A COMPUTER SIMULATION MODEL OF JACK PINE BUDWORM IMPACT IN MICHIGAN'S UPPER PENINSULA

Bradley E. Conway[1], Larry A. Leefers[1], and Deborah G. McCullough[1,2]

ABSTRACT—Periodic outbreaks of the jack pine budworm (*Choristoneura pinus pinus* Freeman) can result in significant volume losses in jack pine (*Pinus banksiana* Lamb.) forests. To predict these losses and to help managers make informed decisions, we developed a simulation model of jack pine budworm impact. The stand-level model was built in Stella II using growth equations from the TWIGS growth and yield model and data from a recent outbreak in the Hiawatha National Forest. The model uses readily available inputs and produces estimates of volume and economic loss. The model allows the user to alter management decisions and evaluate the effects of these strategies.

INTRODUCTION

The jack pine budworm (*Choristoneura pinus pinus* Freeman) is a small needle-feeding caterpillar that feeds almost exclusively on jack pine (*Pinus banksiana* Lamb.)(Howse 1984). Periodic outbreaks of this native North American insect occur every six to ten years and last for two to three years (Volney 1988; Volney and McCullough 1994). Defoliation usually results in reduced growth, damage to the tree's terminal leader (top-kill), and tree mortality (Kulman et al. 1963; Cerezke 1986; Gross 1992; McCullough et al. 1996). Significant losses in merchantable volume of jack pine can result from a single jack pine budworm (JPBW) outbreak (Gross and Meating 1994).

Due to economic and environmental considerations, forest managers in the Lake States are unable to use insecticides to combat JPBW infestations. Instead, managers rely on silvicultural treatments, harvest scheduling, salvage, or cover-type conversion to minimize the timber losses associated with an outbreak (Heym et al. 1993). Forest managers must work under increasing pressure to maximize all benefits from forested land, including benefits from wildlife habitat protection and recreational use. Faced with these often conflicting goals, decision makers need special tools to help allocate resources efficiently and to explain their decisions to the public.

In this paper we describe a computer simulation model of the biological and economic impacts of JPBW outbreaks. This model is a starting point for developing a tool that can be used by managers to help make and justify management decisions. We will discuss the methods used to build the model and some preliminary testing of the model. Finally, the role of models such as this in the development of pest management decision support systems is addressed.

CONCEPTUAL MODEL

The model was constructed in Stella II[3] (High Performance Systems, Inc., Hanover, NH). Stella II is a software package designed to facilitate the construction of dynamic systems models. Stella II provides a simple set of building blocks that can be used to visually represent components of the system. Model components are visually linked in a hierarchical environment. Stella II allows the user to run simulations, create tables and charts of model variables and simulation results, and construct a graphical user interface (GUI) to control model inputs.

[1] Bradley E. Conway, Larry A. Leefers, and Deborah G. McCullough, Department of Forestry, Michigan State University, 126 Natural Resources, East Lansing, MI 48824
[2] Deborah G. McCullough, Department of Entomology, Michigan State University, 243 Natural Science, East Lansing, MI 48824
[3] Stella II is a registered trademark of High Performance Systems, Inc.

The model is based on a with/without comparison in which the user sets values for basic stand variables that determine the characteristics of a pure, even-aged jack pine stand. The model generates two stands that are initially identical and projects each to a future year specified by the user (Fig. 1). The only difference between these two projections is that trees in one stand (the outbreak stand) suffer periodic reductions in volume due to JPBW attacks. At the end of the simulation, a comparison of the merchantable volume and economic value of each stand provides an estimate of the JPBW impact on the timber resource.

