

# HAZARD RATING AND STAND VULNERABILITY TO JACK PINE BUDWORM DEFOLIATION USING GIS

R.J. Hall<sup>1</sup>, W.J.A. Volney<sup>1</sup> and K. Knowles<sup>2</sup>

<sup>1</sup>Canadian Forest Service, Northwest Region

5320 - 122 Street

Edmonton, Alberta T6H 3S5

<sup>2</sup>Manitoba Natural Resources, Forestry Branch

#300, 530 Kenaston Blvd.

Winnipeg, Manitoba R3N 1Z4

## ABSTRACT

A spatial hazard rating system for rating forest stand vulnerability to jack pine budworm (*Choristoneura pinus pinus* Freeman) damage, which is a component of the Jack Pine Budworm Decision Support System, has been developed. This hazard rating system has not been evaluated by comparing its predictions with observations on an independent outbreak. This study was designed to determine how well the hazard rating system, which uses stand attributes, predicted damage resulting from an outbreak in Saskatchewan. Maps of hazard and damage represented by dead tree tops or top kill were produced and overlaid with maps of stand structure that included drainage, species, age, height, and crown closure. There was no relationship between the hazard map and the top-kill map, but this was attributed to the rules used to assign hazard points. Several jack pine (*Pinus banksiana* Lamb.) stands in Saskatchewan that were rated high for hazard sustained neither moderate nor severe damage. The transfer of a hazard rating system from one provincial jurisdiction to another may not be simple due to differences between their respective stand inventory classification systems. Future developments in hazard rating should be based on knowledge of associations between stands that have sustained budworm damage and their structural characteristics. Geographic Information System technology is one approach that may help in defining these associations. Areas of research and development that may improve methods to determine vulnerability and hazard rate stands are identified.

## INTRODUCTION

Jack pine budworm (*Choristoneura pinus pinus* Freeman) is among the important insect pests in Canada (MacLean 1990), and is a major defoliator of jack pine (*Pinus banksiana* Lamb.) forests in Ontario, Manitoba, Saskatchewan, and the Great Lakes States of the United States (Moody 1989; Mallett and Volney 1990). Severe defoliation reduces tree growth and vigor, and may cause top kill (i.e., dead tree tops), mortality, and predispose trees for attack by other destructive agents (Kulman et al. 1963; Mallett and Volney 1990). Significant reductions in radial growth and average volume increments have been reported (Kulman et al. 1963; Gross 1992; Gross and Meating 1994), and these types of losses

could have significant impacts on jack pine timber supply (Volney 1988).

A current effort to develop a management tool to reduce potential losses from this pest is the Jack Pine Budworm Decision Support System (JPBDSS). The JPBDSS is intended to rely primarily on operational data in the standard inventory database of management agencies (McCullough and Marshall 1993). A component of the JPBDSS is a spatial hazard rating of forest stands for vulnerability to budworm defoliation and damage. Hazard rating is the process of identifying and ranking individual stands in terms of their vulnerability to a pest outbreak, and is often used to assign priorities for harvesting and remedial treatments (Doliner and Borden 1984). Hazard rating of stands usually results

in ratings of low, medium and high without corresponding figures for reductions in volume (Maffei and Arena 1993). A link must be created between the hazard rating system and expected impacts so that pest management options and their associated costs could be evaluated by timber and nontimber values gained because of protection. A prerequisite to establishing this link is the evaluation of a hazard rating system for jack pine budworm.

Although a hazard rating system for jack pine budworm has been developed in Manitoba (Knowles 1991), its evaluation on a stand basis had not been undertaken. Such an evaluation may be achieved by comparing damaged stands that resulted from an outbreak, to hazard-rated stands with a spatial approach using a Geographic Information System (GIS). This is attributed to the proportion of severely defoliated trees within a stand often being more representative of damage than ratings of tree needle volume defoliated (Gross and Meating 1994). Within a GIS, stand structure information is often represented on forest inventory maps that describe cover types by a nominal (e.g., species composition) and ordinal (e.g., age, height, crown closure, site quality) forest classification system (Gillis and Leckie 1993). A spatial approach permits investigations about patterns in data represented in a GIS such as hazard ratings and stand structure, and would seek possible relationships between these patterns for understanding or prediction (Bailey 1994).

The purpose of this study is to answer the following questions: 1) What is the relationship between hazard-rated stands and stands that have sustained damage from budworm defoliation?; and 2) To what extent are selected stand attributes associated with hazard-rated stands? The selected attributes include drainage, species composition, stand origin (i.e., age), stand height, and crown closure.

## MATERIALS AND METHODS

The study area is the Torch River Provincial Forest in Saskatchewan for which a moderate to severe defoliation was reported between 1984 and 1987 (Moody and Cerezke 1986; Cerezke and Emond 1989). This area is in the Mixedwood section (B.18a) of the Boreal Forest Region of Canada, where jack pine predominates on sandy areas

(Rowe 1972). Soils of the area are poor to moderate in site quality due to their rapid drainage (Kabzems et al. 1986).

