Mountain Pine Beetle Symposium: Challenges and Solutions

October 30-31, 2003

Kelowna, British Columbia

Edited by: T.L. Shore, J.E. Brooks and J.E. Stone

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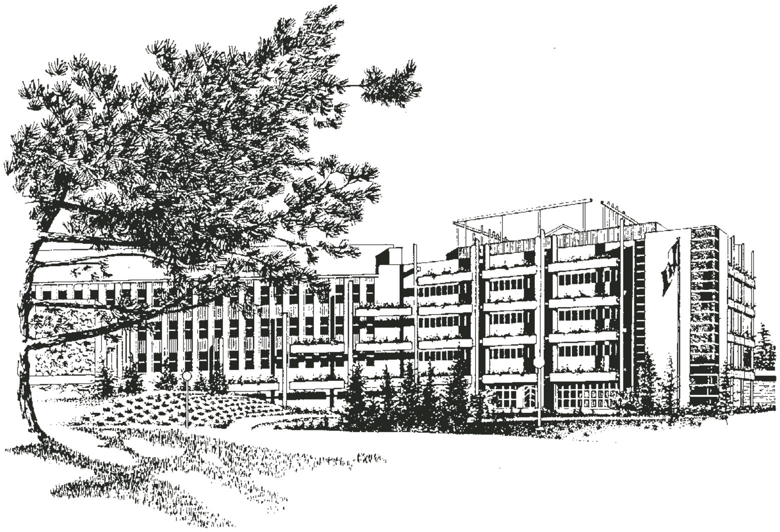

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Introductory Session

Session 1 – Scope of the problem and key issues

Session 2: The mountain pine beetle – the state of the art

Abstract

The "Mountain Pine Beetle Symposium: Challenges and Solutions" was held in Kelowna, British Columbia, Canada on October 30-31, 2003. This meeting was organized by Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre and funded through the Government of Canada Mountain Pine Beetle Initiative. Approximately 250 people representing the forest industry, consultants, universities, provincial and federal government agencies, First Nations, and the general public, from both Canada and the United States attended the meeting. Thirty presentations were given describing the current mountain pine beetle situation (in British Columbia, Alberta and the western United States) and its management and economic implications. Researchers presented the latest information on remote sensing, decision support systems, impacts on stand dynamics and wildlife, phytosanitary risks, climate change effects and preventive management as they relate to mountain pine beetle.

Résumé

Le Symposium sur le dendroctone du pin ponderosa « Des défis et des solutions » a eu lieu à Kelowna, en Colombie-Britannique, les 30 et 31 octobre 2003. Cette rencontre, organisée par le Centre de foresterie du Pacifique du Service canadien des forêts, Ressources naturelles Canada, était financée par le biais du Programme sur le dendroctone du pin ponderosa du gouvernement du Canada. Le symposium a réuni près de 250 personnes provenant de l'industrie forestière, de sociétés d'experts-conseils, d'universités, d'organismes provinciaux et fédéraux, des Premières nations et du grand public, tant du Canada que des États-Unis. On a pu y entendre trente exposés sur la situation actuelle du dendroctone du pin (en Colombie-Britannique, en Alberta et dans l'ouest des États-Unis) ainsi que sur les méthodes de lutte et les répercussions économiques. Les chercheurs ont présenté les plus récentes données sur la télédétection, les systèmes d'aide à la décision, les répercussions sur la dynamique des peuplements et la faune, les risques phytosanitaires, les effets sur le changement climatique et la gestion préventive dont on dispose en rapport avec le dendroctone du pin ponderosa.

Foreword

The Mountain Pine Beetle Symposium: "Challenges and Solutions" was initiated by Natural Resources Canada, Canadian Forest Service in response to the massive epidemic of this insect in British Columbia. At the time of this symposium over four million hectares of forest was under attack in the province and there is no end in sight to the epidemic. Beetle populations have also been increasing in the western United States and are becoming established in western Alberta. The magnitude of this epidemic is unprecedented, and the implications on current and future timber supplies are enormous. Harvesting directed at controlling the beetle or salvaging beetle-killed trees affects a large number of non-timber forest values as well.

In organizing the symposium it was my intention to bring together forest managers and researchers in an environment where they could present and share their concerns and ideas. This was accomplished through 30 presentations and a poster session held over two days with additional opportunities for informal discussion and questions.

Approximately 250 people attended the two-day meeting, representing the forest industry, provincial, state and federal agencies, universities, consulting firms, First Nations communities, and the general public from both Canada and the United States.

Dr. Bill Wilson, Director, Industry, Trade and Economics Program at Natural Resources Canada, Canadian Forest Service in Victoria, opened the meeting by providing a brief background on the mountain pine beetle and the Canadian Government Mountain Pine Beetle Initiative. This was followed by an address from British Columbia's Chief Forester, Larry Pedersen, who described the serious timber supply impacts the province will be facing from this mountain pine beetle epidemic.

The remainder of the meeting was divided into two sessions: "Scope of the Problem and Key Issues" and "State of the Art." The former dealt with describing the problem and how it is being managed, and included talks from the Canadian Forest Service, British Columbia Ministry of Forests, the United States Forest Service, Alberta Sustainable Resource Development, British Columbia Ministry of Land, Water and Air Pollution, Parks Canada, and the forest industry. The latter session dealt with research approaches to improve knowledge and management of the mountain pine beetle, and included talks on decision support tools including stand and landscape level models, atmospheric models, and remote sensing technologies. There were also presentations on phytosanitary risks associated with infested trees, studies on stand dynamics and historical frequency of infestations, climatic effects on population dynamics, silviculture, wildlife, and economics as they relate to mountain pine beetle infestations.

Funding for this event and this publication was provided through the Government of Canada Mountain Pine Beetle Initiative.

Terry L. Shore

An Overview of the Mountain Pine Beetle Initiative

Bill Wilson

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Abstract

The abundant inventory of mature timber in Canadian forests is a mixed blessing. Mixed, because it attracts premium prices due to relatively outstanding performance characteristics (albeit increasingly mitigated by processing technologies) and low development costs, but the mature age class makes these stands vulnerable to a variety of forest health threats. Securing the wealth in publicly owned forests requires investment in effective monitoring and delivery in controlling a host of forest pests. This paper discusses emergence of the mountain pine beetle to epidemic proportions in British Columbia, outlining the major factors contributing to this epidemic and the federal government's efforts to assist British Columbia in responding to the epidemic.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is endemic to western North American lodgepole pine (*Pinus contorta* Dougl.) forests and is an integral component of these forested ecosystems (Safranyik, 1978; McMullen et al. 1986; Koch, 1996;). Unfortunately, the standard system of checks and balances within certain ecosystems appears to have become destabilized in the current mountain pine beetle epidemic in west-central British Columbia (BC). The scale of the infestation, spread across an estimated 4.2 million hectares of forestland, rivals that of any natural forest pest recorded in North American forests.[1]

Key factors held to have altered the lodgepole pine (Pl) ecosystem equilibrium are the public policy on containment of forest wildfires for much of the past half-century and a moderating trend in temperature extremes. Historically, Pl ecosystems are a product of beetle and fire events interacting to produce an age class mix across the landscape. In an eerie fashion, the 2003 fire season in BC worked around the beetle attack (Fig. 1).

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[1] This estimate is based on the aerial survey results of post-2002 beetle flight. The 2003 flight is expected to add considerably to the area of infestation – perhaps doubling the current estimate.

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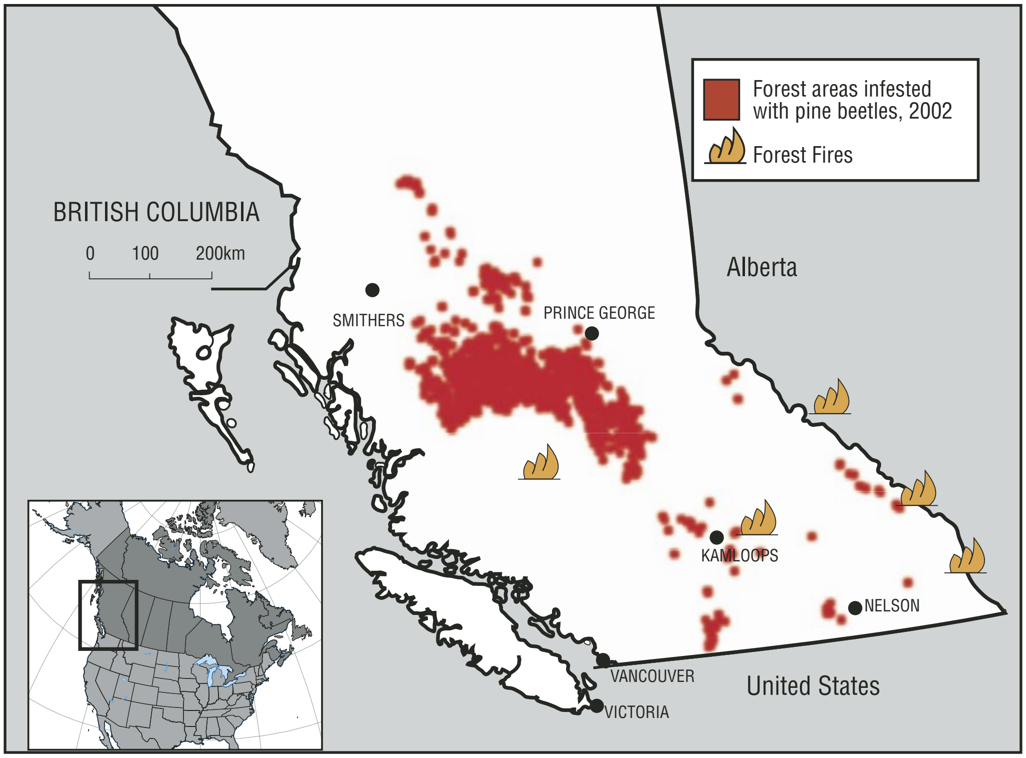

Figure 1. Beetle attack and fire zones – 2003.

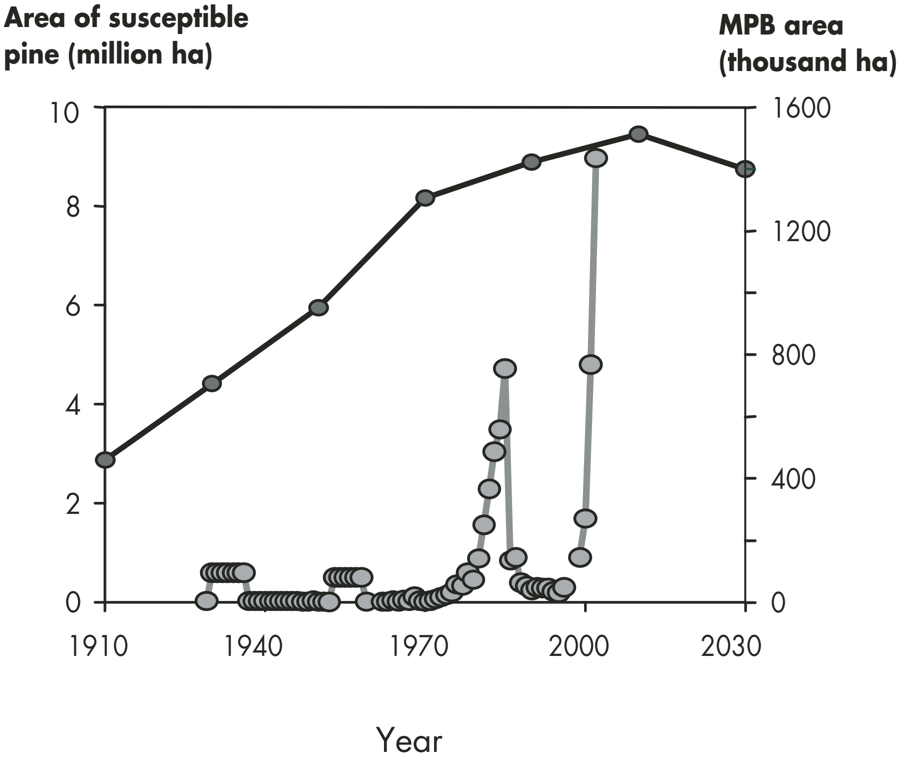

Figure 2. Trends in Pl inventory (black line) and estimated mountain pine beetle (MPB) infestation area (gray line). (Source: Taylor and Carroll 2004.)

Fire control and relatively benign weather combined with a series of major fires in the early 1900s to produce a large inventory of mature Pl (Fig. 2). This large inventory, the ideal food source for mountain pine beetle, and a reduced frequency in cold temperature events required to knock back beetle populations to endemic or to incipient levels has led to the current epidemic.

Vulnerability to mountain pine beetle attack increases markedly with timber age class and BC's Pl forests are largely mature stands (Table 1). It is estimated about 70% of BC's Pl inventory is vulnerable to mountain pine beetle – about 1 billion cubic metres of timber. Additional confounding factors to the epidemic include a lack of early direct beetle control and a large number of inaccessible beetle "hot-spots".

Table 1. Age class and mountain pine beetle vulnerability.

Years	MPB Risk Factor
≤ 60	0.1
61 – 80	0.6
≥ 81	1.0

Source: Shore and Safranyik 1992, Canadian Forest Service
(MPB = mountain pine beetle)

It is clear this current epidemic will serve to alter the fundamental structure and performance of BC's interior forestry. In the absence of a beetle-killing cold weather event, the bulk of mature Pl within the historical range of the mountain pine beetle will be hit within the next five years. Based on weather trends and global circulation models (a key analytical tool in climate change research), the probability for such a beetle-kill event is not high (Fig. 3).

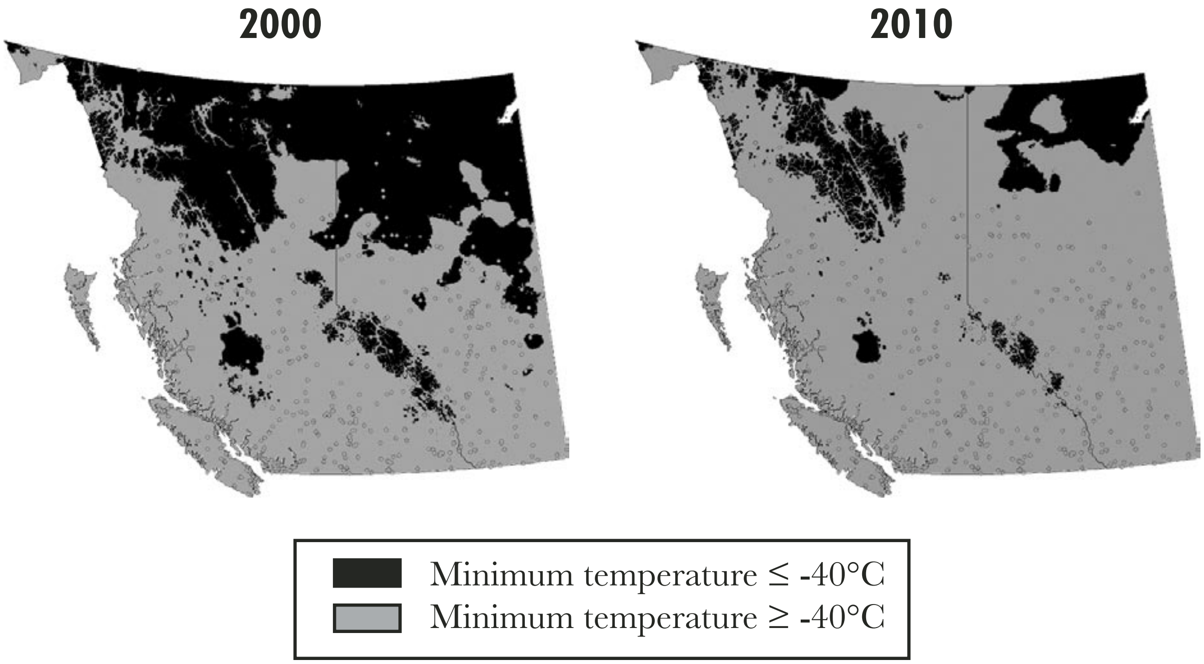

Figure 3. Climate patterns and forecast: 2000 versus 2010. (Source: Régnière et al. 2003)

It is important to recognize, given the current scale of the epidemic, that even with a major cold-weather event producing the beetle mortality rates necessary to cause population collapse, the timber supply, community stability and environmental character of interior forest ecosystems will be greatly affected. Thus, the sector and the region are facing major changes in the medium to long term. A comprehensive and rigorous examination of the impacts and options can reduce the unnecessary loss resulting in responding to these changes.

The Mountain Pine Beetle Initiative – What is it?

The provincial government requested federal assistance in responding to the mountain pine beetle epidemic, and in October 2002, the federal government announced the Mountain Pine Beetle Initiative (MPBI) within a suite of federal programs intended to assist the forest sector[2]. The federal program response is consistent with the content contained in the provincial request. One exception is the federal government is not providing assistance for forest rehabilitation on provincial Crown lands. Investing to secure the value of provincial forests remains the responsibility of the landowner and licensees.

The MPBI is a six-year package of programs with a total budget of $40 million. The objectives are to reduce the impacts of the current mountain pine beetle epidemic and to reduce the risk of future beetle epidemics. The Initiative includes the following programs:

- Mountain Pine Beetle Epidemic Risk Reduction and Value Capture Research and Development;
- Federal Forestlands Rehabilitation Program; and
- Private Forestlands Rehabilitation Program.

