

Integrated Permanent Plot and Aerial Monitoring for the Spruce Budworm Decision Support System

David A. MacLean

Abstract.—Spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks cause severe mortality and growth loss of spruce and fir forest over much of eastern North America. The Spruce Budworm Decision Support System (DSS) links prediction and interpretation models to the ARC/INFO GIS, under an ArcView graphical user interface. It helps forest managers predict budworm outbreak effects on forest structure and productivity, forecast forest growing stock and sustainable harvest levels, optimize protection (biological insecticide use) programs, and use silviculture and harvest scheduling to restructure forests to reduce future damage. The Spruce Budworm DSS has been operationally implemented on 8 million ha of susceptible forest in the province of New Brunswick, and is being implemented on test landbases in Quebec, Ontario, and Alberta. The use of inventory and monitoring data in the DSS will be described in four areas: stand growth model calibration, model validation, pest monitoring, and forest stratification for calculating marginal timber supply benefits.

Spruce budworm (*Choristoneura fumiferana* Clem.) is the most destructive forest pest in Canada, causing about 40 percent of the 81 to 107 million m³ timber volume loss to insects and disease each year (Sternier and Davidson 1982, Power 1991). Sustainable harvest (long-run sustained yield) and current harvest levels for Canada are about 240 and 180 million m³/year, respectively (Rotherham 1991), only roughly twice the volume lost to pests. Clearly, timber supply can be substantially improved if losses to pests can be reduced (MacLean 1990). This has prompted development of the Spruce Budworm Decision Support System (DSS), which uses models, GIS, inventory data, and pest data to assist in insect and forest management decisionmaking (MacLean and Porter 1994, 1995; MacLean *et al.* 1997).

Major budworm outbreaks have occurred over much of eastern North America three times in the 20th century, causing large-scale mortality of host balsam fir (*Abies balsamea* (L.) Mill.) and spruce (*Picea* sp.) (Blais 1983). Spruce budworm is a native insect that feeds on the current-year foliage, reducing growth and eventually causing up to 85 percent mortality in fir and 35 percent mortality in spruce stands (MacLean 1980). Budworm outbreaks typically last about 10 years, and play a role in "recycling" mature or overmature spruce-fir forest to younger age classes, often resulting in a cyclical succession pattern of fir replacing fir. However, budworm outbreaks also kill forest over large areas, reduce timber supply, increase fire risk, and affect most consumptive and nonconsumptive values (MacLean 1990).

The Spruce Budworm DSS links a suite of prediction and interpretation models to the ARC/INFO GIS, under an ArcView graphical user interface (MacLean and Porter 1994, 1995). It assists forest managers in predicting outbreak effects on forest structure and productivity, forecasting forest growing stock and sustainable harvest levels, optimizing protection (biological insecticide use) programs, and using silviculture and harvest scheduling to restructure forests to reduce future damage. The Spruce Budworm DSS has been operationally implemented on 8 million ha of susceptible forest in the province of New Brunswick, and is being implemented on test landbases in Quebec, Ontario, and Alberta. DSS components include a defoliation-based stand growth model (MacLean 1996), a forest inventory projection system that predicts spatial effects of future budworm outbreaks (MacLean and Porter 1996), and a system for planning spray programs based on marginal timber supply benefits (MacLean and Porter 1995, MacLean *et al.* 1997).

In this paper, I will describe the Spruce Budworm DSS and discuss use of forest inventory and monitoring data by the DSS in four areas:

1. **model calibration**, whereby 135 research permanent sample plots (PSP's) have been measured annually since 1985 for defoliation and tree mortality, measured every 3 years for growth, and assessed for a wide variety of site and stand characteristics;
2. **model validation**, for which an independent network of 2,400 PSP's were measured every 3 to 5 years for growth and yield assessment and insect damage by forest industry and the New Brunswick provincial government;
3. **pest damage monitoring**, in which population sampling and aerial surveys are conducted each year

Project Leader, Forest Management Systems, Canadian Forest Service—Atlantic, Natural Resources Canada, P.O. Box 4000, Fredericton, NB, E3B 5P7 Canada.

over the entire forest of New Brunswick, to provide input to the DSS and insecticide protection programs; and

4. **forest stratification for projections**, in which photo-interpreted stand-level species, age, and crown closure are used to determine development classes for timber supply projections and to calculate marginal timber supply benefits of budworm management.