## Mapping Damage From Jack Pine Budworm Defoliation

Color infrared aerial photographs at 1:5000 were acquired during the summer of 1988, one year following the reported collapse of a jack pine budworm infestation (Cerezke and Emond 1989). The aerial photographs depicted patterns of top kill and these patterns were used as an indicator of defoliation severity, because surviving trees with top kill have experienced considerably more defoliation than trees with surviving green tops (Gross 1992). Thus, trees with top kill may indicate stands that are vulnerable to damage (Volney 1994). There has been no standard infestation severity classification system reported in the literature (Table 1); thus, a classification system was devised specifically for mapping top kill (Table 2). Top kill in jack pine stands ranged from nil along the Torch River to moderate and severe within the provincial forest (Fig. 1).

## Forest Inventory Map Data Base

A series of four adjacent 1:12 500 scale forest inventory maps were obtained for the study area, and these maps were joined to create one seamless spatial database that encompassed the Torch River Provincial Forest. The inventory maps were originally acquired from the Forestry Branch of Saskatchewan Environment and Resources Management as ESRI Arc/Info<sup>1</sup> coverages that were originally created in 1984 and updated in 1988. Based on 25 field plots that were established throughout the study area (Hall et al. 1993), field calls of stand composition agreed with the cover type labels on the map. The map data were therefore recent and accurate insofar as the field survey was able to determine. Separate coverages were created for soil drainage, primary species, stand origin, stand height, and crown closure (Table 3) to prepare the data in the SPANS GIS for calculations of associations.

<sup>1</sup>The mention of trade names is for information only and does not imply endorsement.

Table 1. Survey classification systems used for jack pine budworm and spruce budworm defoliation

Reference	Class 1	Class 2	Class 3	Class 4	Class 5	Survey
Jack pine budworm						
Benjamin (1956) cited in Dixon (1985)	none to light	medium (defol. evident)	heavy (crowns red-brown)	severe (top kill and mortality)		aerial
Kulman et al. (1963)	New growth: very light 0 - 25%	light 26 - 75%	medium 76 - 100%	heavy 100%	heavy 100%	field
	Old needles: 0%	0%	0 - 25%	26 - 75%	100%	
Moody (1986)	light tree slightly red	moderate redness clearly evident	severe entire crown red			aerial
Gross (1992)	light 1 - 25%	moderate 26 - 75%	high >75%			field
Spruce budworm						
Ashley et al. (1976)	light <20%	light <20%	heavy 51 - 80%	severe >80%	dead 100%	air photo
Mag and Witter (1979) cited in McCarthy et al. (1983)	no defoliation 0 - 25%	light - moderate 21 - 50%	heavy, no top kill 51% +	severe top kill 51% +		aerial
Twardus (1985)	none 0 - 10%	light 20 - 40%	moderate - heavy 50 - 100%	severe top kill & mortality 50 - 100%		field
Ostaff and Maclean (1989)	0 - 10%	11 - 30%	31 - 60%	61 - 99%	100%	air photo

Table 2. Description of top-kill map classification system

Severity rating	Class limits %	Description
Nil	0	Interpreted forest stand, no visible top kill
Light	1 - 25	Up to 25% of a forest stand by number of trees or scattered trees with small amounts of visible top kill
Moderate	26 - 50	From 26 to 50% of a forest stand by number of trees, or scattered trees comprising at least $\frac{1}{4}$ of the stand with visible top kill
Severe	51 - 100	At least 50% of a forest stand by number of trees and exhibiting significant amounts of top kill
Unclassified	not applicable	Regenerating areas or areas not supporting forest stands