Land-Based Programs

At the operational level, the MPBI is designed to assist private forestland owners and federal forestlands in response to beetle infestations. The federal element works with First Nations reserve lands, the Chilcotin Military Reserve and the Dominion Coal Blocks in an effort to control beetle spread and on the rehabilitation of beetle-killed federal forestlands.[3] Content in the private and First Nations program elements is developed in collaboration with advisory committees drawn from the respective stakeholders (for program details see www.mpbi.cfs.nrcan.gc.ca).

A third federal forestlands element focuses on the federal parks in the Rocky Mountains. This world heritage area has mountain pine beetle infestations and an abundance of mature lodgepole pine. These protected areas afford an opportunity to research aspects of beetle attack, control and impacts not available in forests elsewhere. Forest health challenges are indifferent to institutional boundaries and research related to beetle surveillance, monitoring, risk management decision-support systems and control are being deployed and tested in the national parks. One program element objective is to demonstrate beetle management options to managers of other protected areas.

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[2] The major focus was to assist the sector in response to a U.S. trade action on softwood lumber imports. The package now includes MPBI; the Canada Wood Export Program; the Softwood Industry and Community Adjustment Fund; and the Value-added Research Initiative for Wood Products.

[3] The Chilcotin Military Reserve lands total about 40,000 ha and are located near Williams Lake. The Dominion Coal Blocks total about 20,000 ha in two main blocks and are situated in southeastern British Columbia.

Research Program

The scale of the current beetle infestation overwhelms any direct control in heavily infested areas; at least any acceptable form of control. The mountain pine beetle will work through a major volume of BC's mature Pl. However, focussed research will provide information on the range of impacts, options to mitigate, and systems to reduce the risk of future beetle epidemics. The MPBI research program is a partnership among stakeholders which identifies information needs and develops this information through research.

MPBI research is intended to deliver a strategic response to the beetle epidemic in pursuit of the Initiative's two objectives: reducing the impact of the current epidemic and reducing the risk of future beetle epidemics. Research will address economic, ecological and social information needs. Following is a summary of the MPBI research agenda flowing from forestlands, harvesting, processing and marketing.

Forestlands and ecosystems

This focus is on incorporating beetle risk into forestland management and determining the character of a post-beetle forest ecosystem. Key projects include:

- operational evaluation of beetle risk reduction through stand thinning;
- assessing beetle management implications at landscape levels;
- modelling beetle spread; and the consequences of climate change on beetle spread;
- assessing the potential for remote sensing techniques to improve forest health monitoring;
- integrating silvicultural control of mountain pine beetle with sustainable forest management objectives; and
- modifying existing fire risk-rating systems to better incorporate beetle disturbance and to upgrade control-burn models for fuel reduction use.

Reducing the risk of future beetle epidemic events, indeed most forest health shocks, will require effective monitoring, direct control at the incipient stage[4], and forest landscape modification to increase species and/or age class diversity.

Harvesting and processing

This focus is on examining:

- impacts of beetle-kill on timber quality;
- timeframe for harvesting "grey attack" timber;
- phytosanitary risks;
- impacts of increased beetle recovery fibre on pulping and panel production; and
- assessing the economic and socio-economic impacts of communities located within the beetle zone.

Markets and Products

This focus is to provide information on beetle zone product performance and to assess potential options to utilize salvage timber. The lodgepole pine harvest, the dominant commercial species for the interior region, will increasingly include salvage timber characterized by high desiccation rates, increased sap and bluestain. Capture of lumber value from beetle zone timber is largely dependent on moving products into established export markets; primarily the United States, because the Japanese market, which has emerged as a significant export destination for interior lumber, has little tolerance for bluestain. Unfortunately, the

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[4] The infestation cycle is endemic population, incipient population, outbreak, and the outbreak collapse.

US market for Canada's softwood lumber is currently encumbered with a duty package near 28% and a rapidly appreciating Canadian dollar.

The capability to respond to the volume of beetle zone timber will be constrained by the ability to market timber in some form. There is a need to rigorously assess product options beyond traditional forest products.

The focus is on assessing the potential impacts of beetle salvage on established products and markets. In addition, research will be completed on non-traditional product options.

Conclusions

It has been a tough year for BC. Events bring to mind the riders of the apocalypse – pestilence, drought, fire, and floods. The U.S. softwood lumber trade action compounds the impacts.

The suite of mountain pine beetle natural controls (i.e., host resistance, natural enemies, weather and competition for food and space) has been overwhelmed by the scale of the epidemic. Mountain pine beetle prevention tools (stand density management, species/age class mix, and harvesting at maturity) are under-deployed and direct management options (baiting/repellents, fall and burn, pesticides, mosaic burns, and harvesting) are of limited use, and very inadequate at an epidemic stage (Safranyik et al. 1974). As a consequence, mountain pine beetle will run through much of the mature Pl stands in the heavily infested and threatened areas – short of a major mountain pine beetle-killing weather event.

The pest control focus might be best placed on new outbreaks, including other bark beetles actively chewing through stands elsewhere in BC. Competitive and over-supplied forest product markets rather than processing capacity will constrain efforts on fibre recovery from the beetle zone (Rogers 2001). The social and economic impacts can be expected in the medium to long term, after fibre supply and costs reflect beetle impacts on timber and "grey attack" shelf-life is expiring.

Post-beetle epidemic, Interior forests will be different, and the economic and social basis and structure for many of the region's communities will be challenged. There is no option in which this transition can be avoided. However, the transition can be improved via a thorough assessment of mountain pine beetle epidemic impacts and options to work with these. The Mountain Pine Beetle Initiative is a federal assist to delivering this necessary assessment.

Bill Wilson is Director of Industry, Trade & Economic Research, Canadian Forest Service, Pacific Forestry Centre.

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How Serious is the Mountain Pine Beetle Problem? *From a Timber Supply Perspective*

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Abstract

Timber supply analyses were undertaken to assess the potential mid-term timber supply impacts of the ongoing mountain pine beetle infestation in British Columbia. Twelve management units in central British Columbia comprising 43% (9.9 million ha) of the provincial timber harvesting land base were assessed. The 12-unit analysis projected a significant decline in timber supply 15 years from now, when killed trees might deteriorate beyond a merchantable condition. The projected reduction in mid-term timber supply was 19% relative to the pre-uplift annual allowable cut (AAC) (23.2 million m^3). A timber supply impact assessment was completed separately for the Quesnel timber supply area (TSA). The impact for this very infested area could be up to 29% compared to the pre-uplift level (2.248 million m^3). Similar to the aggregated 12-unit analysis, the decline is forecast to coincide with the deterioration of killed timber, or in about 15 years from now. Solutions are presented which could mitigate the mid-term reduction in timber supply.

Introduction

The mountain pine beetle infestation affecting the central interior of British Columbia (BC) has been ongoing since 1994. In the past two years, the rate of spread and attack intensity have increased dramatically. As of this year (2003), 4.2 million ha of red attack were recorded through aerial overview surveys in the province (BC Ministry of Forests 2004). This represents an increase of 100% since 2002. Given the intensity of this epidemic, efficient management strategies have been developed to help reduce the spread of the infestation and limit the amount of beetle-killed timber in affected zones. However, in some areas with extremely high beetle populations, not all the beetle-killed timber will likely be harvested.

To further develop effective management responses, it is necessary to understand the potential timber supply impacts, and which of the factors associated with the infestation may be subject to management intervention. The review and analysis discussed in this talk examines the possible timber supply impacts in seven timber supply areas (TSAs) and five tree farm licences (TFLs) in BC. An in-depth review of the Quesnel TSA is performed.

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Description of the Mountain Pine Beetle Infestation

There are two key factors which have contributed to the expanding mountain pine beetle epidemic:

- The number of ha of mature, susceptible lodgepole pine (>80 years old) in BC has increased by about three times since 1910 (Taylor and Carroll 2004); and
- Warmer climate conditions have expanded the beetle's range into previously unsuitable areas, such as northern areas and higher elevations (Carroll et al. 2004).

Fire control measures, which have been effective since the mid-1900s, have increased the protection of forest resources. This has lead to an accumulation of old pine forest above historical levels. At present, lodgepole pine of all ages covers 14.9 million ha in the province. Of this, over 8 million ha are stocked with mature, susceptible pine. In terms of merchantable volume, this represents one billion m^3 (British Columbia Ministry of Forests 2003).

The second factor has been hot, dry summers and mild winters in central BC that have allowed the mountain pine beetle population to reach epidemic levels in mature pine forests. Average minimum temperatures during the winter have increased by +2.2ºC to +2.6ºC over the last 100 years (British Columbia Ministry of Water, Land and Air Protection 2002). Favourable conditions have been created, allowing the beetle to spread into previously unsuitable regions. As well, drought stress due to higher summer temperatures has increased the susceptibility of older pine stands to beetle attack. Climate models project that this warming trend will continue.

Based on a summary of British Columbia Ministry of Forests aerial surveys for 1999-2003 (British Columbia Ministry of Forests 2004), the estimated infested area has increased from 165,000 ha in 1999 to 4.2 million ha in 2003 (Fig. 1). These areas describe the annual "red attack" or trees killed by the beetle in the previous year. This area does not include green attack (recently attacked) trees, which will die in the following year.

The aerial surveys include an estimate of the attack severity within stands, based on the percentage of mortality. The severity categories are light (1-10% of trees recently killed); moderate (11-29% of trees recently killed); and severe (over 30% of trees recently killed in an area). Figure 2 describes the aerial surveys between 1999-2003. Since that time, beetle infestations have continued to spread over a significant portion of the south and central interior. At present, 64% of the infestations are described as light, 18% as moderate and 18% as severe. As of 2002, the Mountain Pine Beetle Emergency Task Force had estimated that approximately 108 million m^3 of wood had been infested in BC.

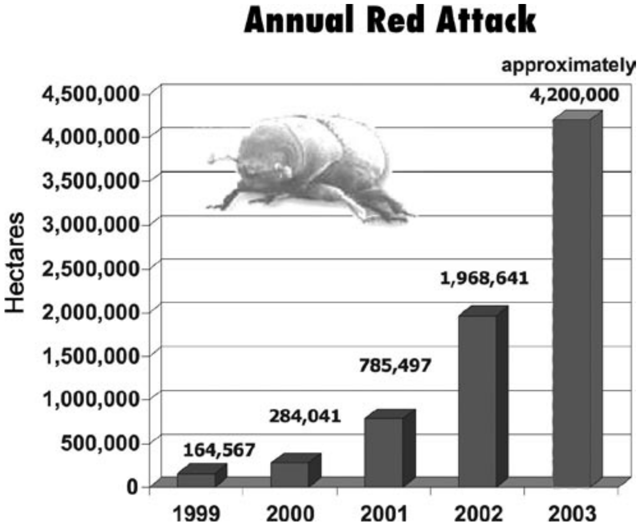

Figure 1. Summary of mountain pine beetle red attack from aerial overview surveys in BC, 1999-2003.

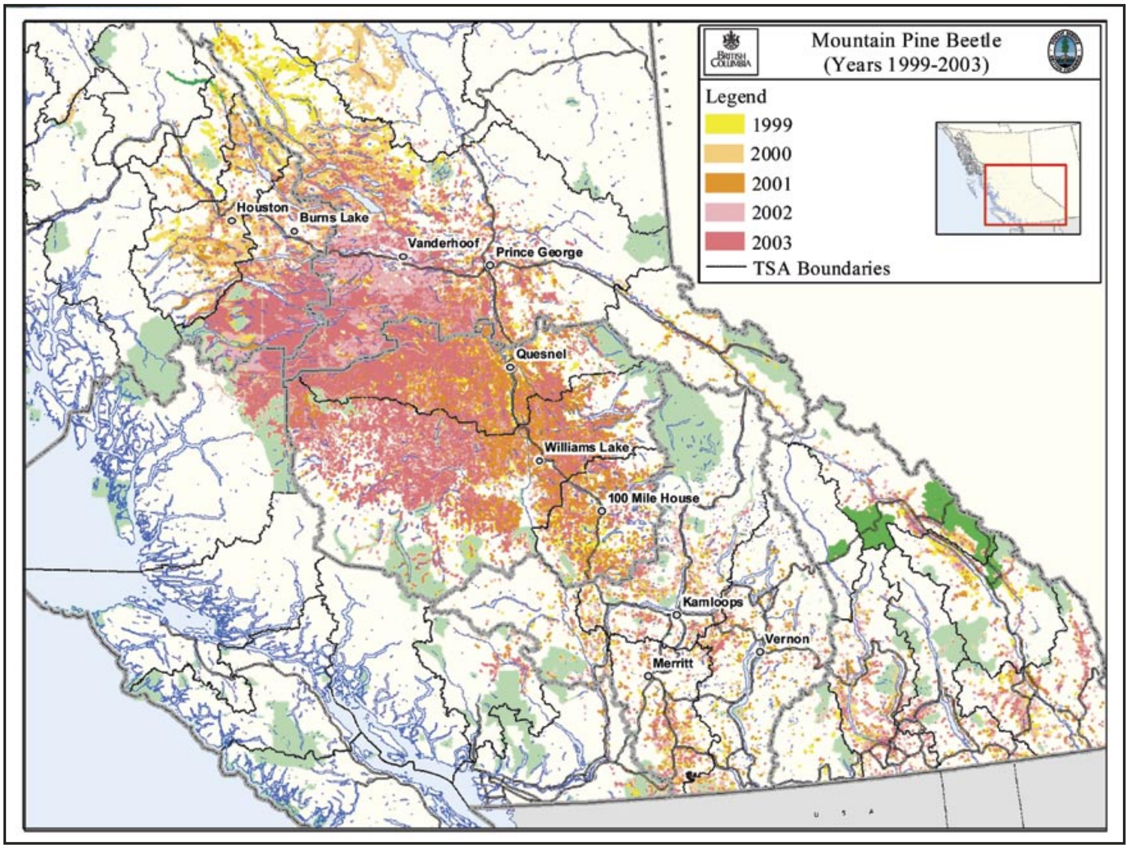

Figure 2. Provincial map of area infested by mountain pine beetle between 1999-2003.

Mountain Pine Beetle Analysis Area (12 units)

Timber Supply Impact Study

To examine the potential impact of the mountain pine beetle on timber supply, the British Columbia Ministry of Forests examined seven TSAs and five TFLs, referred to as management units, represented by the more severely infested areas in central BC, stretching from Houston to Kamloops (Fig. 3).

BC's total interior timber harvesting land base comprises 20 million ha. Of these, the 12 management units occupy 9.9 million ha. Most at risk from the infestation are 3.3 million ha, which contain mature pine-leading stands (forests with >50% pine older than 80 years). Another 1.4 million ha are comprised of stands with 10-50% susceptible pine. This component of the land base may not be as affected by the mountain pine beetle because other tree species exist in the stands (Fig. 4).

The current total allowable annual cut (AAC) for the analysis area (12 management units) is about 30 million m^3. Of this, 6.8 million m^3 is attributable to harvest level increases (uplifts) due to the mountain pine beetle infestation in seven of the 12 affected units (Table 1).

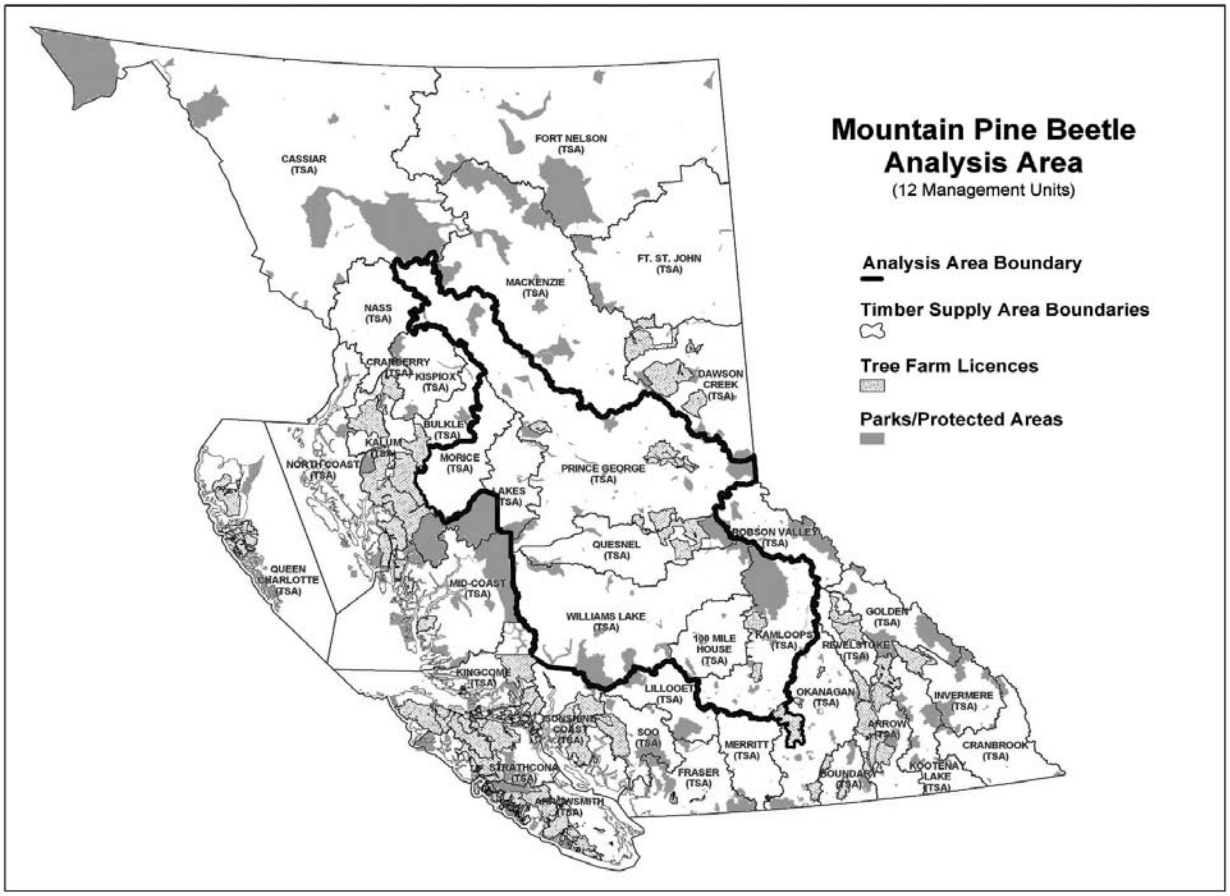

Figure 3. Mountain pine beetle analysis area (12 management units) in central BC.