THE SPRUCE BUDWORM DSS

The Spruce Budworm DSS can be used to determine effects of budworm outbreaks and alternative forest management regimes on timber supply, sustainable harvest levels, and forest structure (MacLean 1998). The primary means of reducing losses from budworm outbreaks are altering forest structure through silviculture (planting, thinning), scheduling harvest to preempt or "capture" mortality, or directly preventing defoliation by insecticide use. The DSS is typically implemented on a forest management unit basis because it uses existing growth and yield projections and harvest schedules for the landbase in estimating effects of budworm outbreaks. The Spruce Budworm DSS graphical user interface (GUI) was originally programmed using the Arc Macro Language (AML) (MacLean and Porter 1995), but ArcView 3.0a now provides a much easier means of attaining GUI functionality.

Rather than real-time prediction of future budworm outbreaks, the Spruce Budworm DSS uses a scenario planning approach to examine "what if" outcomes of user-specified scenarios. Budworm scenarios typically include altering the temporal sequence of defoliation that makes up an outbreak, the timing of when an outbreak begins (e.g., "what if" an outbreak began in the year 1998, 2000, or 2005?), and the length of the outbreak. Scenario planning is a disciplined method for imagining possible futures, which has been applied to a wide range of issues (Schoemaker 1995). Among the many tools a manager can use for strategic planning, scenario planning is unique for its ability to capture a whole range of possibilities, thereby allowing managers to see a wider range of possible futures (Schoemaker 1995).

Spruce Budworm DSS Inventory Projection System

The Spruce Budworm DSS Inventory Projection System (IPS) allows users to "grow" their forest inventory up to 30 years in the future, incorporating the effects of two severities of budworm outbreaks, decisions about whether or not to use insecticides during the outbreak, as well as other management options (MacLean and Porter 1996). IPS allows a manager to visualize future forest conditions by simulating stand development, spruce budworm outbreaks, and forest protection. IPS uses a GIS-based

spatial forest inventory, volume yield curves, and management plan information to project the forest. Its key capability is accounting for the effects of spruce budworm outbreaks and the effects of forest protection to combat budworm defoliation. The timing and nature of these events are controlled by the user on a scenario basis. The system can be used to update old (e.g., 1990) inventory data to the present, using actual past (1990-1998) defoliation data for that landbase from aerial surveys, or to conduct "what if" explorations of the results of combinations of outbreak timing, severity, and protection on future forest structure. Visualization of forecast results is possible through a combination of thematic maps, bar charts, and tables. IPS consists of software modules developed using the C programming language, ARC/INFO's AML, and ArcView's Avenue language, and has been implemented both on a Sun workstation platform and on a PC (MacLean and Porter 1996).

Conducting an IPS projection requires that the user specify the year to project to, the base year of the inventory, the timing of occurrence and severity of a budworm outbreak, and whether protection will be applied during the outbreak (MacLean and Porter 1996). Protection is assumed to limit defoliation to < 40 percent of current foliage each year, prevent budworm-caused mortality, and maintain stand volume development at management plan levels. One can project each ownership on the landbase separately or all together. Management planning procedures in New Brunswick assemble stands into classes based on species, stand age, site productivity, or other criteria. Each of these classes is linked to a set of volume-based yield curves (one curve for each species), and during a projection, each stand is tracked along the appropriate set of curves. When a budworm outbreak occurs, IPS modifies the balsam fir and spruce yield curves by budworm impact vectors to simulate the results of budworm defoliation reducing tree growth rates and increasing mortality. These impacts depend upon the species, stand maturity, outbreak severity (moderate or severe), and protection options selected by the user and are classified into four species mixes: balsam fir, fir-hardwood, spruce, and spruce-hardwood (MacLean and Porter 1996).

Spruce Budworm DSS Protection Planning System

The Spruce Budworm DSS Protection Planning System (PROPS) quantifies the marginal timber supply benefits of protecting stands against budworm defoliation (fig. 1), with the calculation made at the scheduled time of harvest (MacLean *et al.* 1997). It allows the user to determine the effects of different budworm protection strategies, using the biological insecticide *Bacillus thuringiensis* (*B.t.*), on forest development and sustainability, and it quantifies the relative volume benefit of alternative spray blocks.