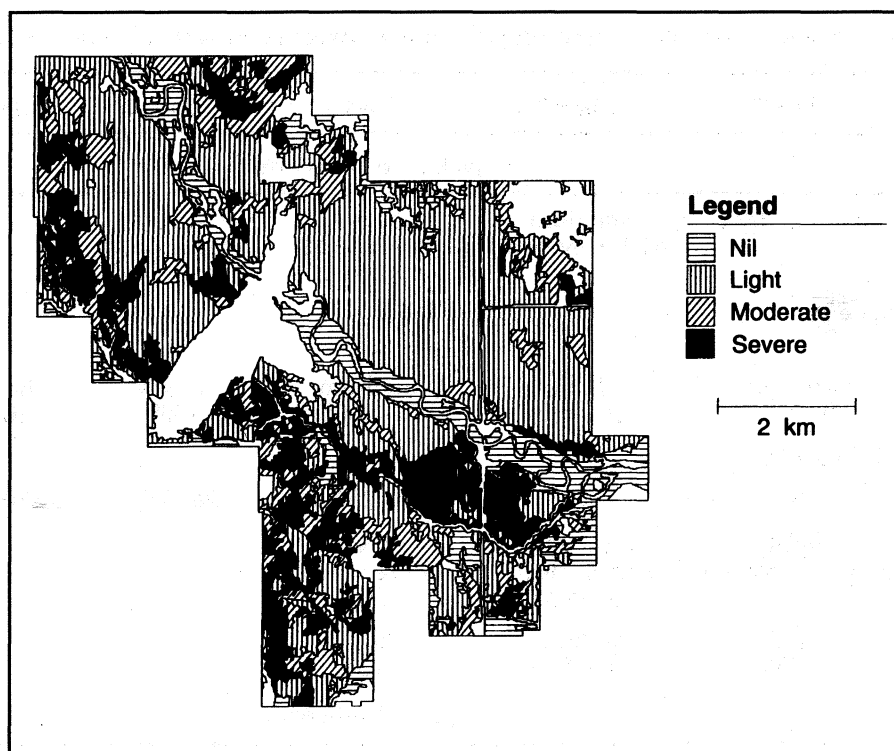


Figure 1. Top-kill map of the Torch River Provincial Forest from interpretation of 1:5000 color infrared aerial photographs.

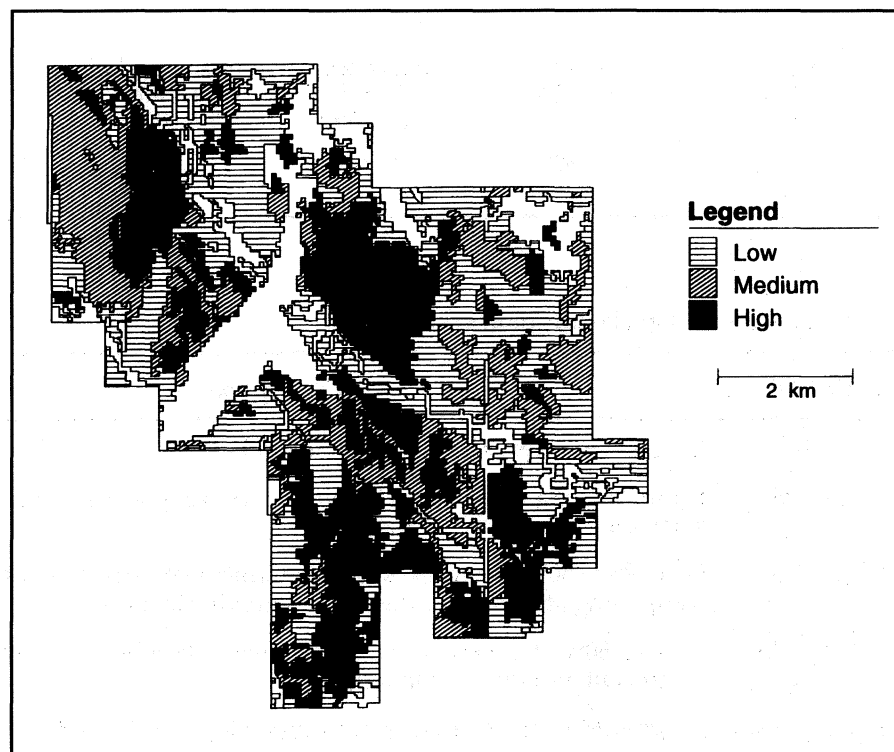


Figure 2. Hazard rating of stands for jack pine budworm applied to the Torch River Provincial Forest.

### Jack Pine Budworm Hazard Rating System

The hazard rating system for jack pine budworm in Manitoba is based on the provincial forest inventory classification system in combination with observations and information about damage from previous outbreaks (Knowles 1991). This system includes considerations for stand value based on stand volume at risk and vulnerability to damage, and assigns points according to stand characteristics. Stand value is assumed to increase as stand volume increases. An initial attempt was made to adapt the hazard rating system to use information from the Saskatchewan forest inventory classification system (Table 3). Thus, stands whose attribute values result in 3 to 11 points were rated low, from 12 to 13 points were rated moderate, and 14 to 16 points were rated high hazard for budworm damage. A map was produced for the study area that depicted the low, medium, and high hazard areas (Fig. 2), and this was used in the determination of associations. For operational use, however, further refinement may be necessary to address the full

range of stand types that may contain jack pine, and to ensure the hazard rating is based on attributes of vulnerable stands.

### Measures of Association

Measures of association, or degree of dependence can be evaluated with a contingency table, which is a two-way cross tabulation of two variables (Clark and Hosking 1986). The  $\chi^2$  statistic can be computed from the contingency table to test for dependence (i.e., association) between two variables, but it does not provide a measure of the strength of the relation (Clark and Hosking 1986). Of the several procedures that do provide these measures, Cramer's V was used because calculated coefficients range from 0 to 1, and it corrects for deficiencies observed with similar measures such as the Contingency Coefficient (Reynolds 1977). Cramer's V and a test of the significance of the association were calculated between the hazard rating map and map of top-kill severity.

Table 3. Manitoba jack pine budworm hazard rating system modified for Saskatchewan forest inventory classification system.

