Development and Analysis of a B.C.

Natural Disturbance Database

FII R0-009 Technical Report

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1. Abstract

Natural disturbances such as wildfires and forest insect outbreaks can have a significant impact on forest age structure and species composition; and, therefore, on regional timber supply and habitat availability. Records of fire history and some forest insect and disease outbreaks, including maps of significant events, have been maintained in British Columbia (BC) since the 1920’s but have not readily been accessible to researchers, resource managers or the public.

Beginning in 2001-2002 historical maps of wildfire and insect outbreaks in B.C. were obtained from several sources and digitized, and provincial coverages were compiled for each disturbance agent.

During 2003-2004 the project team:

- updated the fire database with records from national parks in B.C. and the insect database with maps from 1920-1959 annual reports of the Vernon forest insect laboratory, and survey maps for 1998 and 1999 for Cariboo and Kamloops forest regions;
- completed corrections to the attributes of the 1920-1950 fire records with reference to approximately 500 microfilm fire reports and ledgers in the provincial archives;
- completed check of 1950-2000 spatial fire database against point records for completeness and derived estimates for missing polygons
- completed intersection of fire and insect outbreak coverages with BEC and TSA/TFL/protected area and forest region/district coverages to add these attributes to the polygon records.
- compiled all of the insect outbreak attribute data (approximately 300 000 outbreak records) into an MS Access database;
- uploaded forest insect outbreak spatial and non spatial databases to the PFC Pest Archives web page/ ftp server so that it is publicly available.
- developed a forest fire web map viewer Wildfire Online and installed on the BC Ministry of Forests Protection Branch web site/server.
- carried out an analysis of the effects of changing disturbance rates on lodgepole pine susceptibility to MPB, and an analysis of MPB range expansion in a changing climate
- analysed the distribution of forest fires and forest insect outbreaks and frequencies by biogeoclimatic and administrative unit;
- obtained a copy of the seamless provincial forest inventory and determined the species/ age class distribution by BEC unit as part of an analysis of host susceptibility
- analysed the average and maximum size of fire and insect outbreak polygons by forest district as part of a review of the 60/40 harvest rule for the BC Ministry of Forests Forest Practices Branch.
- provide natural disturbance data to 16 researchers and resource managers for special projects.
- provided a forest fire history animation and interview for a Westland television program on forest fire for the Knowledge Network
- made 2 presentation, prepared two papers using project data, and one article about the project
Further research is needed to quantify disturbance rates in relation to the amount of susceptible host species by ecological unit, and to explore means of incorporating natural disturbance risks in land management planning.

A better understanding of the probability, frequency, pattern, and interactions between natural disturbance events (fire, insects) will help in the development of sustainable management plans and practises in British Columbia. Greater public awareness of the scale of natural disturbances will help gain support for the management of disturbance events/outbreaks.

**Keywords:** Natural disturbance, wildfire atlas, fire history, forest insect and disease outbreaks, forest insect and disease surveys

2. **Introduction**

Natural disturbances such as wildfires and forest insect outbreaks are important to forest dynamics. They can significantly effect forest age class structure and species composition and so regional timber supply and habitat availability. Knowledge of the natural disturbance pattern, frequency and the probability of occurrence is needed to develop sustainable forest management plans and practises. Historic natural disturbance regimes also provide a benchmark against which to evaluate contemporary forestry practises and a basis to develop practises which better emulate natural disturbance; including cut block shape, harvest distribution in time and space, and seral stage distribution. Approaches and techniques to incorporate natural disturbance knowledge into forest management plans are also needed.

In British Columbia, there is wealth of data on natural disturbances in historical records. Between 1925-1988 the BC Ministry of Forests (BCMF) maintained a central map atlas of wildfires (>20 ha). Also, between 1920-1996 the Canadian Forest Service (CFS) mapped significant insect outbreaks. However, these data are not widely available either within or outside these agencies.

3. **Objectives**

This project has five objectives:

1. To develop a digital atlas of major natural disturbances in BC forests using all available wildfire and forest insect outbreak survey data.
2. To make databases available to other researchers, practitioners and the public.
3. To determine the frequency, probability, variation, and pattern of disturbance from analysis of historical fire and insect outbreak data; and the relationship of disturbance to topography, climate, and stand characteristics.
4. To develop and demonstrate techniques to incorporate disturbance information into forest resource management; including timber supply analysis.
5. To communicate knowledge of natural disturbance patterns in B.C. to a wide number of groups including other researchers, resource management practitioners and the public.
3.1 Project Objectives 2003-2004

The project objectives for 2003-2004 (year 3) were to:

1. Update spatial natural disturbance database with recently-acquired data.
2. Enhance database access and visualization.
3. Determine the risk of fire and insect outbreak by biogeoclimatic/administrative analysis units.
4. Investigate interaction between forest fire and forest insect outbreaks.
5. Investigate approaches and methods of incorporating natural disturbance knowledge in operational forest management plans for two pilot areas (Lignum IFPA, Canfor TFL 48).

4. Methods

4.1 Update spatial natural disturbance database

The database which was largely compiled in the first year of the project was updated with fire and insect data from three additional data sources that were recently located.

4.1.2 Vernon Lab forest insect outbreak maps.

Approximately 100 forest insect outbreak maps contained in annual reports of the federal Vernon Forest Insect Laboratory from 1920-1959 were scanned, the scanned images were rubber-sheeted and registered to digital 1:20 000 forest cover maps, and the perimeters traced with heads-up digitizing.

4.1.2 National Parks fire history data

Digital forest fire history files were obtained from Parks Canada for Kootenay, Glacier, Mt. Revelstoke, and Yoho National Parks and integrated into the fire database.

4.1.3 Convert 1997-1998 provincial forest insect survey data to ArcInfo format

The Canadian Forest Service Forest Insect and Disease Survey stopped carrying out provincial aerial overview surveys of forest insect outbreaks in 1996. The BC Ministry of Forests began provincial aerial overview surveys in 1999. However, forest insect outbreak surveys were carried out in Cariboo and Kamloops Region in 1997 and 1998 and were compiled in MicroStation format. We acquired the digital files and had them converted to ArcInfo format by a contractor, HR GIS Solutions of Victoria.

4.2. Enhance database access and visualization.

Fire and insect outbreak data were provided directly to 16 researchers and resource managers for special projects (Appendix B.) Three tools were developed to makedatabases and visualizations publicly available.

4.2.1 FTP site for forest insect coverages
All forest insect coverages were converted to ArcInfo exchange format and put on the Pacific Forest Centre Pest Archives site so that they are publicly available. The web page and data description were created to describe the data and downloading procedures.

4.2.2 Forest fire web map viewer

A web map viewer was developed by a contractor, Pacific Geotech to display the forest fire history maps and installed on the BC Ministry of Forests Protection Branch server. The web map viewer was developed in ArcIMS format. A web page was also created that describes the data.

4.2.3 MS Access forest insect database

Each forest insect outbreak polygon in the database has attributes of: insect species, attack severity, size, and geographic position (lat/lon). These coverages were intersected with biogeoclimatic (BEC) unit, TFL/TSA/protected area and Forest Region/District coverages in order to create ecological and administrative unit attributes for the polygons. The attribute tables for each insect and each year were concatenated into a single file and converted to MS Access format containing approximately 300,000 records. This allows users to query forest insect outbreak history by administrative and ecological unit and insect species.

4.3 Risk of fire and insect outbreak by biogeoclimatic/administrative analysis units.

As stated above, the fire and forest insect coverages were intersected with biogeoclimatic (BEC) unit, TFL/TSA/protected area and Forest Region/District coverages in order to create ecological and administrative unit attributes for the polygons.

Permission was obtained to gain access to a seamless forest inventory of British Columbia from the Ministry of Sustainable Resource Management. This project is one of only 9 projects that have been permitted access to these data. The seamless inventory is unique in that it includes data for Tree Farm Licenses and protected areas. Where data were missing for private land attributes such as species and age are estimated from remote sensing imagery. A copy of the 16 GB database was obtained in February 2004.