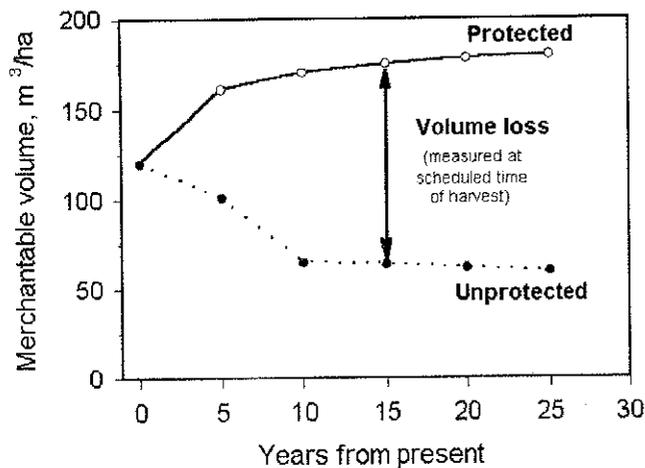


Figure 1.—The concept underlying the Spruce Budworm DSS Protection Planning System (PROPS). Volume projections are made for each class of stands using the model STAMAN, for protected (sprayed with the insecticide B.t. to limit defoliation to < 40 percent of current foliage each year) and unprotected budworm outbreak scenarios. Then volume loss (protected minus unprotected) is calculated, at the scheduled time of harvest for individual stands, and mapped as the protection priority (m^3/ha) for each stand. This example shows volume development for 30 years in an immature balsam fir-spruce stand, with a 10-year budworm outbreak starting in year 0.

MacLean *et al.* (1997) described the implementation of PROPS on a 188,000-ha landbase in northern New Brunswick, Canada. Implementation involved constructing databases that specified future volume reductions for all stand types and all possible levels of defoliation over the next 10 years (1996-2005). PROPS then predicts the marginal timber supply (m^3/ha) benefits, at the scheduled time of harvest, of protecting stands against spruce budworm defoliation in a given year (fig. 2). MacLean *et al.* (1997) conducted a series of strategic planning analyses of the consequences of different future budworm outbreak and protection scenarios on future growing stock and harvest levels. This involved evaluating: (1) different future budworm outbreak scenarios, with and without protection; (2) effects of budworm spraying not meeting foliage protection targets; and (3) effects of part of the landbase not being protected. Analyses demonstrated that period 4 (2010-2015) harvest levels, and to a lesser extent, period 3 (2005-2010) levels, were very sensitive to any reduction in yields caused by defoliation. This was because in period 4, harvest levels nearly equaled operable growing stock. If protection was applied but defoliation exceeded the foliage protection target (limit defoliation to < 40 percent of current foliage) by 20, 30, or 40 percent on 20 percent of the landbase, period 4

harvest level reductions of 110,000, 290,000, and 590,000 m^3 , respectively, would be necessary to maintain sustainability. If only 20 percent of the landbase failed to reach protection targets under severe outbreak conditions, then period 4 harvest would have to be reduced by 590,000 to 930,000 m^3 (MacLean *et al.* 1997).

There was wide variation in the marginal timber supply benefits of protection. For example, one scenario, specifying that a budworm outbreak began in 1996, projected that protecting 50,000 ha of the highest priority stands, at a cost of \$1,000,000 Cdn. would give a payback of 1,980,000 m^3 of timber at the scheduled time of harvest, but protecting the same area of lower priority stands would return only 480,000 m^3 . It was concluded that the only way planned harvest levels for the test landbase could be maintained under severe spruce budworm outbreak conditions was with an aggressive protection policy. For this landbase and management regime, protection against spruce budworm clearly pays (MacLean *et al.* 1997).

PROPS also assists users in planning insecticide spray operations against spruce budworm. The Xtools ArcView Extension¹ was used to build functions to easily add a spray block theme, draw spray blocks, intersect these with a protection priority (volume loss) theme, and display charts of mean volume (m^3/ha) benefit per spray block and tabular output of block area and total volume benefit. The ArcView Dialog Designer Extension² was used to design the toolbar, custom interface, and dialog boxes. Functions are packaged in a Spray Tool toolbar, and include buffering capability to determine spray exclusion areas around water bodies, human habitation, or other non-spray areas. Although chemical insecticides have been used in the past for budworm spraying, only the biological insecticide *B.t.* is used now.

USE OF INVENTORY AND MONITORING DATA IN THE SPRUCE BUDWORM DSS

The Spruce Budworm DSS uses forest inventory and monitoring data for initialization of both forest structure and pest incidence over the last 5 years. Both IPS and PROPS use GIS-based, photo-interpreted inventory data on species composition, age class, and crown closure (a surrogate for stand density) as the basis for projections. PROPS also overlays defoliation data, from annual aerial

¹ Developed by Mike DeLaune, Oregon Department of Forestry, 1998. The Xtools ArcView Extension can be downloaded from <http://www.odf.state.or.us/sfgis>.

² Developed by Environmental Systems Research Institute, Inc. (ESRI), Redlands, CA. Available for download at <http://www.esri.com/software/arcview/extensions/dialog>.

