

**REPORT ON THE STATUS OF STUDIES  
TO ASSESS IMPACTS AND  
TO IMPROVE SAMPLING TECHNOLOGIES FOR  
THE JACK PINE BUDWORM  
UNDERTAKEN UNDER THE  
CANADA/MANITOBA & CANADA/SASKATCHEWAN  
FOREST RESOURCE DEVELOPMENT AGREEMENTS**

by

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This report describes on-going studies. As such, it has not been peer-reviewed and is only an overview of much more detailed studies carried out to understand the impacts of jack pine budworm populations. The conclusions contained here-in, unless published in the scientific literature, are tentative. They reflect the thinking of the author on the date the report was submitted for printing. The material may be cited as a personal communication from the author.

## **INTRODUCTION**

The primary objective of the forest insect and disease program in both the Canada/Manitoba and Canada/Saskatchewan Forest Resources Development Agreements was to improve surveys and impact assessment procedures for major pests. Major pests of the two provinces concerned include the spruce and jack pine budworms and the forest tent caterpillar. A pilot project was undertaken to develop such procedures for one of the defoliating insects in the Region which periodically defoliates trees leading to stand decline. The intent was to develop prototype procedures to survey and assess populations and damage caused by defoliators but specifically targeted to the jack pine budworm. Future work could then be undertaken to modify these techniques for the other defoliators.

The jack pine budworm life system was chosen as the pilot project for two principal reasons. Regionally the jack pine budworm is a periodic problem of jack pine stands but little was known of its impact on stand development. Despite this, a good deal of information is known about this insect and its populations because of their similarity to those of the spruce budworm, a serious pest of spruce-fir forests of eastern North America. As a consequence, considerable information on techniques and procedures relating to the study of insect population behaviour could be adapted to the specific needs of projects dealing with the jack pine budworm in this region. Secondly, and more importantly, jack pine is a major component of the estimated growing stock volume of the forest resource in the two provinces: 21.6 % or 161 million m<sup>3</sup> in Manitoba (Bohning 1987a) and 20.5% or 127 million m<sup>3</sup> in Saskatchewan (Bohning, 1987b). Damage by the insect is thus of considerable concern.

Certain information is required to manage pest populations. This information is used in making decisions on the need to alter management plans, prescribe prophylactic treatments, or suppress populations. In addition, there is a need to understand the short term behaviour of populations (over a few weeks to two seasons) as well as the long term behaviour of the population. The former is useful in dealing with an individual outbreak in specific areas, while the latter is of value in forecasting the probable impact of this pest in timber supply areas in periods of a decade or more. To develop this understanding also requires methodologies to measure and assess populations and their impacts. The studies described in this report were designed to provide the means with which to predict and manage outbreaks of jack pine budworm populations.

Two sets of studies were developed to address the information needs of managers seeking to minimize the impact of jack pine budworm populations. The first set are based on relatively small study plots, which were sampled intensively to obtain details on population density and defoliation estimators. The second set of studies are based on plots in forest stands of different ages designed to provide some understanding of the impact of populations on forest stand development.

Existing information from the Forest Insect and Disease Survey was also examined to determine the characteristics of outbreaks which might be used in predicting the occurrence of outbreaks. As this provides the back ground for much of the material to follow it is dealt with first.

## **OVERVIEW OF JACK PINE BUDWORM OUTBREAKS IN THE REGION**

The jack pine budworm (Choristoneura pinus Freeman) feeds primarily on jack pine (Pinus banksiana Lamb.) foliage and often causes conspicuous defoliation of host stands. Defoliation is often quite extensive and may persist in an area for many years. Jack pine budworm-caused defoliation is accompanied by decreases in radial increment of individual trees, often some killing of tree tops, and occasionally tree mortality (Kulman et al. 1963). These effects ultimately have an, albeit unknown,

impact on the timber supply from jack pine forests. If the impact of jack pine budworm (JPBW) outbreaks are to be quantified and their effect on the regional timber supply is to be assessed, some means of projecting the frequency, duration and extent of these outbreaks must be developed. Although long-term records of JPBW population densities are not available for the forests of the prairie provinces (Ives 1981), the area affected by this species provides an index of population size (Volney 1989). Fluctuations of this index may be examined to develop hypotheses regarding factors influencing the dynamics of jack pine budworm populations.

Outbreaks of a budworm feeding on pine have been reported as early as 1922 (Graham, 1935) but it was not until the formation of the Forest Insect Survey in 1936 that routine compilations of the area affected were possible. The first such compilation was made in 1937 and has continued to be made, annually, up to the present by what has become the Forest Insect and Disease Survey (FIDS) of Forestry Canada. This record now represents a description, spanning 50 years, of the areas affected annually by the JPBW in the prairie provinces.

The objective of this section is to describe the compilation of the time series of areas affected by the JPBW in the prairie provinces and to describe characteristics of the variation in the series. The significance of associations between regional forest fire histories and the extent of JPBW outbreaks is assessed. The utility of exploiting these associations to forecast the occurrence and size of outbreaks is also assessed.

### Geographical Coverage

The region considered in this analysis encompasses the prairie provinces of Canada. However, the first confirmed outbreak of JPBW in Alberta occurred in 1985 (Moody and Cerezke 1986) consequently the analysis was restricted to Manitoba and Saskatchewan. Coverage of the area varied from year to year, reflecting the vagaries of the Survey in response to war, budgetary constraints, institutional re-organizations, and changes in mandate and personnel. Initially, surveys were conducted from the ground by Survey staff and their co-operators including provincial forestry personnel and agents of the Hudson's Bay Company. By 1939 insect samples were being collected throughout the forested areas of Manitoba and Saskatchewan (see maps in Brown 1940). Aircraft were used in these aerial surveys as early as 1939 but became routine in 1947. Early in the Survey, therefore, a large portion of the commercial range of jack pine was surveyed annually. The last year included in the analysis is 1986.

The area damaged was reported on maps prepared by FIDS staff as well as in annual regional reports listing the Township, Range and Section affected. Few of the original sketch maps have survived but much of the information about outbreaks was gleaned from the annual Forest Insect (and Disease -after 1950) Survey Reports; the unpublished Winnipeg Forest Insect Laboratory Annual Technical Reports (1937-1951); the unpublished Annual District Reports of the Forest Insect and Disease Survey, Winnipeg, (1952-1969); and reports on Forest Insect and Disease Conditions (1970-1986) published as information reports by the Canadian Forestry Service, Edmonton. Brandt and McDowall (1968) provide maps and a discussion of outbreaks to 1967. Some of these maps were unavailable elsewhere and were useful in estimating the areas affected.