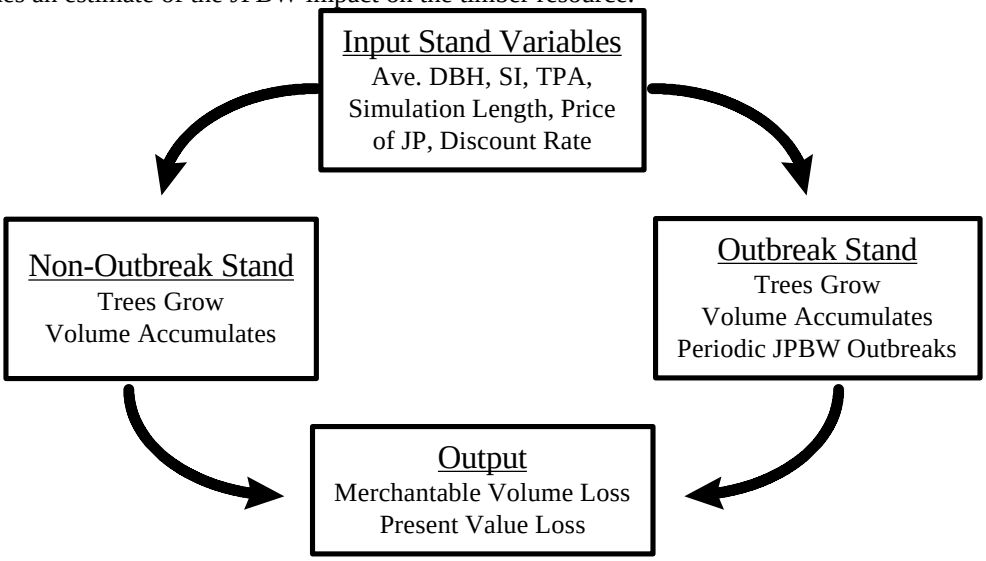

Figure 1. – Conceptual model diagram. DBH = diameter at breast height, SI = site index, TPA = trees per acre.

In both the outbreak and non-outbreak scenarios, stand growth is a composite of growth from seven individual-tree diameter classes. Each diameter class represents an initial percentage of the total number of trees per acre. Jack pine is typically found in even-aged stands (Benzie 1977), and a frequency distribution of the diameter classes in an even-aged stand is likely to be normal (Smith 1986). Therefore, the trees per acre in each diameter class represent a portion of the total trees per acre that corresponds to this normal distribution. Tree growth, mortality, and volume are calculated using the same equations for each diameter class.

NON-OUTBREAK GROWTH AND MORTALITY

Trees in each diameter class grow in diameter at breast height (DBH) and height over the course of the simulation. The equations that determine both DBH and height growth were taken from a USDA Forest Service growth and yield model, the Lake States TWIGS variant of the Forest Vegetation Simulator (LS-TWIGS)(Miner et al. 1988; Bush and Brand 1995). LS-TWIGS is a distance-independent, individual-tree growth model applicable to a number of Lake States tree species, including jack pine. Miner et al. (1988) noted that the LS-TWIGS equations represent the growth of jack pine trees well and have basic, readily available inputs (e.g., DBH and site index). Cubic foot volume equations were also taken from LS-TWIGS. Each diameter class has an associated mortality rate that reduces the number of trees per acre over time in that diameter class; this mortality is based on equations reported in Buchman et al. (1983). We assumed that no ingrowth (i.e., reproduction, seedling establishment and growth) will occur during the simulation.

OUTBREAK GROWTH AND MORTALITY

The model allows the user to select a deterministic or stochastic outbreak sequence. The deterministic outbreak sequence simulates outbreaks during the same years in each simulation. We based the deterministic sequence on the pattern of JPBW infestations that have occurred in Michigan over the past 46 years; the Michigan

Department of Natural Resources' annual forest pest reports provided this historical pattern. The deterministic outbreak sequence allows the user to alter stand inputs or to compare different stands under the same outbreak sequence. The stochastic outbreak sequence simulates outbreaks in a random, periodic sequence every six to twelve years.

Data for quantifying the reduction in volume likely to occur as a result of a JPBW outbreak came from field studies in the Raco Plains area of the eastern Hiawatha National Forest (Fig. 2). The Raco Plains area is characterized by sandy glacial outwash soils and dominated by large areas of jack pine forest (Heym et al. 1993). From 1991 to 1993, a JPBW outbreak occurred in this area. Survey work has been performed in all jack pine-dominated stands in four USDA Forest Service management compartments in the Raco Plains area for the past 5 years (1992-1996)(McCullough et al. 1996). Annually, we have collected data on the amount of jack pine tree mortality and top-kill that has occurred as a result of the most recent outbreak.