Attribute	Value	Hazard points	Attribute	Value	Hazard points
Species association & species	% jack pine		Stand origin	Age (yrs)	
S <sup>a</sup> , jack pine	75 - 100	5	1856 - 1865	125 +	5
S, jack pine, spruce	51 - 74	5	1866 - 1875	115 +	5
SH, jack pine, aspen	51 - 74	4	1876 - 1885	105 +	5
S, spruce, jack pine	26 - 49	3	1886 - 1895	95 +	5
SH, jack pine, spruce, aspen	26 - 49	3	1896 - 1905	85 +	5
SH, spruce, jack pine, aspen	26 - 37	1	1916 - 1925	65 +	4
HS, aspen, jack pine	25 - 50	2	1926 - 1935	55 +	4
H, aspen	0 - 25	0	1936 - 1945	45 +	1
			1946 - 1955	35 +	1
			1956 - 1965	25 +	0
Crown closure	Percent				
A	10 - 30	0			
B	30 - 55	0			
C	55 - 80	3			
D	80 +	4			
			Drainage		
			Very rapidly drained		2
			Rapidly drained		2
			Well drained		1
			Mod. well drained		1

<sup>a</sup>S (softwood), SH (mixed softwood and hardwood), HS (mixed hardwood and softwood), H (hardwood).

Additional insight into the pattern of relationships within map attribute class levels was obtained with Minnick's coefficient of areal correspondence (Minnick 1964). This was computed between the individual map attribute class levels (e.g., age classes within stand origin) and the hazard rating classes. Minnick's procedure is a measure of areal correspondence that determines the degree to which two regions overlap. Its index may be considered an indicator of spatial association, if one assumes that a relation exists between two spatially distributed phenomena that overlap. For example, if high hazard is observed on stands of certain age classes, then stands with those attributes may be inferred as most vulnerable to damage. Values that generally exceeded 0.10 were considered indicative of meaningful associations because there is no probability distribution for Minnick's coefficients. Minnick's coefficient is computed using algebra of sets (Minnick 1964):

$$C_m = \frac{A \cap B}{A \cup B - (A \cap B)}$$

where:  $C_m$  = Minnick's coefficient

$A$  = Map A (e.g., hazard)

$B$  = Map B (e.g., stand origin)

$A \cap B$  =  $A$  intersect  $B$ ; i.e., the area common to  $A$  and  $B$

$A \cup B$  =  $A$  union  $B$ ; i.e., the areas belonging to either  $A$  or  $B$ , or to both  $A$  and  $B$

Coefficients were computed for each pair of classes between hazard-rated stands and individual stand attributes. For example, the 9 stand origin and 3 hazard rating classes resulted in 27 coefficients being computed (Table 4).

## RESULTS AND DISCUSSION

### Test of Independence and Cramer's V between Hazard and Top Kill

An  $\chi^2$  test of independence was based on a contingency table that comprised 1485 randomly selected points within the Torch River Provincial Forest. At a probability level of 0.05, there was no significant relationship between hazard-rated stands and stands mapped for top-kill severity (Calculated  $\chi^2 = 6.5$ , Table  $\chi^2 = 12.6$ , degrees of freedom = 6). Cramer's V between hazard-rated stands and stands with top kill is 0.15, and this low

value suggests a poor relationship that is consistent with the results of the  $\chi^2$  test. One explanation for these results is that the criteria used for determining hazard scores was different from those used for mapping top kill. Hazard rating is based on stand characteristics, and is a relative measure of a given stand's likelihood to sustain damage from defoliation. The Manitoba hazard rating system is additionally based on the premise that stands with increasing crown closure and a higher proportion of jack pine, have a greater volume at risk (Knowles 1991). The map of top kill, however, was based on the interpretation of aerial photographs for patterns of stands with nil, light, moderate and severe amounts of dead tree tops that occurred immediately following the jack pine budworm outbreak (Table 2). The top-kill map is therefore considered a map of vulnerability because it was based on visible damage. Thus, possible revisions to the hazard rating system might be derived from associations between hazard and stand characteristics, and a study of the distribution and structure of stands in the study area.

### Associations between Hazard, Top Kill, and Stand Characteristics

The physiological state of trees, conditioned by site and stand (e.g., age, crown closure) characteristics, influences their vulnerability to budworm damage (Gagnon and Chabot 1990). Once identified, it is these characteristics that should be used in hazard rating (Doliner and Borden 1984). Thus, association of these characteristics with the hazard map will provide insights as to the characteristics of stands that are currently being rated. A tabulation of Minnick's coefficient of areal correspondence for each attribute provides the basis for inferences and speculations on possible revisions that may be needed to the hazard rating system (Table 4 a, b, c, d, e, and f).