The size of areas affected (ie the area, in hectares, which were defoliated) by JPBW were determined by interpreting maps, written reports, and, where applicable, comments by Brandt and McDowall (1968). Wherever possible, the areas used in these analyses are those reported by the FIDS. In other cases the record was interpreted to determine the area affected. Because early outbreaks

were described by listing the Township, Range, and Section affected, the area affected was approximated by counting the Sections defoliated and converting to hectares. In all cases a conservative approach was adopted in determining areas. The estimates are also conservative because it was impossible for the FIDS rangers to have surveyed the entire region. It is reasonable to expect that the lower detection limit for an outbreak in remote areas to be on the order of 10,000 ha (approximately 1 township). However, outbreaks as small as 60 ha have been reported in heavily travelled areas. A detection limit of 10,000 ha is small in comparison to the area of productive forest land in the region (14,900,000 ha in Manitoba and 7,700,000 ha in Saskatchewan (Bohning 1987a & b)).

Geographical units, corresponding to the Forest Management Units used by the Forestry Branch of the Manitoba Department of Natural Resources and the Administrative Districts of the Saskatchewan Department of Parks, Recreation and Culture, Forestry Division were used to specify the locations of JPBW outbreaks.

### **Defoliation Assessment**

Jack pine budworm larvae leave considerable amounts of damaged, but uneaten, foliage entangled with frass in their feeding webs. The uneaten foliage and frass turn brick red upon desiccation. If populations are dense, the trees will be shrouded in this residue and will appear red from a distance. FIDS rangers use the intensity of this color to rate stands as "severely", "moderately", "lightly", or not defoliated. Two intermediate categories permitted in this scheme are "moderate to severe" and "light to moderate". Occasionally insects could be collected from stands that appeared to be un-damaged. These damage categories can be scored on an ordinal scale as follows: 1 where insects are present, 2 for light defoliation, etc., up to 6 for severe defoliation.

### **The Defoliation Data Set**

Every mention of the jack pine budworm in the FIDS records from 1937 to 1986 for the prairie provinces was examined. The appropriate geographical unit identifier and defoliation intensity score were assigned to each record. If the score was 5 or greater, then the area of the geographic unit showing moderate-to-severe, or severe defoliation for that year was transcribed from the report or was determined to the nearest section (259 ha). For any year and geographical unit, the highest defoliation score (on a scale of 1 to 6) was used as the defoliation "severity index". Thus a data set of 454 observations was compiled.

## **RESULTS**

The results of this analysis are detailed by Volney (1989) but an abbreviated description is given here to describe the process used in forecasting outbreak occurrence. It was found that the outbreaks are getting larger through time. This increase is exponential and is significant statistically. The area affected in each of the five outbreak periods over the last half century has increased from just under  $1 \times 10^6$  ha between 1940 to 1949 to just over  $9 \times 10^6$  ha between 1980 to 1989.

There is a strong 10-year periodicity to the outbreaks. This periodicity is largely associated with the periodicity in fire sizes which is also associated with the size of outbreaks. The significance of this is

that one can expect an outbreak period once in the middle of every decade. This pattern was especially apparent in the last three decades with populations being extremely low at the beginning and the end of the decade.

The apparent 10-year periodicity is associated with the periodicity in the sizes of fires which also has a 10 year period in this region. It is believed that fire is indicative of drought in the season. Dry seasons are not associated with outbreaks but wet summers in the middle of the decades appear to be associated with the size of outbreaks. The reason for this association between outbreaks and wet summers is currently under investigation.

The final element that may be used in forecasting the size of outbreaks in the region is the size of the outbreak in the previous season. Years with small outbreaks tend to be preceded by years with small outbreaks. Although this information may not be available for making decadal forecasts the estimated area may be used as a proxy of the outbreak size when forecasting future outbreaks.

The relative significance of the various elements in the forecasting model is given in Table 1. The logarithm of the out break area is the dependent variable of the model, the independent variables include: a linear trend element, an element for the periodicity (period = 10 y), the logarithm of the outbreak size in the previous year, and the sum of the areas burned 4 to 7 years prior to the year in which the out break size is to be forecast. This model consistently over-estimated the size of outbreaks when populations were low and under estimated areas when populations were high and explained 50.4 % of the variation observed in the data set. Note that in these calculations time is given in years and 1936 is year 0 for purposes of calculation. Also, the areas are converted to common logarithms (base 10) and the fire history term is a sum of terms for years 4 through 7 inclusive prior to the forecast year. The terms which make up the fire history term are the residuals obtained from the regression of the logarithm of total area burned against time (1936 = 0). This was done to remove any trend in the area burned.

Table 1. Multiple regression statistics for the full model.

Term	Estimate	Std. Err. <sup>1</sup>	t	P >  t
Intercept	4.22125	0.21824	19.34	0.0001
Trend	0.01585	0.00754	2.10	0.0427
Periodicity	0.04652	0.18134	0.257	0.7990
Outbreak (t-1)	0.33473	0.11142	3.004	0.0048
Fire History	0.22107	0.10416	2.122	0.0407

<sup>1</sup>Std. Err.: Standard error of the estimate.

A useful model to investigate is the one in which the area of the previous year's outbreak is dropped. (The inclusion of the previous year's estimate, in contrast to an observation, for long term projections weakens the predictive reliability of the forecast more than usual as the forecast period increases.) Such a model would provide estimates of outbreak size four years in advance of the event. This model accounts for 38 per cent of the variation in the logarithm of the area affected by the jack pine budworm annually. As with the first model, the maxima are under- and the minima over-estimated but the gross trend in outbreak areas is mimicked. Also the contribution of the periodicity term is negligible (Table 2).

Table 2. Multiple regression statistics for the abbreviated model.

Term	Estimate	Std. Err. <sup>1</sup>	t	P >  t
Intercept	4.11310	0.23501	17.501	0.0001
Trend	0.01459	0.00804	1.815	0.0774
Periodicity	0.16123	0.18933	0.852	0.3998
Fire History	0.30315	0.11323	2.677	0.0109

<sup>1</sup>Std. Err.: Standard error of the estimate

## DISCUSSION

The defoliation history derived from the FIDS reports provides the only long-term record of jack pine budworm activity in this vast region. Although the record cannot be expected to provide quantitative estimates of population densities (Ives 1981), this history has provided a means of obtaining ordinal data on outbreak severity. The record thus provides a means for describing JPBW behaviour over the long-term. Improvements in the quality of data derived from the record are possible and would enhance the quality of the conclusions to be derived from these data. However, it would be an extremely costly process requiring detailed mapping of forest types and fire histories coupled with an interpretation of the tree ring record over the region. This approach may be feasible where location specific information has been recorded and is suitable for analysis in conjunction with geographical information systems. This approach will be necessary for evaluating the impact of jack pine budworm on stand development.

Despite the shortcomings of the data, these analyses have permitted a formulation of hypotheses that may be used to model outbreak behaviour. Provided that the underlying mechanisms causing population change do not change, the models should be useful in providing information on the timing and size of outbreaks for the next 10 years.