Intersections were carried out to determine the amount by age class of lodgepole pine, spruces, hemlocks, true firs, Douglas fir, aspen and poplars as primary to fourth species in a stand by BEC units. These tree species are the major hosts for the ten major forest insect species being examined. Essentially we are determining the size of the susceptible host population by age class by BEC unit.

Insect outbreak probabilities were then normalized by the amount of susceptible host. In order to determine the amount of susceptible age host in each year, an age class backcasting model needs to be used. This work is ongoing. When age class has be estimated for each primary species a life table method will be applied to estimate statistical hazard rates.
4.3.1 Climate change and mountain pine beetle range expansion

A study was carried out to determine if the range of mountain pine beetle has expanded over the period of historical record and if the risk of mountain pine beetle outbreak is increasing due to climate change. Essentially this consisted of using historical climate data to derive climatic susceptibility index surfaces using a spatial interpolation procedure. These climate surfaces were intersected with the coverages of mountain pine beetle outbreak. If mountain pine beetle occurs in areas that with a historically unsuitable climate this is evidence of range expansion. Methods are given in more detail in the paper in Appendix C.

4.4 Interaction between forest fire and forest insect outbreaks.

The mountain pine beetle coverages were intersected with the mountain pine beetle coverages to determine which mountain pine beetle affected stands had an association with fire. A program was written in the SAS language to determine the amount of area burned following mountain pine beetle attack and the time between mountain pine beetle attack and forest fire.

4.4.1 Influence of forest fire on forest age class dynamics and susceptibility to mountain pine beetle.

A study was carried out to examine the influence of forest age class dynamics on susceptibility to mountain pine beetle. The fire coverages were intersected with the pine inventory coverages to determine the burning rate in pine forests. The present age class distribution was backcast by employing a disturbance model that used the burning rate. The methods are fully described in the paper in Appendix D.

4.5 Approaches and methods of incorporating natural disturbance knowledge in operational forest management plans

The proposed work on incorporating natural disturbance knowledge into operational plans in the Lignum IFMA and TFL 35 had to be postponed as explained in the annual progress report. However, we undertook a project with the BC Ministry of Forests Forest Practises Branch to compare natural disturbance opening sizes with current harvest block sizes on a Forest District basis. This is part of a review of the 60/40 harvest rule.

The fire and insect coverages, were intersected with Forest Region/District, TFL/TSA and BEC coverages as described in section 4.2 so that these variables were included in the attribute tables. All of the attribute tables were concatenated into single fire and insect outbreak ascii files. A SAS program was written to process the data and tabulate the average and maximum disturbance size by Forest District.
5. Results and Discussion

5.1 Spatial natural disturbance database updates

The fire database was updated with digital records from Kootenay, Yoho, Mt. Relevestoke and Glacier National Parks. Extensive quality assurance work was undertaken to verify attributes (fire number, ignition date) on the 1920-45 line fire maps with reference to microfilm fire reports of the BC Ministry of Forests Protection Branch and fire ledgers in the BC Archives. Approximately 600 fires were investigated of the approximately 10,000 records in database for this period and corrections made where necessary. An extensive comparison of the fire polygons in the spatial database for the 1950-2000 period was made with a non-spatial MS Access database of all fire locations to determine which fires were missing perimeter polygons. It was determined that 1,000 fires > 20 ha were missing a spatial record although these were mostly in the 20 - 40 ha range; there are 100 missing records for fires > 200 ha. This is approximately 20% of the > 20 ha fires in this period. Proxy polygon boundaries were created by buffering the fire location points as circles. The fire portion of the database is thus as complete and stable as is possible.

The forest insect database was updated by adding outbreak maps from the 1920-1959 period from annual reports of the Vernon Forest Insect Laboratory and digital files for Kamloops and Carriboo Regions for 1997 and 1998. The earlier map records are not as comprehensive and have a lower spatial location accuracy than the 1959-1996 provincial aerial overview survey records but they provide useful information on outbreak periodicity, particularly for southern B.C. The insect outbreak portion of the database is thus as complete as is possible.

In recognition of completing the data compilation, an article on the project was published in Information Forestry (Appendix 1) to increase awareness of database availability among resource professionals.

5.2 Enhancements to database access and visualization.

Over the last year we provided draft copies of the fire and insect outbreak database available to over 20 other research groups and resource managers for special projects. Once the fire and insect databases were completed we completed the second phase of the project, making the data freely available to other researchers, resource managers and the public.

5.2.1 MS Access database

The insect outbreak attribute data for all insects (60) and all outbreak years (80) were concatenated into an MS Access database containing approximately 300,000 insect outbreak records. Each record includes the forest insect species, attack year, severity of attack, polygon size (ha), geographic position (lat/long of polygon centroid), BEC unit, TSA/TFL/protected area and Forest Region/District.

The MS Access database allows users to query the forest insect history of a large number of combinations of administrative and ecological units outside of a GIS environment.
5.2.2 FTP site for forest insect coverages

The forest insect outbreak coverages for 12 major insect species were linked to the Pacific Forest Centre Pest Archives site in ArcInfo exchange format so that they are publicly available. A webpage was also created to describe the data and downloading procedures. There are approximately (12 species x 80 years) 800 files available. The remainder of the coverages for other insect species in the database (some 50 minor species) will be concatenated into one coverage per year for all species and added to the site in 2004/2005.

5.5.3 Web map viewers

A forest fire web map viewer was developed to display the forest fire history maps and is installed on the BC Ministry of Forests Protection Branch server. The web map viewer was developed in ArcIMS format. A webpage was also created that describes the data. The web map viewer contains the perimeters for approximately 15,000 fires > 20 hectares which occurred in BC between 1920-2000. Attribute data (fire number, ignition year/month/day, cause, final size, geographic position) are also displayed.

The forest insect data was made available to a parallel forest heal web map viewer developed by the BC Ministry of Forests Forest Practises Branch.

The web map viewers allow resource managers and the public to view the natural disturbance spatial data outside of a GIS for any particular area. This will allow for increased awareness of natural disturbance patterns and risks, such as risk of wildfire in interface areas.

5.3 Risk of fire and insect outbreak by biogeoclimatic/administrative analysis units.

Forest fire and insect outbreak coverages were intersected with BEC unit and TSA/TFL/protected area coverages to allow calculation of disturbance probability. However, most forest insects are species specific and exhibit an age preference. Thus the susceptibility of the forest varies as the age class structure, and to a lesser degree the species composition changes within an ecological region, and varies between ecological region due to difference in species composition and age structure. In order to determine statistical hazard rates by host species, it is necessary to estimate the amount of susceptible host species over time. We obtained a seamless forest inventory of BC and have determined host species and age distribution by BEC unit. We have developed a procedure to backcast forest age structure which was used in the study described in the following section. We will apply the model to estimate age dynamics and then estimate statistical hazard rates use life table analyses early in 2004-2005.

5.3.1 Climate change and mountain pine beetle range expansion

A study was carried out to test the hypothesis that the range of mountain pine beetle has expanded due to climate change. The current latitudinal and elevational range of mountain pine beetle (MPB) is not limited by available hosts. Instead, its potential to expand North and East has been restricted by climatic conditions unfavorable for brood development. We combined a model of the impact of climatic conditions on the establishment and persistence of MPB populations with a spatially explicit, climate-driven simulation tool. Historic weather records
were used to produce maps of the distribution of past climatically suitable habitats for MPB in British Columbia.