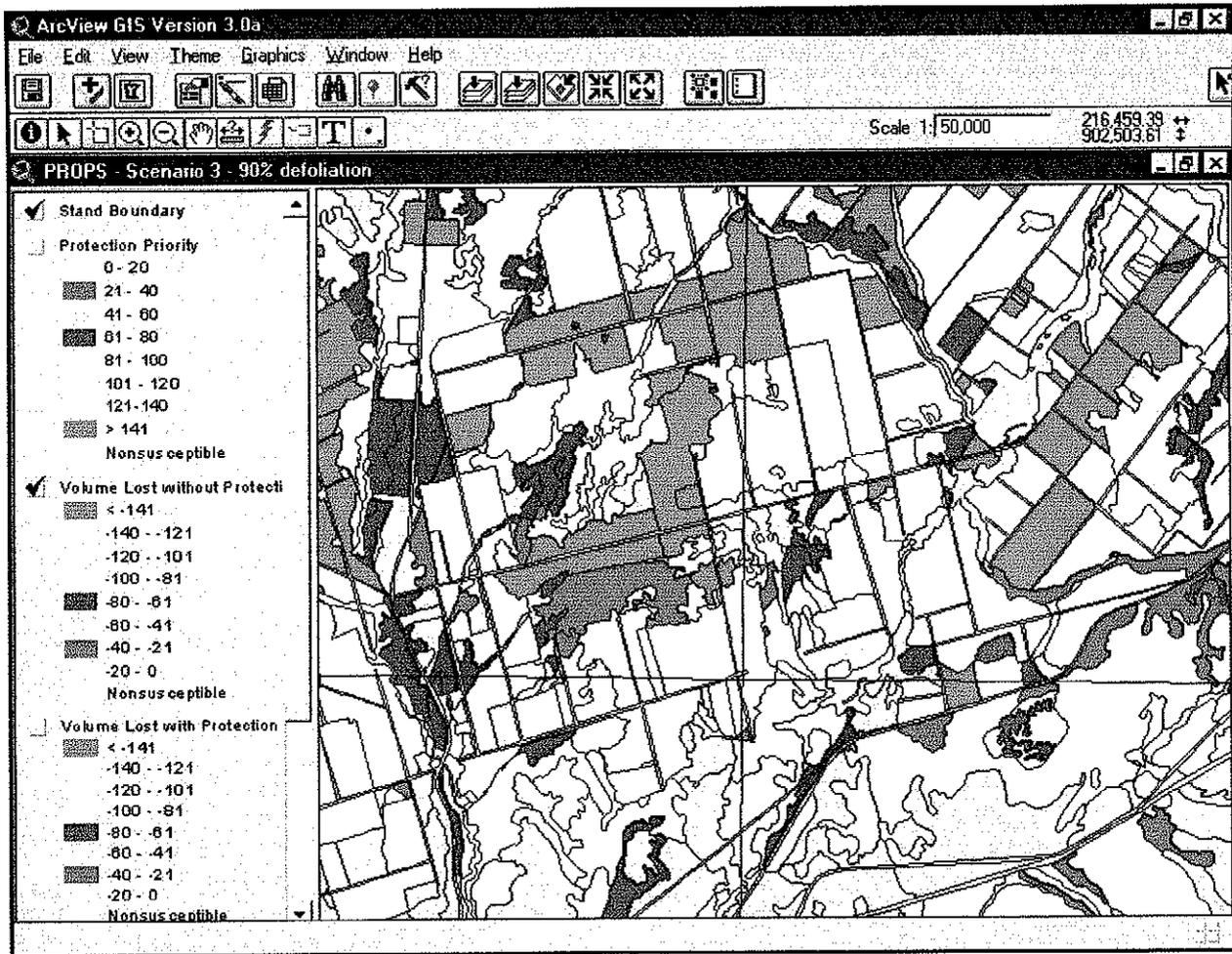


Figure 2.—*Spruce Budworm DSS Protection Planning System (PROPS) viewed in ArcView 3.0. The theme displayed is volume loss caused by spruce budworm defoliation, without insecticide protection, under a scenario of 90 percent current defoliation each year for 10 years. Scale is 1:50,000; stands are for a landbase in northern New Brunswick, Canada. Other themes that can be displayed include volume loss with protection and protection priority, defined as the m^3/ha difference between projections with and without protection.*

sketch-map surveys for the last 5 years, on forest inventory data to assign defoliation to stand polygons. Past defoliation is used to initialize the current condition of stands in PROPS.

In addition to these obvious uses, the Spruce Budworm DSS has made use of or has influenced inventory and monitoring data in four areas: model calibration, model validation, pest damage monitoring, and forest stratification for projections. Each of these will be discussed in the following sections.