The models described here have some value in planning and impact assessment. At present FIDS makes forecasts one year in advance. These forecasts rely on point samples and apply to specific locations where population samples were taken (cf. Moody and Cerezke 1986). The models described here provide a means of determining the area to be affected and provide preliminary forecasts four years in advance. Because the coefficients of determination for these models are low (.38 and .50) and the predictor is on a logarithmic scale, the prediction intervals (uncertainty) of outbreak size are large. Nevertheless, the timing of outbreaks is fairly well predicted by the models. Thus, by using annual monitoring of areas defoliated and four-year forecasts, the forest manager has a basis to re-schedule harvesting and contemplate other treatments as much as four years in advance. Finally the basic information in the model can be used, along with other impact data, to simulate and project the effects of jack pine budworm defoliation on the timber supply of the region.

## DEFOLIATION AND ITS ESTIMATION

### STUDY PLOTS

Intensive studies were carried out in six stands located in Manitoba and Saskatchewan. The detailed locations and characteristics of these plots are provided in Table 3. All plots are within the Boreal Forest Region of Canada described by Rowe (1972). The Manigotogan plot is within the Lower English River subsection (B.14), the remaining two plots in Manitoba are in the Manitoba Lowlands subsection (B.15), and the plots in Saskatchewan are all within the Mixedwood subsection (B.18a). All study sites are in the Boreal Ecoclimatic Province, five of them in the Subhumid Low Boreal Ecoclimatic Region, and the Manigotogan site is in the Subhumid Transitional Low Boreal Ecoclimatic Region (Ecoregions Working Group, 1989).

Table 3. Location of intensive study plots.

Province	Location	Elevation (m)	Latitude	Longitude	Stand No.	Provincial Inventory Map Sheet
Man.	Sandilands	305	49°36'51"	96°06'27"	98	TWP 7 RGE 10 EPM
	Kettle Hills	305	52°19'33"	100°37'57"	34	TWP 38 RGE 23 WPM
	Manigotogan	260	51°04'35"	96°00'00"	240	TWP 24 RGE 11 EPM
Sask.	Nisbet	455	53°13'23"	105°56'35"	297	Z 13 E 43 N 589
	Ft. a la Corne	430	53°19'52"	104°29'05"	119	Z 13 E 53 N 590
	Torch River	370	53°33'31"	104°04'05"	58	Z 13 E 56 N 593

Three plots were established at each site within the stand. The plots were established in 1985 for the Manitoba sites and in 1986 in Saskatchewan. Each plot, laid out using a transit and surveyor's tape, was a 50 X 50 m square which was partitioned into 25 10 X 10 m cells. All trees within these plots were tagged with aluminum number tags for future identification, and their heights, diameter at breast height, and heights to the base of the live crown determined. This information was used as a listing of candidate trees within the stands from which to draw sample trees for sampling.

### SAMPLING PROCEDURE

Nine sample trees were selected from each plot at the beginning of each jack pine budworm generation starting in the year of study establishment and concluding in 1988. The crowns of the sample trees were stratified in to three (Upper, Mid, and Lower) levels and whole branches removed for purposes of sampling. The samples were removed with pole pruners according to the following protocol: one whole branch was removed from each crown level of each sample tree and an additional branch was removed from a crown level selected at random but with the restriction that all crown levels be equally represented in the samples from the plot. The result was a sampling program with all locations, plots within locations and trees within plots were equally represented with crown levels sampled with partial replication. The partial replication permitted estimates of variation among branches to be made without resorting to complete replication. Once the sample branches were obtained, their lengths and widths were measured and the were sectioned into a 45 cm tip, an additional 15 cm portion (which when combined with the tip provided a 60 cm tip) and the remainder of the branch.

The branch sections were returned to the laboratory in labelled paper bags where they were examined for defoliation. Twigs were assigned to one of 13 damage classes by visually estimating the amount of damage to the current year's foliage, determining whether the terminal bud was damaged, and whether there was feeding on the previous year's foliage. The defoliation classes corresponded to 0 %, 1 - 10 %, 11 - 20 %, etc. to 91 - 100 %, damage to the terminal bud, and 100 % defoliation of the current year and some defoliation in the previous year. A defoliation index was obtained for each branch section by summing the product of the frequency of twigs in each defoliation class and the mid point percentage of the respective defoliation class. The "mid point" percentages assigned to the two extreme classes were 100 and 110% respectively. All twigs were classified in the Manitoba samples and an arbitrary subsample of 10 twigs per section were classified in the Saskatchewan samples.

The data thus accumulated were analyzed using the general linear models procedure (SAS Institute Inc. 1985).

### RESULTS

During the course of these observations the estimated percent defoliation on individual plots spanned a range from 0.0 % to 81.3 %, with the overall least squares mean estimates for the stands varying from 76.7 to 0.10 % (Table 4). This represents most of the range in defoliation that one is likely to encounter in nature, for it is seldom that every tree in a plot would be 100 % defoliated. The characteristics of the data base accumulated thus provide an opportunity to determine the nature of variation in defoliation over the entire range likely to be encountered by the manager.

It is evident from these data that the decline of the level of defoliation was different in the different locations. The drop in defoliation in the Kettle hills plot was quite steep between 1985 and 1986, whereas this drop was more gradual in the Manigotogan plots in the same period. In both the sandilands and Kettle Hills plots the level of defoliation increased somewhat over the 1986 values and then declined in 1988 again. By contrast, there was a continual, steady decline in the Manigotogan plots.

In Saskatchewan, the level of defoliation never amounted to more than a trace (less than 5%) in the Torch River plots. The defoliation in the Nisbet plots sustained light levels of defoliation for one year beyond that in the Fort a la Corne plots. Both these plots were moderately defoliated in 1986 when the study was established.

Table 4. Least squares mean estimates for percent defoliation in the study sites.

Province	Location	1985	1986	1987	1988
Manitoba	Kettle Hills	76.70	3.57	7.76	0.29
	Manigotogan	35.91	23.67	9.63	3.72
	Sandilands	66.13	0.93	9.89	1.36
Saskatchewan	Ft. a la Corne	-	60.76	0.75	0.48
	Nisbet	-	50.76	12.81	1.22
	Torch River	-	1.82	1.19	0.10



Details of the analysis of variance and least squares means estimates for plots in each year and province are presented in the Table 5. There is a fairly consistent pattern to the way in which the level of defoliation varies within study sites. These sources of variation contribute to the uncertainty in the estimates made from sampling branches from different parts of the crown. Locations, plots within locations (except in Saskatchewan in 1987), trees, and crown level (except in Saskatchewan in 1988) were all significant sources of variation.

Table 5. ANOVA results for percent defoliation in Manitoba and Saskatchewan

Manitoba					
Source <sup>1</sup>	df	1985	1986	1987	1988
Locat. L	2	*	*	*	*
Plot P(L)	6	*	*	*	*
Crwn Lvl C	2	*	*	*	*
C X L	4	*	*	*	*
Tree T(P)	72	*	*	*	*
Section S	2	n	n	n	n
L X S	4	n	n	n	n
C X S	4	n	n	n	n
Error <sup>2</sup>		626	625	617	615

  

Saskatchewan				
Source <sup>1</sup>	df	1986	1987	1988
Locat. L	2	*	*	*
Plot P(L)	6	*	n	*
Crwn Lvl C	2	*	*	n
C X L	4	*	*	*
Tree T(P)	72	*	*	*
Section S	2	n	n	n
L X S	4	n	n	n
C X S	4	n	n	n
Error <sup>2</sup>		627	622	621

<sup>1</sup> Main effects are denoted with a single letter, nesting by brackets eg. plots in locations = P (L), and interactions by letters separated by X.