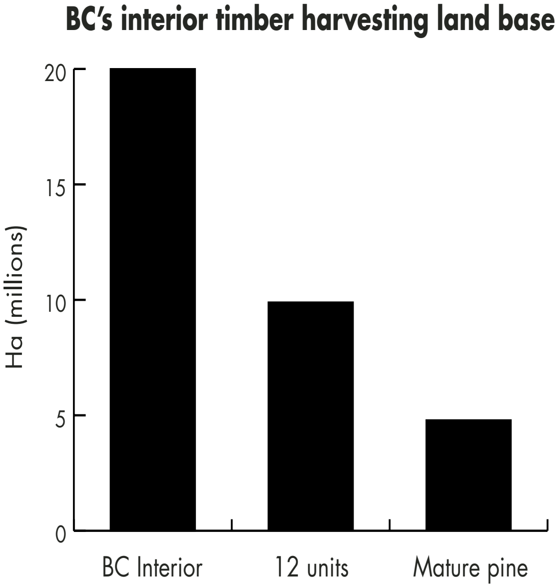

Figure 4. BC's interior timber harvesting land base.

Table 1. Current AAC totals and uplifts attributable to the mountain pine beetle in seven management units in the analysis area.

Management Units	AAC (m^3/ year)	Uplifts (m^3/ year)
Lakes	2,962,000	1,500,000
Prince George	12,244,000	3,000,000
Quesnel	3,248,000	1,000,000
Williams Lake (since 1980s)	3,768,000	850,000
TFL 42 (Fort St. James)	160,000	40,000
TFL 5 (near Quesnel)	300,000	177,200
TFL 53 (near Quesnel)	500,000	261,000

Assumptions for Assessing the Timber Supply Impact in the 12 Management Units

The analysis examined only the impacts of the current beetle infestation and an estimate of the extent to which it might spread. No attempt was made to forecast beetle infestations that may occur in future decades, or future changes to forest management practices such as reforestation and fire management. The following key assumptions reflect the best estimate of the possible dynamics of the infestation averaged over the 12 units:

- Initial harvest rate was set at 30 million m^3/year;
- Half of the high risk pine (>80 years old and >50% pine) equalling 1.6 million ha was assumed to be fully attacked by 2002;
- Attacked and killed trees would take 15 years to deteriorate to an unmerchantable condition; and
- Over the first 15 years, harvesting consists of 60% pine and 40% other species.

Projected impacts and key observations

Figure 5 shows the projection of timber available for harvest, based on the assumptions described. The timber supply is projected to decline significantly in 15 years after the attacked and killed trees have deteriorated, and are no longer considered merchantable. The following projections illustrate possibilities that could reduce the impact on future timber supply:

- If harvest levels are higher than 30 million m^3/year, then unsalvaged losses could be less than the projected 200 million m^3;
- If more pine is harvested rather than the current profile of 60% pine and 40% other species, then there will be fewer unsalvaged losses; and
- If stands with the highest amount of mortality are harvested within the first 15 years, the timber supply impacts will be reduced.

Other projections showed that where infestation and mortality exceeded 50%, there would be proportionately more severe impacts on the mid-term timber supply. Several TSAs exist with a large component of mature lodgepole pine, such as the Quesnel TSA, where the level of mortality could be higher than 50%. An in-depth analysis for the Quesnel TSA was performed.

Projected Impacts

12 Units

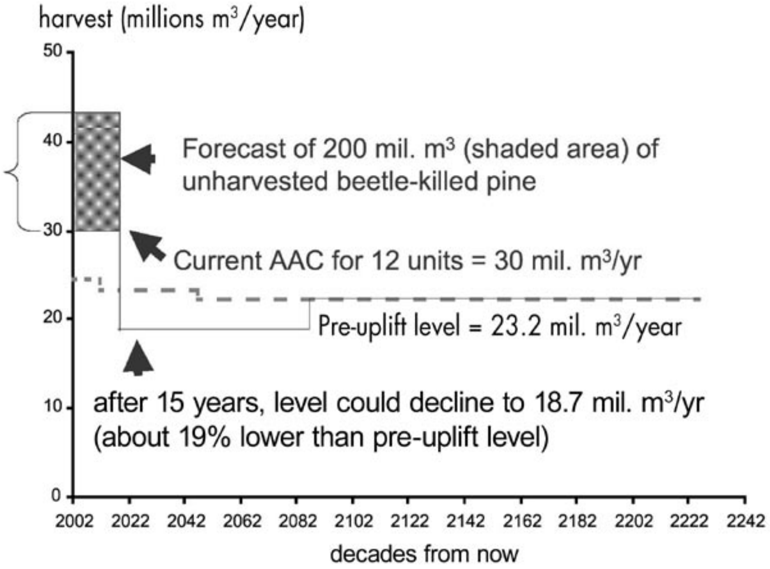

Figure 5. Projected impacts of mountain pine beetle on future timber supply.

Quesnel TSA

A more detailed analysis was undertaken for the Quesnel TSA. In this analysis, as in the assessment of the 12 management units, only the current infestation was examined. The Quesnel TSA landbase is approximately 1.6 million ha. The area considered available for timber harvesting is about one million ha. Susceptible pine stands comprise 590,000 ha, while an additional 150,000 ha are considered somewhat susceptible (25-50% pine). The age of susceptibility was estimated to be 60 years in the Quesnel TSA rather than 80 years estimated for the 12 units, due to observed high levels of attack in younger pine forests (personal observation, BC Ministry of Forests staff).

Key assumptions for Quesnel

For the Quesnel analysis, the following key assumptions reflect an estimate of the possible growth and intensity of the infestation:

- The cumulative infested area in 2002 was 215,300 ha (by severity class 45% high, 22% severe, 16% very severe, and 17% over-run);
- The rate of spread was projected to be 40% per year, until all 590,000 ha of pine-leading stands were infested (Fig. 6);
- The initial harvesting rate was 3.2 million m³/year; and
- The average shelf life of pine was estimated to be 13 years for the Quesnel TSA.

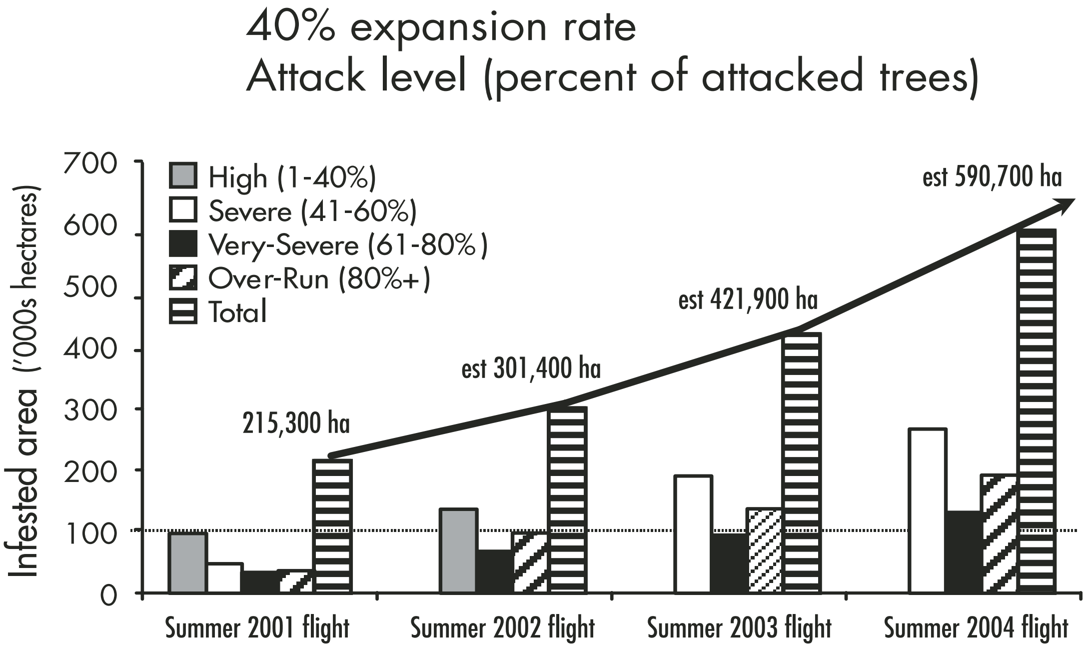

Figure 6. Expansion rate of mountain pine beetle in the Quesnel TSA analysis.

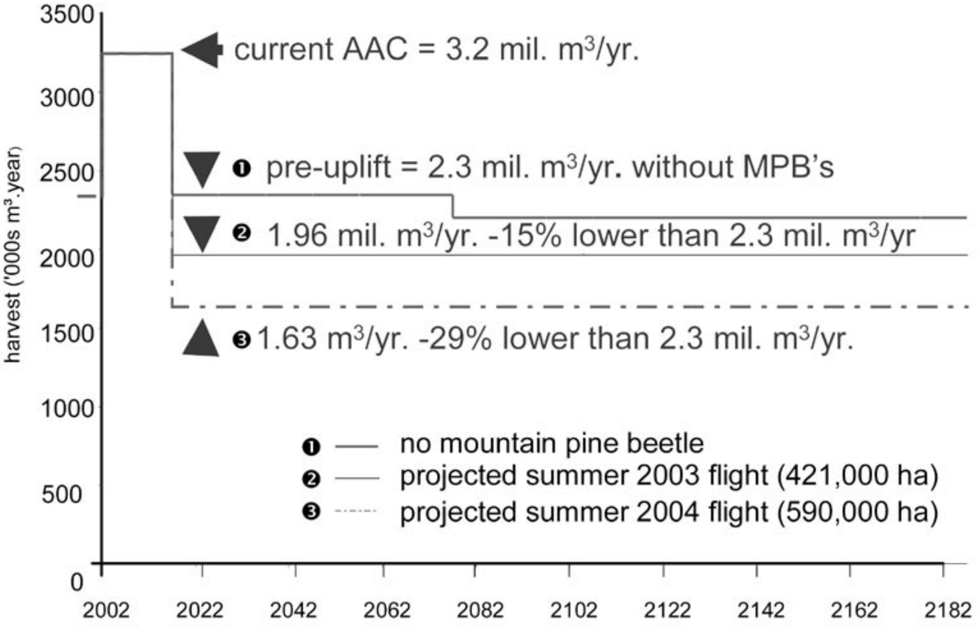

Figure 7. Projected impacts of mountain pine beetle on future timber supply in the Quesnel TSA. (MPB = mountain pine beetle)

Projected impacts and key observations for the Quesnel TSA

Figure 7 shows the timber supply projections for three scenarios:

- If there were no mountain pine beetle infestation;
- If the infestation stopped at the projected summer 2003 level (421,900 ha); and
- If the infestation stopped at the projected summer 2004 level (all 590,000 ha of pine-leading stands are attacked by varying severity classes, but not over-run).

The projection for no beetle infestation follows the base case forecast in the most recent Timber Supply Review analysis (British Columbia Ministry of Forests 2001). The level of 2.3 million m^3/year was the AAC for the Quesnel TSA prior to 2001 (British Columbia Ministry of Forests 2001). Then the AAC was increased to 3.248 million m^3 to address the mountain pine beetle infestation.

If the infestation stopped at the projected summer 2003 level, i.e., with a very cold 2003/2004 winter and no further spread of the infestation, the timber supply would decline from its current AAC level (3.248 million m^3/year) to 1.96 million m^3. This is approximately 15% lower than pre-uplift levels (Fig. 7).

The lowest forecast levels in Figure 7 show the potential effect if the beetle continues to spread by 40% during the summer of 2004, until all available pine has been infested. Given that the rate of spread in this area is closer to 200%, it is likely that the infestation has already reached the level projected for 2004. After 15 years, the projected analysis shows a timber supply of 1.63 million m^3/year, a 29% decrease of the mid-term harvest. If the infestation continues beyond next summer, future timber supply will decline still further. However, it is unlikely that 100% of the pine will be killed. In the past, large-scale outbreaks have collapsed due to localized depletion of suitable host trees, in combination with adverse weather effects (Safranyik 1978).

It has been determined that harvesting at the current AAC of 3.248 million m^3 will likely not keep up with the infestation. If the current AAC is maintained for 15 years, 42 million m^3 could be harvested, leaving about 34 million m^3 unsalvaged. With higher harvest levels, timber losses could be reduced, although the decline of the mid-term timber supply level would still occur. If next winter is sufficiently cold, or if pine retains its merchantability for longer, the projected declines may not be as great.

Summary of Timber Supply Analyses and Challenges Ahead

The 2003 data and analysis results for the 12 management units in central BC show the seriousness of the problem. However, impacts could be reduced if:

- harvesting is directed to the more severely infested stands and at reducing the spread of the infestation;
- harvesting focuses more on pine than on other species; or
- the infested forests are regenerated more quickly.

The extent of the infestation is uncertain and the deterioration rate of killed trees is beyond management intervention. However, timber supply declines might be lessened if harvests were focused in areas where deterioration rates were more rapid. If warm weather trends continue for the next one to three years, then it is likely that the mountain pine beetle infestation will have a significant impact on the available timber supply over the mid-term. To minimize this impact, continued aggressive action toward harvesting beetle-killed timber, the development of local economic, social and environmental strategies, and the collaboration between interested communities toward the completion of a responsive provincial strategy, will help to mitigate the severe impacts of the mountain pine beetle on the people and forests of central BC.

Larry Pedersen is Chief Forester with the British Columbia Ministry of Forests.

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The bionomics of the mountain pine beetle in lodgepole pine forests: establishing a context

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Abstract

Due to the significant impacts of mountain pine beetle (*Dendroctonus ponderosae* Hopk.) epidemics on the pine forests of western North America, there exists an extensive body of literature devoted to its bionomics. This paper reviews the critical aspects of mountain pine beetle biology and ecology that enable its eruptive population fluctuations in lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests: dispersal and colonization; insect-host interactions; cold tolerance; and synchrony and phenology. The potential for mountain pine beetle populations to establish, persist and ultimately increase to outbreak levels is a function of the beetle's capacity to locate, colonize and reproduce within highly resistant host trees situated in thermal environments conducive to overwintering survival and with sufficient heat accumulation to maintain a synchronous univoltine life cycle. Management strategies and tactics intended to mitigate the impact of outbreaks must be based on an understanding of the effects these constraints have on populations and the subsequent adaptations that the mountain pine beetle has evolved to overcome them.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopk.) is a native insect that occurs in pine forests over much of western North America, extending from northern Mexico to northwestern British Columbia (BC) and from the Pacific Ocean east to the Black Hills of South Dakota (Wood 1982). Normally mountain pine beetle populations are innocuous, and only a few scattered infested trees are to be found within a forest. However, during outbreaks, which occur at irregular intervals and may persist for periods of 5 to 20 years, trees may be killed over vast areas (Safranyik 1988). In recent years, the mountain pine beetle has caused extensive mortality over millions of hectares of forests in central BC (Ebata 2004). In stands managed for commercial production, the direct economic losses during such an outbreak are usually greater than that indicated by the volume loss because most mortality is among the larger-diameter trees (Safranyik et al. 1974). In addition to extensive timber losses, mountain pine beetle epidemics may increase fuel loading, hasten succession to the climax forest type, affect watershed quality, wildlife composition, and recreational values (Safranyik et al. 1974; McGregor 1985).

Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Due to the impacts of the mountain pine beetle on forest resource values, many aspects of its biology and population dynamics have been studied during the last 60 years. Consequently, there exists an extensive body of literature devoted to this insect. This paper comprises a review of mountain pine beetle bionomics. It is not intended to be exhaustive, but is instead meant to be a comprehensive discussion of aspects of mountain pine beetle ecology that form the basis of its temporal and spatial dynamics in pine forests. Furthermore, even though virtually all species of pine within its range are suitable hosts for the beetle (Furniss and Schenk 1969; Smith et al. 1981; Wood 1982), due to the size, intensity and commercial impact of epidemics, this review will concentrate on mountain pine beetle in lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests.