Model Calibration

The STAMAN stand model is an integral component of the Spruce Budworm DSS, and is used to quantify the stand-level effects of budworm outbreaks (MacLean 1996). STAMAN is a simulation-based stand table

projection model that calculates periodic (5-year) increment and survival for tree classes defined by species, dbh, and age, to project overall stand development over time (Vanguard Forest Management Services Ltd. 1993). STAMAN is programmed in FORTRAN, and both UNIX and DOS versions are available. A conventional stand table format is used to define the structure of a stand at any point in time, with each species described as cohorts of trees, aggregated by size (dbh) and age. Stand development is determined by the rates of growth of single trees, survival, and recruitment of new stems (i.e., ingrowth). Relationships are calibrated using plot data. STAMAN is used by forest industry in New Brunswick to determine stand volume yields for forest management planning.

STAMAN was modified and calibrated to allow it to predict effects of spruce budworm defoliation on stand development (Vanguard Forest Management Services Ltd.

1993). This involved adding functions to optionally modify growth and mortality relationships to account for damage from pests. Defoliation effects were incorporated into STAMAN as incremental impacts that reduced tree growth and increased mortality. This approach required the definition of functional relationships that predict growth and survival independent of defoliation effects, as well as relationships between the severity of defoliation and the resulting levels of growth loss and mortality; then, the user specifies defoliation levels over time. A network of 135 spruce and fir research PSP's has been measured annually since 1985 for defoliation and tree mortality, measured every 3 years for growth, and assessed for a wide variety of site and stand characteristics (MacLean and Erdle 1986, MacLean and MacKinnon 1997). Details of plot selection criteria, establishment, and measurement methods were presented by MacLean and Erdle (1986). Each stand was sampled with three variable-radius (prism) plots (basal area factor 2.0 m²/ha) located 120 m apart. Trees were permanently numbered, identified by species and crown class, and measured for standard mensurational characteristics. This data set was used to define and calibrate budworm impact relationships for STAMAN (Vanguard Forest Management Services Ltd. 1993, Erdle and MacLean unpublished). Screening of a number of tree and stand variables, as well as defoliation, indicated that incremental growth reduction was related only to defoliation, but that survival reduction was a function of defoliation, tree species, and stand age (Erdle and MacLean unpublished).

Spruce budworm is one of few insect pests for which stand dynamics models and extensive, detailed impact data are available. Most other pest DSS, either currently available or under development, deal solely with qualitative estimation of risk or vulnerability. More effort needs to be focused on quantification and the development of models that predict effects of a variety of insect pests and other disturbances on stand dynamics. Such models are necessary for accurate, sustainable resource management planning. PSP measurements that include defoliation and pest data are the best source for calibrating impact relationships.

Model Validation

Validation and refinement of stand volume predictions should be ongoing, given the importance of yield prediction in determining sustainable harvest levels and planning future forest structure. Assessment of uncertainty of yield predictions, and research and monitoring designed to reduce uncertainty, are inherent to adaptive management of forests. Management planning in most jurisdictions is an iterative process, whereby plans are periodically revised, timber supply and annual allowable cut (AAC) are recalculated, and changes to the forest

landbase are updated. In New Brunswick, 5-year operating and 25-year management plans required under provincial legislation are revised every 5 years. These plans must include 80-year projections of timber supply. Each iteration, or revision of management plans, should be seen as a "window of opportunity" to revise models and recalibrate relationships to improve or validate projections.

In New Brunswick, the STAMAN model has been used to develop volume yield curves for each forest class, generally comprised of species, age, density, and silvicultural treatment groupings. In 1987, a cooperative PSP measurement program was begun, whereby forest industry and the New Brunswick Department of Natural Resources and Energy (NBDNRE) established a network of over 2,400 PSP's, specifically for use in calibrating or validating stand growth models. These fixed-area plots with permanently numbered trees are measured every 3 to 5 years (depending upon age class) for a wide range of mensurational characteristics including dbh, height, crown dimensions, ingrowth, mortality, and cause of mortality. Because of the importance of spruce budworm defoliation in New Brunswick, each tree in the plots is also assessed for current-year and cumulative (all age classes of foliage) defoliation, in 20 percent classes. This ongoing monitoring of indicators of stand development, designed for validation and reduction of uncertainty, is a critical component for improving management planning. Although insect damage assessment is not the primary reason for the plot network, it is significant that defoliation is being assessed as one of the variables influencing stand development.