<sup>2</sup> the error row indicates the degrees of freedom for the particular analysis.

\* Indicates the effect was significant at least at the 0.05 level of significance, and indicates that the effect was not significant.

The consistently significant interaction between crown level and location (Table 5) indicates that trees in different locations have a different pattern of defoliation within the crown. The most consistent result is that there are no differences among the estimates obtained by using shoots from different parts of the branch to estimate defoliation. This applies for the different locations and among crown levels because none of the interactions with branch section or the main effect due to branch section is a significant source of variation.

### ESTIMATING DEFOLIATION

Variance components from the ANOVA may be used to determine the best allocation of effort to estimate defoliation. The significant sources of variation that can not be controlled by the observer, know as "random effects", were found to be plots within locations, trees within plots and branches within trees. The other sources of variation such as locations and crown levels from which branches are taken can be controlled. Defoliation in trees is fairly consistent: the upper crown is always defoliated to a greater extent than the lower crown. This suggests that somewhere in the mid-crown is an "average" condition for the tree. For survey work, the exact location of this "average" will not matter to a great extent, as long as the observer takes a branch from the mid crown. The allocation of effort to the different locations is a matter for the manager to decide. Presumable stands of greater value will be represented to a greater degree than stands of lower value. The sampling process described below will provide estimates of the level of defoliation within a single stand. The manager can decide how many and which stands should be sampled.

The portion of the sample branch, whether it be 45 or 60 cm tips or the whole branch, used to estimate defoliation has no detectable effect on the estimate. These results also apply if a fixed subsample of twigs, such as was done in Saskatchewan, was used. It would therefore appear that a sample as small as 10 twigs per branch would be adequate for these estimates. This simplifies the problem of sampling for defoliation considerably. Furthermore, if mid-crown branches are sampled, the logistics of obtaining samples even on tall trees is further simplified. The problem of optimal allocation of sampling effort then becomes one of determining the relative contributions of branches, trees, and plots to the error of the estimate.

An analysis of the various sources of random variation indicated that the contribution of the different random sources of variation is different for different levels of defoliation (Volney, unpubl. ms.). Thus there is no universally optimum sampling scheme. The strategy taken here is to recommend one that has the power to differentiate among stands that are moderately or severely defoliated. This is also the most difficult call to make because stands that have intermediate levels of defoliation have the highest variance components for trees and plots within locations. At extremely high or low levels of defoliation, the damage to foliage tends to be more uniform within the stand. The manager is un-likely to spend time categorizing stands in which there is a trace of defoliation.

The compromise technique for estimating defoliation would require that ten arbitrarily selected shoots be classified from mid-crown branches. The branches would be selected from 9 trees from each of 3 plots within a location. Thus a total of 270 shoots would be used to determine the level of defoliation within the stand. The effort required to do this with a two person crew, which includes a careful examination of the shoots, would be approximately six person hours. This time does not include travel to the site. The standard error of the estimate will be 5% of the mean between 50 and 60 % defoliation (Volney, unpubl. ms.). The standard error will be lower in stands in which defoliation is outside of the 50 to 60 % range. This procedure will correctly distinguish between stands that are 50 % and 75 % defoliated 95 % of the time. The 75 % threshold is generally considered the lower limit of "severe" defoliation in stands.

### SAMPLING POPULATIONS

The need to sample jack pine budworm populations in Manitoba and Saskatchewan arises out of the need to study populations in relation to the damage they cause and, more importantly from the pest manager's point of view, for assessing populations to make management decisions. These assessments may include surveys of incipient populations on an annual basis, assessments of control treatments, and relating populations to other management tools such as calibrating pheromone traps for assessing low level populations. With these concerns in mind, it was decided to investigate how 4 life stages of the jack pine budworm could be sampled efficiently. These life stages are the egg masses, the early larval stages, the late larval stages, and the pupae. The latter stages are all associated with the shoots or "candle" whereas the egg masses are deposited on needles. Because the shoot provides a convenient basis for assessing damage (see above) and is also related to the productivity of the tree, it would be efficient to be able to compare populations on a common basis such as the shoot.

Previous work on sampling jack pine budworm egg mass populations have utilized a variety of measures including branch tips of various lengths, clusters of shoots, and even area of branches. It is not clear whether any of these are universally better than the others or whether the biological suitability of the shoot based estimate is severely compromised by inferior statistical efficiency. Thus the different methods of expressing jack pine budworm egg mass populations were compared.

#### Methods

The same material used in assessing defoliation was searched for egg masses and the counts were converted to egg masses per branch, per shoot and per m<sup>2</sup> of the foliated branch. Again the branches were sectioned into the distal 45 cm, the additional 15 cm which, when combined with the tip, corresponds to 60 cm tip, and the remainder used for obtaining whole branch estimates. A series of ANOVA calculations were performed on this data set for each means of expressing density and for each set of collections in a Province by year.

The larval and pupal populations estimates were obtained using the same collection methods. However, the only means of expressing density was based on the shoot count. The reason for this is that in order to relate densities to defoliation and ultimately tree volume increment, it is thought that the number of shoots bears a stronger relationship to these measures than numbers per unit area of foliage or per branch. The shoot is also the unit fed on by the larvae. Thus by expressing density on this basis we would anticipate lower estimates of variance components in the density estimates. (Although some branches have foliage, they may not produce shoots, and thus do not form part of the food resource for the jack pine budworm. Consequently these branches contribute to the variance of the estimate if one uses foliage area or branch as a density basis, but they can be excluded from the sample universe.)

#### Results

##### Egg masses

In comparing the ANOVA results for the various methods of expressing density, it was quite clear that no one method was consistently superior (Table 6). When populations were in the moderate range, the shoot count method gave the best overall results in terms of the coefficient of variation and R<sup>2</sup> in both Manitoba and Saskatchewan. However, at low densities, the branch method was better. In an attempt to provide a more objective basis for the comparison, the ranks of the coefficient of

variation and the value of the  $R^2$  together with the simplicity of the design that would be required to obtain an estimate and the ease of interpreting the estimate was compared (Table 7). There is really little reason to choose between the two methods except that the shoot count method provides a direct basis for comparison with shoot count based density estimates obtained from the pupal and larval stages. This fact and the fact that there is little or no statistical penalty in using the shoot based method of expressing density, makes the shoot count density estimator the method of choice.

