Use of pheromones and other semiochemicals in integrated production
IOBC wprs Bulletin Vol. 25(•) 2002
pp. •-•

The use of geostatistics and GIS as tools for analyzing pheromone trap data at a landscape level: an update

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Abstract: Spruce budworm, *Choristoneura fumiferana* (Clemens) (Lepidoptera: Tortricidae), is the most important defoliator of forest trees in the boreal forest of North America. The species undergoes dramatic and periodic outbreaks, which result in extensive defoliation and tree mortality of fir-spruce forests. A network of pheromone traps for monitoring populations of the budworm has been placed, throughout the distribution of the moth, annually since the mid-1980's. Cooperators from government agencies and private forestry companies in Canada and the United States deploy traps using standardized sampling protocols. A computerized software system has been developed using geostatistics to convert the male moth counts, at point locations, to complete spatial coverage maps for use in geographic information systems (GIS). The system uses variograms to model autocorrelation between sample points and a technique known as kriging to interpolate between sample points. The resultant maps can be used to predict incipient outbreaks and predict defoliation. Benefits of the system for predicting changes in budworm dynamics and problems associated with coordinating a network with many diverse collaborators over an extensive geographic area are discussed.

Key words: spruce budworm, *Choristoneura fumiferana*, geographic information systems, geostatistics, spatial analysis, pheromone

Introduction

A brief description of the biology and recent history of spruce budworm, *Choristoneura fumiferana* (Clemens) (Lepidoptera: Tortricidae), in North America is discussed in the context of its population periodicity. The dynamics of budworm populations and its economic impact on spruce-fir forests necessitated the development of a spruce budworm pheromone-trapping network for monitoring population densities. Herein, the evolution of the network is discussed. The advent of using spatial analysis techniques in ecology at a landscape level and the adoption of these techniques to spruce budworm data analysis are presented. A set of software tools was developed to use these techniques to analyse budworm pheromone-trap data. Some of the issues that have arisen in coordinating and managing this data set are described. How these techniques can be employed to manage budworm populations is presented.

Spruce Budworm Periodicity

Spruce budworm is an outbreak species and the most destructive defoliator in the fir-spruce forests of North America. Larvae of this native pest feed on the needles of balsam fir and white, black and red spruce. Populations undergo dramatic increases in population density during outbreaks and the outbreaks exhibit a cyclical periodicity. Unlike other species of outbreak insects, the period of spruce budworm outbreaks is very long and can last for 35-40 years (Royama 1992). Sanders (1996) graphed the eruptive change in larval densities that occurred during the course of the recent outbreak at one location in northern Ontario (i.e., Black Sturgeon Lake). He also demonstrated that male moth numbers captured in pheromone traps were correlated with these larval densities.

Annual data on defoliation by the spruce budworm for Canadian provinces and territories for 1975 to 1998 were extracted from the National Forestry Database Program (Canadian Council of Forest Ministers): http://nfdp.ccfm.org/frames2_e.htm

Defoliation in Nova Scotia and Prince Edward Island began in 1977 and declined to low levels by 1987. The area of defoliation in Newfoundland and New Brunswick was extensive in 1975 and steadily declined in the former province by the mid-80’s but persisted into the mid-90’s in New Brunswick. Recent defoliation in the Maritimes has been negligible. In Ontario and Quebec, defoliation was at a very high level in the late 70’s and early 80’s. In Quebec, the area of defoliation had declined to moderate levels by the late 80’s and has been relatively insignificant in recent years. Defoliation levels remained high longer in Ontario as a result of regional differences in timing of the outbreak in that province (Candau et al. 1998). In western Canada, defoliation by the spruce budworm was very low in the late 70’s and early 80’s (except in Manitoba where it was variable). From the late 80’s to the present, defoliation has increased in the west. However, the area defoliated in the west is relatively small compared to the huge areas of defoliation in the east during the 70’s and 80’s. The overall trend in defoliation history across Canada has been a steady decline from 1975 to the present, with a 50-fold reduction in area defoliated. Extremely low levels of defoliation by spruce budworm in eastern North America in recent years and the prospect of another spruce budworm outbreak, suggests that this would be an opportune time to use an early warning system for predicting population increases.