Predicting the mountain pine beetle's impacts on the landscape and implementing effective management strategies to mitigate losses during an outbreak can only happen if those efforts are built upon a solid understanding of the beetle's bionomics. The potential for mountain pine beetle populations to establish, persist and ultimately increase to epidemic levels in lodgepole pine forests depends on the capacity for beetles to locate and colonize suitable host trees in environments with favourable climatic conditions. This paper discusses the critical aspects of mountain pine beetle bionomics required for outbreak development: dispersal and colonization, insect-host interactions, cold tolerance, and synchrony and phenology.

Dispersal and colonization

Dispersal

Although dispersal is arguably one of the most important aspects of mountain pine beetle ecology, it is perhaps the least understood. The dispersal phase begins with emergence and ends as beetles orient toward new host trees. Dispersal flights may be short range (i.e., within a single stand), or long range (i.e., among stands). At the population level, these types of dispersal lead to either the growth of local infestations (i.e., spot growth), or the proliferation of new ones (i.e., spot proliferation), respectively (Safranyik et al. 1992; Safranyik, 2004).

Prior to emergence, young beetles complete maturation by feeding on the inner bark and on spores of fungi and other microorganisms which line the walls of their pupal chambers. This enables the flight muscles to increase in size (Reid 1958), and the mycangia (specialized compartments on the maxillae) to become charged with spores, thereby ensuring transport of necessary fungi and microorganisms to new trees (Whitney and Farris 1970; Safranyik et al. 1975). Upon completion of maturation feeding, temperature becomes the primary determinant of the onset of emergence and the initiation/duration of the dispersal period. Emergence occurs only when ambient temperatures exceed 16°C (Reid 1962a; Schmid 1972; Billings and Gara 1975) and declines above 30°C (Gray et al. 1972; Rasmussen 1974). Most beetles emerge during the mid-afternoon when temperatures reach approximately 25°C (Fig. 1).

From year to year, the peak of emergence may vary by as much as 1 month, but normally varies by less than 10 days (Reid 1962a; Safranyik 1978). Throughout most of BC, peak emergence usually occurs between mid-July and mid-August. The window of peak emergence normally lasts 7 to 10 days, but can be as long as several weeks during cool and/or rainy periods (Safranyik et al. 1975).

Although the estimated lower and upper temperature limits for beetle flight are 19° and 41°C, respectively (McCambridge 1971), most beetles fly when temperatures are between 22° and 32°C (Safranyik 1978). Within the optimum temperature range, flight propensity increases with increasing light intensity and humidity. Once temperatures exceed 35°C, beetles begin to respond negatively to light (Shepherd 1966), and above 38°C flight is severely restricted (McCambridge 1971).

In general, bark beetles do not fly in winds that exceed their maximum flight speed (Seybert and Gara 1970; Meyer and Norris 1973). For large-bodied bark beetles like the mountain pine beetle, the maximum wind speed for flight, and therefore the probable maximum flight velocity, is approximately 2 ms^{-1} (Rudinsky 1963).

The initial flight by newly emerged mountain pine beetles tends to disperse them widely throughout the forest (Raffa and Berryman 1980; Safranyik et al. 1992). Indeed, even in the presence of aggregation pheromones, the majority of beetles will disperse out of a stand (Safranyik et al. 1992). The tendency for beetles immediately following emergence to be non-responsive to aggregation pheromones suggests that a flight period is required before they adopt a host-seeking behaviour. This interpretation is supported by Shepherd (1966) who found that flight exercise increased the responsiveness of mountain pine beetle to host stimuli.

During short-range, within-stand dispersal, most beetles fly several meters above the ground; below tree crowns, but above the undergrowth (Schmitz et al. 1980; Safranyik et al. 1989). The direction of this flight is normally downwind until beetles encounter an attractive odour plume at which point they turn and fly back upwind toward the source (Safranyik et al. 1989, 1992). Beetles that do not disperse from the stand in which they develop usually locate suitable host trees within 2 days of emergence, but are capable of searching for several days (Safranyik et al. 1992).

There is a paucity of information about long-range, above canopy dispersal by the mountain pine beetle. However, Safranyik et al. (1992) found that, based on the vertical distribution of flying beetles, up to 2.5% of a population may attempt long-range dispersal above the canopy. This estimate was determined from a relatively small incipient population and would likely be much higher during an outbreak when locally available host trees have been depleted. Given that beetles fly during warm, fair-weather periods that are often accompanied by air inversions near the ground and by upward convection currents (Chapman 1967), it has been suggested that some beetles are caught in, and directed by, warm convective winds and could easily be carried 20 km or more (Furniss and Furniss 1972). This thesis is supported by collections of mountain pine beetles from snowfields above the timberline, many kilometers from potential host trees, indicating that long-range dispersal likely occurs during outbreaks and may be an important factor in the spread of epidemics.

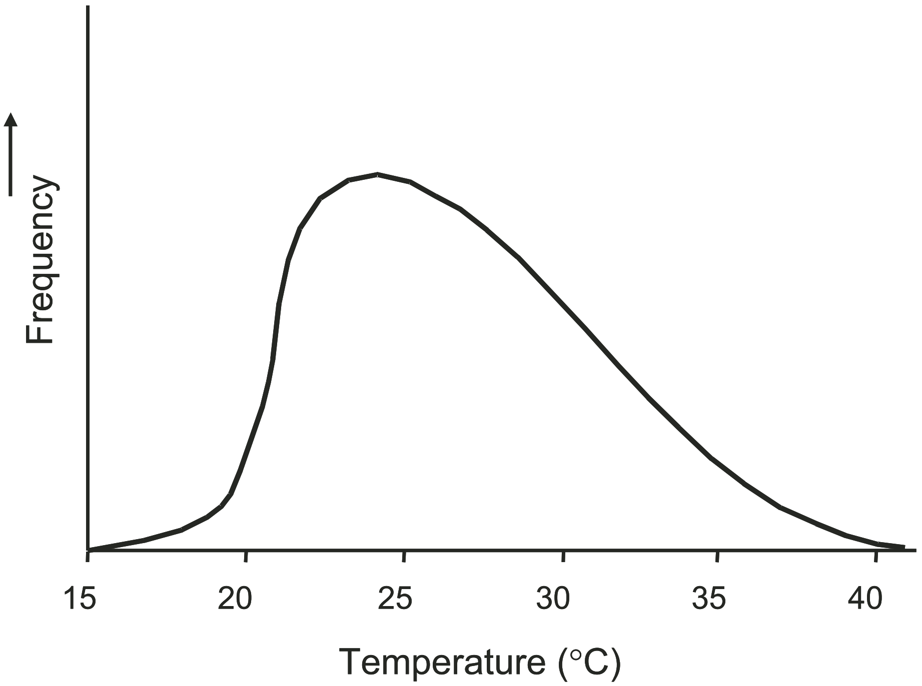

Figure 1. Frequency of emergence of mature mountain pine beetle in relation to temperature. Adapted from McCambridge (1971).

Colonization

Colonization involves establishment of initial attacks on host trees by pioneer beetles followed by aggregation and mass attacks of these trees in response to a combination of volatiles produced by the host tree and the beetle.

Some debate exists as to the mechanism of initial host selection by pioneer beetles. Evidence suggests that vision plays a key role in locating host trees. Several authors have reported tree diameter as a landing stimulus (Hopping and Beall 1948; Cole and Amman 1969), and large, dark silhouettes (Shepherd 1966) and vertically oriented cylinders (Billings et al. 1976) are attractive to beetles. By contrast, Hynum and Berryman (1980) suggest that beetles land at random during the pre-aggregation phase and that the greater number of beetles landing on larger trees is simply due to their larger surface area.

Although the dominant theory of host selection by mountain pine beetle proposes that pioneer females utilize a combination of random landings and visual orientation followed by direct assessment of host suitability after landing (e.g., Pureswaran and Borden 2003), there is evidence that dispersing adults orient to lodgepole pine trees suffering from injury or disease (Gara et al. 1984). Furthermore, Moeck and Simmons (1991) showed that mountain pine beetles are attracted to odours of host material in the absence of visual cues.

After pioneer beetles land on a potential host tree, the decision to initiate a gallery is made based upon gustatory assessment of compounds present in the bark (Raffa and Berryman 1982a). If a tree is considered acceptable, females begin to construct a gallery and in the process instigate a mass attack (see Borden et al. 1987 and references therein). As pioneer females penetrate the bark they release the pheromone trans-verbenol which acts in combination with myrcene, a tree volatile, to attract mainly male beetles. Responding males release exo-brevicomin and later frontalin, which in combination with trans-verbenol and myrcene attracts mainly females. Autoxidation of another tree volatile, ∝-pinene, and microbial conversion of trans-verbenol (and cis-verbenol) result in production of the anti-aggregation pheromone verbenone. As the beetles approach optimal colonization density on a tree [approximately 60 attacks per m^2 of bark (Raffa and Berryman 1983a)], verbenone in combination with large amounts of exo-brevicomin and frontalin results in close-range redirection of responding beetles to nearby trees.

The process of mass attack on an individual tree is normally completed in 1-2 days. The subsequent redirection of beetles to nearby trees results in clusters of dead trees (i.e., a spot infestation).

Insect-host interactions

In the course of a mass attack, female beetles begin constructing galleries in the phloem and males join them once the gallery has been initiated. Following mating, females extend the galleries vertically and plug the entrance hole with boring dust. Males often assist females at this stage, but sometimes leave the gallery shortly after mating. Typically 60 – 80 eggs are laid singly in niches (approximately 2 eggs/cm) along the margins of the gallery (e.g., Safranyik et al. 1974). However, oviposition will cease if the moisture contents of the inner bark and outer sapwood drop below approximately 105% and 60% oven dry weight, respectively (Reid 1962b). If this occurs, the female will re-emerge to make a second flight and attack. Consequently, there may be significant differences in the number of eggs per gallery between trees in the same infestation. Eggs hatch within about 2 weeks and larvae mine the phloem circumferentially, developing through four instars. Broods normally overwinter as larvae and complete their development in the spring.

The mountain pine beetle preferentially attacks large-diameter trees. This is because characteristics of the stem that are related to tree diameter are the primary determinants of a tree's potential to produce beetles once it has been successfully colonized. For example, attack densities are higher on trees with rough versus smooth bark as females prefer to initiate galleries in bark crevices (Safranyik 1971). In addition, trees with thick bark tend to produce more brood than thin-bark trees due to the protection it provides from natural enemies and temperature extremes (Reid 1963; Safranyik et al. 1974). Similarly, the number of surviving progeny is positively related to phloem thickness (Amman 1972; Amman and Cole 1983), bark surface area (Reid 1963; Cole and Amman 1969) and sapwood moisture retention (Reid 1963) due to the greater quantity and quality of resources available for brood development. Bark roughness, thickness and surface area, phloem thickness and sapwood moisture retention all increase as trees increase in diameter (e.g., Safranyik et al. 1975; Shrimpton and Thomson 1985). In practical terms, this means that on average lodgepole pine trees ≤25 cm in diameter are beetle sinks (i.e., more beetles attack than emerge), whereas trees >25 cm are beetle sources [i.e., more beetles emerge than attack (Safranyik et al. 1974)].

Although the mountain pine beetle prefers to colonize larger trees within a stand, such trees are normally the fastest growing, most vigorous trees at a given age and site quality (Shrimpton 1973a). As a consequence, they are also the best able to defend themselves from attack. Successful colonization by the mountain pine beetle is conditional upon the death of its host tree. This intense selection pressure has resulted in the evolution of a complex array of defenses that enable resistance by lodgepole pine to attack. These defenses include resins released from constitutive resin ducts severed as beetles bore through the bark (Smith 1963; Shrimpton and Whitney 1968; Reid and Gates 1970; Berryman 1972), and secondary induced resinosus by tissues surrounding the wound (Reid et al. 1967; Shrimpton and Whitney 1968; Berryman 1972; Shrimpton 1973b; Raffa and Berryman 1982b; 1983a,b). The flow of constitutive resin slows attacking beetles and their accompanying microorganisms and may even expel them from a tree (i.e., pitch out). The induced response involves localized breakdown of parenchyma cells, the formation of traumatic resin ducts, and ultimately the production of secondary resin comprising increased concentrations of monoterpene and phenolic compounds (Raffa and Berryman 1982b; 1983a). If the induced response is rapid and extensive, the beetles and associated microorganisms will be confined and killed in a lesion of dead tissue.

The mountain pine beetle employs two strategies to overcome the defenses of lodgepole pine. The first relies upon cooperative behaviour in the form of mass attack as described above. By rapidly concentrating attacks on selected trees in response to aggregation pheromones the beetles exhaust the host's defensive response (Safranyik et al. 1975; Berryman 1976; Raffa and Berryman 1983a; Berryman et al. 1989). If sufficient beetles arrive at a rate that exceeds the resistance capacity of a particular tree, then colonization will be successful.

The second strategy derives from the close association between the mountain pine beetle and several microorganisms. Beetles usually carry a number of different organisms into a tree, but two blue stain fungi, *Ophiostoma clavigerum* and *O. montium*, are consistently present (Whitney and Farris 1970; Six and Paine 1998; Six 2003). Spores of the fungi are inoculated into trees as beetles bore through the bark. These spores germinate quickly and penetrate living cells in both phloem and xylem (Safranyik et al. 1975; Ballard et al. 1982, 1984; Solheim 1995) causing desiccation and disruption of transpiration (Mathre 1964), effectively terminating resin production by the tree. The relationship between the mountain pine beetle and its associated blue stain fungi is a symbiotic one; the fungi benefit as they are transported from tree to tree, and the beetles benefit through the pathogenic activity of the fungi, physical conditioning of the phloem environment for larvae, and necessary contributions the fungi make to the beetle's diet (reviewed by Paine et al. 1997; Six and Klepzig 2004).

At the stand level, resistance by lodgepole pine to colonization by the mountain pine beetle and blue stain fungi is affected by the normal process of stand aging. Depending on site quality, stands tend to be most resistant between 40 and 60 years and decline rapidly with age (Safranyik et al. 1974) (Fig. 2). Initiation of the drop in resistance roughly corresponds to the point at which, in fully stocked stands, current annual increment peaks and basal area growth culminates (Safranyik et al. 1974, 1975; Raffa and Berryman 1982b). Thereafter, the vigour of trees declines as they reach maturity and begin to compete for resources. Under these conditions, if trees have reached sufficient size, mountain pine beetle populations can increase rapidly (Safranyik, 2004). As a general rule, by the time stands reach 80 – 100 years, they are considered to be highly susceptible to mountain pine beetle.

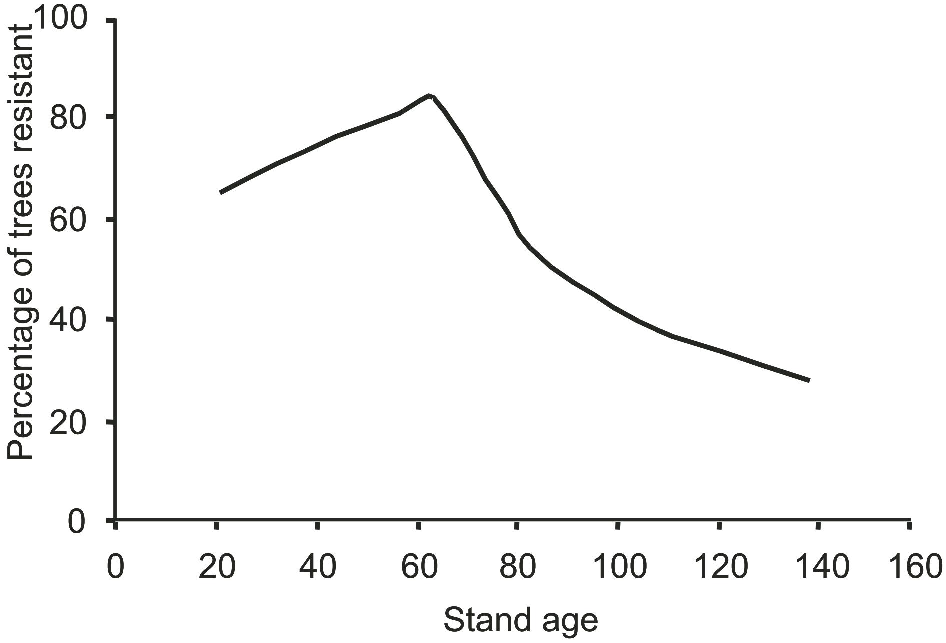

Figure 2. Change in the frequency of lodgepole pines resistant to colonization by blue stain fungi in relation to stand age. (Redrawn from Safranyik et al. 1974.)