Table 6. ANOVA results for egg mass populations for three methods of expressing egg mass densities. Manitoba

Source <sup>1</sup>	df	Egg masses/cm <sup>2</sup>				Egg masses/shoot				Egg masses/branch			
		'85	'86	'87	'88	'85	'86	'87	'88	'85	'86	'87	'88
Location(L)	2	*	*	n	*	*	*	n	n	*	*	n	*
Plot P(L)	6	n	*	n	*	*	*	n	n	n	*	n	*
Crwn Lvl C	2	*	*	n	*	*	*	n	n	*	*	n	*
C X L	4	*	*	n	*	*	*	n	*	*	*	n	*
Tree T(P)	72	*	*	*	*	*	*	*	*	*	*	*	*
Section S	2	n	n	n	n	*	n	n	n	n	n	n	n
L X S	4	n	n	n	n	*	n	n	n	n	n	n	n
C X S	4	n	n	n	n	*	n	n	n	n	n	n	n
Error <sup>2</sup>		611	629	623	619	611	628	615	613	611	629	623	619

## Saskatchewan

Source <sup>1</sup>	df	Egg masses/cm <sup>2</sup>			Egg masses/shoot			Egg masses/branch		
		'86	'87	'88	'86	'87	'88	'86	'87	'88
Locat. L	2	*	*	*	*	*	*	*	*	*
Plot P(L)	6	*	*	n	n	*	n	*	*	n
Crwn Lvl C	2	*	*	n	*	n	n	*	n	n
C X L	4	*	*	*	*	n	*	*	*	*
Tree T(P)	72	*	*	*	*	*	*	*	*	*
Section S	2	n	*	n	n	n	n	*	*	n
L X S	4	n	*	n	n	n	n	*	*	n
C X S	4	n	*	n	n	n	n	n	n	n
Error <sup>2</sup>		608	606	580	606	606	593	610	606	593

Table 7. Comparison of the sampling characteristics of egg mass populations based on three methods of expressing density.

Province	year	Method <sup>1</sup>	Ranks			
			C.V.	R <sup>2</sup>	DESIGN	INTERP.
Manitoba	1985	area	3	3	1	3
		shoot	1	2	3	1
		branch	2	1	1	3
	1986	area	3	3	1	3
		shoot	2	1	1	1
		branch	1	1	1	3
	1987	area	2	3	1	3
		shoot	3	2	1	1
		branch	1	1	1	3
	1988	area	2	1	3	3
		shoot	3	3	1	1
		branch	1	2	3	3
Saskat.	1986	area	3	3	2	3
		shoot	1	1	3	1
		branch	2	2	1	3
	1987	area	3	1	3	3
		shoot	2	3	1	1
		branch	1	2	2	3
	1988	area	2	1	1	3
		shoot	3	1	1	1
		branch	1	3	1	3
Aggregate	All	area	3	3	2	3
		shoot	2	2	1	1
		branch	1	1	1	3

<sup>1</sup>The methods are: egg masses per: unit area, shoot and branch. The best method is assigned a rank of 1, the worst 3.

The range of densities over which populations were sampled spans 4 orders of magnitude (Table 8). The population densities of the Manitoba sites in 1985 probably represent close to the peak populations that developed in those stands during the outbreak. Similarly, the egg mass populations of the Saskatchewan plots in 1986 were probably the highest for those plots in the 1980s. In the last year of the study egg masses were still detectable but the defoliation levels were negligible.

Table 8. Least squares estimates of egg masses per 10,000 shoots

Province	Location	1985	1986	1987	1988
Manitoba	Kettle Hills	530.0	38.0	0.0	2.0
	Manigotogan	87.1	22.0	5.0	0.5
	Sandilands	137.0	18.0	3.0	1.0
Saskatchewan	Ft. a la Corne	-	46.0	0.2	0.0
	Nisbet	-	362.0	19.7	1.0
	Torch River	-	6.0	0.2	- <sup>a</sup>

<sup>a</sup>Least squares estimate negative, population negligible.

The problems of comparing egg populations with larval populations, and defoliation are greatly simplified because the unit of expressing density in one which can be related directly to the productive capacity of trees.

#### Early larval populations

Early larval populations were sampled in 1986 to 1988 in Manitoba and in 1986 and 1988 in Saskatchewan. The important sources of variation in the distribution of the early larvae were very similar to those for egg masses and included locations plots, within locations, crown levels and trees within plots. There were some instances where plots and crown levels were not significant sources of variation (Table 9). The most important result from a sampling perspective is that the branch section was never a significant source of variation. The conclusion is that where there are viable shoots the probability of finding a larva there depends mainly on the crown level, tree and plot at a particular location. In 1988 plots, crown level and the interaction with crown level were not significant sources of variation in larval density in the Manitoba plots. This is in contrast to other years in Manitoba and 1988 in Saskatchewan. Early larval populations were extremely low in Manitoba in 1988 (Table 10). The distribution of larvae was essentially random within the stands in Manitoba in that year.

Population densities of early larvae, like egg mass densities, span 4 orders of magnitude over the period and geographical range investigated. Populations were detected in all locations sampled even though the densities were as low as 4 larvae per 100,000 shoots. At the low densities, however, the pattern of distribution is essentially random; indicating that stratification of samples is unlikely to be rewarding in improving sampling efficiency from a statistical perspective.

Table 9. ANOVA results for early larval populations.

Source <sup>1</sup>	df	Manitoba			Saskatchewan	
		'86	'87	'88	'87	'88
Location(L)	2	*	*	*	*	*
Plot P(L)	6	*	*	n	n	*
Crwn Lvl C	2	*	*	n	*	*
C X L	4	*	*	n	*	*
Tree T(P)	72	*	*	*	*	*
Section S	2	n	n	n	n	n
L X S	4	n	n	n	n	n
C X S	4	n	n	n	n	n
Error <sup>2</sup>		626	617	616	554	594

Table 10. Least squares mean estimates of early larval populations per 10,000 shoots

Province	Location	1986	1987	1988
Manitoba	Kettle Hills	343.8	6.6	0.4
	Manigotogan	720.4	83.9	15.2
	Sandilands	92.9	23.2	9.2
Saskatchewan	Ft. a la Corne	-	44.9	1.1
	Nisbet	-	763.1	149.5
	Torch River	-	170.3	0.5

### Late larval populations

Late larval populations tend to have the same pattern of distribution as the other stages but with minor variations at high densities. With the high populations of 1986, crown level was not an important source of variation in density (Table 11). This was again the case with the extremely low population densities in Manitoba in 1988. Whereas the distribution tended to be random in low populations, the destruction of current year's upper crown foliage in the early years of the study, resulted in a redistribution of larvae which appeared more uniform. Plots were a consistent source of variation except in the Saskatchewan sites in 1988. This was entirely due to the population in the Nisbet stands which would sustain the second year of moderate to severe defoliation. The late larval populations were redistributed within the stand where ever foliage survived.

The late larval population densities were lower, and in many cases below the detection threshold for sampling (Table 12). They did, however, span 3 orders of magnitude over the period sampled. The ability to sample the low population densities would probably require a ten-fold increase in density. It is unlikely that densities at this level will be sampled operationally in any case.

Table 11. ANOVA results for late larval populations.