Based on a map overlay between hazard (Fig. 2) and top kill (Fig. 1), the low hazard stands were associated with the nil and light top kill categories (Table 4a). This association suggests the criteria for defining these classes are similar. Stands with medium hazard were associated with the light, moderate and severe top kill categories. The criteria for medium hazard may have been too broad because it corresponds with three damage classes. Stands with high hazard were mainly associated with light top kill, although associations with the moderate and severe top-kill classes were expected. An insight into why these results occurred was

Table 4. Minnick's coefficient of areal correspondence between hazard rating and stand characteristics

## a) Top-kill severity

Hazard	Nil	Light	Moderate	Severe
Low	<b>0.22</b>	<b>0.28</b>	0.10	0.10
Medium	0.02	<b>0.18</b>	<b>0.15</b>	<b>0.19</b>
High	0.02	<b>0.33</b>	0.10	0.14

## b) Drainage

Hazard	Rapid	Well	Moderate - well
Low	<b>0.34</b>	0.02	<b>0.16</b>
Medium	<b>0.28</b>	0	0
High	<b>0.36</b>	0	0

## c) Primary species

Hazard	Jack pine	Aspen	White spruce	Black spruce
Low	<b>0.28</b>	<b>0.28</b>	0.01	0.03
Medium	<b>0.29</b>	0	0	0
High	<b>0.39</b>	0	0	0

## d) Stand origin (median of class in years, Table 3)

Hazard	115	105	95	85	65	55	45	35	25
Low	0.001	0.01	0.02	0.04	0.07	<b>0.27</b>	<b>0.27</b>	0.12	0.01
Medium	0.00	0.00	<b>0.41</b>	0.24	0.007	0.006	0.10	0	0
High	0.00	0.00	0.05	<b>0.26</b>	0.002	<b>0.39</b>	0	0	0

## e) Stand height

Hazard	5 m	10 m	15 m	20 m	25 m
Low	<b>0.24</b>	<b>0.35</b>	0.14	0.003	0.0001
Medium	0.08	0.04	<b>0.29</b>	<b>0.23</b>	0
High	0.002	<b>0.31</b>	0.13	<b>0.22</b>	0

## f) Crown closure

Hazard	10 - 30%	30 - 55%	55 - 80%	80%
Low	<b>0.30</b>	<b>0.26</b>	0.14	0.05
Medium	0.14	<b>0.39</b>	0.01	0.10
High	0	0	<b>0.59</b>	<b>0.20</b>

Note: Table values in bold indicate coefficients considered significant.

based on inferences between the hazard map (Fig. 2) and stand attribute maps (i.e., drainage, primary species, stand origin, stand height, crown closure).

Coefficients for rapid drainage were associated with low, medium and high hazard (Table 4b). Rapid drainage results in a greater likelihood for moisture stress, and is consistent with studies that cite high risk to jack pine budworm (Jones and Campbell 1986), and frequent outbreaks with drier sites (Volney and McCullough 1994).

Hazard at all levels was associated with jack pine stands (Table 4c). Low hazard was also associated with the other species that occurs in the study area. Pure jack pine was predominant, and, therefore, there was little opportunity for hazard ratings to be assigned to mixed stands that comprise jack pine.

Low hazard was associated with stands at age-class midpoints of 45 and 55 years, medium hazard at 85 and 95 years, and high hazard at 55 and 85 years (Table 4). The association of the older stands with medium and high hazard is consistent with mature jack pine stands that are reportedly more vulnerable than younger stands (Dixon and Benjamin 1962). The high hazard at 55 years, however, may be too liberal and is attributed to the 4 points

assigned for hazard (Table 3). There is a relatively large proportion of jack pine in the 55-year age class that may only be 10-m in height (Fig. 3). More than half the 10-m stands, however, also occur in the C and D crown closures that were assigned 3 and 4 hazard points, respectively. These results suggest further review of the hazard point rating system for age and crown closure is warranted.

For stand height, low hazard was associated with the shorter stands of 5 and 10 m (Table 4e; Fig. 3). Medium hazard stands were associated with 15- and 20-m stands, and high hazard was associated with 10- and 20-m stands. The low and medium hazard-rated stands appear consistent with previous reports that describe the general characteristics of vulnerable stands (Dixon and Benjamin 1962; Kulman et al. 1963). Association between high hazard and 10-m stands requires further review because the result was likely influenced by the hazard points assigned to age and crown closure.

The associations between crown closure and hazard reflect the points assigned for different crown closure classes (Table 3, 4f). High hazard was associated with C and D crown closure stands because they were assumed to contain greater volumes than more open stands, and would have