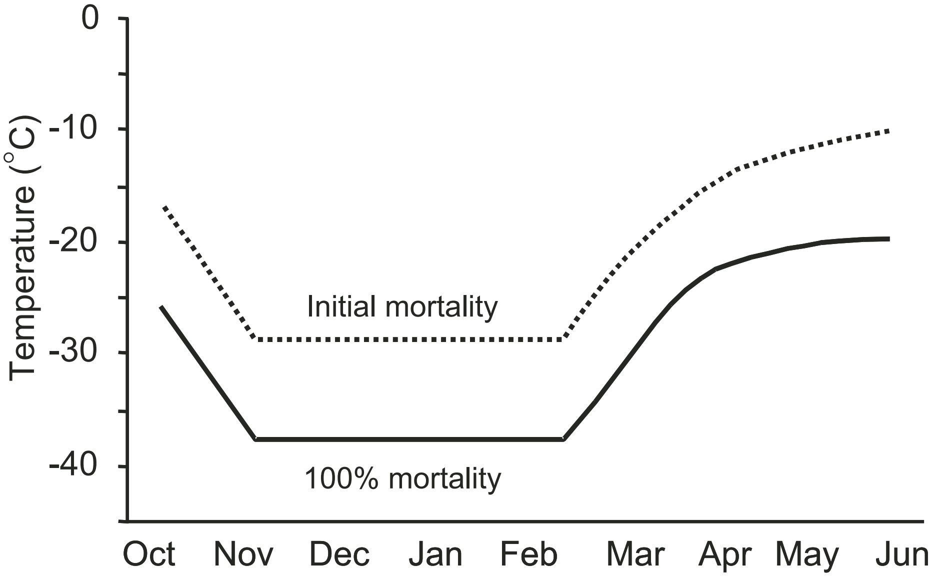

Figure 3. Tolerance limits of third- and fourth-instar mountain pine beetle larvae to 2.5 hours exposure to low temperatures. (Adapted from Wygant 1940.)

Cold tolerance

Exposure to cold temperature is often the largest single source of mortality in mountain pine beetle populations (Safranyik 1978; Cole 1981). Not surprisingly, the beetle has evolved an effective mechanism by which it can tolerate temperatures commonly encountered during winter within its range. Cold tolerance is acquired through the production and accumulation of glycerol, a polyhydric alcohol, in the hemolymph (i.e., blood) as temperatures decline during autumn (Somme 1964; Bentz and Mullins 1999). Tolerance to cold varies with life stage. Eggs are least tolerant, followed by pupae, adults then larvae (Safranyik et al. 1974). Reid and Gates (1970) determined the lethal temperature for eggs to be -18°C. Logan et al. (1995) estimated that the lethal temperature range for pupae is between -18°C and -34°C, and adults between -23°C and -34°C. Larvae are the most cold-tolerant stage, and tolerance increases as larvae mature (Amman 1973; Safranyik et al. 1974; Langor 1989; Safranyik and Linton 1998; but see Bentz and Mullin 1999). Lethal low temperatures manifest between -23° and -29°C for first instars, -23° and -34°C for second instars, and −29° and -40°C for both third- and fourth-instar larvae (Logan et al 1995).

Given the gradual accumulation of glycerol, cold-hardiness is greatest during the period from December to February when winter temperatures are usually lowest. Late larval instars are the normal overwintering stage and can withstand temperatures near -40°C for extended periods during this time (Wygant 1940). However, if low temperatures occur early in the year before the mountain pine beetle is able to produce sufficient glycerol, or late in the winter after the beetle has begun to metabolize it, significant mortality in a population can occur (Wygant 1940; Safranyik et al. 1974). For example, if -30°C were to occur in mid-winter, little mortality would be expected. However, if this temperature were to occur at the end of October, or middle of March, then nearly 100% mortality can be expected (see Fig. 3). Interestingly, in 1984 and 1985 a major outbreak in the Chilcotin region of British Columbia collapsed due to the occurrence of a series of days during which temperatures dropped to below -30°C in late October and early November, respectively (Safranyik and Linton 1991).

Many factors can moderate the effects of low temperatures on mountain pine beetle mortality. Thick bark and deep snow will insulate beetle broods from declining ambient temperatures (Wygant 1940; Safranyik et al. 1974). In addition, the rate of decline of subcortical temperatures is slower for large- versus small-diameter trees due to the greater capacity of large objects to store heat (Safranyik and Linton 1998). Beetle attack characteristics will also affect the potential for mortality due to cold. As temperatures approach lethal lows, mortality is negatively related to attack, brood and egg gallery densities, due to the insulating effects of air pockets created by gallery construction (Safranyik and Linton 1998). Consequently, for cold weather events to impose significant mortality upon a mountain pine beetle population, temperatures must decline and remain low for several days to ensure that subcortical temperatures reach lethal levels.

Synchrony and phenology

One generation per year is the most common life cycle for mountain pine beetle populations throughout their range (Safranyik 1978). Adults disperse, attack and colonize new trees in mid- to late summer thereby enabling their broods to develop to third- or fourth-instar larvae, the most cold-tolerant life stages, before the onset of winter. However, variations in the life cycle can occur with year-to-year variations in weather. For example, during an unusually warm summer adults may emerge and attack several weeks earlier than average. Often beetles from this flight will re-emerge later in the season and infest a second tree (Reid 1962a). Similarly, as a consequence of unusually mild winters, a high proportion of parent beetles may survive and emerge prior to the emergence of their progeny (Amman and Cole 1983), usually during late May and early June. These beetles often construct egg galleries in the green phloem of trees that were strip-attacked, resistant, or attacked late in the season of the previous year (Rasmussen 1974). Attacks that occur early or late in the season have little chance of contributing to infestations because of high mortality due to the poor synchrony between the occurrence of cold tolerant life stages and the onset of winter, and the overall lack of coincidence with the general mountain pine beetle population (Amman 1973; Safranyik 1978).

Unlike many insects in seasonal environments, the mountain pine beetle does not have a diapause to functionally synchronize populations with critical phenological events (Logan and Bentz 1999). Development is under direct temperature control suggesting that in environments with temperature regimes outside a narrow optimal range, population synchrony would degrade over time. However, the high mortality associated with asynchrony has selected for adaptations that (i) ensure adult emergence is temporally coincident, thereby maximizing chances for successful mass attacks, and (ii) phenologically timed to enable broods to mature to cold tolerant life stages before winter (Logan and Bentz 1999; Logan and Powell 2001).

Temporally coincident adult emergence is facilitated by stage-specific responses to temperature (Bentz et al. 1991). Late-instar larvae have higher temperature thresholds for development than early instars, preventing progression to cold-susceptible advanced life stages before the onset of winter. Due to their lower developmental thresholds, early instars originating from late-hatching eggs are able to "catch up" and become synchronous with the rest of the population after temperatures have become too cool for late-instar larval development (Bentz et al. 1991). To ensure that populations maintain their phenological timing, the mountain pine beetle has also evolved regional differences in its developmental rate. Given the large differences in heat accumulation in the northern versus southern portions of its range, populations of the mountain pine beetle in the north have evolved to develop faster for a given input of temperature than beetles from the south (Bentz et al. 2001). These two adaptations ensure that populations can maintain a synchronous univoltine life cycle that is phenologically coincident with critical seasonal events over an extremely broad range of climatic conditions.

In cooler environments, such as at high elevations and near the northern edges of the distributional range, heat accumulation is often insufficient for completion of the typical univoltine life cycle and mountain pine beetle populations become semivoltine. Stretching the life cycle over 2 years results in severe mortality consequences since the beetles will be forced to overwinter twice, often in cold-susceptible stages (Amman 1973; Safranyik 1978). Moreover, a 2-year life cycle slows the beetles' physiological clock in relation to the chronological clock, prolonging critical life history events such as adult emergence and dispersal (Logan et al. 1995; Logan and Powell 2001). This will significantly reduce colonization success since the mountain pine beetle relies on mass attack to overcome host resistance.

Generally, in areas where mountain pine beetle populations can maintain a univoltine life cycle the frequency of adverse weather conditions is not great enough to prevent development of outbreaks or to reduce populations to endemic levels. By contrast, in semivoltine populations climate becomes a dominant factor affecting both the distribution and abundance of mountain pine beetle (Safranyik 1978).

Conclusions

The potential for mountain pine beetle populations to establish, persist and ultimately increase to outbreak levels in lodgepole pine forests depends on the capacity for beetles to locate, colonize and reproduce within highly resistant host trees situated in thermal environments conducive to overwintering survival and with sufficient heat accumulation to maintain a synchronous univoltine life cycle. Understanding the effects these constraints have on populations and the subsequent adaptations that the mountain pine beetle has evolved to overcome them is the critical foundation of a successful management program intended to minimize the impacts of epidemics.

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Mountain Pine Beetle Epidemiology in Lodgepole Pine

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Abstract

The following brief synthesis of mountain pine beetle epidemiology is based on host-beetle interaction. In the first part I briefly describe the relationship between the dynamics of lodgepole pine and mountain pine beetle. The second part describes the phases in the infestation cycle and their main characteristics. This synthesis is based on published information on infestation behaviour in western Canada, augmented by personal experience relating to the subject area.

Lodgepole pine stand dynamics and the epidemiology of the mountain pine beetle

The mountain pine beetle is native to the pine forests of western North America. As a consequence of the close interaction between the mountain pine beetle with its associated blue stain fungi and lodgepole pine (Safranyik et al. 1975), mountain pine beetle epidemiology is a reflection of the population dynamics of lodgepole pine.

The female beetles require a minimum bark thickness (Fig. 1) and the presence of bark scales and ridges in the bark to establish successful attacks (Safranyik 1971). Hence, the potential attack sites on the bole are largely determined by the density and distribution of these bark characteristics. Young trees with thin bark and small diameter (dbh) older trees (Fig. 2) are rarely attacked or sustain lethal attacks. Because beetle brood production is much lower in small dbh trees compared with large dbh trees (Fig. 3), populations breeding in small trees grow at much slower rates compared to large trees.

Attacks by the mountain pine beetle are mediated by blue stain fungi. The spores of blue stain fungi are carried into the tree by the beetles. The spores germinate quickly, penetrate and kill living cells in both the phloem and xylem (Safranyik et al. 1975). This process aids the establishment of successful attacks in the tree. Trees respond to the invasion by the beetle-blue stain complex with a flow of liquid resin from resin ducts (primary resin) damaged by the attacking organisms and production of additional resin in living cells next to the damaged area (secondary resin). When resin production is rapid and massive and the phloem and sapwood next to the wound becomes impregnated by resinous substances, beetles are killed or repelled and the fungi are confined and die.

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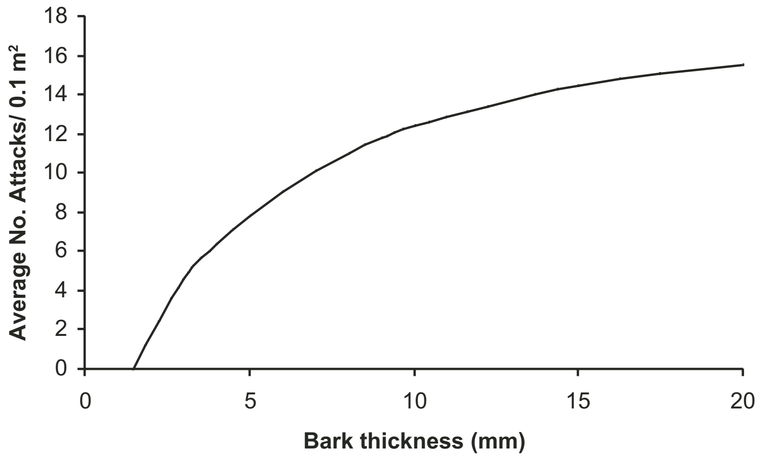

Figure 1. Example of the relationship between the combined thickness of the bark and phloem and the average number of mountain pine beetle attacks in lodgepole pine. Horsethief Creek data, 1966. (Redrawn from Safranyik 1971.) Minimum bark thickness for attack averaged 2.4 mm.

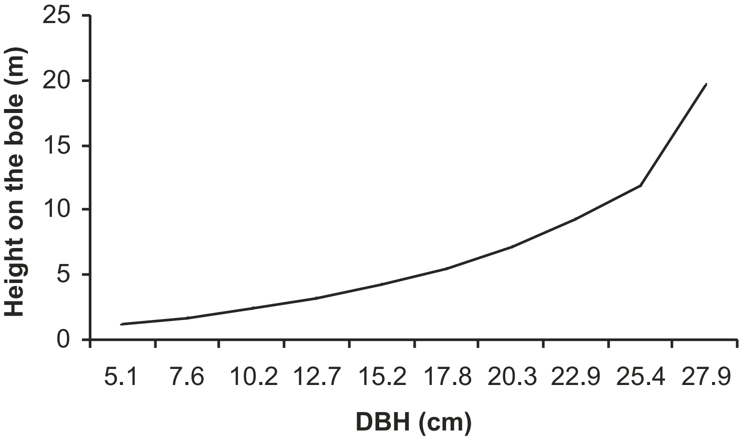

Figure 2. Relationship between the average height of the 2.4 mm total bark thickness and dbh on bole of lodgepole pine. (From Safranyik 1968.) The height on the bole corresponding to ca 2.4-mm-thick bark represents the theoretical maximum attack height.

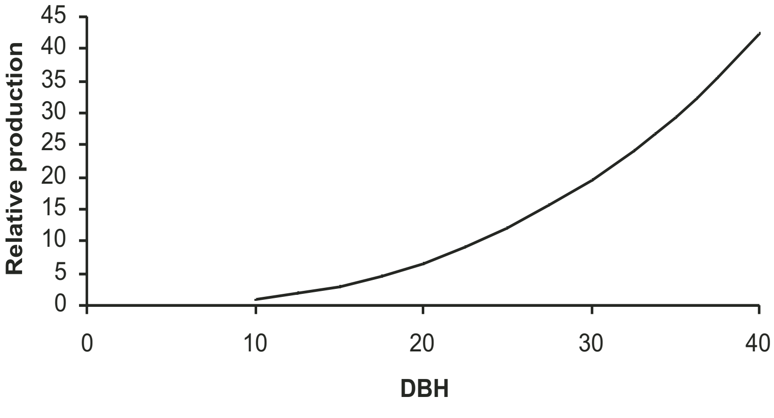

Figure 3. Brood productivity of lodgepole pine trees of different dbh relative to a 10-cm-dbh tree. (Based on Safranyik et al. 1975 and Safranyik 1988.)

Host resistance increases with age, approximately in parallel with the increase in the Current Annual Increment (CAI) (Safranyik et al. 1975) and culminates at an age when natural stands attain maximum stocking on all physiographic sites. Near the culmination of CAI, on at least the better sites, many trees are of sufficient size and density to sustain an increasing beetle population. However, mainly due to high tree resistance, attacks at this stage of stand development are intermittent and confined to a few scattered, weakened or damaged trees.

The increased competition among trees for resources (that follows the attainment of maximum density and the culmination of CAI), coupled with a decline in tree resistance, increases the abundance in space and time of low vigour trees in most unmanaged stands. These trees are frequently attacked by a number of secondary bark beetle species. However, some of the trees will be co-attacked by mountain pine beetle. This time period marks the beginning of the establishment of sustainable endemic mountain pine beetle populations in at least some of the stands. Since these mountain pine beetle populations exist mainly in suppressed and otherwise weakened trees, stand hygiene is an important factor in the maintenance of endemic beetle activity.

A large number of factors interact to restrain the potential of mountain pine beetle populations from increasing. These include insect predators and parasites, avian predators, mites, nematodes, disease, competition for food and space, tree and stand factors, and climate and weather. During endemic periods, populations suffer very high levels of mortality from a combination of these factors, so that reproduction and mortality tend to balance. Some of the most important mortality factors are related to the scarcity and patchy distribution of suitable trees, host quality and inter-specific competition. The brood trees are frequently confined to the smaller diameter classes; trees with thin phloem that have been attacked by secondary bark beetle species, both prior to and following mountain pine beetle attacks. Attacks by some of the secondary species occur during the late spring period. This, combined with small tree size, leads to faster drying and deterioration of the phloem compared with either trees of larger size or trees that had been attacked only by mountain pine beetles later in the season. Also, as the sub-cortical cooling rate during the winter is inversely related to tree size, winter mortality is greater in small diameter trees.

Incipient infestations, which are the beginning stages of an outbreak, develop when local beetle populations have grown to a minimum size sufficient to successfully mass attack the average large diameter component of stands. Because tree resistance tends to increase with tree diameter (Shrimpton 1973), the main factor(s) for the development of incipient populations are those that affect either a decline in tree resistance or an increase in beetle population size. The decline in tree resistance can be either temporary such as following periods of drought, or permanent due to senescence or disease. A number of consecutive years with warm and dry weather during the flight and dispersal period combined with mild winters favour sustained increases in beetle populations. Hence, a decline in host resistance combined with favourable conditions for beetle establishment and survival are thought to be the main factors for the development of incipient infestations.

Outbreaks exist at the landscape level. Outbreak populations develop because of the growth and expansion in space and time of incipient populations and local endemic populations, and long-range dispersal. Large areas of susceptible host, such as mature lodgepole pine, combined with continued, favourable weather conditions for beetle establishment, development, and survival are the main causes of outbreaks. During outbreaks the following factors are the main determinants of yearly changes in population and damage levels: 1) size of the parent beetle population; 2) stand characteristics such as species composition, density, age and diameter distribution; 3) the spatial distribution of stands of different susceptibility; and 4) weather factors. Outbreaks are loosely synchronized over much of the distributional range of the mountain pine beetle. This may be due to the so-called Moran effect (Moran 1953). This theory states that if regional populations are under the influence of the same density-dependent factors, they will be correlated under the influence of density-independent factors such as the effects of climate and weather.

Outbreak populations collapse primarily from one or a combination of the following two factors: 1) unseasonably cold weather conditions during the late fall to early spring period; 2) the large diameter susceptible host component of stands has been killed. In the final stages of population decline, increased mortality from natural enemies and competitors can have an impact. At the landscape level, within the outbreak areas, the relative severity of mortality in the various stands will generally reflect tree and stand susceptibility as defined in Shore and Safranyik (1992). Mortality will generally be confined to the larger diameter classes. Locally, however, most of the host trees can be killed down to 8-10 cm dbh.