Source <sup>1</sup>	df	Manitoba			Saskatchewan	
		1986	1987	1988	1987	1988
Location(L)	2	*	*	*	*	*
Plot P(L)	6	*	*	*	*	n
Crwn Lvl C	2	n	*	n	*	*
C X L	4	*	*	n	*	*
Tree T(P)	72	*	*	*	*	*
Section S	2	*	n	n	n	n
L X S	4	n	n	n	n	n
C X S	4	n	n	n	n	n
Error <sup>2</sup>		624	620	625	585	579

Table 12. Least squares mean estimates of late larval populations per 10,000 shoots

Province	Location	1986	1987	1988
Manitoba	Kettle Hills	145.2	0.2	0.0
	Manigotogan	247.4	17.8	0.2
	Sandilands	26.4	3.5	5.1
Saskatchewan	Ft. a la Corne	-	20.0	0.0
	Nisbet	-	531.3	77.6
	Torch River	-	22.8	0.0

### Pupal populations

Because of the declining populations and the even lower pupal densities only three comparisons of the distribution of pupae were feasible (Table 13). Trees are always a significant source of variation. In addition, crown level and plots are a significant source of variation in pupal densities on at least in at least one of the three cases. As in the case for sampling the other stages, branch section was not a significant source of variation.



Table 13. ANOVA results for pupal populations.

Source <sup>1</sup>	df	Manitoba			Saskatchewan	
		1986	1987	1988	1987	1988
Location(L)	2	*	-	-	*	n
Plot P(L)	6	*	-	-	n	n
Crwn Lvl C	2	n	-	-	*	n
C X L	4	n	-	-	*	n
Tree T(P)	72	*	-	-	*	*
Section S	2	n	-	-	n	n
L X S	4	n	-	-	n	n
C X S	4	n	-	-	n	n
Error <sup>2</sup>		418			589	589

The pupal populations sampled were from populations that were in decline. Consequently the populations were all low because this is the time in the generation when densities approach their lowest point. The range over which observations were made spanned three orders of magnitude (Table 14). There is sufficient evidence however in these data to suggest that the effort required to sample pupal populations operationally is feasible for populations as low as 1 pupa per 10,000 shoots. For life table work a different approach may be necessary at low densities.

Table 14. Least squares mean estimates of pupal populations per 10,000 shoots

Province	Location	1986	1987	1988
Manitoba	Kettle Hills	19.7	0.0	0.0
	Manigotogan	-	0.0	0.0
	Sandilands	4.5	0.0	0.0
Saskatchewan	Ft. a la Corne	-	0.03	4.6
	Nisbet	-	37.9	5.9
	Torch River	-	0.3	0.0

## DISCUSSION

The results suggest that sampling populations of jack pine budworm at the densities encountered in this study could quite simply be based on an estimator which expresses density as a function of insects per shoot. For the most part, it does not matter what portion of the branch the sample unit is selected from. For purposes of operational sampling a terminal 45 cm on which a shoot count is made should prove an acceptable unit. For life table work a similar sample unit with partial replication using whole branch sampling should protect against the possibility that mortality factors effect populations on different parts of the branch differently. There are certain sources of variation that are consistently significant. Trees are always a significant source of variation. In addition, plots appear to be an important source of variation in most cases. The sampling strategy that should therefore be adopted would suggest that a sufficient number of plots and trees be included in any sampling scheme to capture the variation in the stand and yet provide an adequate sample for decision purposes.

There are several options to consider in choosing an optimal sampling design for operational purposes. The population levels that caused moderate defoliation is one that could be targeted for design purposes. This is the population level that would be of most concern to the manager and would be most variable in the estimates used in operational sampling. The intent is to design a technique that would be useful in assessing populations if management actions had been taken. For these reasons, the characteristics of the 1985/86 generation in Manitoba were taken to design the sampling plan. The results of these calculations are presented in Table 15 assuming that the assessment can be done by a two person crew in 240 person minutes (2 h per stand per crew of 2 people).

The optimal designs to sample the larval stages are the same. The big difference is that to collect and examine branches for the early stages takes longer and the design target of 240 minutes could not be met whereas the target is met when the late larvae are sampled. For both the pupal and the egg mass populations, the time required to complete the sampling is less than the target of 240 minutes per stand. In the case of the pupae, however, the standard error of the estimate approaches 160% of the mean. It is desirable to have this estimate lower than 100% of the mean for survey sampling. A consequence of this is that assessments should be designed, if possible, to avoid sampling the pupal stage.

The distribution of the plots within the stand should be in some sense random. Because little is known about the variation of population density with micro-sites, little will be lost by locating plots systematically along a transect across the stand. The selection of trees within the plots could be simplified for survey purposes. This would be easiest if two co-dominant trees closest to the plot centre were selected for assessments. The calculations in the table assume that mid-crown branches are sampled and only the distal 45 cm tips are examined. If samples are to be taken to assess a treatment by sampling before and after the application, then there will be considerable gains if the same trees are sampled on the two occasions. Further efficiencies are possible if the same branches can be examined, non-destructively, over time. This is likely to be impractical, however, in most operational surveys.

Table 15. Characteristics of optimal sampling schemes to assess population densities per 10,000 shoots.

Characteristic	Early Larvae	Late Larvae	Pupae	Egg Masses
Time to collect branch	10	5	5	10
Time to locate tree	5	5	5	5
Time to locate plot	10	10	10	10
Var. comp.: plots $\times 10^{-8}$	31210	17060	130	49000
Var. comp.: trees $\times 10^{-8}$	39850	42245	824	48306
Var. comp.: branch $\times 10^{-8}$	630442	148392	4498	127912
Mean density $\times 10^{-4}$	387	139	12	249
Target cost (min.)	240	240	240	240
Branches/tree	2	2	3	2
Trees/plot	2	2	4	2
Plots	6	6	2	4
Std. Error of Mean $\times 10^{-4}$	186	112	19	162
Std. Err./ Mean Density (%)	48	82	157	65
Actual cost (min.)	320	240	180	220

If repeated sampling is contemplated a compromise design may have to be selected. Such a design might be the optimal design for sampling larvae. This requires that 6 plots, each with two trees from which 2 branch tips are examined be used. Note that although this design gives a lower standard error for the estimate of pupal and egg mass densities than in the optimal design for these stages, the design is less efficient because of the added time required for sampling (Table 16).

Table 16. Characteristics of a compromise sampling design.

## Compromise: 6 plots, 2 trees/plot, 2 branches/tree

Characteristic	Early Larvae	Late Larvae	Pupae	Egg Masses
Cost of design (min.)	320	240	240	320
Std. Error of Mean $\times 10^{-4}$	186	112	17	134
Efficiency of design (%)	100	100	79	57

**STAND IMPACT STUDIES**

Stand impact studies were initiated with the co-operation and aid of the provincial forestry agencies in both Manitoba and Saskatchewan. All studies were initiated **AFTER** outbreaks had occurred in the region. These studies may therefore be regarded as preparatory to the next outbreak. A series of semi-permanent prism plots were established in south-eastern Manitoba and in the Moose Lake area of Manitoba in the fall of 1985. Trees in these plots were measured and estimates of volumes derived using the Manitoba Natural Resources, Forestry Branch volume equations and the prism factor to derive estimated volumes per hectare. These plots were visited annually to assess mortality rates following the last jack pine budworm outbreak in the mid 1980s.