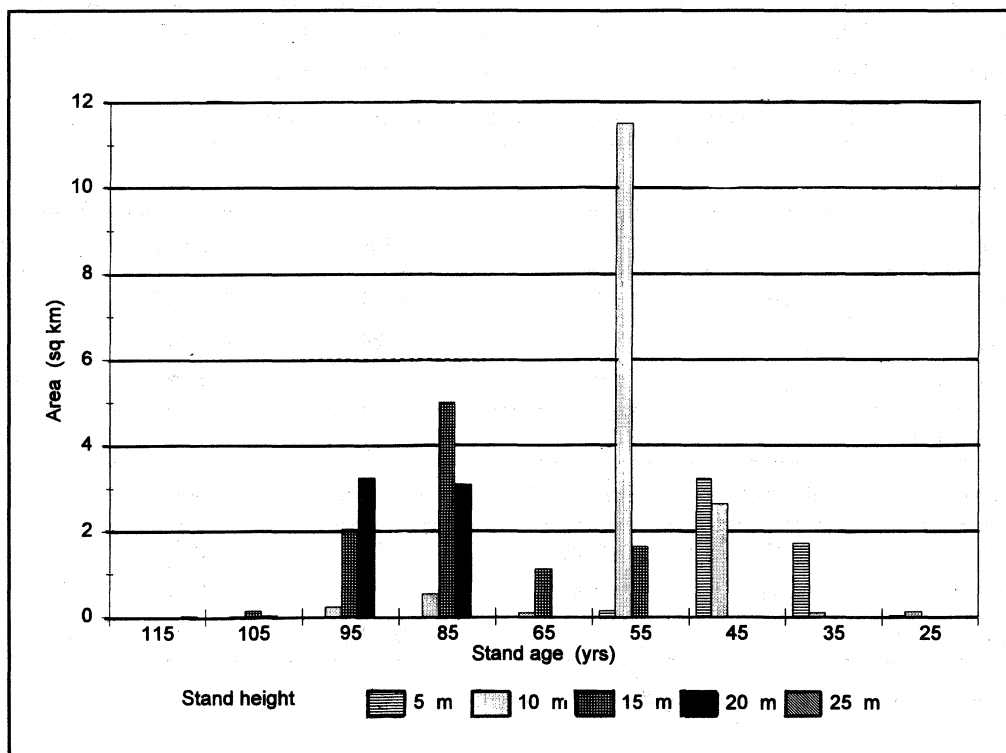


Figure 3. Total area of stand height by stand age.

more value at risk (Knowles 1991). This assumption was evaluated by assessing the distribution of crown closure by stand height (Fig. 4). The C crown closure stands were prevalent for stands ranging from 10 to 20 m in height, and the D crown closure stands were prevalent for stands 5 to 10 m in height. There were more stands in the A and B than D crown closures with 15- to 20-m heights. Thus, the 4 hazard points assigned to the D crown closure do not correspond to the structure of mature stands in Saskatchewan that tend to comprise mostly A, B, and C crown closures. There may also be differences in how crown closure is interpreted between Manitoba and Saskatchewan. Crown closure 4 in Manitoba is commonly associated with mature stands with large trees, but is similar by definition to D crown closure in Saskatchewan (Gillis and Leckie 1993).

### CONCLUSIONS

A stand's vulnerability may be considered as the sum of characteristics, including stand structure and environment, that predispose it to damage during an attack of a given severity (Gagnon and Chabot 1990). Hazard rating that is based on characteristics of the forest should incorporate knowledge about the relationships between vulner-

ability and stand structure. In this study, an evaluation of the hazard rating system that was modified for the Saskatchewan forest inventory was undertaken. Jack pine budworm damage (Fig. 1) was not statistically associated with stand hazard (Fig. 2), and this was attributed to the rules used to assign points during hazard rating. The species and drainage map associations with hazard, were consistent with the literature that generally describes the stands that would sustain damage (Dixon and Benjamin 1962; Kulman et al. 1963; Volney and McCullough 1994). There were deviations, however, with stand age and crown closure. Knowledge about the structure of mature stands that are at greatest risk is needed and should be incorporated into the hazard rating system. Results from this study suggest there was some difficulty in transferring a hazard rating system from one provincial jurisdiction to another. The system devised in Manitoba combines stand characteristics as measures of vulnerability and timber volume at risk, albeit, in relative rather than in quantitative terms. This system is not directly compatible to the Saskatchewan inventory system and is in part, due to differences in assessing crown closure.

The use of map data in a GIS with spatial analysis methods offers an approach to develop the relationships between hazard and vulnerability