Spruce Budworm Pheromone Trapping Network

The elucidation of the sex pheromone of the spruce budworm in the 1970’s (Sanders and Weatherston 1976) provided a method for sampling populations of male moths. It was envisioned that a network of pheromone traps placed throughout the distribution of spruce budworm would provide a cost-effective method of sampling budworm populations. The technique would be less labour intensive than were conventional methods of sampling egg or larval populations (Sanders 1980). The network would not only provide an early warning system for impending outbreaks, but would also provide an index of population size at higher densities. The spruce budworm pheromone-trapping network had its origins in the Canada/US spruce budworm (CANUSA) project in the mid-1980s (Allen et al. 1986). Standard sampling protocols were advocated for use by all collaborators. This facilitated making comparisons between jurisdictions. The sampling protocol which dictated where and when traps should be deployed is described by Sanders (1996). The standard trap used in the network is the non-saturating Multipher trap that allows large numbers of moths to be captured. All trap locations were georeferenced using Universal Transverse Mercator (UTM) coordinates at a 10-km by 10-km resolution. Traps were deployed throughout the distribution of *C. fumiferana* in Canada and the United States (excluding Alaska, British Columbia, Yukon Territory and Northwest Territories). At the peak of trapping in 1995, 1110 pheromone-trap sampling locations were used across the continent (Figure 1). Collaborators have included provincial, state and federal government agencies in the United States and Canada, as well as industrial participants.

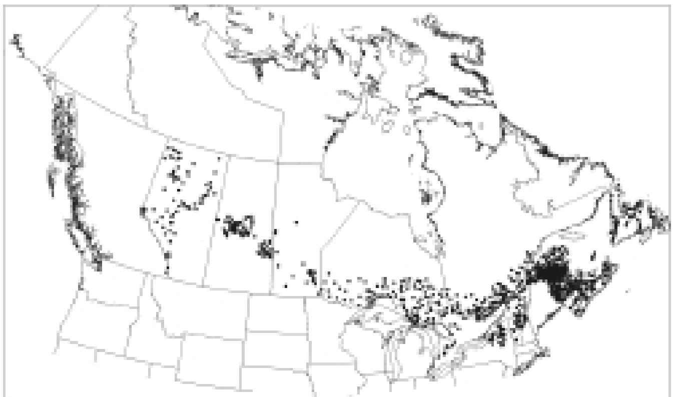


Figure 1. Distribution of pheromone-trap sampling locations for spruce budworm across North America in 1995.

Spatial Analysis

Liebhold et al. (1993) demonstrated that spatial analysis techniques, employing both geostatistics and geographic information systems (GIS), could be used to analyze population processes in insect populations at a landscape scale. Herein, the geostatistical technique known as kriging is used to interpolate point data (i.e., the number of male moths) from the trapping locations and construct surface maps that can be employed in a GIS. The interpolation technique relies on an autocorrelation function, known as a variogram, to provide weighting of nearby points used in the estimates.

Data Management Software

A set of software tools was developed to analyze data from the spruce budworm pheromone-trapping network (Lyons et al. 1997; Lyons and Sanders 1998). The tools were designed to be inexpensive and user friendly, and run on a desktop computer under the Microsoft Windows operating environment. It was anticipated that cooperators would be able to analyze and manipulate their own data, as well as data from adjacent jurisdictions. The software system includes both commercial and in-house developed software. The graphic user-interface, written in the Microsoft Visual Basic programming language, links the program modules. Modules used in the system include Microsoft Access as the database software and Idrisi as the GIS software. Output maps can be enhanced using the structured drawing program CorelDRAW. The Geographic Calculator is used for projection conversions. The Kriging module was originally written in Visual Basic and C++ but has now been entirely converted to the former. We have invested considerable effort in correcting deficiencies in the software. A recurring problem with the software involved problems with conversion of database files to newer versions of Access. The solution to this problem in the latest version (2.1) of our software has been to simplify the database structure that was described by Lyons et al. (1997). Data are now stored in two separate tables within the database file. Georeferenced data are stored in one table, while trap catch data is stored in a second table. A unique identifier in each table facilitates linking the two. In addition, the system is now capable of producing maps for all provinces (except British Columbia) and several regions (Maritime Provinces, Prairie Provinces, Northeast and North America). Typical output from the software system is a contour map showing categorized moth captures (e.g. Figure 2A). Since the process interpolates between sample points, extrapolates beyond sample points and uses points around the vicinity of the region being mapped, the GIS can be used to limit the contour map to the boundaries of the area in question (e.g. Figure 2B) and to a fixed radius around sample points (e.g. Figure 2C) (see Lyons et al. 1998).