The course of epidemics

We recognize four phases in the population cycle of the mountain pine beetle: endemic, incipient epidemic, epidemic and post-epidemic (declining) populations. These four phases represent distinct differences in beetle population size and damage potential. There is also some suggestion of changes in beetle population quality during the population cycle. However, this aspect of beetle biology is insufficiently understood and needs further study.

Endemic populations are those that exist between outbreak collapse and the development of incipient populations. Endemic populations are in a dynamic balance with their environment in which the host population appears to be the most important. For populations to maintain this balance (to remain more or less static) in time and space for several generations, they must suffer very high levels of generation mortality from a combination of factors, such as host resistance and nutritional quality, natural enemies, competitors, and weather factors. The following example will illustrate this point. Female beetles lay about 60-80 eggs, about two-thirds of which are female (Reid 1962). Based on this sex ratio, an average of 60 eggs per female parent represents 40 potential female offspring. Only one of these eggs needs to become an adult to establish a successful attack and replace the parent female. Hence, in order for the population to remain static between successive generations, brood mortality must be in the order of (39/40) x 100 = 97.5%.

Endemic beetle populations have the following characteristics:

- Infest weakened and decadent trees;
- Frequently found in trees attacked by secondary bark beetle species. Hence, trees containing mountain pine beetles can be very difficult to locate on the ground and even from the air since many of these trees will be in the intermediate to suppressed crown classes, the faded crowns of which are partially hidden below the crowns of taller, uninfested trees;
- Currently attacked trees are often not located near brood trees;
- There is no obvious relationship between the probability of attack and tree dbh; and
- Yearly tree mortality is normally less than volume growth.

Historically, in British Columbia, the duration of the endemic phase varied between 10 to 15 years.

Incipient epidemic populations are those that can successfully mass attack the average large diameter tree in a stand. The main factors responsible for the development of incipient epidemic populations have been described. The minimum beetle population size necessary for colonizing the larger diameter component in a stand is called the epidemic threshold (Berryman 1982) population level. In most situations, incipient epidemic populations are the beginning stages of epidemics. Exceptions are situations where stands suffer from temporary weakening such as drought conditions in younger stands. In these situations incipient populations usually decline to endemic levels once the stands have recovered.

Incipient epidemic populations have the following characteristics:

- Most infested trees are in the larger diameter classes;
- Clumps of infested trees are scattered and confined to some stands;
- The infested clumps vary considerably in size and number from year to year but tend to grow over time; and
- Frequently, the groups of infested trees first appear in the following situations: draws and gullies, edges of swamps or other places with wide fluctuations in the water table; places where lodgepole pine is growing among patches of aspen, perhaps indicating the presence of root disease; dry, south and west-facing slopes.

Initially, incipient populations grow relatively slowly, so that averaged over a number of generations the rate of increase may not exceed twofold. As a consequence, there may not be much noticeable change in infestation levels for five or more years. In some cases, infested spots may even die out for a year or two. Eventually, however, in most situations there will be sustained yearly growth in beetle population size with corresponding increases in the size and number of infested spots. Spot infestations will coalesce into larger patches and new infested spots may develop in adjacent stands. This situation marks the beginning of the onset of epidemic level infestations. This pattern of beetle population growth is typical in areas that contain large contiguous areas of mature lodgepole pine.

Epidemic populations result from the growth of incipient populations in time and space over the landscape as a result of sustained favourable weather for beetle establishment and survival combined with an abundance of susceptible hosts. Epidemic populations have the following characteristics:

- Resilient to large proportional losses through natural mortality;
- Generation mortality is usually in the range of 80% - 95%, corresponding to potential rates of population increase of twofold to eightfold. The usual annual rate of increase, however, is twofold to fourfold when measured over the entire epidemic area.
- Infestations are widespread and exist at the landscape level.
- There are usually large annual increases in both infested areas and numbers of infested trees.

During epidemics in unmanaged stands, tree mortality is usually proportional to tree dbh above a certain minimum value. The minimum dbh where little or no mortality occurs varies with stand characteristics and infestation intensity, but is usually near 10 cm. The expected rate of mortality above this minimum dbh is 1.5% - 4.0% with every 1 cm increase in dbh. As a consequence, trees in the larger dbh classes are often severely depleted. Expressed in terms of the number of trees killed in a dbh class in a given area (N_k), the relationship between mortality and dbh class (D_c) is as follows:

$$N_k = 0,\ D_c \le a/r$$
$$N_k = N_c\,(rD_c - a),\ \ a/r < D_c < (1+a)/r$$
$$N_k = N_c,\ D_c \ge (1 + a)/r$$

where N_c, a, and r, respectively, are the number of trees in dbh class D_c, a = constant; therefore the minimum dbh for killed trees is a/r, and r = mortality rate per unit dbh above a/r. The other symbols were previously defined. This relationship indicates that tree mortality is a function of both dbh class and the number of live trees within that dbh class. Interestingly, the same relationship can be derived based on an assumption of random search by the attacking beetles and landing proportional to the silhouette (dbh) of trees above a minimum size (Safranyik et al. 2004).

Outbreaks can re-occur in the same stands until the large dbh component has been severely depleted. Suppression of infestations at this population phase is very difficult due to the very large proportion of the beetle population that must be destroyed annually to affect a decline in infestation trend. Using the number of infested trees as an index of beetle population level and the ratio of the number of currently infested trees ("green attack") to the number of trees infested by the parent generation of beetles ("red attack"), as an index of beetle population trend, the rule of thumb for suppression is as follows:

$P > 100\{1\text{-} (R){:}\ (G)\}$ where P is the percent of infested trees treated, R is red attack and G is green attack.

For example, if the ratio of green attack to red attack were three-fold, more than 67% of the infested trees would need treatment to affect a decline in population and damage levels. It is very likely that a similar level of control effort would have to be maintained for several years until the infestation collapsed.

Depending primarily on the cause of epidemic collapse, the size distribution of trees attacked by post-epidemic populations may be different from that attacked during epidemics. For example, following sudden major declines in beetle numbers due to lethal low temperature events, the residual beetle population generally breed in the same type of trees that were attacked prior to the decline. However, due to the much lower beetle numbers, many trees may only be partially attacked and in some fully attacked trees, the rate of accumulation of attacks will be reduced. Consequently, brood survival will be reduced due to increased host resistance. Inter-specific competition for food and space is another major factor impacting beetle survival (Safranyik et al. 1999). When the collapse of epidemics is primarily due to local depletion of suitable hosts, subsequent generations of beetles breed in trees of reduced nutritional quality or increased resistance, and will probably suffer mortalities of similar magnitude as those occurring in endemic populations.

In British Columbia, the historical average duration of epidemics is approximately 10 years, normally lasting more than 5 years; the longest recorded epidemic continued for 18 years. Based on the assumption of mean outbreak duration of 10 years, minimum duration of 5 years, and a geometric temporal distribution of outbreak terminating events, two models were developed for predicting the probability of collapse as a function of years from the start of the outbreak (Fig. 4). Model 1 is based on a fixed expected probability of outbreak collapse in year i (P) for years 6 to 18 given that it has not collapsed prior to year i In Model 2, the expected probability of collapse increased with years after year 6.

Model 1: $Y1_i = 0,\ i \leq 5$

$$Y1_i = \sum_{j=1}^{n} P(1\text{-}P)^{(j\text{-}1)}$$

i = years from the beginning of the outbreak; $Y1_i$ = the cumulative distribution of the probability of outbreak collapse as a function of years from the start of the outbreak. $n = (i - 5)$; P = expected (average) probability of outbreak collapse (1/(10-5) = 0.2) for years 6-18; $\sum$ = summation sign.

In Model 2, P_j is calculated as the product of the average probability of outbreak collapse (P in Model 1) and the ratio $(m + 1 - i)/(m - i)$, where m = maximum observed outbreak duration (18 yrs.).

Model 2: $Y2_i = 0,\ i \leq 5$

$$Y2_i = \sum_{j=1}^{n} \left[\left\{\prod_{k=1}^{j} (1\text{-}P_{k\text{-}1})\right\} P_j\right]$$

P_j = probability of outbreak collapse in year j given that it has not occurred in preceding years; $\prod$ = product sign, $Y2_i$ = the cumulative distribution of the probability of outbreak collapse as a function of years from the start of the outbreak and the other symbols are as stated earlier.

Figure 4 indicates that based on Model 2, the probability of the collapse ($Y2_i$) of the current outbreak next year and 3 years from now is approximately 83% and 94%, respectively, assuming that it started in 1993. These probabilities are approximately 12% higher than the corresponding estimates based on Model 1 ($Y1_i$). Models 1 and 2 were based on outbreak characteristics preceding the current of outbreak. Sustained changes in climatic conditions may alter the course of current and future outbreaks.

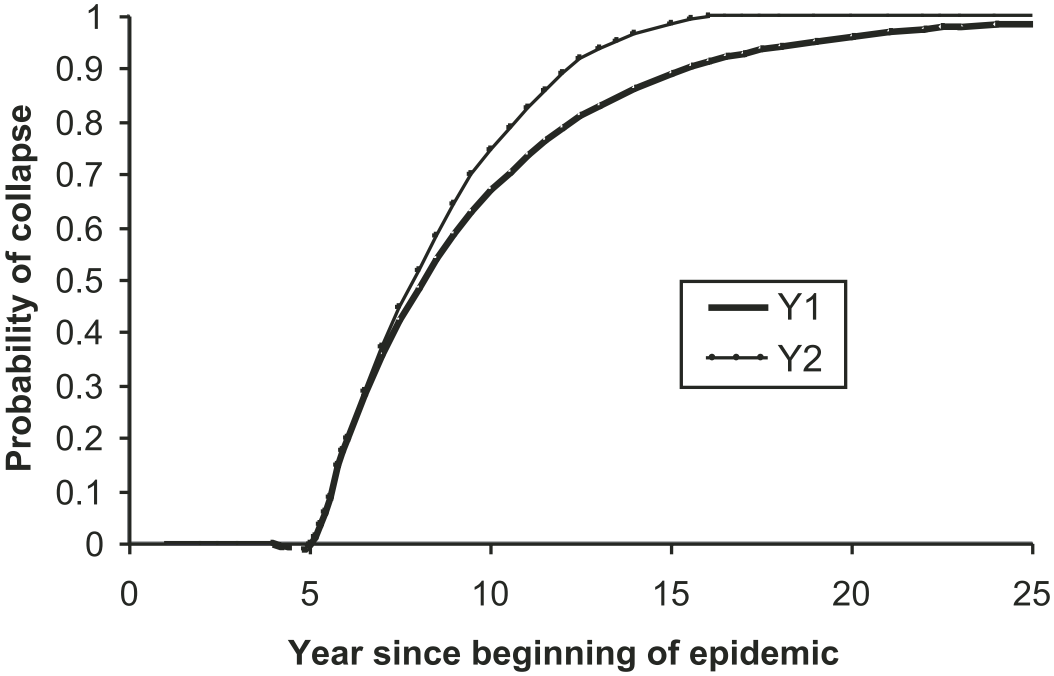

Figure 4. Predicted probability of outbreak collapse as a function of years since the start of the outbreak. Curves Y1 and Y2 are based on Model 1 and 2, respectively (see text for details).

Management implications

The interactions between lodgepole pine and the mountain pine beetle with its associated blue stain fungi have the following management implications:

- Long-term management should focus on lodgepole pine, not the mountain pine beetle.
- In spite of the best efforts of prevention, outbreaks will occur which require efficient control strategies and tactics.
- Effective direct control programs are based on early detection and implementation, and continuous commitment.

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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*) 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 mountain pine beetle activity to forest age structure, and projected future forest conditions relevant to mountain pine beetle 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 mountain pine beetle. 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 mountain pine beetle 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 mountain pine beetle 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, mountain pine beetle-susceptible pine forests in British Columbia is beyond the natural range of variability at a 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-

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Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

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 be 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 (BC) 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 BC (British Columbia 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 BC 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 water deficit influence mountain pine beetle populations directly through impacts on beetle survival, and/or indirectly through influences to host-tree quality/resistance (Safranyik et al. 1975; Carroll et al., 2004). In areas where summer heat accumulation is limited or where winter minimum temperatures are below a critical threshold, mountain pine beetle infestations cannot establish and persist (see Carroll et al.2004).

The second requirement for outbreak development is that there must be an abundance of susceptible host trees (Safranyik 1978). Since mountain pine beetle 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 mountain pine beetle. However, senescing or unthrifty trees tend to have thinner phloem and are thereby less suitable to mountain pine beetle (e.g., Berryman 1982). Thus, within areas that are climatically benign for mountain pine beetle, 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 BC were infested by the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) (Ebata, 2004).

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 mountain pine beetle infestations in BC, explore links between disturbance and host

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[1] BC Ministry of Forests Protection Branch web site www.for.gov.bc.ca/protect/suppression/

susceptibility to mountain pine beetle, and present a simple age-class projection model to explore the influence of decreased forest fire and other disturbances on the amount of mountain pine beetle-susceptible pine forests.

Historical Mountain Pine Beetle Activity

The mountain pine beetle has been present in BC's forests for millennia. Evidence of mountain pine beetle 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., 2004). Mountain pine beetle 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 mountain pine beetle outbreak records. The annual overview maps can be viewed at: www.for.gov.bc.ca/hfp/FORSITE/overview/webmap.htm; and in animated form at www.pfc.cfs.nrcan.gc.ca/entomology/mpb/historical/index_e.html.

The total cumulative area infested by mountain pine beetle between 1959 and 2002 (i.e., up to and including attacks during 2001) was approximately 4.5 million ha. 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 (British Columbia Ministry of Forests 1995); see below].

Some highlights of recorded infestations in BC [updated from detailed reviews by Powell (1966) and Wood and Unger (1996)] are given below:

1) Significant outbreaks in the 1920s were recorded around Aspen Grove and in the Kettle Valley in lodgepole and ponderosa pine.
2) In the 1930s and 40s large areas of mountain pine beetle-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.
3) 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.
4) Major infestations developed in the 1970s and 1980s on the Chilcotin plateau and in southeastern BC.
5) 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 four to five significant outbreak periods in BC during the last century. They also suggest that mountain pine beetle 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).

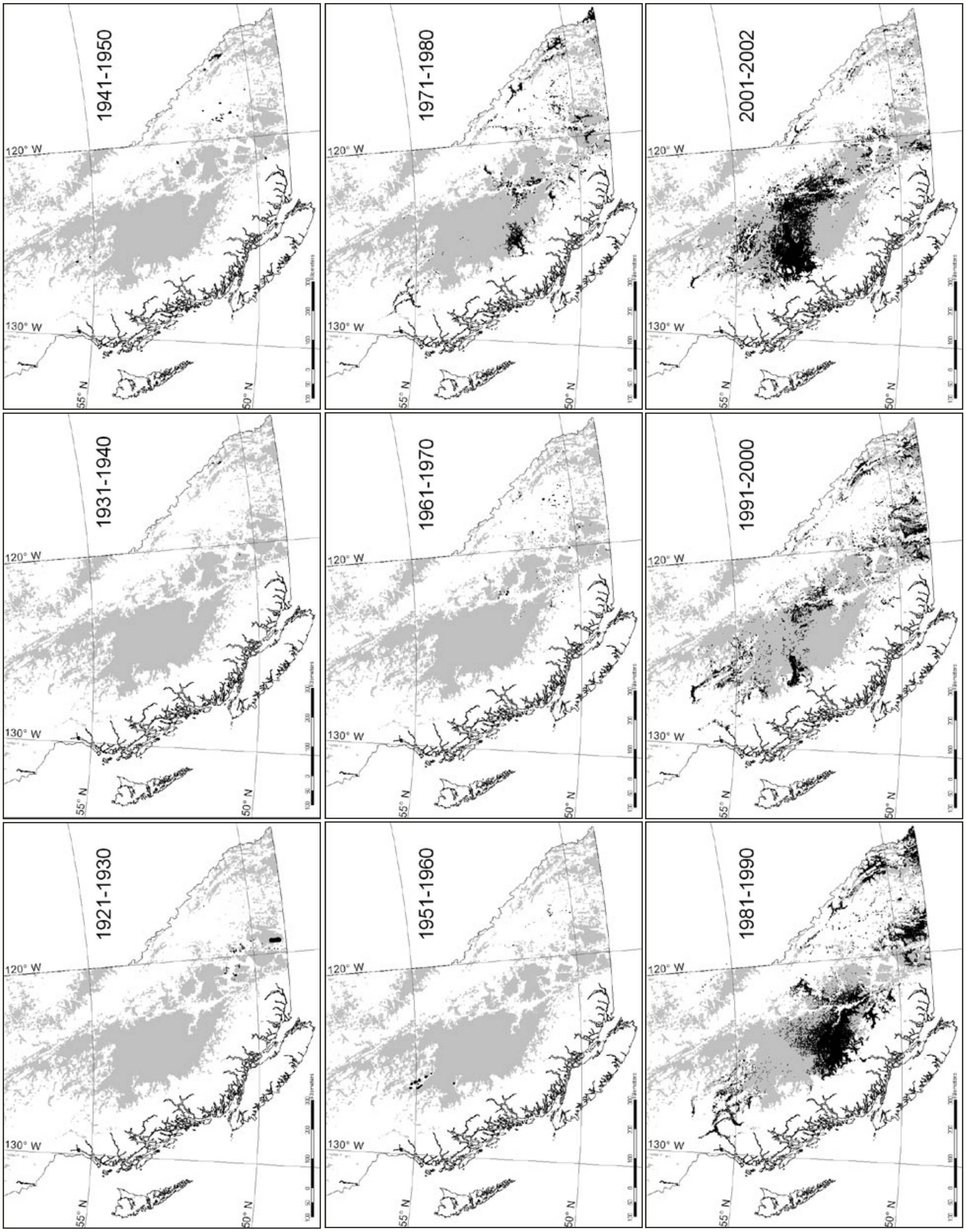

Figure 1. Historical distribution of mountain pine beetle infestations (black) overlaid on pine distribution (gray) in British Columbia during 1920-2002 from forest insect survey records.