A summary of the present status of jack pine trees in the southeastern Manitoba plots is presented in Table 17. The stands in south-eastern Manitoba surveyed are almost pure jack pine.

Table 17. Stand conditions in south-eastern Manitoba (Forest Management Unit 20).

Stand identification			Volume per ha (m <sup>3</sup> )	Percent volume in category				
TWP	RG	SDT#		Healthy	Decl- ining	Dead	Top Kill	Other
1	12	128	107.1	92	4	0	1	0
2	12	20	80.9	53	4	t	t	42
4	9	107	72.9	94	3	3	0	0
4	9	138	47.9	91	9	0	0	0
4	9	145	16.6	75	15	10	0	0
4	9	299	55.2	95	0	5	0	0
4	10	445	80.3	68	5	4	0	23
4	10	491	75.1	90	8	2	t	0
4	10	511	52.3	83	14	3	0	0
4	10	691	80.3	94	4	2	0	0
5	9	6	36.2	86	10	4	0	0
5	9	42	65.4	88	9	2	t	0
5	9	117	49.9	76	7	8	9	0
5	9	145	53.5	86	10	2	2	0
5	9	190	32.7	100	0	0	0	0
5	10	524	21.7	95	3	2	0	0
5	10	543	35.9	82	9	2	0	0
5	10	555	84.3	93	9	6	3	0
5	10	570	118.6	94	2	3	0	0

Few of these stands are mature and represent stands that would have experienced one and at most two jack pine budworm cycles. The levels of mortality range from 0 to 10 % with the volume of trees in the declining category ranging from 0 to 14 %. This may be the expected range of back ground mortality in young stands subject to repeated budworm attacks in south eastern Manitoba.

Observations in the stands in the Moose lake area yielded similar results. Over the 5 years of monitoring, the range of mortality was between 0 and 7 % (Table 19). The percent of tree volume in the declining category was some what higher than for stands in south-eastern Manitoba. The percentage ranged as high as 27 % of the standing volume. Growing conditions in the Moose lake area are considerably different than in south eastern Manitoba and these stands would have experienced at most one previous jack pine budworm outbreak. The higher percentage of declining trees in the Moose Lake stands suggest that the possibility for higher levels of mortality in the next outbreak is real.

Table 18. Stand conditions in the Moose Lake area of Manitoba (Forest Management Unit 53).

Stand identification			Volume per ha (m <sup>3</sup> )	Percent volume in category				
TWP	RG	SDT#		Healthy	Decl- ining	Dead	Top Kill	Other
56	21	10	75.8	81	13	4	0	2
56	21	11	26.3	79	14	7	0	0
56	21	12	26.7	87	12	1	0	0
56	21	47	33.2	72	27	0	0	0
56	21	54	95.9	94	5	1	0	0

Fixed area plots were established in the Torch River Forest of Saskatchewan and in the Thompson area of Manitoba. These plots were also monitored annually to obtain mortality rates following the outbreak and provide base line information before the next outbreak starts.

Results of surveys of stands in the Torch River Forest provide an indication of the rates of mortality that might be expected in stands of various ages growing in the same region and experiencing as many as 4 outbreaks (Table 19). The percent volume mortality ranges from extremely low of 0% to as much as 40%. The stands with the high mortality rates are presently old and declining in standing volume. Some of these stands now have Armillaria sp. infections and it has been found that is associated with jack pine budworm damage (Mallett and Volney 1990). In the stands that have been studied, the declining radial increment of jack pine trees is indicative of this decline. There is a possibility that this information can be used to hazard rate the stands in this area and thus schedule harvesting to minimize the loss to jack pine budworm outbreaks in the merchantable stands. The extent and severity of root rot infections could be used as auxiliary information to hazard rate stands.

Table 19. Stand condition in the Torch River Forest, Saskatchewan.

Stand number	Volume per ha (m <sup>3</sup> )	Percent volume in category				
		Healthy	Declining	Dead	Top Kill	Other
1	24.1	72	0	28	0	0
3	23.1	77	0	22	1	0
4	56.7	78	1	21	0	0
5	363.2	71	2	26	0	0
6	26.9	73	3	23	0	0
7	301.0	68	1	29	1	0
15	422.1	89	1	10	t	0
32	5.3	85	0	15	0	0
42	82.8	85	1	14	t	0
45	71.8	86	2	11	0	0
46	99.9	63	2	35	0	0
48	198.3	85	1	14	0	0
49	67.5	70	0	30	0	0
50	183.4	75	3	22	0	0
51	102.1	69	0	31	0	0
52	24.5	94	0	6	0	0
53	22.8	84	0	16	0	0
54	17.2	84	0	16	0	0
55	30.7	84	2	13	2	0

Table 19 (Continued). Stand condition in the Torch River Forest, Saskatchewan.

Stand number	Volume per ha (m <sup>3</sup> )	Percent volume in category				
		Healthy	Declining	Dead	Top Kill	Other
57	16.4	60	0	40	0	0
62	203.0	88	2	10	t	0
64	35.4	90	5	5	0	0
67	93.9	93	0	7	0	0
68	72.4	90	0	10	0	0
70	79.2	75	1	24	0	0
71	344.7	71	1	28	0	0
76	39.0	88	0	12	0	0
99	20.7	90	0	10	0	0
100	59.3	81	3	16	0	0
101	47.9	85	3	11	0	0
102	23.7	81	0	19	0	0
103	4.5	100	0	0	0	0
104	32.5	78	0	22	0	0
105	29.2	96	0	4	0	0
112	39.6	62	4	34	0	0
113	105.2	82	3	15	0	0
117	106.7	77	1	22	t	0
118	7.1	86	0	14	0	0

Table 19 (Continued). Stand condition in the Torch River Forest, Saskatchewan.

Stand number	Volume per ha (m <sup>3</sup> )	Percent volume in category				
		Healthy	Declining	Dead	Top Kill	Other
120	97.2	77	1	22	0	0
121	24.6	92	0	8	0	0
122	23.8	95	0	5	0	0
123	233.1	80	1	18	1	0
124	56.5	91	1	8	0	0
125	54.2	96	0	3	1	0
126	49.1	72	0	25	3	0
134	51.7	79	0	21	0	0
135	4.6	45	10	34	11	0
138	137.1	61	0	39	0	0
151	172.4	83	4	12	1	0
152	32.5	91	0	9	0	0
157	5.1	82	0	15	3	0
158	19.6	68	4	28	0	0
159	26.7	92	0	8	0	0
183	68.2	79	2	15	4	0
184	303.5	76	1	23	0	0
189	74.7	88	0	12	0	0
190	103.5	88	1	11	0	0



Table 19 (Continued). Stand condition in the Torch River Forest, Saskatchewan.