Issues

Some of the issues or problems that have been identified over the course of the project include: 1) changes in cooperators, 2) changes in sampling protocol, 3) forest cover differences, 4) taxonomic problems, 5) variable georeferencing systems, 6) changes in lure potency, 7) changes in trap numbers and 8) a sample point density bias.

Over the course of the network, a significant number of changes have occurred in participating agencies and companies, and in the staff conducting the survey work. This has resulted in problems in continuity of reporting. Some jurisdictions, for various reasons, have implemented changes to the original sampling protocol. For ex-

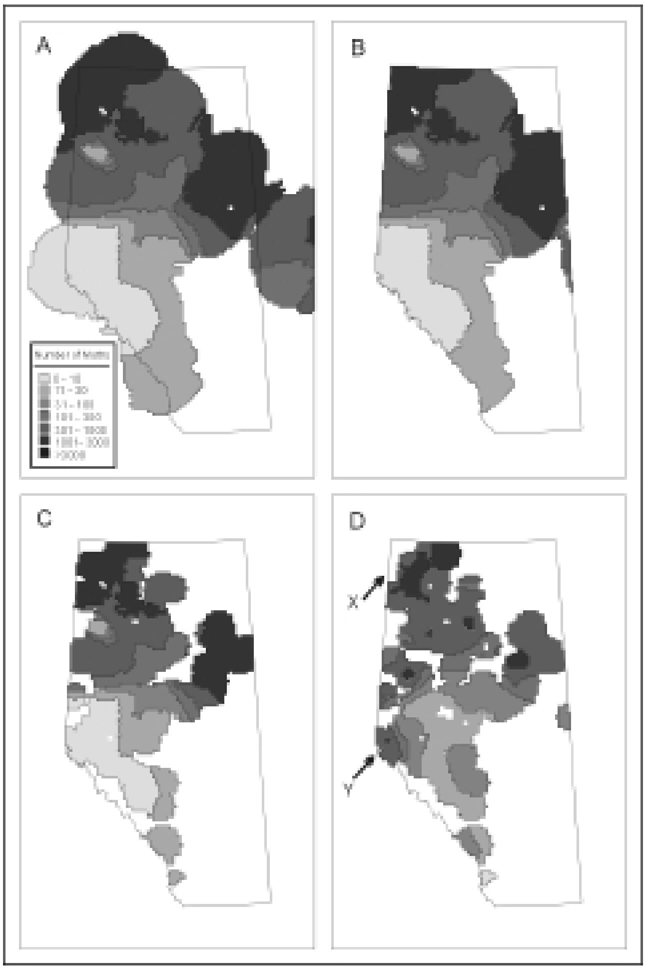


Figure 2. Estimated number of male moths of the spruce budworm captured in pheromone traps in Alberta in 1999; as interpolated using the kriging technique (A), limited to Alberta (B), limited to within 50 km of a sample location (C), and the estimated number of male moths captured in pheromone traps in 1998 (D). Areas of the latter, indicated by arrows labeled X and Y, are locations where population trends (1998 to 1999) are opposite.

ample, the number of traps employed in some jurisdictions deviate from the three traps described in the protocol. Any deviations from the established protocol make comparisons between jurisdictions suspect. There are also significant differences in forest cover types in different jurisdictions. Western Canadian budworm habitat is predominately white spruce forests, while eastern forests contain various mixes of red, white and black spruce, and balsam fir. Moth densities that are correlated with damage levels vary between these habitats. This suggests that comparisons between jurisdictions should be restricted to comparisons within ecological zones.

The pheromone lure used in the spruce budworm pheromone-trapping network is attractive to all spruce/fir-feeding species of *Choristoneura*. In areas where these other species occur, there is the potential problem of capturing species other than *C.*

fumiferana. In eastern Canada this is not a problem since *C. fumiferana* is the only spruce/fir-feeding species. However, in western Canada other species of *Choristoneura* might be captured in pheromone-baited traps. This is apparently happening the mountains of western Alberta. When the interpolated moth captures for 1998 and 1999 are compared for Alberta (Figure 2D & C, respectively), there is an increase in density of moths in northwestern Alberta (X in Figure 2D), while there is a decline in the west central portion of the province (Y in Figure 2D). In this latter region, the high populations in 1998 probably represent the two-year-cycle budworm, *C. biennis* Freeman that is only in the adult stage every second year. The erroneous decline in budworm numbers in 1999 in this area is a result of the non-adult producing year for this species.