Forest Fire Cycle Length and Forest Susceptibility to Mountain Pine Beetle

We suggest that before management, lodgepole pine forest susceptibility to mountain pine beetle would have been controlled by the forest fire regime, principally the fire cycle length. By constraining the window of age-related susceptibility to mountain pine beetle 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).

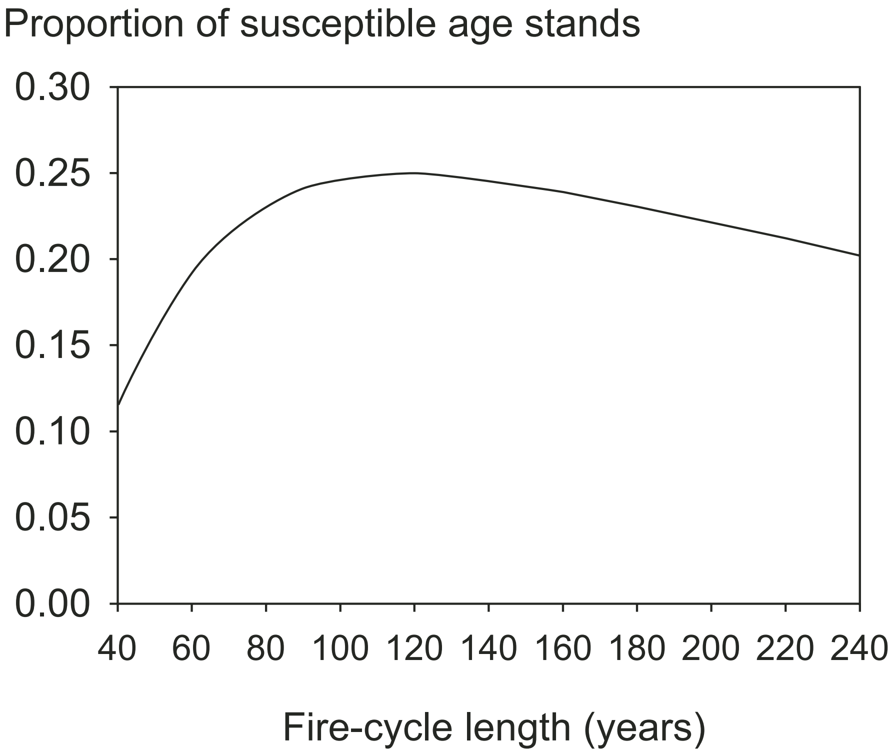

Figure 2. Relationship between fire-cycle length and the proportion of stands susceptible to mountain pine beetle in forests with a negative exponential age-class distribution.

Examples of age distributions for 60- and 100-year fire-return cycles and a "normal" fully regulated forest[2] 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 mountain pine beetle 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).

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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.

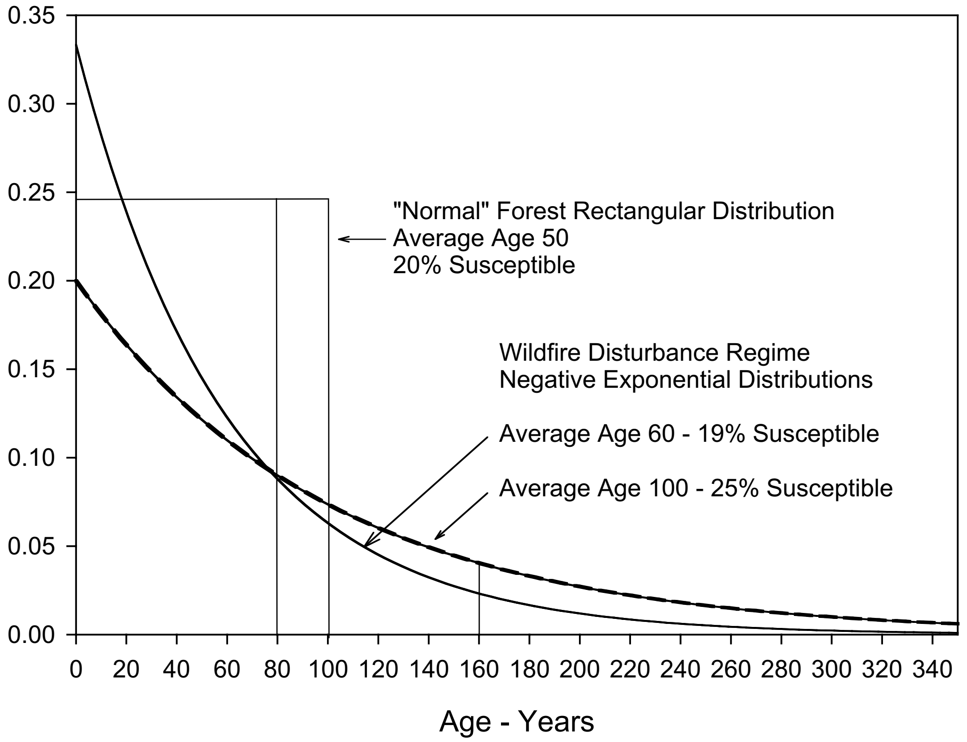

Figure 3. Theoretical distribution of age classes susceptible to mountain pine beetle in a normal forest with a 100-year rotation, and in forests with 60- and 100-year fire cycles.

Modelling Historic Forest Age Distribution and Susceptibility to Mountain Pine Beetle

To assess past and present mountain pine beetle activity in relation to forest age structure, and examine projected future forest conditions relevant to mountain pine beetle, 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) (British Columbia 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).

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 mountain pine beetle has increased from about 18% to 53% between 1910-1990 (Fig. 5).

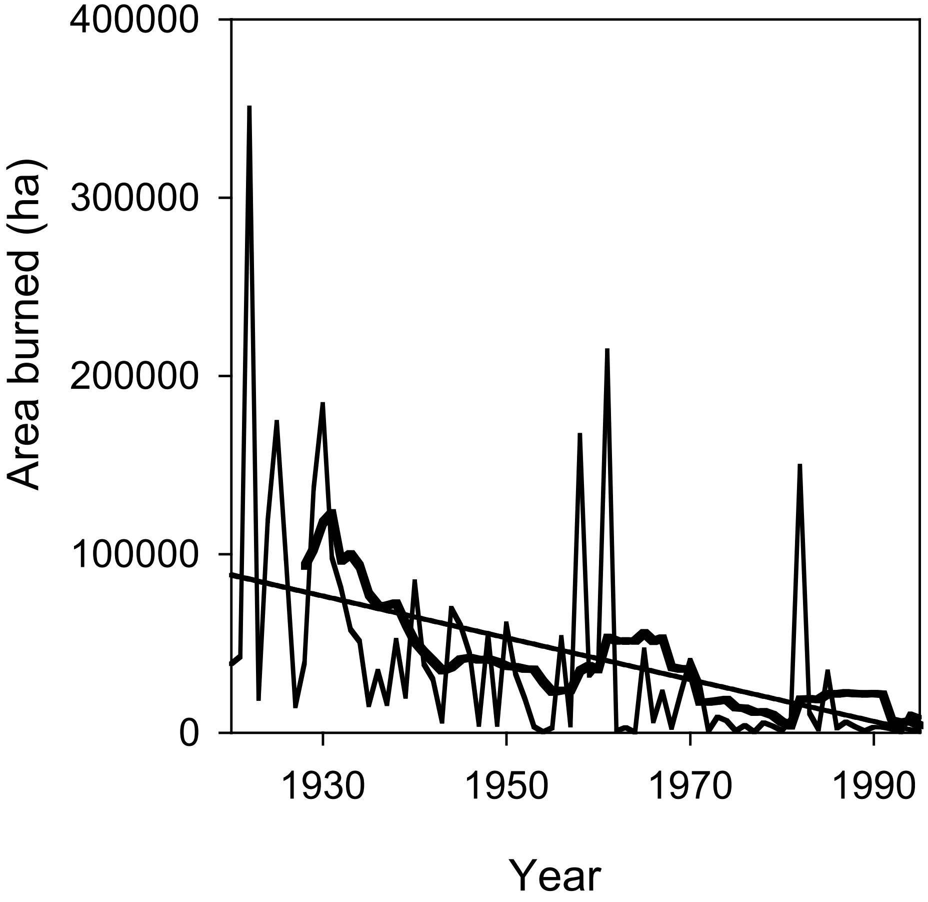

Figure 4. Area burned by forest fires during 1920-1995 in pine-dominated forests in BC. Annual area burned (solid line), ten-year running average (bold line) and linear regression model (straight line).

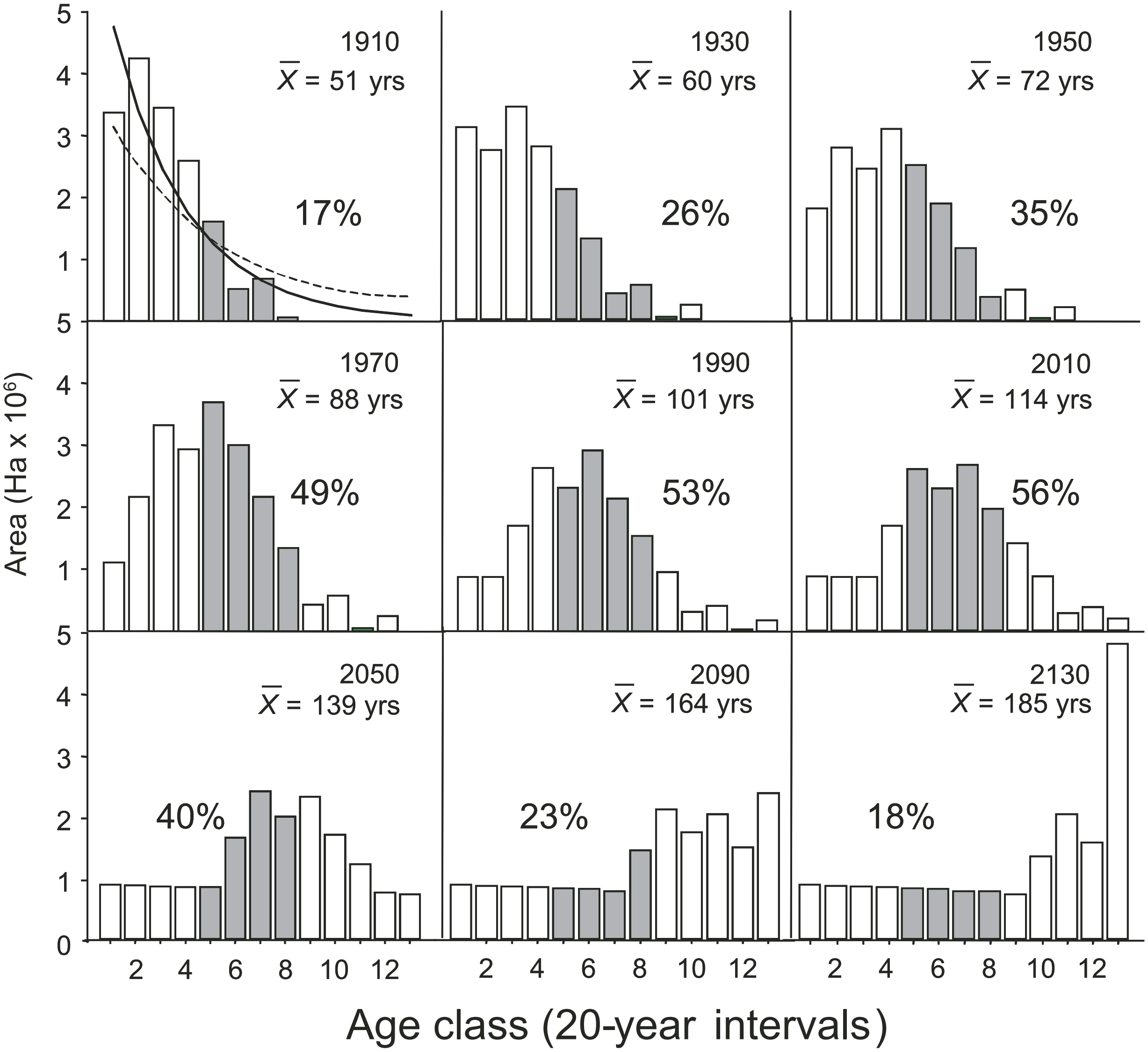

Figure 5. Age class distribution of pine forests in BC projected from 1990 inventory data. Age classes susceptible to mountain pine beetle are shaded (percentage of total provided). The theoretical age distribution resulting from a 60- (solid line) and 100-year (dashed line) fire cycle is shown in the 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 mountain pine beetle outbreak area against the amount of susceptible pine suggests that mountain pine beetle activity was positively correlated with the increase in the amount of susceptible pine (Fig. 6).

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 mountain pine beetle epidemics (Carroll et al. 2004).

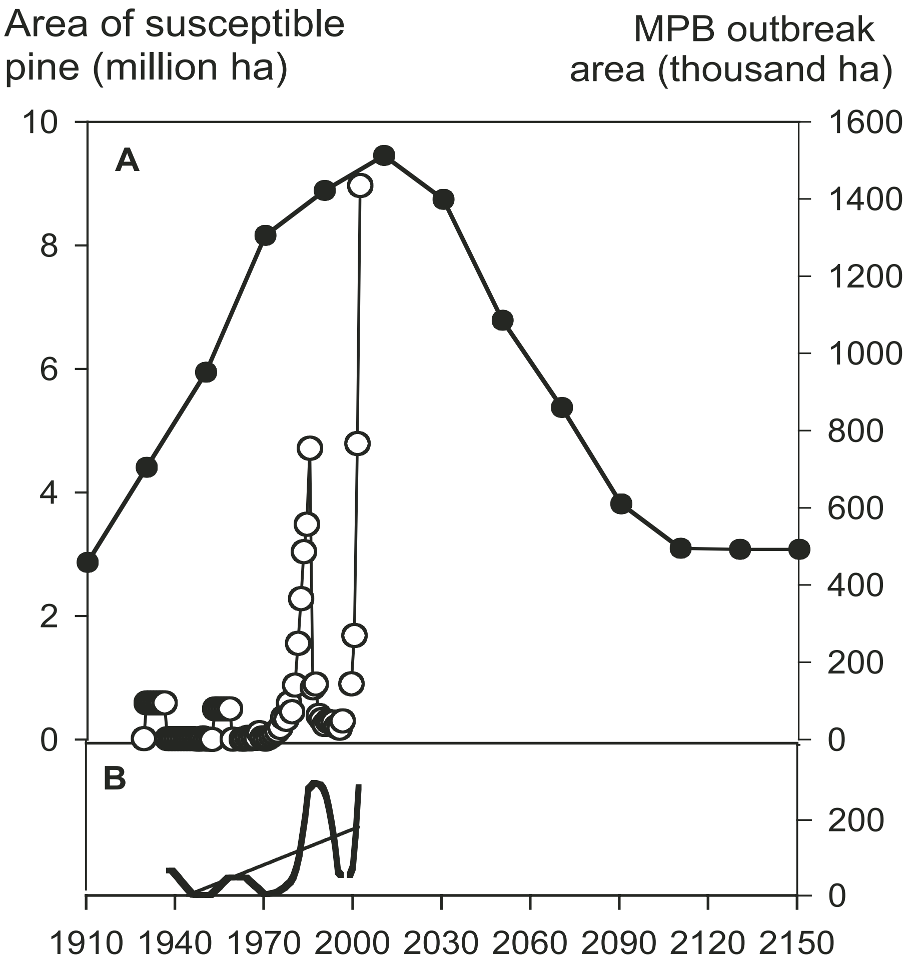

Figure 6. A). Estimated area of mountain pine beetle-susceptible pine (solid circles - million ha) and of mountain pine beetle (MPB) outbreaks (empty circles - thousand ha) in BC. B) Ten-year running average mountain pine beetle outbreak area and linear regression model (thousand ha). Gap is a result of no survey conducted in 1997 and 1998.

Conclusions

There have been at least four major mountain pine beetle outbreaks during the last 85 years. Mountain pine beetle 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 mountain pine beetle-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 a 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 three times more area of pine in BC in age classes susceptible to mountain pine beetle in 1990 when compared with backcast estimates for 1910. Currently, depletions by mountain pine beetle 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 (2004) 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 to developing a long-term management strategy.

Acknowledgements

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S.W. Taylor is a Forestry Officer and A.L. Carroll is a Research Scientist with the Canadian Forest Service, Pacific Forestry Centre.