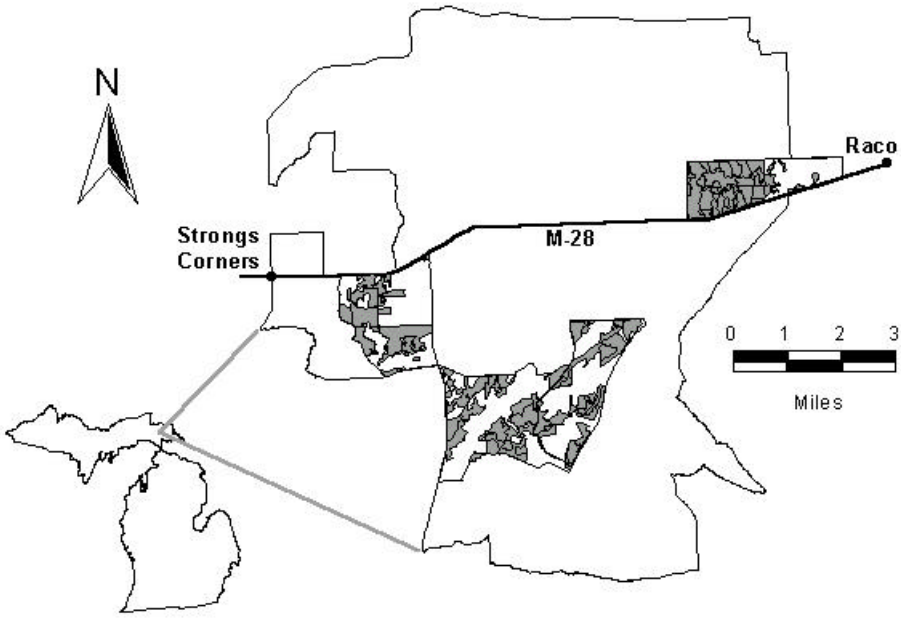

Figure 2 – 1996 sample stands in the Raco Plains area of the Hiawatha National Forest.

In 1992 we observed tree mortality to be only 1%. This is what we would expect endemic tree mortality to be. Outbreak-affected tree mortality increased dramatically in 1993, 1994, and 1995 then leveled off in 1996 (McCullough et al. 1996). This suggests that a JPBW outbreak affects tree mortality for three years and that a time lag exists between the start of the outbreak and the onset of outbreak-affected mortality. Predictive equations for annual outbreak-affected mortality were derived from these data using least squares linear regression. Mortality was determined to be a function of site index and stand basal area.

A thorough examination of the length of dead tops on top-killed trees revealed that rarely does the dead wood in the top-kill affect the amount of merchantable volume in a tree. Other studies have reached the same conclusion regarding top-kill (e.g., Gross and Meating 1994). For these reasons and for simplicity, we did not simulate top-killed trees in the model.

To evaluate the growth loss that has resulted from the most recent JPBW outbreak, we selected 60 live dominant or codominant jack pine trees at random from the Raco Plains study site in 1996. These trees were selected from stands that represented a range of all possible age, site quality, and stocking combinations. We felled and removed discs at intervals along the stem of each tree.

To measure annual ring width, we dried, sanded one face, and located two average radii on each disc. We measured and cross dated annual ring widths along these radii to the nearest 0.01 mm using an optical digitizing scanner and WinDENDRO[4] image analysis software (Regent Instruments, Inc., Quebec, Qc). We used this

[4] WinDENDRO is a registered trademark of Regent Instruments, Inc.

measurement data to plot mean annual ring widths of each disc against year of ring formation and noted JPBW outbreak and recovery years in this graphical analysis (Fig. 3).