Overlays of annual MPB occurrence on these maps were used to determine if the beetle has expanded its range in recent years due to changing climate. An examination of the distribution of climatically suitable habitats in 10-year increments derived from climate normals (1921 – 1950 to 1971 – 2000) clearly shows an increase in the range of benign habitats. Furthermore, an increase (at an increasing rate) in the number of infestations since 1970 in formerly climatically unsuitable habitats indicates that MPB populations have expanded into these new areas. Given the rapid colonization by MPB of former climatically unsuitable areas during the last several decades, continued warming in western North America associated with climate change will allow the beetle to further expand its range northward, eastward and toward higher elevations. A full description of the study is given in Appendix D.

5.4 Interaction between forest fire and forest insect outbreaks.

Forest fire coverages were intersected with pine inventory coverage to determine the annual burning rate in lodgepole pine (Figure 1). Forest fire coverages were then intersected with the mountain pine beetle coverages to determine areas where both fire and mountain pine beetle had occurred. These data were analysed to determine the burning rate following mountain pine beetle outbreak, and the time between mountain pine beetle attack and fire occurrence.

On a provincial basis, the burn rate appears to be lower in mountain pine beetle outbreaks than in pine forest as a whole (Table 1). However, these data are inconclusive. There may have been more intensive fire suppression and a lower burning rate in southern areas affected by mountain pine beetle than in northern areas which were not affected by mountain pine beetle during the 1959-2000 period. Also, it is not known how much of the mountain pine beetle affected area was salvage logged, changing the fuel properties. More intensive analysis will be carried out in 2004-2005 on a regional basis. However, there appears to be little evidence for a significant burn rate following mountain pine beetle attack.
Table 1. Burn rate in pine forest and pine forest following MPB outbreak in BC during 1959-2000.

<table>
<thead>
<tr>
<th></th>
<th>Area (ha)</th>
<th>Area burned (ha)</th>
<th>Burn rate (% annual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine leading forest</td>
<td>14 000 000</td>
<td>735 869</td>
<td>0.128</td>
</tr>
<tr>
<td>Cummulative mountain</td>
<td>4 050 159</td>
<td>31 594</td>
<td>0.019</td>
</tr>
<tr>
<td>pine beetle outbreak</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An average annual area burned by year following mountain pine beetle attack was also determined from the intersection of the fire and mountain pine beetle outbreak coverages. The time since mountain pine beetle attack was determined. Because of the relatively short observation period (40 years) there are decreasing number of observations with years since attack. Nevertheless, there seems to be a trend to a higher burning rate in the first 3 years, and in years 10-17 following mountain pine attack. This is consistent with current beliefs about the flammability of the lodgepole pine fuel complex following mountain pine beetle attack: flammability increases in the first few years when trees have dead red needles, decreases after the needles have fallen, then increases again as the dead trees fall down.
5.4.1 Disturbance, pine forest age dynamics, and mountain pine beetle susceptibility

During the past 85 years, there have been four large-scale outbreaks by the mountain pine beetle (*Dendroctonus ponderosae*) (MPB) in the pine forests of British Columbia. Using contemporary forest inventory data in combination with wildfire and logging statistics, we developed a simple age-class projection model to estimate changes in pine age-class distribution between 1910 and 2110. We compared past and present MPB activity to forest age structure, and projected future forest conditions relevant to MPB susceptibility. “Backcast” forest conditions suggest that during the early 1900s, approximately 17% of pine stands were in age classes susceptible to mountain pine beetle attack. Since then, the amount of area burned by wildfire in British Columbia has significantly decreased. This reduction in wildfire has resulted in an increase in the average age of pine stands to the present day such that approximately 55% of pine forests are in age classes considered susceptible to MPB.

At the present rate of disturbance, average stand age is forecast to continue to increase, but the amount of susceptible pine will decline following 2010 and stabilize at about 18% by 2110. The extent of MPB outbreaks was correlated with the increase in amount of susceptible pine during 1920-2000. However, outbreak extent increased at a greater rate than the increase in susceptible forest indicating that other factors such as climate may be affecting MPB epidemics.

Theoretical fire-return cycles of 40 - 200 years would generate a long-term average susceptibility range of 17 - 25% over large areas. This suggests that the extent of age-related, MPB-susceptible pine forests in British Columbia is beyond the natural range of variability at provincial scale. A full description of the study is given in Appendix E.
5.5 Methods of incorporating natural disturbance knowledge in operational forest management plans

We were delayed in examining natural disturbances in two pilot areas, Lignum IFMA and TFL 35 and incorporating natural disturbance information into operational planning processes due to time required to quality assure the disturbance data. A preliminary analysis of fire incidence in the Lignum IFMA was carried out, and work will continue with Lignum in 2004/2005. An NSERC proposal was submitted to examine with Drs. Nelson, Kimmins and Seely of the University of British Columbia to support further work on natural disturbance risks in TFL 35.

5.5.1 Natural disturbance sizes
The average and maximum size of forest fires and of the ten most significant forest insect outbreaks was determined by Forest District using the fire database and concatenated insect database in 5.2.1. A summary of disturbance sizes is given in Appendix E. This was done in order to compare natural disturbance sizes with the present harvesting practises as part of a review of the 60/40 harvest rule. Forest disturbances have a much greater range in size than harvest blocks and larger maximum sizes.

6. Conclusions and Management Implications

1. Updated spatial natural disturbance database.

The completed natural disturbance database is one of the most longest and geographically extensive records of disturbance history in North America, containing some 15,000 forest fire and 300,000 insect outbreak polygons and associated attributes. This will be an invaluable data source for researchers studying natural disturbance and managers seeking to emulate natural disturbance patterns or appraise natural disturbance risks.

The MS Access version of the database will allow users to query pest history by administrative and ecological unit. This will be an important data source for forest companies that have assumed responsibility for forest health planning for Defined Forest Management Areas.

2. Database access and visualization.

The database visualization tools provided by this project will allow for greatly increased awareness of natural disturbance risks. For example, the forest fire web map viewer, Wildfire Online, helps to address one of the recommendations of the Auditor General's report on interface fire risk, to increase public awareness of fire risk.

During 2004-2005 we provided natural disturbance data to 24 other researchers and resource managers. However, now that the data are available on the PFC Pest Archives ftp site the data will be publicly available.

3. Risk of fire and insect outbreak by biogeoclimatic/administrative analysis units.
The analysis of fire and insect outbreak probabilities will be an important data source for fire and forest health management planning. The determination of fire and insect outbreak probabilities by administrative and BEC units will allow these risks to be explicitly accounted for in timber supply analysis.

4. Interaction between forest fire and forest insect outbreaks.

Determining the interaction between forest fire and mountain pine beetle was an important recommendation of the Roger's report. Knowledge of fire risk in mountain pine beetle areas will help to guide fire management planning and resourcing levels for affected areas. Preliminary analyses in 2003-2004 indicate that the rate of burning in areas affected by mountain pine beetle during 1959-2000 was relatively small, perhaps because of intensive suppression, but that the burning rate was variable with time since outbreak. This preliminary work will help to guide more detailed analysis in 2004-2005.

5. Approaches and methods of incorporating natural disturbance knowledge in operational forest management plans.

The average and maximum size of fire and insect disturbances has a much larger range than harvest blocks. This provides important information to the regulation of harvest block sizes and distribution.

Acknowledgements

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Literature Cited


New database defines forest-disturbance patterns

A database developed by the Canadian Forest Service and the British Columbia Ministry of Forests will help researchers and planners predict the future by understanding the past. The Natural Disturbance Database digitally catalogs information from more than 15,000 wildfires and 300,000 insect infestations that occurred in British Columbia during the last 80 years. The compiled data makes it possible to recognize patterns and peer into the future.

“As we begin to understand what happened in the past with fire or infestation,” says Pacific Forestry Centre Forestry Officer Steve Taylor (staylor@pfc.cfs.nrcan.gc.ca), who leads the project, “we can use that information to help us assess what may happen, in terms of probability of disturbance, size, and even its shape. We can better understand how disturbance risk is affected by weather, topography, and different forest characteristics, like forest composition and age.”