Pest Damage Monitoring

Each year, NBDNRE conducts two spruce budworm surveys to determine expected population levels for the upcoming year and to assess levels of damage that have occurred; monitoring data from both surveys are annually updated and used in the Spruce Budworm DSS. These surveys use methods that have been refined over many years (Dorais and Kettela 1982) and are similar in most provinces in eastern Canada. The population survey involves collecting midcrown branch samples at up to 2,000 sample points across the province, determining the number of second-instar (overwintering stage) spruce budworm larvae present, and using this in projecting expected defoliation levels in the upcoming year.

A separate aerial sketch map survey is used to estimate current-year defoliation each year (Carter and Lavigne 1993). These annual surveys are conducted to provide extensive overviews of the distribution and severity of budworm feeding throughout the province, for use in designing protection programs. Because they are the only

source of defoliation data over large forest areas, they have also been used in the Spruce Budworm DSS. Trained, experienced observers in Cessna 172-type aircraft (at an altitude of 150 to 300 m) systematically fly east-west flight lines approximately 2 to 5 km apart over known budworm infestation zones. Since 1991, aircraft used in the survey have been equipped with Loran C navigation systems to improve the accuracy of mapping. Aerial assessments are conducted during a 1- to 2-week period, immediately following the completion of spruce budworm feeding. At this time, a distinct reddish-brown coloration of dry foliage appears, due to budworm severing and webbing together needles in the process of feeding. Areas with noticeable reddish-brown coloration of foliage are recorded on 1:190,000 scale (1 inch = 3 mile) maps in three defoliation classes: light (11-30 percent), moderate (31-70 percent), and severe (71-100 percent) (Carter and Lavigne 1993). Areas with no noticeable defoliation are assigned to a nil (0-10 percent) class.

To assess possible use in DSS, MacLean and MacKinnon (1996) evaluated the accuracy of aerial sketch mapping estimates of spruce budworm defoliation from 1984 to 1993 in 222 to 325 sample plots in spruce-fir stands in New Brunswick. Aerial defoliation estimates were compared with ground-based binocular estimates of current defoliation for an average of 10 trees/plot (range 5-20). Overall, 56 percent of plots were correctly rated by aerial sketch-mapping in four classes (nil, light, moderate, and severe), with 37 percent of the plots underestimated and 7 percent overestimated. The predominant error (26 percent of plots) was rating defoliation as nil (0-10 percent) from the air when it was actually light (11-30 percent). This error was deemed not important in terms of predicting tree response, since data from the literature indicated that defoliation less than 30 percent did not cause tree mortality, although if continued, it would reduce growth. Using three defoliation classes (by combining nil-light, 0-30 percent), 82 percent of the plots were correctly classified by aerial sketch mapping. MacLean and MacKinnon (1996) concluded that aerial sketch mapping of spruce budworm defoliation is a viable technique that can be used for both surveys and DSS that estimate forest response to budworm outbreaks and management activities.

Forest Stratification for Projections

Forest management planning and timber supply analyses generally involve assembling stands into classes based on tree species, age, site productivity, density, silvicultural treatment, or other criteria. Each of these classes is linked to a set of volume-based yield curves (either a cumulative volume over age curve or species-specific curves within each class), and during timber supply projections using

forest estate models such as Woodstock or FORMAN, each stand is tracked along the appropriate set of curves. In New Brunswick, provincial legislation requires that AAC be determined as the nondeclining long-run sustained yield from 80-year timber supply projections. Management planning must also include wildlife habitat and biodiversity considerations as well as timber.

There has tended to be a substantial increase in the number of classes used to characterize the forest in New Brunswick in recent years. Three Crown Licenses, covering areas ranging from 134,000 to 403,000 ha, each identified 30 to 66 "basic strata" based on species groupings, crown closure, and ecological unit. However, the number of yield curves used was much higher, at 103, 394, or 561. Yield curve classes were defined based on 10 to 19 species groups, 5 development stages, 3 to 5 site classes, 2 to 3 density classes, and 5 to 8 silvicultural treatments.