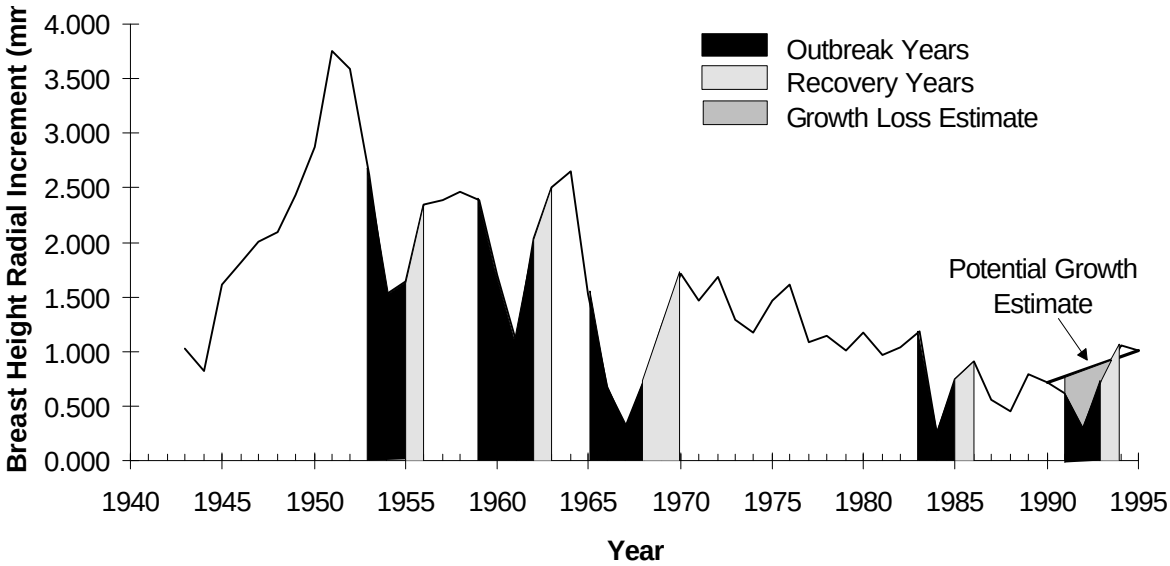

Figure 3 – Annual radial increment at breast height of a single sample jack pine with historical JPBW activity highlighted.

To estimate radial growth loss, we used only the breast height disc and followed a method similar to that used to evaluate growth loss of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) defoliated by western spruce budworm (*Choristoneura occidentalis* Freeman)(Thomson and Van Sickle 1980; Alfaro et al. 1982). We began by calculating the mean annual increment for the five years before the 1991-1993 JPBW outbreak (1982, 1987-1990) for each sample tree. Growth in 1983-1986 was not included in this calculation because there was a JPBW outbreak and recovery during this period. This five-year mean and the 1995 increment (after recovery) were used as end points (set at 1990 and 1995, respectively) to determine a line segment that represented potential growth in the absence of the outbreak (Fig. 3). The equation of this line segment was then used to calculate potential growth for 1991-1993 (outbreak) and 1994 (recovery) for each sample tree. Growth loss attributable to the most recent outbreak was estimated by subtracting the potential values from the observed values for the outbreak-affected years. If the observed value was greater than the predicted value, then we assumed that the growth loss was zero. Predictive equations for annual growth loss for the outbreak-affected years were determined by least squares linear regression. Growth loss was determined to be a function of tree DBH, site index, and crown ratio.

Although an actual JPBW infestation will only last for two to three years, an outbreak will affect radial growth and tree mortality for a longer period of time (Kulman et al. 1963; Cerezke 1986; Gross 1992; McCullough et al. 1996). Each outbreak in the model affects the stand for five years. Radial growth is reduced in each of the first four years of an outbreak. The increased mortality associated with an outbreak occurs in the third to fifth outbreak-affected years. Outbreak growth loss and mortality for each of these years are determined by the regression equations described above. The mortality rate during the interval between outbreaks in the outbreak stand is equal to the mortality rate in the non-outbreak stand.

The model produces estimates of merchantable volume loss and present value loss by comparing the volume and value of the outbreak and non-outbreak stands at the end of the simulation. We assume that the user knows the price of jack pine pulpwood at the end of the simulation. Typically, management costs for jack pine are a function of the area of the stand and can be considered independent of the JPBW outbreaks (Heym et al. 1993). Therefore, costs are the same for both scenarios and are assumed to have no effect on the determination of the present value loss.

MODEL VERIFICATION

Currently, data from other jack pine stands outside the area we surveyed are not available; however, additional data will be collected and used for validation in 1997. To evaluate the performance of the model, we selected a sub-sample of 25 stands at random from the Raco Plains sample stands that had both mortality and growth loss data. We ran each of these stands through a six-year simulation with a JPBW outbreak beginning in year one and ending in year three. We did this in an attempt to simulate the 1991-1993 JPBW outbreak. We compared the annual and total percentage mortality predicted for each of the 25 simulations to the mortality observed in the field studies. Figure 4 shows the mean annual percent mortality resulting from a single JPBW outbreak as observed in the field and as predicted by the model. A one-way analysis of variance (ANOVA) indicated that there was no significant difference between the observed and predicted mortality for the 25 sample stands ($F = 0.298$; $P < 0.588$; $\beta = 0.083$ [total mortality]). Though results are not statistically different, Figure 4 illustrates that the model consistently underestimated mean annual mortality slightly in each simulation year.