Beginning in the 1920s, provincial officials maintained an atlas of wildfires larger than 20 hectares, and federal forestry officers mapped major infestations by insects such as mountain pine beetle and spruce budworm. Until this project brought it to light, much of the information was stored in offices and filing cabinets, and few people knew it existed.

The database’s importance became clear last summer, when wildfire swept through the Kelowna area, burning thousands of hectares of forest, forcing 25,000 people to evacuate, and destroying hundreds of houses. “Everyone was surprised by the size of that fire,” Taylor says. “But if we look at the map of historical fires, we can see that other fires just as large have occurred there again and again.”

The data being made available will not only help municipalities and governments assess fire risk in places where forest meets suburbia, it will allow researchers to analyze how the range of mountain pine beetle, an insect infesting more than 4.2 million hectares of the province’s forests, is changing, and whether fire risk increases in infested areas. The database will also help forest managers mimic effects of natural disturbances as companies try to manage forests more sustainably.

Forest managers will be able to use the information to refine timber-supply models. “Right now it’s really difficult to estimate timber losses due to natural disturbances,” says Taylor. “Current timber-supply models only inexacty account for these losses. The database will allow for a more quantitative approach.”

“The power of this tool in developing a better understanding of disturbance and its relationship to other ecological processes has tremendous potential,” says Bruce Blackwell, a consultant with BA Blackwell and Associates, of Vancouver, who used the database when he was assessing the long-term impacts of fire risk in the southern interior. “I expect the database will be invaluable in the assessment of factors other than fire, including forest health and risk assessment of important resource values.”

Three years in the making, the database is undergoing testing and analysis by Taylor and his team. Elements of it are posted on the project website, with more and more being made available as analyses are completed. Within a year, everything will be available.

The Pacific Forestry Centre website features animated maps of areas affected by the province’s 12 biggest natural disturbance agents. Visit www.pfc.cfs.nrcan.gc.ca/fires/disturbance

From the cover:
The Natural Disturbance Database contains information from thousands of fires, including the Ware Creek fire, which cleared a mountainside in northeastern British Columbia in the mid-1990s.

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Appendix C. Wildfire Online Webmap Viewer Webpage and Examples

BC WILDFIRE HISTORY ONLINE

BC Wildfire History Online displays the perimeter locations of the approximately 15,000 wildfires that have occurred in British Columbia since 1917 that were greater than 20 hectares in size. While these are only about 5 percent of the total number of wildfires that occurred in BC during this period, they represent about 98 percent of the total area burned. The fire identification number, date of ignition, probable cause and final size is also available for each fire by clicking within the fire perimeter while using the “Identify” feature. BC Wildfire Online is one of the most complete and significant records of wildfire history in North America.

Click [here](http://example.com) to view BC Wildfire History Online.

![BC Ministry of Forests fire atlas map of the West Kootenays area, 1920-1950. Lightning caused fires are yellow and person-caused fires are red.](image)

About the Fire Maps

Beginning in 1917, the BC Ministry of Forests completed a report for each wildfire actioned, and mapped fires greater than 20 hectares. A central “fire atlas” was maintained until 1987 whereby the fire map boundaries and the fire ID number were transferred to a set of base maps. The fire reports and fire atlas are a record of the fires discovered and/or actioned by the BC Ministry of Forests. Fires in remote areas that were not discovered, and fires that occurred in the Railway Belt (federal land extending out 32-km on both sides of the CPR right-of-way) until 1930 and in national parks up to the present day were not included.

Large wildfires are often visible in aerial photography and satellite imagery for several years afterwards due to changes in vegetation cover. Beginning in the 1960s wildfires greater than 5 ha were also recorded on forest cover maps during forest inventory updates. These boundaries were usually taken from air photographs using photogrammetric methods.
About 90% of the fire perimeters in BC Wildfire Online were digitized from the fire atlas and individual fire reports, 4% of the perimeters were captured from forest inventory maps and satellite imagery, and 6% were represented as circles or ovals if no map was available. Because most of the original maps were sketch maps, the accuracy of the fire perimeter locations is much less than would be expected with most conventional GIS databases. As well, unburned remnant areas within wildfires were not usually mapped unless the fires and the remnants were very large, so the maps overestimate the actual area burned in each fire.

Acknowledgements

The wildfire polygon database was compiled by the Canadian Forest Service and the BC Ministry of Forests Research Branch and was funded in part by the B.C. Forest Innovation and Investment Account through the BC Natural Disturbance Database Project
http://www.pfc.cfs.nrcan.gc.ca/fires/disturbance/index_e.html
Appendix D. MPB Symposium Paper: Disturbance, forest age, and mountain pine beetle outbreak dynamics in BC: A historical perspective

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Abstract

During the past 85 years, there have been four large-scale outbreaks by the mountain pine beetle
(Dendroctonus ponderosae) (MPB) in the pine forests of British Columbia. Using contemporary forest inventory data in combination with wildfire and logging statistics, we developed a simple age-class projection model to estimate changes in pine age-class distribution between 1910 and 2110. We compared past and present MPB activity to forest age structure, and projected future forest conditions relevant to MPB susceptibility. “Backcast” forest conditions suggest that during the early 1900s, approximately 17% of pine stands were in age classes susceptible to mountain pine beetle attack. Since then, the amount of area burned by wildfire in British Columbia has significantly decreased. This reduction in wildfire has resulted in an increase in the average age of pine stands to the present day such that approximately 55% of pine forests are in age classes considered susceptible to MPB. At the present rate of disturbance, average stand age is forecast to continue to increase, but the amount of susceptible pine will decline following 2010 and stabilize at about 18% by 2110. The extent of MPB outbreaks was correlated with the increase in amount of susceptible pine during 1920-2000. However, outbreak extent increased at
a greater rate than the increase in susceptible forest indicating that other factors such as climate may be affecting MPB epidemics. Theoretical fire-return cycles of 40 - 200 years would generate a long-term average susceptibility range of 17 - 25% over large areas. This suggests that the extent of age-related, MPB-susceptible pine forests in British Columbia is beyond the natural range of variability at provincial scale.

**Introduction**

In forests originating from age-independent stand-replacing disturbance processes such as wild fire, the rate of disturbance is the key determinant of forest age dynamics. Where fires occur randomly in space at a more or less constant rate, and stands have an equal probability of burning irrespective of age and location, forest age structure will reach a steady state approximated by the negative exponential distribution (Van Wagner 1978; Li and Barclay 2001). By contrast, in forests where tree age- or size-dependent disturbance processes predominate, such as clearcut harvesting or forest insect mortality, the forest age structure determines the maximum potential disturbance rate. No matter the type or pattern of disturbance, forest age distributions can been seen as exhibiting a kind of ecological memory (Peterson 2002). Therefore, when switching between age-independent and age-dependent disturbance regimes it may be many decades before the forest age structure reaches a new quasi steady state.

Although logging began in British Columbia over 100 years ago, our forests are still in transition from an unmanaged state influenced by various natural disturbance processes to a managed condition in which we attempt to suppress natural disturbances and impose forest harvesting as the dominant disturbance regime. In the lodgepole pine forests of BC, the effects of changing the disturbance regime are playing out on a vast scale.
Pine stands cover some 14 million hectares of forest land in British Columbia (BC Ministry of Forests 1995). Five pine species, lodgepole, ponderosa, western white, whitebark, and limber occur in BC but lodgepole pine is by far the most abundant by area. Lodgepole pine stands in BC are almost entirely of fire origin and principally from stand replacing crown fires, although there is evidence of a surface fire regime in lodgepole pine stands on the dry cold Chilcotin plateau in central BC (unpubl. data). Lodgepole pine trees are easily killed by fire; however, in the process seeds are released from serotinous cones. Following crown fires where the majority of trees are killed, virtually even-aged pine stands are usually re-established within a few years. Fire frequency varies throughout the range of lodgepole pine from less than 100 years to over 500 years (Brown 1975). Based on an analysis of forest inventory data, Smith (1981) suggested that the average fire-cycle in lodgepole pine forests in BC was about 60 years.

