%	Forecast	<75%	>75%
<50%	**23**	2	<75%	**30**	2
>50%	6	**4**	>75%	2	**1**

Note: Bold values along diagonal give frequency of correct forecasts for observations above and below thresholds. The same data were used to test two thresholds: moderate to severe (>50%) and severe (>75%) defoliation.

on the densities of egg masses and pollen cones for the test data set gives an idea of the precision of the relationship. There was a significant relationship between observed density of feeding budworms and both egg-mass and pollen-cone density ($F_{[2,32]} = 24.6, p < 0.001, R^2 = 0.61$) in this data set, with a standard error of estimate of 0.265. Using mean values of the data and *t*-value of 0.05, a future observation of 3 egg masses and 8.5 pollen cones per 1-m branch would predict 7.4 ± 3.4 budworms per 100 shoots.

To test the accuracy of the model in forecasting defoliation, we used the independent data set illustrated in Fig. 1 and the threshold densities estimated above. The model (eq. 1) predicts the density of feeding budworm from the density of egg masses and pollen cones. This density of feeding budworm predicted by the model then specified the expected defoliation category for that stand. We evaluated the performance of the model by comparing the defoliation forecast against the actual, observed defoliation in these stands. The results for two defoliation thresholds (less than or greater than 50% and less than or greater than 75%) are shown in matrix format (Table 1). The result for the 30% defoliation category was similar to that for the 50% defoliation category and so is not shown. Table 1 shows that the method proposed here gives greater than 75% accuracy in forecasting even the lower defoliation category. Notably from an operational point of view, the method was particularly efficacious (89% correct) for the most severe category of defoliation (>75% defoliation).

Discussion

Our method of forecasting defoliation is based on conventional methods of sampling egg masses and overwintering larval stages of the jack pine budworm. By themselves, however, neither egg-mass nor overwintering-larval densities provide a reliable forecast of defoliation. Much of the variation in jack pine budworm survival that has hampered forecasting defoliation from these conventional measures arises from the relationship between budworm survival and the abundance of pollen cones in the infested stand. The abundance of pollen cones varies greatly among sites in any one year, so that even stands with comparable densities of overwintering jack pine budworm will eventually have very different densities of feeding budworms and hence defoliation (Nealis and Lomic 1994). Further, the abundance of pollen cones appears to decrease as defoliation persists in a stand (Nealis 1995). This may account for observed year-to-year differences in the relationship between egg-mass or overwintering larval densities and subsequent defoliation. Incorporating the ecological relationship between budworm survival and abundance of pollen cones as part of the forecast method results in a decision-support tool that is both robust in application and firmly placed within the context of the population biology of the insect.

This forecast method also permits operational flexibility depending on management objectives and the information and resources available. For example, having determined defoliation thresholds of concern to the local situation, pest managers can either estimate the number of egg masses and solve eq. 1 to estimate the density of pollen cones that would result in the given density of feeding larvae and consequent level of defoliation or vice versa. The density of either pollen cones or egg masses can be determined using fixed-size or sequential sampling schemes (Lomic 1995), so that savings in operational costs, with known compromises to accuracy and risk assessment, can be considered.

The parameters used in model development were derived from data collected during operational surveys in support of suppression programs in Ontario during the 1980s and 1990s. Given the experience gained over that time, a number of improvements can be identified now that will further improve the frequency of correct forecasts using the model presented here. Increasing sample size, for example, would estimate parameters of the model more precisely. Nealis and Lysyk (1988) show that for overwintering jack pine budworms, a 10-branch sample size would put the estimate of insect density only within 15 to 20% of the actual mean at most densities of jack pine budworm encountered. Similarly, Volney (1992) suggests at least 15 branch samples are required to estimate defoliation at the stand level over the entire range of measurable defoliation. Thus the sample sizes of the survey data used here for both model development and testing ($n = 6$) are likely quite imprecise. Despite these caveats, we would argue that inasmuch as our method is intended to give pest managers with limited resources the capability of rapidly categorizing risk of defoliation for a large number of stands, the sampling efforts represented by the data used here are not far from what, in practice, would be considered feasible. At the same time we caution against operational expediency as a justification for imprecise sampling methods. Forecasts will only be as good as the density estimates gained from sampling. Volney (1992) has proposed improvements to methods of estimating defoliation and Lomic (1995) has developed guidelines for sampling both egg masses and pollen cones. After a few seasons employing these improved sampling methods, even more reliable estimates of the parameters of the model can be calculated and the standard error of the estimate reduced.

A more problematic area of model refinement lies in understanding dynamic changes in jack pine budworm survival throughout an infestation event. The residual variability in the relationship between the early-instar feeding budworm and defoliation shown in Fig. 1 is the result of survival rates of jack pine budworm between the early-stage feeding larvae and subsequent late-stage feeding larvae, which cause most of the defoliation. A significant source of variation in budworm survival between these two stages is parasitism (Nealis 1991). Although predictions of levels of mortality resulting from specific parasitoids associated with overwintering stages of budworms can be incorporated easily in forecast schemes (Nealis and Lysyk 1988), our current ability to precisely predict levels of parasitism of later stages is poor. Repeated sampling of both jack pine budworms and their parasitoids over the course of an infestation may allow us to assign probabilities specifying the liklihood of a given level of parasitism given other population parameters. Trends in rates of parasitism, for example, may be associated with the immediate history of local outbreaks in the area (Nealis 1991), as appears to be the case with trends in the abundance of pollen cones (Nealis 1995). Including these relationships would represent additional points of integration of monitoring, ecology, and forecasts for the support of operational decisions in management of the jack pine budworm.

Acknowledgments

We thank G. Howse, H.D. Lawrence, and the Forest Insect and Disease Survey for access to the survey data used in developing and testing the model and I. Ochoa, D. Oliver, D. Ortiz, and P. Roden for extraction of data records from survey summaries and for assistance in the field. Jan Volney made helpful comments on the original draft. This work was supported, in part, by a grant from the Northern Ontario Development Agreement.

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