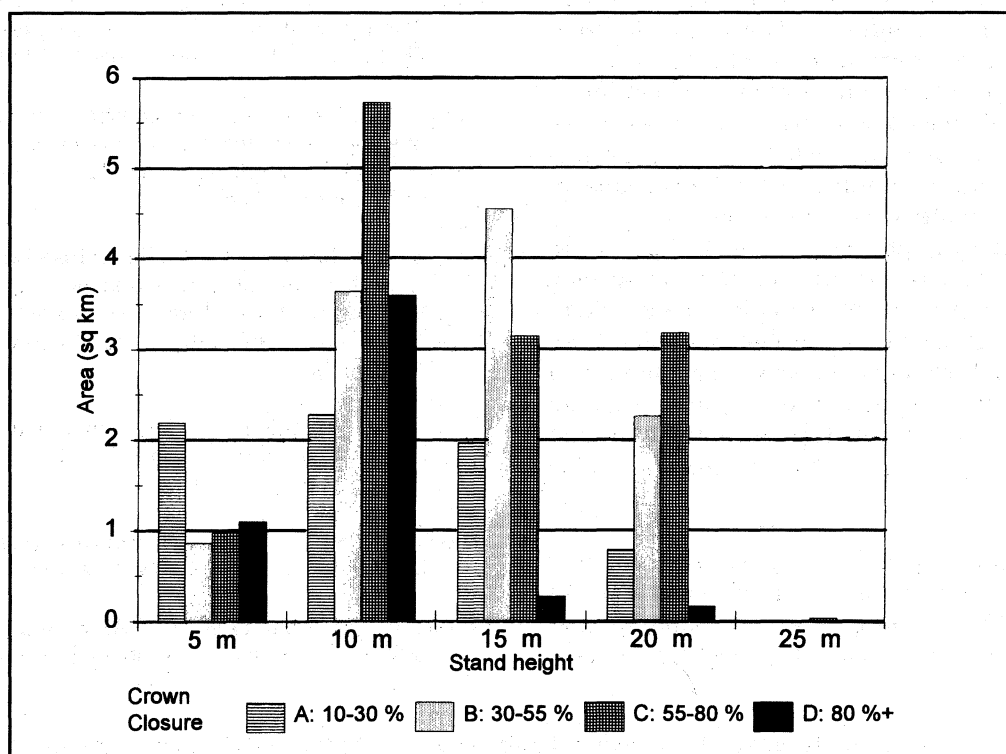


Figure 4. Total area of crown closure by stand height.

with stand characteristics. This provides the vehicle to develop and validate the hazard rating system before linking the hazard classes to damage impact on stand volumes. Together, this will provide one component of the JPBDSS, a tool that is intended to assist managers in determining planning options that will reduce future losses to the jack pine timber supply.

### FUTURE RESEARCH AND DEVELOPMENT

The following three points are suggested for future work that may improve upon the knowledge of stand vulnerability and techniques for hazard rating stands for jack pine budworm damage:

1. The refinement of any hazard rating system for jack pine budworm must be undertaken in terms of stand characteristics (e.g., stand origin) that are related to vulnerability to budworm damage. Spatial analysis provides the vehicle to test hypotheses and explore these relationships. Once the hazard rating system has been defined, quantitative data on impact to stand volumes could be linked to hazard so that pest management options and their associated costs could be evaluated.
2. The degree to which the relationships above can be defined is influenced by the classification systems used in production of the forest inventory map. Further improvement in identifying vulnerable stands will only be possible as these systems become more detailed. Due to increasing demands for information in forest management, inventory classification systems are changing by requiring existing attributes to be mapped to a larger number of more specific classes. In Alberta for example, crown closure is being reviewed for possible expansion from four broad classes to ten classes that range from zero to 100%<sup>2</sup>. Future inventory maps that are based on more detailed specifications may help to more specifically characterize vulnerable stands.
3. GIS technology and user expertise is moving from spatial summarization to spatial analysis (Bailey 1994). GIS, however, have more specialized tools for summarization than for analysis.

Summarization has been defined as the "selective retrieval of spatial information within defined areas of interest, and the computation, tabulation or mapping of those summary statistics" (Bailey 1994). Statistically based spatial analysis extends beyond summarization by providing a suite of tools for "further understanding of relationships between patterns or to provide models for their prediction" (Bailey 1994). A hazard rating model to predict potential impact based on stand characteristics may be one application of these techniques that merits consideration.

### ACKNOWLEDGMENTS

Partial funding and support for this project, including the acquisition of aerial photographs and field survey data was from the Canada-Saskatchewan Forest Resources Development Agreement. Appreciation is expressed to Mr. J. Benson, Forestry Branch, Saskatchewan Environment and Resources Management, for GIS data of the Torch River Provincial Forest. The anonymous reviews of this manuscript are greatly appreciated, and helped improve the final paper.

### REFERENCES

- Ashley, M.D.; Rea, J.; Wright, L. 1976. Spruce budworm damage evaluations using aerial photography. *Photogramm. Eng. Remote Sens.* 42(10): 1265-1272.
- Bailey, T.C. 1994. A review of statistical spatial analysis in geographical information systems. Pages 13-44 in *Spatial analysis and GIS*. Taylor and Francis, Bristol, Pennsylvania.
- Cerezke, H.F.; Emond, F.J. 1989. Forest insect and disease conditions in Alberta, Saskatchewan, Manitoba and the Northwest Territories in 1987. For. Can., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-300.
- Clark, W.A.V.; Hosking, P.L. 1986. *Statistical methods for geographers*. John Wiley and Sons, New York, New York.
- Dixon, J.C. 1985. Jack pine budworm surveys. Dep. Biol., Univ. Wisconsin, Eau Claire, Wisconsin.
- Dixon, J.C.; Benjamin, D.M. 1962. An evaluation of susceptibility of jack pine forests to defoliation by the

<sup>2</sup>D.J. Morgan, Alberta Environmental Protection, Lands and Forest Services. Personal communication. December 8, 1994.