The initial version of PROPS calculated *absolute* volume loss, in cubic meters per hectare, for every yield curve class used by industry planners. In the first test implementation on the Repap N.B. Inc. Crown License 4, based on 1992-1997 management plan information, there were 85 forest classes. However, subsequent operational implementation of PROPS for that and other landbases, using 1997-2002 management plan information, typically involves 400 to 500 classes, as a result of adding other factors into stratification. This substantially increased the effort involved in PROPS implementation, and resulted in changing PROPS to determine *relative* (percentage) volume reduction as a function of classes based on factors that cause differential budworm impact, rather than for all forest classes deemed significant in projections by forest planners. In PROPS, 13 species composition classes in natural stands were based on spruce-fir, hardwood, and other softwood content; seven treated stand classes were based on thinning, planting, and spruce-fir content; and one nonsusceptible stand type (spruce-fir <10 percent) was included. Volume losses for each of the 20 susceptible stand types were calculated for immature (0 to 40 years), mature (41 to 80 years for fir; 41 to 100 years for spruce), and overmature (>80 years for fir; >100 years for spruce) age classes in natural stands, and for two age classes of silviculturally treated stands (0-20, >20 years). This resulted in a total of 54 budworm impact classes, substantially less than the number of forest management planning strata. In PROPS, each forest management planning stratum is matched with the appropriate budworm impact class, and relative volume loss for that budworm impact class is used to calculate absolute volume loss for the stratum. Relative volume losses for mature stands ranged from 33 to 51 percent for normal budworm outbreak and from 51 to 71 percent for severe budworm outbreak scenarios.

CONCLUSIONS

Accurate forest inventory and monitoring data are critical prerequisites for sustainable management planning. In the spruce-fir forests of eastern North America, outbreaks of spruce budworm cause more uncertainty about future forest productivity and structure than just about any other factor. This has prompted the development of the Spruce Budworm DSS, which uses forest inventory and budworm monitoring data, along with a stand growth model, timber supply (or forest estate) model, interpretation rulebases, GIS, and computer technology, to calculate volume losses and effects of management strategies.

In essence, DSS can be viewed as a "value-added" conversion of inventory and monitoring data. Availability of accurate, up-to-date, digital (GIS-based) forest inventory data is a prerequisite to decision support. The raw monitoring data on spruce budworm population level (number of second instar larvae on sample branches) and aerial sketch-map defoliation form inputs into a modeling system to determine stand- and forest-level effects on current and future volume and forest structure. Stand structure changes or productivity estimates are more meaningful values for decisionmaking than are number of budworm or percentage defoliation.

Given the necessity of digital data in a GIS and full coverage of the landbase of interest for use in DSS, remote sensing methods of data collection for monitoring and inventory will undoubtedly become more important in the future. Remote sensing is currently workable for some of the easy-to-detect forest changes, such as areas harvested or burned, but requires further development for most stand development changes.

The real value of decision support systems lies in the ability to do "what if" scenario planning analyses to determine effects of alternative disturbance or management regimes, including doing nothing, on future forest growing stock, sustainable harvest levels, wildlife habitat, etc. These analyses can then be used to determine relative costs and benefits, in terms of timber volume, dollars, or other values. The uncertainty caused by our inability to accurately predict the timing of a natural disturbance event, such as fire or a pest outbreak, can be overcome by evaluating scenarios that bound the likely timing and effects—thinking in terms of "best case," "worst case," and "most probable" scenarios is often helpful.

The province of New Brunswick was one of the first jurisdictions in North America to establish a GIS-based forest inventory. Beginning in 1982, new 1:12,500 color aerial photography was interpreted for the whole province, and NBDNRE actually had the first-ever ARC/INFO license. New Brunswick is now annually updating for

harvest, silviculture, and burned areas, and is reinventorying the full landbase on a 10-year cycle, concentrating on updating attributes of existing stand polygons for "slow" stand development changes. The availability of over 15 years of GIS-based inventory data has facilitated the development of timber supply and wildlife habitat modeling, DSS for pest management and harvest scheduling, and advanced ecological land classification systems. Some of the monitoring and inventory lessons learned in attempting adaptive management using GIS databases, now into its fourth 5-year planning cycle in New Brunswick, include: (1) the importance of continuing efforts to calibrate and validate stand projection models, to decrease uncertainty; (2) the value of an extensive permanent plot network to provide empirical data for growth and yield calibration/validation; (3) the efficiency of cooperative industry/government efforts to maintain PSP networks and develop growth and yield estimates, rather than "each forest company on its own"; (4) the importance of monitoring and accounting for natural disturbance factors in sustainability and forest structure projections, if natural disturbance is causing major effects; and (5) the efficiency of basing forest stratification for natural disturbance estimation on impact relationships between pest damage and stand characteristics, rather than using the timber supply or management planning stratification.

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LITERATURE CITED

- Blais, J.R. 1983. Trends in the frequency, extent, and severity of spruce budworm outbreaks in eastern Canada. *Canadian Journal of Forest Research*. 13: 539-547.