The georeferencing system outlined in the original protocol required that data be reported in Universal Transverse Mercator (UTM) projection coordinates at a resolution of 10 km by 10 km. Thus, coordinate data consisted of a 2-digit zone number, a 2-digit easting value and a 3-digit northing value. The system described herein requires the use of geodetic coordinates (latitude/longitude) to locate sample points. Different jurisdictions report coordinate data differently. For example, all resource data for New Brunswick is georeferenced using a coordinate system known as a NB double stereographic projection. Data for New Brunswick must be converted to geodetic coordinates using special software. This adds one additional level of complexity to the spatial analysis of these data. Quebec also uses a unique georeferencing system, but also provides data in geodetic coordinates. Ontario in 1997 added an additional digit to the easting and northing values for reported UTM coordinates increasing the precision of the referenced location. Increased resolution of plot locations facilitated by inexpensive and progressively more accurate global position system (GPS) units have resulted in increased precision in reporting sample points. This however makes comparison of previous and current sample points difficult.

There have been several changes in lure type and potency over the duration of the network. This has complicated the comparisons of trap catch from year to year. Sanders (1996) outlined how these differences were dealt with and the functions that were employed to correct these differences to a standardized year. These same functions have been used to correct GIS maps produced by our software system.

There have been considerable changes in the number of trapping locations in different jurisdictions during the course of the pheromone-trapping network (Table 1). These differences in number of sample points have confounded the temporal analysis of the trap data. There has been an increase in emphasis in the use of pheromone traps for monitoring budworm populations as budworm numbers decline. Conventional techniques, using branch sampling, are ineffectual at low budworm densities. The Maritime Provinces and the Prairie Provinces have dramatically increased the number of sample points. Ontario increased the number of sample points to a peak in 1994 but has undertaken a subsequent decline in sampling intensity. The number of trapping locations in the United States has been relatively low following a large emphasis in the use of pheromone traps in the mid-1980's. Of all the jurisdictions, Quebec has had the most consistent sampling program using pheromone traps.

Table 1. Number of pheromone-trapping locations for spruce budworm in each region by year

Year	Newfoundland	New Brunswick	Nova Scotia	Prince Edward Is.	Quebec
1984	0	0	0	0	0
1985	0	0	0	0	0
1986	42	27	11	1	274
1987	47	27	11	1	242
1988	50	25	8	1	229
1989	45	6	6	1	226
1990	42	14	21	1	190
1991	50	18	25	1	198
1992	49	25	35	3	204
1993	50	48	48	3	209
1994	49	249	58	3	206
1995	49	334	67	3	209
1996	44	99	133	0	202
1997	0	198	119	0	194
1998	0	148	129	0	199
1999	0	225	130	0	204
Year	Ontario	Manitoba	Saskatchewan	Alberta	United States
1984	26	0	0	0	26
1985	37	12	0	0	120
1986	54	14	0	0	302
1987	73	13	5	13	368
1988	75	13	5	13	188
1989	68	13	2	7	148
1990	84	13	0	1	75
1991	85	13	0	26	81
1992	186	13	131	47	100
1993	156	22	121	78	83
1994	162	62	128	78	93
1995	122	40	130	78	78
1996	111	29	133	85	89
1997	94	31	122	126	75
1998	97	31	131	183	88
1999	48	33	84	231	89

Fleming et al. (1999) described problems in the interpolation method when some sample points are clustered in areas of high density and variability. Supplemental sampling of second-instar larvae in New Brunswick in such an area (Figure 3), resulted in a variogram that indicated greater semivariance in classes of nearby points. Removal of the supplemental points from the analysis produced a more conventional-shaped variogram. Similar clustering of pheromone trap sites has occurred during the history of the network, especially when trap densities in a jurisdiction have undergone dramatic changes.