- jack pine budworm. Univ. Wisconsin, Madison, Wisconsin. For. Res. Note 78.
- Doliner, L.H.; Borden, J.H. 1984. Pestterms: a glossary of forest pest management terms. B.C. Minist. For., Victoria, British Columbia. Pest Manage. Rep. 3.
- Gagnon, R.R.; Chabot, M. 1990. A system to evaluate spruce budworm stand vulnerability: principles and use. Can. For. Ind. 110(4):28-39.
- Gillis, M.D.; Leckie, D.G. 1993. Forest inventory mapping procedures across Canada. For. Can., Petawawa Nat. For. Inst., Petawawa, Ontario. Inf. Rep. PI-X-114.
- Gross, H.L. 1992. Impact analysis for a jack pine budworm infestation in Ontario. Can. J. For. Res. 22:18-831.
- Gross, H.L.; Meating, J.H. 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.
- Hall, R.J.; Titus, S.J.; Volney, W.J.A. 1993. Estimating top-kill volumes with large-scale photos on trees defoliated by the jack pine budworm. Can. J. For. Res. 23:1337-1346.
- Jones, A.C.; Campbell, J. 1986. Jack pine budworm: the Minnesota situation. Pages 7-9 in Jack Pine Budworm Information Exchange, January 14-15, 1986, Winnipeg, Manitoba. Manit. Nat. Resour., For. Prot. Branch, Winnipeg, Manitoba.
- Kabzems, A.; Kosowan, A.L.; Harris, W.C. 1986. Mixed-wood section in an ecological perspective Saskatchewan. Sask. Parks Renewable Resour., For. Div., Prince Albert, Saskatchewan. Can. For. Serv., Tech. Bull. 8.
- Knowles, K. 1991. Jack pine budworm decision support system status report. Manit. Nat. Resour., For. Prot. Branch, Winnipeg, Manitoba. Int. Rep.
- Kulman, H.M.; Hodson, A.C.; Duncan, D.P. 1963. Distribution and effects of jack pine budworm defoliation. For. Sci. 9(2):146-156.
- MacLean, D.A. 1990. Impact of forest pests and fire on stand growth and timber yield: implications for forest management planning. Can. J. For. Res. 20:391-404.
- Maffei, H.M.; Arena, J.V. 1993. Forest insect and disease risk and occurrence maps in GIS: application to resource analysis. Pages 8-14 in Proceedings: Spatial Analysis and Forest Pest Management. U.S. Dep. Agric., For. Serv., Northeast. For. Exp. Stn., Morgantown, West Virginia. Gen. Tech. Rep. NE-175.
- Mallett, K.I.; Volney, W.J.A. 1990. Relationships among jack pine budworm damage, selected tree characteristics, and *Armillaria* root rot in jack pine. Can. J. For. Res. 20:1791-1795.
- McCarthy, J.; Olsen, C.E.; Witter, J.A. 1983. Assessing spruce budworm damage with small format aerial photographs. Can. J. For. Res. 13:395-399.
- McCullough, D.G.; Marshall, L.D. 1993. Jack pine budworm decision support system: a case study. Compiler 11(1):14-20.
- Minnick, R.F. 1964. A method for the measurement of areal correspondence. Pap. Mich. Acad. Sci. Arts Lett. 49:333-344.
- Moody, B.H. 1986. The jack pine budworm history of outbreaks, damage and FIDS sampling and prediction system in the prairie provinces. Pages 15-22 in Jack Pine Budworm Information Exchange, January 14-15, 1986, Winnipeg, Manitoba. Manit. Nat. Resour., For. Prot. Branch, Winnipeg, Manitoba.
- Moody, B.H. 1989. Forest insect and disease conditions in Canada 1988. Can. For. Serv., Ottawa, Ontario.
- Moody, B.H.; Cerezke, H.F. 1986. Forest insect and disease conditions in Alberta, Saskatchewan, Manitoba, and the Northwest Territories in 1985 and predictions in 1986. Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-276.
- Ostaf, D.P.; MacLean, D.A. 1989. Spruce budworm populations, defoliation, and changes in stand condition during an uncontrolled spruce budworm outbreak on Cape Breton Island, Nova Scotia. Can. J. For. Res. 19:1077-1086.
- Reynolds, H.T. 1977. The analysis of nominal data. Sage Publications, Beverly Hills, California.
- Rowe, J.S. 1972. Forest regions of Canada. Environ. Can., Can. For. Serv., Ottawa, Ontario. Publ. 1300.
- Twardus, D.B. 1985. Surveys and sampling methods for population and damage assessment. Pages 27-42 in Managing trees and stands susceptible to western spruce budworm. U.S. Dep. Agric., For. Serv., Tech. Bull. 1695.
- 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. 1994. Jack pine budworm. Nat. Res. Can., Can. For. Serv., Northwest Reg., North. For. Cent., Edmonton, Alberta. For. Leaflet. 32.

Volney, W.J.A.; McCullough, D.G. 1994. Jack pine budworm population behavior in northwestern Wisconsin. *Can. J. For. Res.* 24:502-510.

# **JACK PINE BUDWORM BIOLOGY AND MANAGEMENT**

Proceedings of the  
Jack Pine Budworm Symposium  
Winnipeg, Manitoba  
January 24-26, 1995

W.J.A. Volney, V.G. Nealis, G.M. Howse,  
A.R. Westwood, D.R. McCullough, and B.L. Laishley, editors

**INFORMATION REPORT NOR-X-342**

Canadian Forest Service, Northwest Region  
1995

This symposium and publication were funded by the  
Canada-Manitoba Partnership Agreement in Forestry