Forest fire suppression began in BC approximately 100 years ago. The effectiveness of fire suppression is widely believed to have increased in the 1960s. By 2002, the BC Ministry of Forests average annual initial attack success rate (fires constrained to < 4 ha in size) was 95% (1992-2002 average)\(^1\). Logging of lodgepole pine began for railway ties also about 100 years ago but large-scale exploitation for lumber and pulp did not occur until the 1960s. Consequently the disturbance rate across the vast pine forests of B.C. has been greatly reduced from the pre-management level.

Mountain pine beetle is also a major cause of mortality in lodgepole pine. For a mountain pine beetle outbreak to develop, two requirements must be satisfied. First, there must be a sustained period of favourable weather over several years (Safranyik 1978). Factors including summer heat accumulation, winter minimum temperatures, weather conditions during the dispersal period and

\(^1\) BC Ministry of Forests Protection Branch website  http://www.for.gov.bc.ca/protect/suppression/
water deficit influence MPB populations directly through impacts on beetle survival, and/or indirectly through influences to host-tree quality/resistance (Safranyik et al. 1975; Carroll et al., these proceedings). In areas where summer heat accumulation is limited or where winter minimum temperatures are below a critical threshold, MPB infestations cannot establish and persist (see Carroll et al. these proceedings).

The second requirement for outbreak development is that there must be an abundance of susceptible host trees (Safranyik 1978). Since MPB larvae develop within the phloem tissue of their hosts, large-diameter trees with their thicker phloem are the optimal resource for the beetle (e.g. Amman 1972). Shore and Safranyik (1992) have shown that once lodgepole pine stands reach ≥80 years old they are generally the most susceptible to MPB. However, senescing or unthriftly trees tend to have thinner phloem and are thereby less suitable to MPB (e.g. Berryman 1982). Thus, within areas that are climatically benign for MPB, forest age-class structure will be the primary factor influencing host susceptibility and outbreak severity.

Mountain pine beetle infestations have been recorded in southwestern Canada for about 85 years. In 2003, approximately 4 million ha of pine forests in British Columbia were infested by the mountain pine beetle (Dendroctonus ponderosae Hopk.) (MPB) (Ebata, these proceedings).

A better understanding of the historical context of the present epidemic and of the lodgepole pine forest may help to direct longer-term management strategies. In this paper we review the historical distribution of MPB infestations in British Columbia, explore links between disturbance and host susceptibility to MPB, and present a simple age-class projection model to explore the influence of decreased forest fire and other disturbances on the amount of MPB-susceptible pine forests.

**Historical Mountain Pine Beetle Activity**
The mountain pine beetle has been present in BC's forests for millennia. Evidence of MPB infestations from many decades ago has been found directly in lesions on lodgepole pine trees, and dendrochronological studies suggest significant outbreaks from previous centuries (see Alfaro et al., these proceedings). MPB outbreaks were observed directly in the early 1900s by J.M. Swaine (the first Dominion Entomologist) during field surveys in western Canada. Following the establishment of the Dominion Forest Biology Lab in Vernon in 1919, significant outbreaks occurring in southern BC were surveyed and mapped.

In 1959, the Canadian Forest Service, Forest Insect and Disease Survey (FIDS) implemented annual systematic province-wide aerial overview surveys of forest insect outbreaks. Infestations were classified into “low”, “moderate” and “high” severity classes corresponding to <10%, 10-30% and >30% attacked (i.e. red) trees, respectively. The extent of infestations and damage were mapped and summarized each year until 1996. Subsequently, the BC Ministry of Forests took over this function and has carried out annual overview forest health surveys since 1999. In 2001, we completed digitizing the historical MPB outbreak records. The annual overview maps can be viewed at: http://www.for.gov.bc.ca/hfp/FORSITE/overview/webmap.htm; and in animated form at http://www.pfc.cfs.nrcan.gc.ca/entomology/mpb/historical/index_e.html.

The total cumulative area infested by MPB between 1959 and 2002 (i.e. up to and including attacks during 2001) was approximately 4.5 million hectares. Of this, 35%, 25% and 40% of the infested area fell in low, moderate and high severity classes, respectively.

Infestations are summarized by decade in Figure 1 overlayed upon the distribution of stands in which pine species predominate [derived from the 1994 Forest, Range, and Recreation Resource Analysis (BC Ministry of Forests 1995); see below]. Some highlights of recorded infestations in
Significant outbreaks in the 1920s were recorded around Aspen Grove and in the Kettle Valley in lodgepole and ponderosa pine.

In the 1930s and 40s large areas of MPB caused mortality were recorded in Kootenay and Banff National Parks. Smaller infestations were recorded in western white pine in the Shuswap region and in coastal BC.

During the 1950s and 60s, one of the longest duration outbreaks ever recorded (18 years) was observed around Babine Lake and Stuart Lake in north-central BC. A smaller infestation was observed in shore pine (Pinus contorta var. contorta) on Vancouver Island.

Major infestations developed in the 1970s and 1980s on the Chilcotin plateau and in southeastern BC.

During the 1990s, the present outbreak began to develop in north central BC and is the largest recorded outbreak to date.

In total, the forest insect survey records indicate that there have been 4 – 5 significant outbreak periods in BC during the last century. They also suggest that MPB outbreaks have been increasing in the total area affected over time. However, infestations have not occurred throughout the full range of the beetle’s primary host; lodgepole pine (see Fig. 1).

**Forest Fire Cycle Length and Forest Susceptibility to MPB**

We suggest that before management, lodgepole pine forest susceptibility to MPB would have been controlled by the forest fire regime, principally the fire cycle length. By constraining the
window of age-related susceptibility to MPB for lodgepole pine between 80 and 160 years (the latter due to thinning phloem associated with senescence) and applying it to various negative exponential age distributions resulting from different fire cycle lengths we can see that the proportion of stands susceptible to mountain pine beetle increases with fire cycle length to a maximum of 25% with a 120-year fire-return cycle, and then declines (Fig. 2).

**Figure 2.** Relationship between fire-cycle length and the proportion of stands susceptible to mountain pine beetle in forests with a negative exponential age-class distribution.

Examples of age distributions for 60 and 100-year fire-return cycles and a “normal” fully regulated forest with a 100-year rotation length are shown in Figure 3. On average, approximately 17-25% of stands in a lodgepole pine forest would be in age classes susceptible to MPB in a wildfire-dominated disturbance regime with fire-return intervals between 40 and 200 years. This proportion might be exceeded on a regional basis where there is deviation from the negative exponential age-class distribution because of spatial and temporal auto-correlation in wildfire occurrence (e.g. Andison 1996).

**Figure 3.** Theoretical distribution of age classes susceptible to mountain pine beetle in a normal forest with a 100-year rotation, and in forests with 60 and 100-year fire cycles.

**Modelling Historic Forest Age Distribution and Susceptibility to MPB**
To assess past and present MPB activity in relation to forest age structure, and examine projected future forest conditions relevant to MPB, we developed a simple age-class projection model to estimate changes in pine age-class distribution in BC from 1910 to 2110. Two disturbance types,
wildfire and logging, were included in the simulation. Pine age class data were extracted from the 1994 Forest, Range, and Recreation Resource Analysis (FRRRA) (BC Ministry of Forests 1994) for the 1990 base year. The age data were in 20 year classes from 0-140 years, 140-250 years and >250 years. The 140-250 year age-class polygons were randomly reassigned to new 20-year age classes between 140-240 years. It was assumed that 45.0, 29.5, 19.5, 2.5 and 1 % of stands in the 140-250 age class were in the 140-160, 160-180, 180-200, 200-220, and 220-240 age classes, respectively. Andison (1996) derived these proportions by field sampling the stand age of approximately 100 stands between 140 and 250 years old in west-central BC.