Stand number	Volume per ha (m <sup>3</sup> )	Percent volume in category				
		Healthy	Declining	Dead	Top Kill	Other
195	6.8	93	0	7	0	0
196	25.8	89	0	11	0	0
197	25.7	91	6	4	0	0
199	294.3	76	4	19	1	0
201	35.1	78	4	17	0	0
208	82.2	59	4	37	0	0
210	213.8	85	3	10	2	0
211	198.8	84	1	15	0	0
224	64.7	80	0	20	0	0
226	28.1	73	2	25	0	0
228	187.3	83	1	16	0	0

Perhaps the most dramatic effect of the 1980s jack pine budworm outbreak was in the Thompson area (Table 20).

Table 20. Condition of the jack pine component of stands surveyed in the Thompson area.

Stand number	Jack Pine Volume per ha (m <sup>3</sup> )	Percent stems in category				
		Healthy	Declining	Dead	Top Kill	Other
88	130.6	66	8	25	2	0
107	37.4	39	28	33	2	0
171	58.9	55	12	33	1	0
180	38.9	42	15	42	2	0
185	39.0	52	37	7	4	0
186	93.9	44	10	45	1	0
280	82.3	45	23	31	1	0
469	33.8	50	6	43	1	0
840	16.9	70	4	25	2	0

The stands in this area are mixedwood stands including fairly sizeable components of trembling aspen, black poplar and black spruce. Jack pine forms the over storey of these stands and are consequently the larger trees. The percent mortality on the jack pine component of these stands is quite high (Table 20). Estimates of stem mortality over the 5 following the outbreak range from 7 to 45 %. All but one stand has now lost 25 % of the jack pine component. Judging from the this, almost all the jack pine will be dead by the end of the next outbreak. In surveying these stands all the dead trees and most of the trees with dead tops had root systems which were attacked by secondary organisms. The identification of these organisms is difficult because many of the attacks in these cases were initiated by insects whose galleries were invaded by fungi. It is thought that the competition in the stands, the jack pine budworm and these secondary organisms have combined to influence the mortality in these stands.

The four different areas represent stands in different stages of development and it is therefore difficult to compare conditions of mortality and growth among them. However, they may very well represent a chrono-sequence which can be investigated to develop predictors of future damage. The remeasurement of these stands and their reaction to the next outbreak will provide answers to many of these questions.

### CONCLUSIONS

As a result of these studies we now have a fairly reliable predictors of the long term behaviour of jack pine budworm outbreaks. Although the cumulative effects of these outbreaks are largely unknown at present, the information derived from mapping historical outbreaks will allow an investigation of this aspect by visiting extant stands. This information can be exploited in conjunction with the current impact plots and the results of any simulations of budworm impact on plots may be assessed against this database. This is the objective of perusing this study through to the end of the next outbreak. The result will be a well defined basis for predicting the effects of jack pine budworm, and the complex of other organisms which follow or may aggravate outbreaks, on the timber supply.

The detailed information on sampling defoliation and the different stages of the insect population has been developed, at least for declining and sparse populations. This should provide the pest manager with a firm basis for sampling and assessing populations in the coming years. There is a need to confirm some of these recommendations for expanding jack pine budworm populations. However, this may be done in the context of continuing life table studies.

The statistical basis for conducting life table studies by sampling branches has also been investigated in these studies. It appears that the major sampling questions have been answered. The level of effort required to assess populations of a given density to a certain level of precision is now known. The behaviour of sampling estimators has been described and the ability to convert among sampling schemes using different sampling units has been investigated. This latter exercise allows a retrospective analysis of other data sets using sampling schemes other than the one recommended in this report. The sampling of insect populations in the expanding phase will require some additional attention. This should be accomplished in two years of sampling in the study plots.

Relating insect population densities to defoliation is not feasible in the present study. The populations were all declining over the period during which the study was conducted. The results of using results from the present study would thus seriously under estimate the potential of a population if they were applied to expanding population. This relationship remains a crucial bit of information, however. The sampling proposed for the expanding population will answer this question. The information on sampling already accumulated can be used to advantage in the design of these studies.

The installation of the impact study plots in a variety of geographical locations and in a variety of age classes give a firm foundation to the conclusions that can be derived from the database. Jack pine budworm mortality can be quite large. The sources of variation in mortality have been associated with the condition of the root system. Further work to document the secondary organisms which contribute to tree mortality can be accumulated in on-going surveys. Nevertheless, procedures to hazard rate stands can now be based on the incidence of root disease, age, and recent tree diameter increment. Refinements of this process are possible and can be assessed by implementing such hazard ratings in the recurring surveys of the impact plots.

The link between populations, defoliation, growth reduction and increased risk of mortality needs to be developed. Critical information on the nature of the process has been accumulated. In addition, the database developed in the current study provides a base line on which to base comparisons from the next and subsequent outbreaks. A critical element is missing, however. Specifically, the number of insects related to the different levels of defoliation and the resulting growth-loss has to be measured on the same trees. This can only be obtained by making observations of the annual defoliation levels on the plots involved in the next outbreak. (Recall that the impact

studies were inaugurated after the outbreak in the current study plots.) Only investigations of the intensive study plots in combination with observations with the extensive impact plot system can provide the requisite information.

Much progress has been made on developing a pest management system for the jack pine budworm. If such a system is to be based on an understanding of the population dynamics of the insect, the stand dynamics together with forecasting and treatment technologies, my conclusion is that we are half-way there. What is missing is essentially the dynamics of expanding populations and the factors which control their rate of growth. (It is critical to study the natural enemy complexes of expanding populations to get at the process.) In addition, treatment methodologies to cope with incipient populations may be required. The detection of these populations may be feasible with the work presently being pursued by Manitoba Natural Resources using pheromones to detect population changes at permanent monitoring stations.

From a long-term perspective, the understanding developed in relating outbreaks to the occurrence of drought has profound implications in the manner in which the jack pine budworm populations will react under climate change. With the changes experienced in the past 50 years it appears that the reaction of the populations has been to expand further north and further west. There is no suggestion that the periodicity of the outbreaks has changed, although there are locations, such as south-eastern Manitoba, where the periodicity of outbreaks is shorter than 10 years. Because jack pine grows on marginal, the more xeric, sites of the region it is quite likely that the budworm population will provide a sensitive indicator of the effects of climate change. An understanding of this process is critical if the forecasting tools to be developed are to be useful under changing edaphic conditions.

From a general perspective, an approach has been developed that can be adapted to understand the pest management needs for other defoliators that interfere with the productivity of forest stands in the region. The basic process of sampling defoliator populations in tree crowns has been adapted to sample the spruce budworm on white spruce. Minor modifications will be necessary to adapt these techniques to monitor aspen defoliators. Analysis of other defoliator populations can be approached in a similar fashion. The basic data-gathering procedure for impact plot assessment can proceed along the means developed for the jack pine. Indeed this procedure is now being applied in the assessment of permanent forest inventory plots. The adoption of these procedures in the management of defoliator populations in the provinces should be the goal of our technology transfer efforts in the coming years.

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