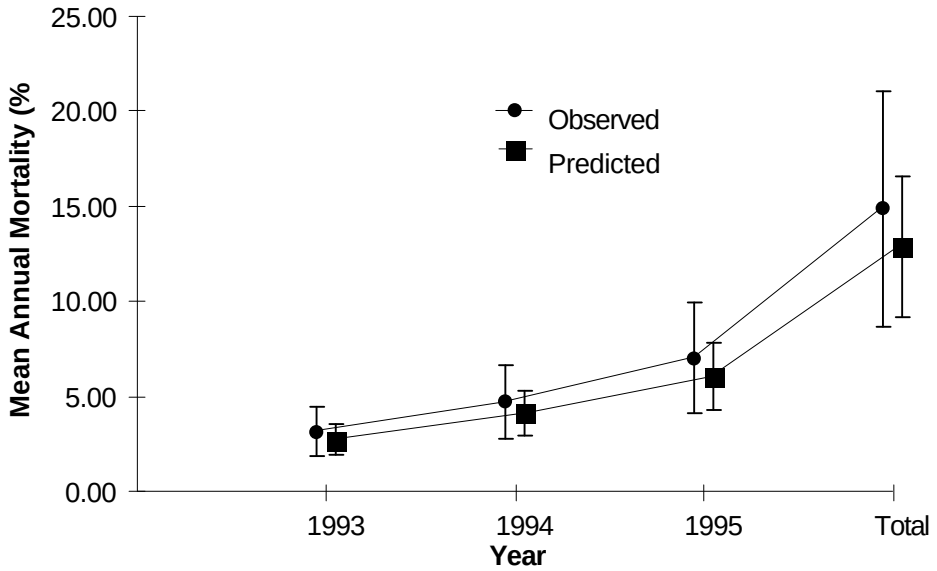

Figure 4. – Predicted and observed mean annual percent mortality with 95% confidence intervals.

To verify growth loss, we determined the diameter class that most closely resembled the sampled tree for that stand (i.e., the tree that was felled and measured). We selected the simulated growth loss for that diameter class and compared it to the observed growth loss. Figure 5 presents simulated and observed mean diameter growth loss for each year of the simulation. As with mortality, a one-way ANOVA indicated that there was no significant difference in any year between observed and predicted growth loss ($F = 0.124$; $P < 0.726$; $\beta = 0.064$ [total growth loss]). While there were no significant differences, the model slightly overestimated total growth loss attributable to a single JPBW outbreak.

Verification indicated that observed and predicted growth loss and mortality are very similar, but these results are not necessarily valid for all JPBW outbreaks in this area. Data from additional jack pine stands are needed to validate these predictions. In addition, we have assumed that the relationships between mortality, growth loss, and stand characteristics are linear (i.e., based on linear regression). Other studies suggest that these relationships may be non-linear (e.g., McCullough et al. 1996). Continued refinement of these important relationships should give the model more predictive power.