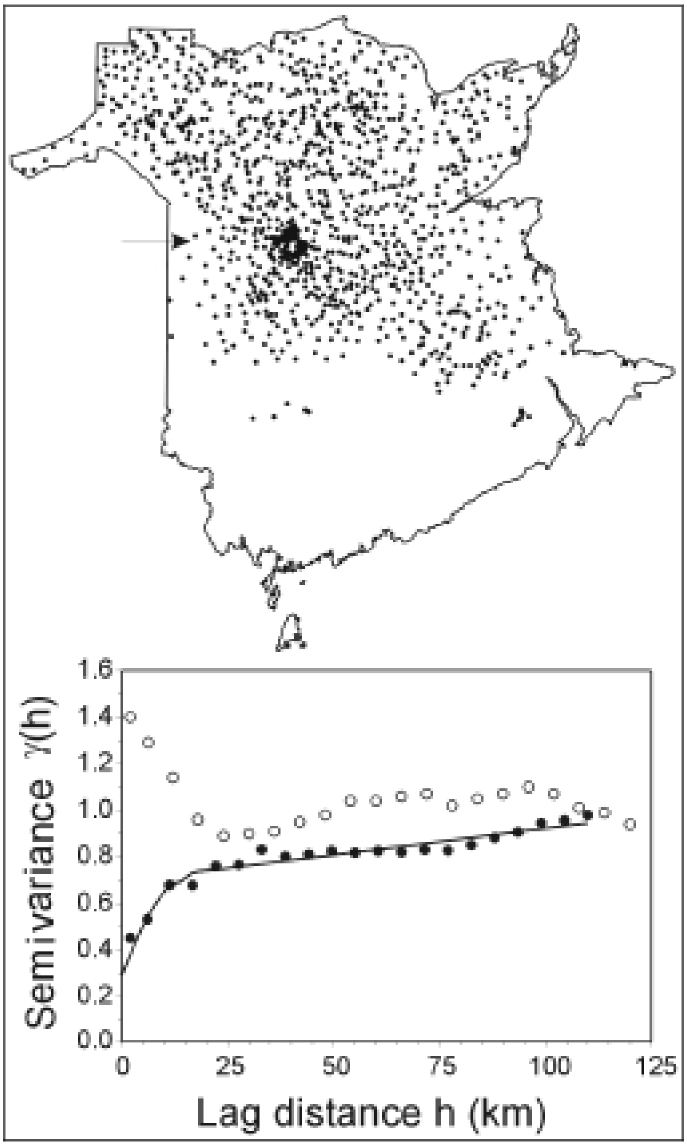


Figure 3. Distribution of sample locations for second-instar larvae of spruce budworm in New Brunswick and the corresponding variograms including (open circles) and excluding (closed circles) supplemental sample points (after Fleming et al. 1999). The arrow indicates the location of supplemental points.

Applications

At low densities of spruce budworm, intensive sampling of branches produces few larvae. At some point in the increasing phase of the population, sampling once again becomes practical. Sanders (1996) suggested that a moth density of 100 moths/trap was an appropriate threshold for instigating conventional larvae sampling methods. This value is correlated with approximately three larvae/branch. Output maps from the software system can be reclassified in the GIS to display areas where moth densities exceed this value and threshold maps can be produced (Figure 4).

Figure 4. Areas of Ontario where male moth densities exceed the 100 moths/trap threshold in 1998.

The province of Alberta has specific densities of moths that they use to predict damage in the following year. These forecasts are unique to this province. Densities of less than 500 moths per trap predict a low risk of outbreak, 500 to 2000 moths predict a moderate risk, while densities greater than 2000 moths/trap predict a high risk of outbreak. Thus the output maps for Alberta can be reclassified in the GIS to reflect these moth densities and produce what they would refer to as a risk of outbreak map (Figure 5).

Two simple GIS functions can be used to manipulate output maps from our system and create a useful management map. Difference maps can be constructed by subtracting maps from two consecutive years (i.e., $map_{D} = map_{t} - map_{t-1}$). The resulting map can be reclassified to show areas of increasing populations (i.e., positive values), decreasing values (i.e., negative values) and stable populations (i.e., zero values). For example, the moth density map for Ontario in 1998 (Figure 6A) was subtracted from the moth density map for 1999 (Figure 6B) and a difference map was produced (Figure 6C).

One of the more powerful applications using these kriged maps surfaces is when these maps are used as variables in predictive models. In the following example a logistic regression model was constructed that uses the interpolated pheromone trap catch map (phero) as an input variable along with maps of previous year's defoliation (defol) and defoliation frequency (deffreq) to predict defoliation probability (p). Defoliation frequency was the sum of all defoliation maps for the province of Ontario, generated from aerial surveys, for the years 1941 to 1999, divided by the number of maps.