The total amount of disturbed area in pine forests was estimated in 20-year periods for the 80 years 1910-1990 from age-class data (assuming that pine forests regenerated immediately following disturbance) modified by disturbance estimates using a backcasting method as follows. Beginning in 1990, the amount of area in each age class was estimated for the prior 20 year period by taking the amount of area disturbed in that time step (the current 0-20 year class) and redistributing it across the other age classes. Wildfires were assumed to occur across all age classes in proportion to the area in each class. Logging was assumed to occur in ≥100-year age classes only and in proportion to the area in each 20-year age class.

The area disturbed by fire in pine forests in BC between 1919-2000 was determined by intersecting coverage of wildfire boundaries in the BC digital fire atlas with the FRRRA pine coverage using a GIS. There is a strong trend in decreasing area burned in pine-dominated forests (Fig. 4).

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2 The "normal" forest is an even-aged forest with an equal amount of area by age class to a fixed rotation age, that is, a rectangular distribution. While rarely achieved, it is the most simple and fully regulated condition and a useful model for comparison.
Figure 4. Area burned by forest fires during 1920-1995 in pine-dominated forests in BC. Annual area burned (solid line), ten-year running average (bold line) and linear regression model (straight line).

The area logged between 1910-1990 was then determined as the difference between the total disturbed area and the burned area, except where historical records indicated that there was no appreciable logging of pine. In forecasting beyond 1990, the age of areas in each age cohort were incremented by 20 years in each time step. It was assumed that the disturbance rate and ratios beyond 1990 were constant and unchanged from the 1970-90 period.

The results of our age class modelling suggest that the amount of pine within the age classes most susceptible to MPB has increased from about 18% to 53% between 1910-1990 (Fig. 5).

Figure 5. Age class distribution of pine forests in BC projected from 1990 inventory data. Age classes susceptible to MPB are shaded (percentage of total provided). The theoretical age distribution resulting from a 60 (solid line) and 100 year (dashed line) fire cycle is shown in the 1910 plot.

The projected future conditions suggest that average stand age will continue to increase under the present disturbance regime until approximately 2010, after which the proportion of susceptible pine is projected to decline to near 1910-levels by 2130 and stabilize at about 18% (Fig. 5).

Plotting the annual MPB outbreak area against the amount of susceptible pine suggests that MPB activity was positively correlated with the increase in the amount of susceptible pine (Fig. 6).

Figure 6. A). Estimated area of MPB-susceptible pine (solid circles - million ha) and of MPB outbreaks (empty circles - thousand ha) in BC B). 10-year running average MPB outbreak area and linear regression model (thousand ha).
However, the average infestation area has increased sharply since 1980 and at a greater rate than the increase in the amount of susceptible pine. This suggests that other factors such as climate that may have been limiting in the past have also become more favorable for MPB epidemics (Carroll et al. these proceedings).

**Conclusions**

There have been at least four major MPB outbreaks during the last 85 years. MPB infestations have been observed in all species of pine, but they are principally found in lodgepole pine and infestation size appears to be increasing. The size of mountain pine beetle infestations varies with short-term changes in weather and long-term changes in host availability. In unmanaged forests with a natural fire regime, the average proportion of MPB-susceptible stands would reach a maximum of 25% given a 100 to 120 year fire-return cycle, declining with more- or less-frequent fires (Fig. 2).

Clutter et al. (1983) state that if the harvest in a fully regulated forest is changed to a new level there are three possible outcomes:

1) The forest structure will reach a new steady state;
2) The forest will be totally depleted;
3) The forest will become unmanaged (the amount of timber lost to natural mortality exceeds harvesting).

The disturbance regime of the pine forests of central BC is in transition from a fire-dominated regime where disturbance is not strongly age-dependent to a condition regulated mainly by harvesting of older stands at lower rate. Backcasting suggests that a large pine age cohort originated around 1880-1920 in BC, in an amount consistent with a 60-year fire-cycle. With the introduction of fire management, these age cohorts have matured and are now susceptible to
mountain pine beetle. At present, the forest age structure is in transition from an approximately negative exponential to an approximately rectangular distribution. Consequently, our analyses suggest that there was approximately 3 times more area of pine in BC in age classes susceptible to MPB in 1990 when compared with backcast estimates for 1910. Currently, depletions by MPB are exceeding depletions by harvesting. In time, given that disturbance rates remain relatively constant, a new quasi steady state with lower susceptibility may be reached. More detailed modelling at a regional scale is needed to define possible future forest structures.

The area of mountain pine beetle infestations was correlated with the estimated amount of susceptible age pine between 1920 and 2000. At the present rate of disturbance, the mean pine forest age will continue to increase, although by 2010 forest age-susceptibility is projected to decline. This decline may be accelerated if the current mountain pine beetle outbreak depletes much of the available host. There may not be a corresponding decline in outbreak severity if climate factors become less limiting in the next decades and the available habitat expands. Safranyik (these proceedings) suggests that in the long-term our focus should be on management of lodgepole pine, not on management of the mountain pine beetle. Understanding the factors influencing lodgepole pine forest dynamics is critical to understanding host susceptibility and the first step in a long-term management strategy.

Acknowledgements

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Figure 1. Historical distribution of mountain pine beetle infestations in British Columbia during 1920-2002 from forest insect survey records.
Figure 2. Relationship between fire-cycle length and the proportion of stands susceptible to mountain pine beetle in forests with a negative exponential age-class distribution.
Figure 3. Theoretical distribution of age classes susceptible to mountain pine beetle in a normal forest with a 100-year rotation, and in forests with 60 and 100-year fire cycles.
Figure 4. Area burned by forest fires during 1920-1995 in pine-dominated forests in BC. Annual area burned (solid line), ten-year running average (bold line) and linear regression model (straight line).
Figure 5. Age class distribution of pine forests in BC projected from 1990 inventory data. Age classes susceptible to MPB are shaded (percentage of total provided). The theoretical age distribution resulting from a 60 (solid line) and 100-year (dashed line) fire cycle is shown in the 1910 plot.
Figure 6. A). Estimated area of MPB-susceptible pine (solid circles - million ha) and of MPB outbreaks (empty circles - thousand ha) in BC. B). 10-year running average MPB outbreak area and linear regression model (thousand ha).
Appendix E. MPB Symposium Paper: EFFECTS OF CLIMATE CHANGE ON RANGE EXPANSION BY THE MOUNTAIN PINE BEETLE IN BRITISH COLUMBIA

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Abstract

The current latitudinal and elevational range of mountain pine beetle (MPB) is not limited by available hosts. Instead, its potential to expand North and East has been restricted by climatic conditions unfavorable for brood development. We combined a model of the impact of climatic conditions on the establishment and persistence of MPB populations with a spatially explicit, climate-driven simulation tool. Historic weather records were used to produce maps of the distribution of past climatically suitable habitats for MPB in British Columbia. Overlays of annual MPB occurrence on these maps were used to determine if the beetle has expanded its range in recent years due to changing climate. An examination of the distribution of climatically
suitable habitats in 10-year increments derived from climate normals (1921 – 1950 to 1971 – 2000) clearly shows an increase in the range of benign habitats. Furthermore, an increase (at an increasing rate) in the number of infestations since 1970 in formerly climatically unsuitable habitats indicates that MPB populations have expanded into these new areas. Given the rapid colonization by MPB of former climatically unsuitable areas during the last several decades, continued warming in western North America associated with climate change will allow the beetle to further expand its range northward, eastward and toward higher elevations.

**Introduction**

Because they are cold blooded, every aspect of an insect’s life cycle is dependent upon temperature. As a consequence, these organisms should respond quickly to changing climate by shifting their geographical distribution and population behaviour to take advantage of new climatically benign environments. Rapid ecological and genetic adaptation by insects in response to global warming has already been documented in Europe (Thomas et al. 2001). However for North America, despite the development of several models predicting climate change impacts (e.g. Logan and Powell 2001), there is little empirical evidence that global warming has affected insect populations.