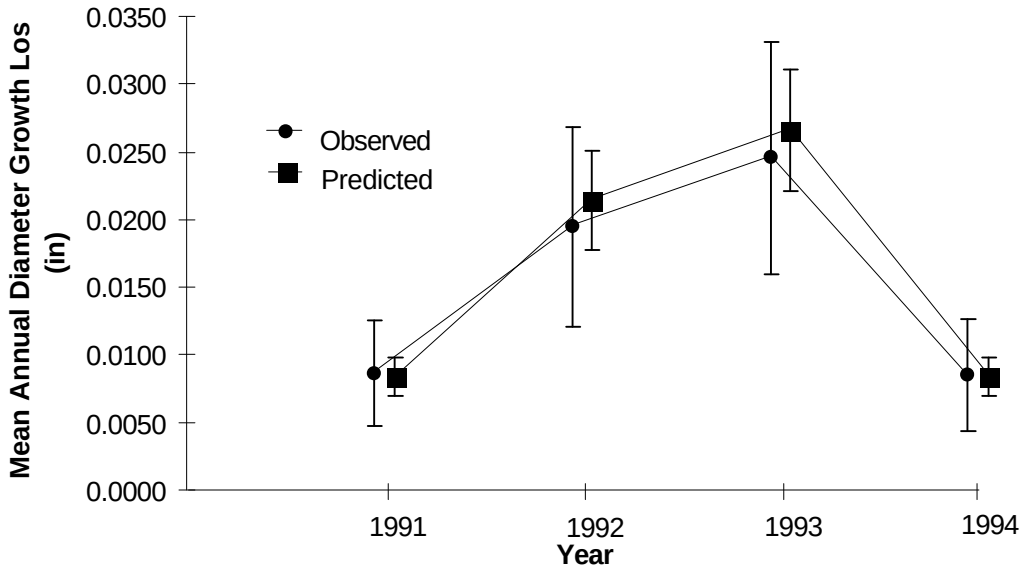

Figure 5. – Predicted and observed mean diameter growth loss with 95% confidence intervals.

TRIAL SIMULATIONS

Sixty-four trial simulations were run to determine the amount of merchantable volume and present value loss that could be expected in some typical stand types. The stands selected for these trial simulations were various combinations of four initial average stand DBH's, four site index values, four initial stand densities, and two simulation lengths. All trial simulations used a price of $20 per cord for jack pine pulpwood and a discount rate of 4%. On average these trial simulation stands experienced three JPBW outbreaks over the course of the simulation. Results of these trial simulations ranged from 5.9% to 49.7% loss in merchantable volume and from $3 to $103 per acre present value loss. The mean percent loss in merchantable volume and present value was 31.3% and $40 per acre, respectively.

During the trial simulations, it was observed that the average DBH of the trees in the outbreak stand was greater than the average DBH of the trees in the non-outbreak stand at the end of the simulation. This pattern is due to the assumption that diameter growth is inversely related to stand density. The outbreak stand suffers increased tree mortality during periodic outbreaks. Thus, outbreaks act as thinnings that reduce stand density and increase diameter growth. Between-outbreak diameter growth in the outbreak stand more than offsets diameter growth reductions that occur during the outbreaks. As a result, tree mortality is a more important factor affecting volume and economic loss than growth loss.

CONCLUSIONS AND FUTURE DEVELOPMENT

Annually, forest pests, such as the JPBW, play an important role in determining stand composition and timber supply. Forest managers need special tools to help them predict the effects insects will have on future timber supply and to help them develop management plans that reduce the future occurrence and severity of damage from insect attacks (MacLean and Porter 1996). These tools include decision support systems (DSS). A DSS is a computer software system that incorporates forest inventory data and models of pest activity and impact (MacLean and Porter 1996). A DSS is typically designed to improve the current situation of the forest manager by aiding in the decision-making and justification process (Marshall and McCullough 1995). Important questions about management strategies and resource allocation can often be answered more efficiently with the help of decision support systems.

Forest pest impact models, such as the one described above, are important components of decision support systems. However, the model described above is only the first step toward the development of such a tool. Continued improvement of the mortality and growth loss relationships is essential. In addition data from other areas in Michigan and the Lake States region are needed to validate these relationships. This stand-level model should be transformed into a forest-level model by applying it to a number of stands simultaneously. This, along with incorporation of geographic information systems (GIS), could be accomplished by programming the model in a different development environment such as ArcView's Avenue[5] programming language (ESRI, Redlands, CA) or a conventional language such as C++.

ACKNOWLEDGMENTS

The authors would like to thank Doug Heym, Hiawatha National Forest District Silviculturalist, for his enthusiastic help and support of this project. We are also grateful to Nathan Siegert, Dr. Raymond Miller, and everyone at the Upper Peninsula Tree Improvement Center for their help in the collection and measurement of the growth loss data. Input provided by Dr. Jianguo Liu greatly enhanced this project. Funding for this study was provided by the Michigan Agricultural Experiment Station as part of its Status and Potential of Michigan's Natural Resources (SAPMINR) program.