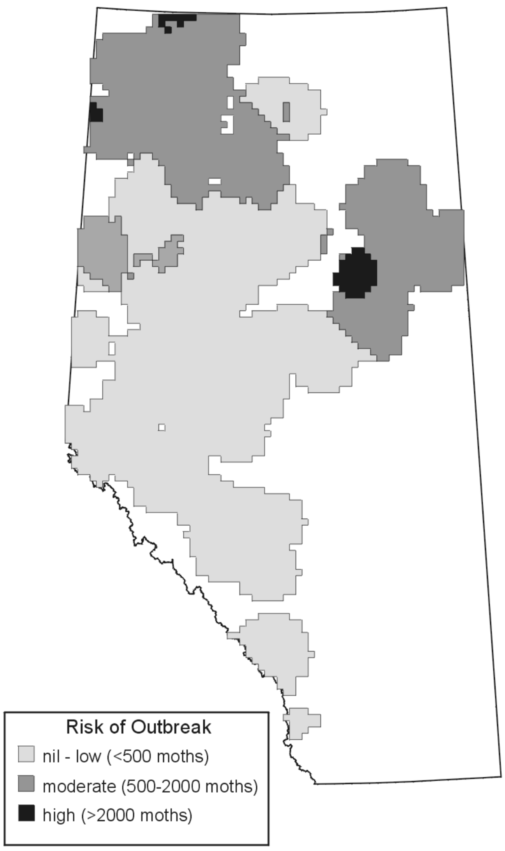
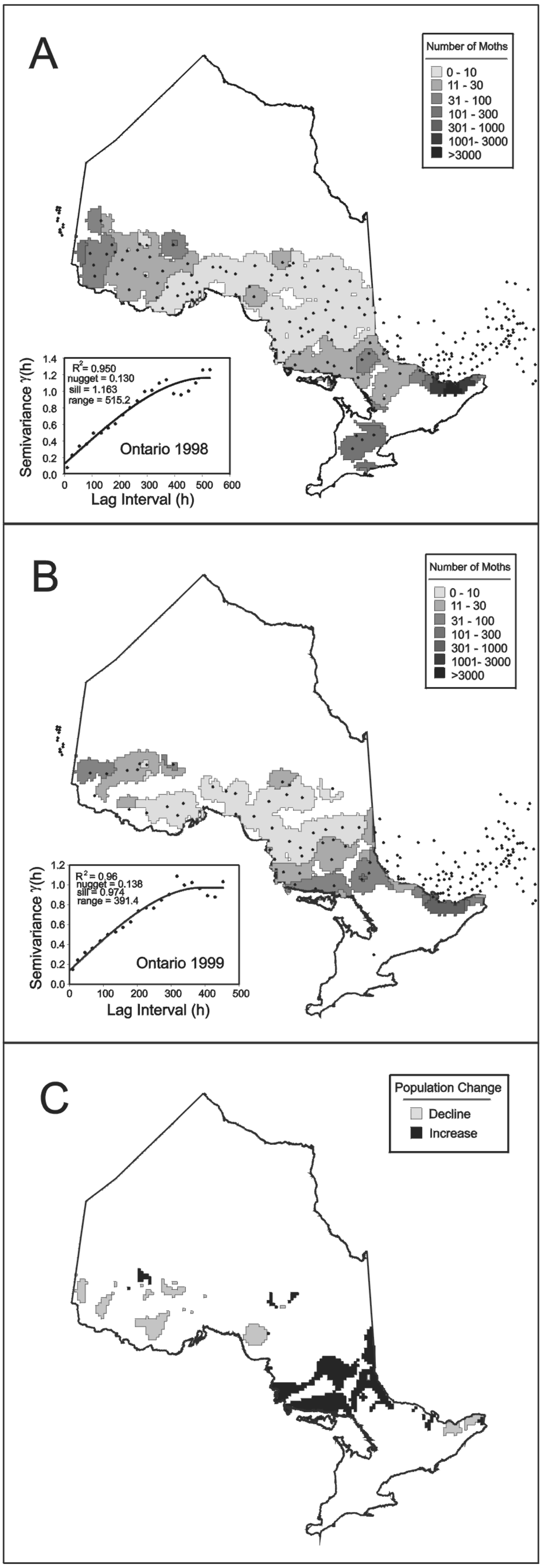


Figure 5. Risk/hazard map for spruce budworm in the province of Alberta in 2000 based on pheromone trap catches in 1999.