- Carter, N.E.; Lavigne, D.R. 1993. Protection spraying against spruce budworm in New Brunswick 1992. Fredericton, NB, Canada: New Brunswick Department Natural Resources and Energy. 38 p.
- Dorais, L.; Kettela, E.G., eds. 1982. A review of entomological survey and assessment techniques used in regional spruce budworm, *Choristoneura fumiferana* (Clem.), surveys and in the assessment of operational spray programs. Report Commission for Standardization of Survey and Assessment Techniques. Quebec, Canada: Eastern Spruce Budworm Council, Quebec Department Energy and Resources.
- MacLean, D.A. 1980. Vulnerability of fir-spruce stands during uncontrolled spruce budworm outbreaks: a review and discussion. *The Forestry Chronicle*. 56: 213-221.
- MacLean, D.A. 1990. Impact of forest pests and fire on stand growth and timber yield: implications for forest management planning. *Canadian Journal of Forest Research*. 20: 391-404.
- MacLean, D.A. 1996. The role of a stand dynamics model in the spruce budworm decision support system. *Canadian Journal of Forest Research*. 26: 1731-1741.
- MacLean, D.A. 1998. Landscape management for restructuring forest areas. In: Nabuurs, G.J.; Nuutinen, T.; Bartelink, H.; Korhonen, M., eds. Forest scenario modeling for ecosystem management at landscape level; 1997 June 24 -July 4; Wageningen, The Netherlands. Proc. No. 19. Joensuu, Finland: European Forest Institute: 25-45.
- MacLean, D.A.; Erdle, T.A. 1986. Development of relationships between spruce budworm defoliation and forest stand increment in New Brunswick. In: Solomon, D.S.; Brann, T.B., eds. Environmental influences on tree and stand increment; 1985 September 23-27; Durham, NH. Misc. Publ. 691. Orono, ME: Maine Agriculture Experiment Station, University of Maine: 106-115.
- MacLean, D.A.; MacKinnon, W.E. 1996. The accuracy of aerial sketch mapping of spruce budworm defoliation in New Brunswick. *Canadian Journal of Forest Research*. 26: 2099-2108.
- MacLean, D.A.; MacKinnon, W.E. 1997. Effects of soil drainage on susceptibility and vulnerability of balsam fir to spruce budworm in New Brunswick. *Canadian Journal of Forest Research*. 27: 1859-1871.
- MacLean, D.A.; Porter, K.B. 1994. Development of a decision support system for spruce budworm and forest management planning in Canada. In: Decision making with GIS - the fourth dimension: proceedings, GIS '94, 8th annual symposium on Geographic information systems; 1994 February 12-14. Vancouver, BC: Polaris Conferences Inc. 2: 863-872.
- MacLean, D.A.; Porter, K.B. 1995. A DSS for budworm and forest management: maximizing protection benefits and forecasting inventories. In: Power, J.M.; Strome, M.; Daniel, T.C., eds. Proceedings, Decision support 2001; 1994 Sept. 12-16; Toronto, ON. Bethesda, MD: American Society of Photogrammetry and Remote Sensing: 530-540.
- MacLean, D.A.; Porter, K.B. 1996. The role of forest inventory projection in the spruce budworm decision support system. In: Shore, T.L.; MacLean, D.A., eds. Proceedings of the workshop on Decision support systems for forest pest management; 1995 October 14-19. FRDA Rep. 260. Victoria, BC: Canadian Forest Service, Pacific Forestry Centre: 15-24.
- MacLean, D.A.; Porter, K.B.; MacKinnon, W.E. 1997. Using the spruce budworm DSS to help define protection policy. In: Integrating spatial information technologies for tomorrow, proceedings GIS'97, 11th annual symposium on Geographic information systems; 1997 February 17-20; Vancouver, BC. Fort Collins, CO: GIS World Inc.: 94-98.
- Power, J.M. 1991. National data on forest pest damage. In: Brand, D.G., ed. Canada's timber resources. Inf. Rep. PI-X-101. Chalk River, ON: Canadian Forest Service, Petawawa National Forestry Institute: 119-129.
- Rotherham, T. 1991. Timber harvest statistics: past practice and present needs. In: Brand, D.G., ed. Canada's timber resources. Inf. Rep. PI-X-101. Chalk River, ON: Canadian Forest Service, Petawawa National Forestry Institute: 105-110.
- Schoemaker, P.J.H. 1995. Scenario planning: a tool for strategic thinking. *Sloan Management Review*, Winter 1995: 25-40.
- Sterner, T.E.; Davidson, A.G. 1982. Forest insect and disease conditions in Canada, 1981. Ottawa, ON: Canadian Forest Service.
- Vanguard Forest Management Services Ltd. 1993. STAMAN stand growth model and Calibration of STAMAN model for defoliation impacts. In: Forest protection planning to sustain long-term wood supplies. Fredericton, NB, Canada: Contract Report to Canadian Forest Service - Maritimes Region: B1-B39, C1-C18.