REFERENCES CITED

ALFARO, R.I., G.A. VAN SICKLE, A.J. THOMSON, AND E. WEGWITZ. 1982. Tree mortality and radial growth losses caused by the western spruce budworm in a Douglas-fir stand in British Columbia. *Can. J. For. Res.* 12: 780-787.

BENZIE, J.W. 1977. *Manager's handbook for jack pine in the North Central states*. U.S. Department of Agriculture, Forest Service. Gen. Tech. Rep. NC-32. 18 p.

BUCHMAN, R.G., S.P. PEDERSON, AND N.R. WALTERS. 1983. A tree survival model with application to species of the Great Lakes region. *Can. J. For. Res.* 13:601-608.

BUSH, R.R. AND G. BRAND. 1995. *The Lake States TWIGS variant of the forest vegetation simulator*. U.S. Department of Agriculture, Forest Service 29 p.

CEREZKE, J.H. 1986. Impact studies of the jack pine budworm, *Choristoneura pinus pinus*, in Nisbet Provincial Forest, Saskatchewan. In *Jack Pine Budworm Information Exchange*, January, 1986, Winnipeg, Manitoba. Manitoba Nat. Resour., For. Prot. Branch, Winnipeg, Manitoba. pp. 25-38.

GROSS, H.L. 1992. Impact analysis for a jack pine budworm infestation in Ontario. *Can. J. For. Res.* 22: 818-831.

GROSS, H.L. AND J.H. MEATING. 1994. *Impact of the 1982-1986 jack pine budworm infestation on jack pine in northeastern Ontario.* Nat. Resour. Can., Can. For. Serv., Ont. Reg., Great Lakes For. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-431. 19 p.

HOWSE, G.M. 1984. Insect pests of jack pine: biology, damage and control. In *Jack pine symposium*. Ontario Ministry of Natural Resources, Great Lakes For. Res. Centre, Sault Ste. Marie, Ontario. COJFRC Symp. Proc. O-P-12. pp. 131-138.

[5] ArcView and Avenue are registered trademarks of Environmental Systems Research Institute (ESRI), Redlands, CA.

HEYM, D., D.J. EVANS, S. KATOVICH, K. KEACH, T. KURZ, M. LANASA, M. MILLER, AND L. WHITCOMB. 1993. *Raco Plains jack pine ecosystem project*. U.S. Department of Agriculture, Forest Service. Sault Ste. Marie Ranger District, Hiawatha National Forest. Sault Ste. Marie, MI

KULMAN, H.M., A.C. HODSON, AND D.P. DUNCAN. 1963. Distribution and effects of jack pine budworm defoliation. *For. Sci.* 9: 146-157.

MACLEAN, D.A., AND K.B. PORTER. 1996. Role of forest inventory projection in the spruce budworm decision support system. In *Decision Support Systems for Forest Pest Management, Proceedings of a Workshop at the Joint Meeting of the Entomological Society of Canada and British Columbia*, October 1995, Victoria, BC. Can. For. Serv. FRDA Rep. No. 260. pp. 15-24.

MARSHALL, L.D., AND D.G. MCCULLOUGH. 1995. Pest management decision support systems: a new challenge for forest entomologists. *For. Chron.* 71:288-290.

MCCULLOUGH, D.G., L.D. MARSHALL, L.J. BUSS, AND J. KOUKI. 1996. Relating jack pine budworm damage to stand inventory variables in northern Michigan. *Can. J. For. Res.* 26: 2180-2190.

MINER, C.L., N.R. WALTERS, AND M.L. BELLI. 1988. *A guide to the TWIGS program for the North Central United States.* U.S. Department of Agriculture, Forest Service Gen. Tech. Rep. NC-125. 105 p.

SMITH, D.M. 1986. *The Practice of Silviculture*. John Wiley & Sons. 527 p.

THOMSON, A.J. AND G.A. VAN SICKLE. 1980. Estimation of tree growth losses caused by pest activity. *Can. J. For. Res*. 10: 176-182.

VOLNEY, W.J.A. 1988. Analysis of historic jack pine budworm outbreaks in the Prairie provinces of Canada. *Can. J. For. Res.* 18: 1152-1158.

VOLNEY, W.J.A., AND D.G. MCCULLOUGH. 1994. Jack pine budworm population behaviour in northwestern Wisconsin. *Can. J. For. Res.* 24: 502-510.