Figure 6 (overleaf). Estimated numbers of male moths of the spruce budworm in Ontario in 1999 (A) and 1998 (B). The positive and negative differences in the estimates for the two years indicate increasing and decreasing populations (C). Estimated numbers of male moths greater than 100 moths/trap indicate areas where larval sampling should be conducted (D).



A
Number of Moths
0 - 10
11 - 30
31 - 100
101 - 300
301 - 1000
1001- 3000
>3000
R² = 0.950
nugget = 0.130
sill = 1.163
range = 515.2
Ontario 1998
Semivariance γ(h)
Lag Interval (h)
B
Number of Moths
0 - 10
11 - 30
31 - 100
101 - 300
301 - 1000
1001- 3000
>3000
R² = 0.96
nugget = 0.138
sill = 0.974
range = 391.4
Ontario 1999
Semivariance γ(h)
Lag Interval (h)
C
Population Change
Decline
Increase

The following equations are the model:
logit(p) = -13.51 + 3.44log(phero +1) + 25.07log(deffreq +1) + 2.73defol

$$p = \frac{e^{\text{logit}(p)}}{(1 + e^{\text{logit}(p)})}$$

The concordance value (Table 2) for this model was extremely high at 97%. Solving the equations using the pheromone trap catch map for 1999 and the defoliation map for 1999 as input values results in an output map (e.g. Figure 7) which predicts the probability of defoliation in Ontario for the year 2000. Since moth captures are low in Ontario and there was only limited previous defoliation, the model only predicts two very small areas with probabilities of defoliation greater than 0.10 for 2000. A complete description of the model will be published elsewhere.

Table 2 Statistics for logistic regression models incorporating individual and combined variables

Variable(s)	Concordant (%)	Discordant (%)	Tied (%)
deffreq	68.3	26.7	5.0
defol	79.1	0.8	20.2
phero	92.3	7.4	0.3
deffreq, phero	94.7	4.7	0.6
deffreq, defol	90.5	8.2	1.4
defol, phero	96.6	3.2	0.2
deffreq, defol, phero	97.0	2.8	0.2

Future Directions

The data-analysis system for the spruce budworm pheromone-trapping network has now been developed to a stage whereby it is capable of quickly generating maps for a variety of jurisdictions and regions. It is now essential that the system be integrated into the spruce budworm management program of the individual jurisdictions. This requires feedback from the end users. To ensure that region-to-region and year-to-year comparisons can be made, a consistent source of pheromone must continue to be available to all cooperators every year and sampling must be undertaken using consistent protocols. In addition the lures must be calibrated by comparing them with the previous year’s lures. This requires that current year’s lures and previous year’s lures be placed together in the field in representative locations covering a range of budworm densities. The moth captures at paired locations are then compared using regression analysis. Data generated from the spruce budworm pheromone-trapping network traps must be analysed by a single agency so that continent-wide maps can be produced.

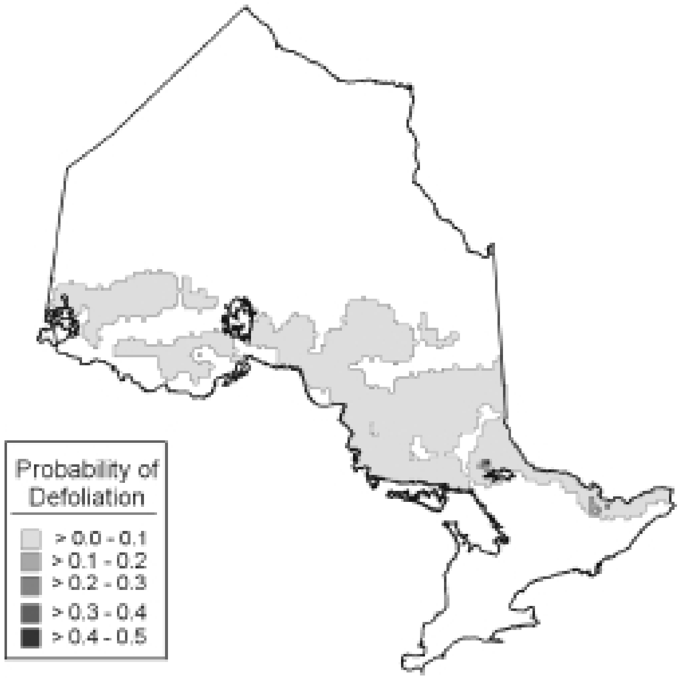


Figure 7. Probability of defoliation by the spruce budworm in Ontario as predicted from the logistic regression model.

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