In long-lived ecosystems such as forests, insects are often primary disturbance agents (e.g. Dale et al. 2001; Logan et al. 2003). The mountain pine beetle (MPB) is one of the most significant sources of mortality in mature pine forests in western North America (Safranyik et al. 1974). MPB will successfully attack most western pines, but lodgepole pine is its primary host throughout most of its range. Although it is widespread – occurring from northern Mexico,
through 12 U.S. states and 3 Canadian provinces – MPB outbreaks in Canada are mainly restricted to the southern half of British Columbia (BC) and the extreme south-western portion of Alberta (note: one outbreak has been recorded in the Cypress Hills at the southern junction of the Alberta – Saskatchewan border). Despite its significant distribution, the current latitudinal and elevational range of MPB in western Canada is not restricted by the availability of suitable host trees. Indeed, lodgepole pine extends North into the Yukon and Northwest Territories, and East across much of Alberta. Instead, the potential for MPB to expand North and East is currently limited by climate (e.g. Safranyik 1978). It is anticipated that under global warming, former climatically hostile environments will become climatically benign allowing MPB to significantly expand its range (Logan and Powell 2001).

Currently, MPB populations are at epidemic levels in British Columbia. Observations suggest that infestations may be occurring in areas previously considered climatically unfavourable (Safranyik et al. 1975). This study was initiated to determine if (i) there has been a shift in climatically benign habitats for MPB during the recent past, and (ii) MPB populations have expanded into these new habitats.

**Methods**

*Climatic suitability for MPB*

To quantify the climatic suitability of habitats for MPB, we adapted a model of the impact of climatic conditions on the establishment and persistence of MPB populations originally developed by Safranyik et al. (1975). The model combines the effects of several critical aspects of climate on the beetle and its host trees (Table 1). It was developed from the analysis of
climatic variables measured at 42 locations for the period 1950 to 1971 (Safranyik et al. 1975). The locations were chosen to represent the historic range of MPB in BC.

An index of climatic suitability for MPB \( (F) \) was derived as follows:

\[
F = \prod_{i} X_1 \times X_2
\]

(1)

where \( P_i \) is the number of years with the joint occurrence of \( P_1 \) through \( P_4 \) in runs of \( \geq 2 \) consecutive years divided by the total number of years (see Table 1). The values of \( F \) range from 0 to 1. Climatic suitability classes (CSCs; Table 2) were created by comparing index values with the frequency of MPB infestations across its historic range (Powell 1966).

**Climate data**

Historic daily weather data (1920 – 2000) for BC were obtained from Environment Canada, Meteorological Services (2002). The number of stations reporting data over the period ranged from 703 in 1920 to 2924 in 1990. To generate a stochastic series of daily values that minimize the effect of short-term weather anomalies and focus on longer-term climatic trends, we first converted the data to monthly normals (30-year means and extreme minima and maxima). We then produced stochastic daily values from the normals using a daily weather generator developed by Régnière and Bolstad (1994).

**Landscape-level simulations**

We constructed landscape-wide projections of climatically suitable habitats for MPB, generated by the climatic suitability model, using BioSIM\textsuperscript{©} software (Régnière et al. 1995; Régnière 1996). BioSIM requires two inputs; digital representations of the terrain and suitable weather data. We
extracted a digital elevation model of British Columbia from the US Geological Survey ≈1-km-resolution global coverage. Point sources of weather data (i.e. stations) are usually sparse relative to the spatial resolution required for mapping biological phenomena. Therefore, spatial interpolation methods must be used to obtain air temperature and precipitation information for unsampled points across a landscape from a limited source of geo-referenced weather stations. We used the ‘gradient-plus-inverse distance squared’ algorithm developed by Nalder and Wein (1998), an approach that combines multiple linear regression and distance-weighting.

We generated a series of maps depicting the distribution of CSCs for MPB as a function of climate normals derived from the historic daily weather data in 10-year intervals from 1921-1950 to 1971-2000. Simulations were run for 500 randomly located points in British Columbia. Universal kriging (with elevation as a drift variable) was used for interpolation between simulation points. The map outputs comprise grid coverages of CSC values for ≈1.2 million 64-ha cells.

Range expansion
From 1959 to 1996, the Canadian Forest Service, Forest Insect and Disease Survey (FIDS), in cooperation with the BC Ministry of Forests, conducted annual aerial assessments of forest insect and disease conditions in BC and the Yukon. During these surveys, boundaries of MPB infestations were recorded on 1:250,000 NTS topographic maps (for details see Van Sickle et al. 2001). We digitized these maps (≈1000 in total) using ArcInfo® geographic information software (GIS), joined them into annual province-wide coverages (Albers projection, NAD87), and converted them to shape files.
To quantify whether range expansion by MPB has occurred during the past 30 years, we chose the map of climatic suitability classes based on the 1941-1970 climate normals to represent the historic distribution of climatically suitable habitats for MPB. The gridded map was reclassified to produce an Arc shape file. We overlayed annual MPB infestation maps using ArcInfo to create new MPB × CSC polygons. Because the climatic suitability grid cells generated by BioSIM are relatively small (64 ha), the intersection process divided many of the large MPB infestation polygons into several MPB × CSC polygons. We summarized the number of infestations in each CSC class by year such that only one intersection per MPB × CSC class was counted per infestation polygon.

Range expansion was assessed by regressing the number of MPB infestations versus year for each of the CSCs derived from the historic distribution of climatically suitable habitats (i.e. based on the 1941-1970 normals). We used polynomial regressions only when they explained significantly more of the variation in the data ($P<0.05$) than simple linear regressions. Since outbreak populations are often forced to briefly occupy sub-optimal habitats prior to their collapse due to the localized depletion of high-quality stands (e.g. Safranyik et al. 1999), data for the peak of the last (i.e. 1983 to 1985, inclusive) and current (i.e. 1997 to present) province-wide outbreaks were not included in the analysis.

**Results and Discussion**
During the latter half of the last century, there has been a substantial shift in climatically benign habitats for MPB northward and toward higher elevations. Areas most suitable for MPB (i.e. high and extreme CSCs) have expanded dramatically in south-central and south-eastern British Columbia (Fig. 1). Interestingly, based upon a comparison of the area affected by the present MPB outbreak with the CSC coverage derived from the most recent weather data [i.e.1971 - 2000 (Fig. 2)], our maps delineate extremely well the areas currently experiencing epidemic populations.

Mountain pine beetle populations have followed the apparent shift in climatically suitable habitats during the past 3 decades. Prior to 1968, no infestations had ever been recorded in areas with very low and low CSCs (Safranyik et al. 1975). Since then, the increase (at an increasing rate) in the number of infestations over time in the historically very low and low CSCs (Fig. 3) indicates that there has been sufficient change in the climatic conditions in these habitats to have allowed the establishment and persistence of MPB populations. It is important to note that the increase in the occurrence of MPB in these formerly climatically unsuitable areas can only be explained by changes in climate. Although temporal changes in the distribution of susceptible hosts (i.e. the amount of mature lodgepole pine) will affect the distribution of MPB infestations, unless the climatic conditions outlined in our model are met within a mature pine stand, successful establishment of a beetle population is precluded (Safranyik et al. 1975; Safranyik 1978).

As expected, if climatic conditions have improved in historically unsuitable areas, then conditions should ameliorate, and the number of infestations increase, in the more suitable
habitats. This was the case in the historically moderate and high CSCs (Fig. 3). However, by the mid-1980s the number of infestations in the habitats that were previously most suitable to MPB (i.e. extreme CSC) declined dramatically (Fig. 3). There are two potential explanations for a decrease in the number of infestations in the formerly extreme CSC: it may be a consequence of (i) a reduction in the amount of mature pine in these habitat types due to disturbance (i.e. harvesting, fire, past MPB outbreaks), or (ii) adverse effects of warmer temperatures due to climate change. Tayor and Carroll (these proceedings) have shown that the amount of mature lodgepole pine has increased dramatically in BC during the past century. Therefore, the decline in infestations is most likely due to the adverse effects of changing climate. Studies by Logan and Bentz (1999) and Logan and Powell (2001) have shown that if heat accumulation during summer is sufficiently high, MPB populations may be forced into partial multivoltinism (segments of the population have more than one generation per year) which will cause cold-susceptible stages (eggs, pupae, adults) to overwinter and interrupt flight synchrony and mass attack success in the following year.

Given the rapid colonization by MPB of formerly climatically unsuitable areas during the past three decades, our results strongly suggest continued range expansion by the beetle with further global warming. At the same time, the apparent degradation of extreme CSCs due to partial multivoltinism as a consequence of excessive warming in recent years, also suggests that southern and low-elevation regions may become less suitable for resident MPB populations. Unfortunately, a recent study (Bentz et al. 2001) has found a genetically-based latitudinal gradient in development rates for MPB suggesting that in the longer term southern MPB populations that are better adapted to warm temperatures may move North.
In the past, large-scale MPB outbreaks collapsed due to localized depletion of suitable host trees in combination with the adverse effects of climate (Safranyik 1978). The results of our investigation suggest that in the absence of an unusual weather event (i.e. an unseasonable cold period or an extreme winter), the current outbreak may not entirely collapse as in the past. Expansion by the beetle into new habitats as global warming continues will provide it a small, continual supply of mature pine, thereby maintaining populations at above-normal levels for some decades into the future.

Historically, MPB populations have been most common in southern British Columbia. Non-forested prairies and the high elevations of the Rocky Mountains have contributed to confining it to that distribution. With the substantial shift by MPB populations into formerly unsuitable habitats during the past 30 years, it is likely that the beetle will soon overcome the natural barrier of high mountains as climate change proceeds. Indeed, with a conservative increase in average global temperature of 2.5 °C associated with a doubling of atmospheric CO$_2$, as suggested by the Intergovernmental Panel on Climate Change as a plausible global warming scenario (Houghton et al. 1990), Logan and Powell (2001) predict a latitudinal shift of more than 7° N in the distribution of thermally benign habitats for MPB. Perhaps as evidence of this shift, in recent years small but persistent MPB populations have been detected along the northeastern slopes of the Rockies in Alberta – areas in which the beetle has not been previously recorded (Alberta Sustainable Resource Development 2003). The northern half of Alberta and Saskatchewan is forested by jack pine, *Pinus banksiana* Lamb., a susceptible species (Cerezke 1995) that may soon come in contact with MPB.
Acknowledgements

G. Thandi, B. Erickson and J. MacDuff provided technical assistance. The cooperation of the BC Ministry of Water, Land and Air Protection, and the BC Ministry of Forests is gratefully acknowledged. This study was supported by a grant from the Natural Resources Canada, Canadian Forest Service, Mountain Pine Beetle Initiative and by the Forest Innovation and Investment Initiative.

References


Table 1. Description of climatic variables utilized to construct a model of climatic suitability of habitats to mountain pine beetle populations (adapted from Safranyik et al. 1975).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Rationale</th>
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</thead>
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<tr>
<td>$P_1$</td>
<td>&gt; 305 degree-days above $5.5^\circ$C from Aug. 1 to end of growing season (Boughner 1964), \textit{and} $&gt;833$ degree-days from Aug. 1 to Jul. 31</td>
<td>A univoltine life cycle synchronized with critical seasonal events is essential for MPB survival (Logan and Powell 2001). 305 degree-days is the minimum heat requirement from peak flight to 50% egg hatch, and 833 degree-days is the minimum required for a population to be univoltine (adapted from Reid 1962).</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Minimum winter temperatures $&gt;-40^\circ$C</td>
<td>Under-bark temperatures at or below $-40^\circ$C causes 100% mortality within a population (Safranyik and Linton 1998).</td>
</tr>
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<td>$P_3$</td>
<td>Average maximum Aug. temperatures $\geq 18.3^\circ$C</td>
<td>The lower threshold for MPB flight is $\approx 18.3^\circ$C (McCambridge 1971). It is assumed that when the frequency of maximum daily temperatures $\geq 18.3^\circ$C is $\leq 5%$ during August, the peak of MPB emergence and flight will be protracted and mass attack success reduced.</td>
</tr>
<tr>
<td>$P_4$</td>
<td>Total precipitation Apr. to Jun. $&lt; \text{long-term average}$</td>
<td>Significant increases in MPB populations have been correlated with periods of two or more consecutive years of below-average precipitation over large areas of western Canada (Thomson and Shrimpton 1984).</td>
</tr>
<tr>
<td>$X_1$</td>
<td>Variability of growing season precipitation</td>
<td>Since $P_4$ is defined in terms of a deviation from average, the coefficient of variation of precipitation was included. Its numerical values were converted to a relative scale from 0 to 1 (see Safranyik et al. 1975).</td>
</tr>
<tr>
<td>$X_2$</td>
<td>Index of aridity(^1)</td>
<td>Water deficit affects the resistance of lodgepole pine to MPB, as well as subsequent development and survival of larvae and associated blue-stain fungi. An index of aridity (Ung et al. 2001) was used to approximate water deficit.</td>
</tr>
</tbody>
</table>

\(^1\)The index of aridity replaces the water deficit approximation (National Atlas of Canada 1970) in the original model of Safranyik et al. (1975).
Table 2. Climatic suitability classes (CSCs) for mountain pine beetle derived from an index of climatic suitability (adapted from Safranyik et al. 1975).

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<th>Climatic suitability</th>
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<td>Very low</td>
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<tr>
<td>High</td>
<td>0.16 – 0.35</td>
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<tr>
<td>Extreme</td>
<td>0.36+</td>
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Figure 1. Historic distributions of climatic suitability classes (CSCs) derived from climate normals (30-year monthly means and extreme minima and maxima) for the mountain pine beetle in British Columbia. “Very low” CSCs are habitats with climatic conditions unsuitable for mountain pine beetle whereas “extreme” CSCs are those considered climatically optimal.
Figure 2. Mountain pine beetle infestations (all severity classes) from 1998 to 2002 (a), and the distribution of climatic suitability classes derived from 1971-2000 climate normals [30-year monthly means and extreme minima and maxima (b)] for the mountain pine beetle in British Columbia. “Very low” CSCs are habitats with climatic conditions unsuitable for mountain pine beetle whereas “extreme” CSCs are those considered climatically optimal.
Figure 3. Number of infestations versus year and climatic suitability class derived from 1941-1970 climate normals [30-year monthly means and extreme minima and maxima] for mountain pine beetle in British Columbia. “Very low” CSCs are habitats with climatic conditions unsuitable for mountain pine beetle whereas “extreme” CSCs are those considered climatically optimal.
## Appendix F. Natural Disturbance Opening Size by Forest District Under 40/60 Hectare Harvest Rules

### COAST FOREST REGION - 40 HECTARE RULE

<table>
<thead>
<tr>
<th>Forest District</th>
<th>2-year cycle budworm</th>
<th>black-headed budworm</th>
<th>Douglas fir forest tent caterpillar</th>
<th>mountain pine beetle</th>
<th>spruce beetle</th>
<th>western hemlock looper</th>
<th>western fire spruce budworm</th>
<th>Grand Total</th>
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### NORTH COAST FOREST DISTRICT - 60 HECTARE RULE

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SOUTHERN INTERIOR FOREST REGION - 40 HECTARE RULE

Note "Headwaters Forest District" in this table and all charts means former Clearwater Forest District portion only

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### SOUTHERN INTERIOR FOREST REGION - 60 HECTARE RULE

Note "Headwaters Forest District" in this table and all charts means former Robson Valley Forest District portion only

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### NORTHERN INTERIOR FOREST

61
## REGION - 60 HECTARE RULE

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