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Current Status of Mountain Pine Beetle in British Columbia

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Abstract

Province-wide aerial overview surveys have been conducted in British Columbia by the Ministry of Forests since 1999 and earlier by the Forest Insect and Disease Survey, Canadian Forest Service. The results of the 2003 overview survey shows that the size of the mountain pine beetle infestation has doubled since 2002 increasing from 1.98 million ha to approximately 4.1 million ha and is now the largest infestation of mountain pine beetle ever documented. The greatest changes have occurred in the central interior plateau where the area infested increased by 4.3 times in the former Cariboo Forest Region. The outbreak is expected to continue unabated until the host is depleted or a lethal cold-winter event occurs.

Introduction

The B.C. Ministry of Forests has conducted an annual provincial aerial overview survey since 1999. Prior to 1996, overview surveys were conducted by the Forest Insect and Disease Survey unit of the Canadian Forest Service. The survey has documented the damage caused by the mountain pine beetle, *Dendroctonus ponderosae* (Hopkins), and many other disturbance agents. This report provides preliminary data on the mountain pine beetle infestatation from the most recent compilation of the 2003 aerial survey. At the time of presentation at the Kelowna symposium, final survey results were not available but are now included in this report.

Methods

Fixed-wing aircraft are used for aerial overview surveying. Flights are conducted in the summer months preferably on clear days at an alititude of about 1000 m and at an airspeed of about 175 kph. If the terrain is generally flat, the survey follows a grid whose swath width varies depending on the intensity of damage present. Mountainous terrain is flown along contours. Two mappers are seated so observations are made from both sides of the aircraft at one time. Sketch mapping records damage in one of two ways: as spot (point) infestations varying in size from 1 tree to 50, or as polygons which are larger patches of mortality and defoliation that are assigned a damage severity class. The severity classes for mortality are: Light (1-10% of the stems within the polygon), Moderate (11-30%), and Severe (30%+). The points and polygons are drawn on customized 1:100,000 maps that use recent LANDSAT 7 black and white images

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as a base that are overlayed with other information that aid in navigation (i.e., roads, place names, recent cutblocks, contours, etc.). The flight lines are tracked using a hand-held GPS receiver (Garmin II+) that is capable of recording positions at user specified time intervals. A spatial file is downloaded from the receiver and serves as a digital record of the survey progress (Fig. 1).

Once completed, the rough sketch maps from each observer are consolidated onto a final sketch map that will be digitized. Digitized data is checked for errors and omissions and then forwarded electronically in GIS file formats to the provincial data roll-up contractor to be stitched together with maps from other surveyors. The final product is a provincial coverage containing point and polygon data for all detected damaging agents for the year. The spatial data is tabulated and summarized by Region, District, and pest and included into the Ministry of Sustainable Resource Management's Land and Resource Data Warehouse (LRDW) where it becomes accessible province-wide to those granted access, and may be viewed using an ArcIMS web map viewer developed specifically for displaying this forest health information. Data summaries and maps, along with links to historical data and the overview data collection standards, are posted on the Ministry of Forests Aerial Overview Survey web site.

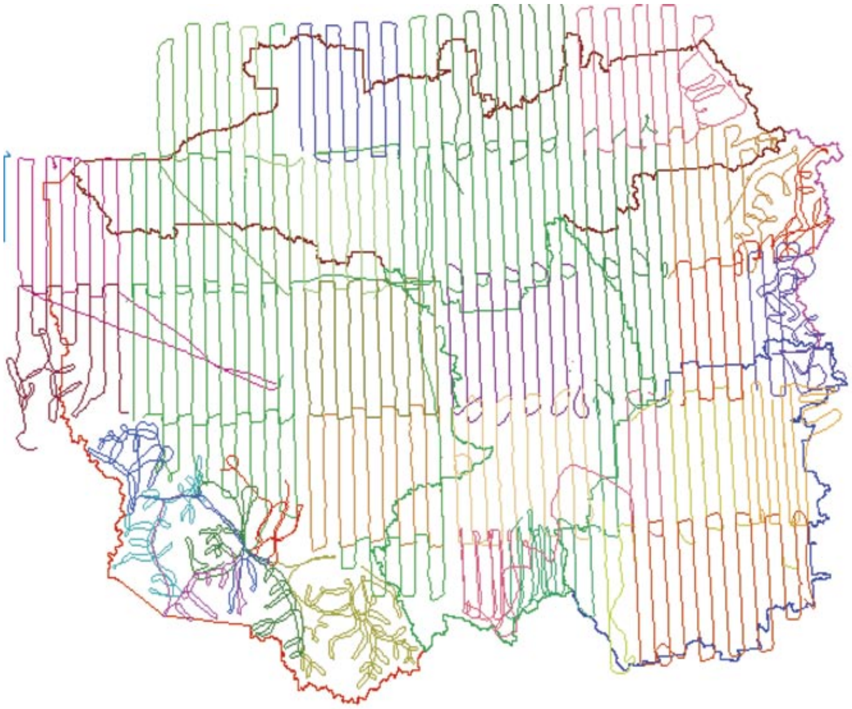

Figure 1. Example of GPS track record for the 2003 overview survey of the former Cariboo Forest Region. Different coloured lines indicate different survey dates. Note the variation in flight lines between flat (grid pattern) and mountainous (contour) topography.

Results and Discussion

Area of damage caused by the mountain pine beetle increased from 1.98 million ha in 2002 to about 4.1 million ha in 2003. This increase represents an increase in area of approximately 2 times and is the largest area ever recorded of damage caused by the mountain pine beetle. Table 1 summarizes the area attacked by the beetle in the three Forest Regions for all forested lands excluding national parks. Comparing regional data from 2002 and earlier, with 2003 data requires the earlier data to be consolidated following the amalgamation of six regions into three in April 2003. The Northern Interior Forest Region is comprised of the former Prince George and Prince Rupert Forest Regions (minus Robson Valley and North Coast Forest Districts). The Southern Interior Forest Region now contains the former Nelson, Cariboo and Kamloops Forest Regions plus the former Robson Valley Forest District. The Coastal Forest Region is nearly identical to the former Vancouver Forest Region with the addition of the North Coast Forest District.

Table 2 and 3 separate these data into damage occuring within and outside of the boundaries of Provincial parks. Non-park lands include all forested vacant crown land, Tree Farm Licences, woodlots, community forests, private land, federal lands, and other tenured land in timber supply areas. Non-park lands include both areas designated in the Timber Harvest Land Base (THLB) and Non-Timber Harvest Land Base (NTHLB).

Table 1. Provincial forestland infested by mountain pine beetle in BC in 2003. The change in area since 2002 is also provided.

	Area (ha)				
	Light (1%-10%)	Moderate (10%-30%)	Severe (30+%)	Total	Change since 2002
Coast	87,773	51,946	75,051	214,770	1.2 X
NIFR	674,434	317,285	439,893	1,431,612	1.2 X
SIFR	1,845,981	382,571	191,869	2,420,421	4.1 X
Provincial Total	2,608,188	751,802	706,813	4,066,803	2.8 X

Table 2. Area infested by mountain pine beetle in B.C. in 2003 in provincial parks.

	Area (ha)			
	Light (1%-10%)	Moderate (10%-30%)	Severe (30+%)	Total
Coast	81,183	48,312	72,731	202,225
NIFR	148,361	83,681	88,248	320,290
SIFR	67,537	9,814	8,900	86,252
Provincial total	297,081	141,807	169,879	608,767

Table 3. Area infested by mountain pine beetle in B.C. in 2003 on non-park forest land.

	Area (ha)			
	Light (1%-10%)	Moderate (10%-30%)	Severe (30+%)	Total
Coast	6,591	3,634	2,320	12,545
NIFR	526,073	233,604	351,645	1,111,318
SIFR	1,778,444	372,757	182,969	2,334,170
Provincial total	2,311,108	609,995	536,934	3,458,033

Tables 4, 5 and 6 show the distribution of damage by the new Forest Regions sub-totaled by the former Forest Regions to help compare damage from previous years. When separated into former Regions, differences in the expansion rate of mountain pine beetles become more obvious. The most southern Districts actually show a slight decrease in area infested. However, it is likely that the overall number of trees killed has increased, causing an intensification of damage covering a similar area. The rate of expansion is limited in these Districts due to past outbreaks and a smaller area of susceptible lodgepole pine. The greatest increases in area affected occurred in the former Cariboo Forest Region, now part of the Southern Interior Forest Region. The changes occurred when small spot infestations mapped in 2002 expanded into light infestations covering entire stands. The outbreak has intensified in the Quesnel Forest District and has expanded across the remaining mature pine stands in the Chilcotin Forest District, Central Cariboo District (formerly Horsefly and Williams Lake) and threatens to engulf the 100 Mile Forest District. Ongoing outbreaks near Kamloops may expand into neighbouring drainages where beetle suppression activities have been concentrated.

Table 4. Area infested by mountain pine beetle in 2003 in the Southern Interior Forest Region with the change in area since 2002.

	Area affected (ha)				
Region	Light (1%-10%)	Moderate (10%-30%)	Severe (30+%)	Total	Change
Cariboo					
Non-Park	1,752,472	346,792	163,635	2,262,900	4.3 X
Parks	65,841	7,354	7,714	79,307	5.4 X
Total	1,818,313	354,146	171,349	2,342,207	4.3 X
Kamloops					
Non-Park	21,966	15,883	7,996	45,845	1.3 X
Parks	720	1,645	388	2,753	1.3 X
Total	22,686	17,528	8,384	48,598	1.3 X
Nelson					
Non-Park	3,620	9,875	11,190	24,685	1.2 X
Parks	72	483	1,896	2,452	1.7 X
Total	3,692	10,358	13,086	27,137	1.2 X
SIFR Total	1,844,690	382,032	192,819	2,417,942	4.0 X

Table 5. Area infested by mountain pine beetle in the Northern Interior Forest Region in 2003 with the change in area since 2002.

	Area affected (ha)				
Region	Light (1%-10%)	Moderate (10%-30%)	Severe (30+%)	Total	Change
Prince George					
Non-Park	418,740	186,404	231,153	836,297	1.4 X
Parks	25,430	17,863	47,046	90,339	1.3 X
Total	444,170	204,267	278,199	926,636	1.5 X
Prince Rupert					
Non-Park	107,719	47,407	120,638	275,764	1.0 X
Parks	123,835	66,149	41,706	231,691	1.0 X
Total	231,554	113,556	162,344	507,455	1.0 X
NIFR Total	675,724	317,823	440,543	1,434,091	1.2 X (1.2 out, 1.0 in Parks)

Table 6. Area infested by mountain pine beetle in the Coastal Forest Region in 2003 with the change in area from 2002.

	Area affected (ha)				
	Light (1%-10%)	Moderate (10%-30%)	Severe (30+%)	Total	Change
Non-Park	6,591	3,634	2,320	12,545	0.7 X
Parks	81,183	48,312	72,731	202,225	1.3 X
CFR Total	87,774	51,946	75,051	214,770	1.2 X

In the Northern Interior Forest Region (Table 5), the overall infestation size increased by 1.2X since 2002. The area infested outside provincial parks increased by 1.3X as compared to 1.0X within the parks. Increases in area affected were predominantly seen in the former Prince George Forest Region concentrated within Vanderhoof, Prince George and Ft. St. James Forest Districts. Infestations in the former Prince Rupert Forest Region remained relatively unchanged in size from 2002. The infestation's growth may be slowing due to intensive management, natural factors, or because the infestation has intensified within the same areas. Further analysis is required to determine if any of these factors explain the minimal change in infestation size.

In the Coastal Forest Region, mountain pine beetle is restricted to three Forest Districts – Mid-Coast (now North Island – Central Coast), Squamish, and Chilliwack Forest Districts. The Mid-Coast Forest District includes the southern half of Tweedsmuir Provincial Park, which contains more than 200,000 ha of infested pine. The Squamish and Chilliwack Forest Districts have relatively small but active mountain pine beetle populations that are limited by the availability of susceptible lodgepole pine. The 3,670-ha infestation north of the resort village of Whistler has received some media attention due to its potential to increase the risk of fire damage to the site of the 2010 Winter Olympic games.

At this time it is highly probable that the area infested will increase in 2004. The magnitude of the increase is difficult to predict, but a doubling of the current area to over 8 million ha is possible given previous years' trends. However, if the infestations intensify rather than spread, the area affected will be less than 8 million ha. This province-wide outbreak will only be slowed or stopped when the host has been depleted or by a cold weather event of temperatures reaching –40°C for at least one week. Management efforts are being directed toward suppressing small populations on the periphery of the outbreaks, but these measures will only buy a limited amount of time unless the outbreak-ending cold weather event occurs.

Conclusions

Mountain pine beetle infestations continue to expand throughout BC. The central interior plateau is the most heavily affected, but infestations in the Kamloops area are also problematic. Opportunities to slow the expansion and suppress small infestations are becoming limited, although it is still possible in the northern districts and on the periphery of the larger outbreaks.

Acknowledgments

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Mountain Pine Beetle: Conditions and Issues in the Western United States, 2003

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Abstract

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is by far the most destructive insect pest of pine species in western North America. It is once again at outbreak levels in many parts of the western United States, currently affecting more than 1.5 million acres (0.7 million ha). The infested area in the western US nearly doubled from 2001 to 2002. While infesting most pines within its range, and causing significant concerns in ponderosa, western white, and whitebark pines, lodgepole pine is the most frequently infested and most heavily damaged of the beetle's hosts. Nearly 90% of the current mortality is in lodgepole pine. Management strategies and tactics have been developed to better deal with the devastating impact of mountain pine beetle infestations across the western US.

Mountain Pine Beetle History in the United States

Outbreak populations of mountain pine beetles have occurred in western North America for much of the past 30 years. During the 1990s, populations were at relatively low levels, having decreased from more than 4.6 million acres (2.1 million ha) in 1981. It is unlikely that such a high level of infestation will reoccur, due to a lack of suitable hosts; however, more than 1.5 million acres (0.7 million ha) are currently infested and populations continue to increase in many western states. Because of their prevalence, and the rapidity with which they can alter forest conditions, mountain pine beetles have significantly affected management philosophies, decision-making processes, and silvicultural activities for the last several decades of the 20th century. It now appears they will also impact the 21st century.

In the northern Rocky Mountains, and wherever host species occur in the intermountain West, mountain pine beetle outbreaks have been reported with some regularity since the early 1900s. Devastating outbreaks in the late 1970s and early 1980s—unprecedented and perhaps never to be repeated—began in vast areas of mature lodgepole pine from northern Utah into British Columbia (BC). By 1978, millions of acres in western Montana and other western states were infested. We have estimated that in northern Idaho and western Montana, alone, from 1975 to 1995, more than 3 million acres (1.4 million ha) were infested to some extent—and more than a quarter-billion trees were killed. Recent outbreaks, not yet as extensive, are extremely damaging in some areas (Unpublished office reports, USDA Forest Service, Northern Region).

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Management Issues, Concerns, and Strategies

Until the mid-1970s, pest and land managers in the US somewhat naively believed that beetle-killed trees were a manifestation of an insect "problem" and the solution was the destruction of the pest. Attempts at implementing this solution were many and varied—virtually all of them unsuccessful. It is certain many beetles were killed. What is less certain is that any long-term alteration of outbreak effects was realized.

By the mid-1970s, we came to realize that the real problem was not a plethora of beetles, but rather, a preponderance of susceptible hosts. We noted that most host stands experiencing mountain pine beetle outbreaks shared remarkably similar characteristics. Most were older stands, densely stocked with large-diameter trees that had begun to slow in growth due to advanced age, overstocking, and/or drought. Recognizing these commonalities was an important step in developing management strategies and tactics for reducing beetle-caused mortality.

One of the first major accomplishments was the advent of a hazard-rating system for lodgepole pine, developed by Amman et al. (1977), in which we recognized those stand conditions most likely to support a mountain pine beetle outbreak. They were stands:

- in which average diameter was greater than 8 inches (20 cm);
- in which age exceeded 80 years; and
- were growing at elevation/latitudes conducive to beetle survival.

At about the same time, Stevens et al. (1980) demonstrated similar, recognizable conditions existed in ponderosa pine stands. Their work showed that high-hazard ponderosa pine stands were:

- ones in which average diameter exceeded 10 inches (25 cm);
- had stocking >150 square feet of basal area/acre (34.4 m^2/ha); and
- single-storied and mostly single-aged.

Hazard-rating models for the mountain pine beetle have been recently updated and improved. The one currently in use for lodgepole pine was developed by Shore and Safranyik (1992). Schmid et al. (1994) developed the current hazard rating system for ponderosa pine.

Knowing which conditions defined the likelihood of beetle infestation led to the realization that stand conditions could be altered to minimize the impact of the beetle. Thinning studies conducted during the late-1970s and early-1980s demonstrated that beetle-caused mortality could be reduced by creating less-than-favorable conditions for beetles (McGregor et al. 1987). Silvicultural recommendations for dealing with existing and threatening mountain pine beetle outbreaks now include:

- regeneration;
- sanitation/salvage;
- basal area reductions with or without species discrimination;
- thinning to promote non-host species; and ultimately
- creation of a mosaic of age, size, or species diversity.

In 1984, pheromone "tools" became available to the land manager and in some situations made silvicultural treatments more effective (Borden et al. 1983). Tree baits are now used somewhat routinely—at least in situations where trees can be removed. Pheromone traps have been used primarily for monitoring, but trap-out scenarios are now becoming more promising. Verbenone, an apparent mountain pine beetle anti-aggregant, has shown promise in protecting high-value trees and stands from beetle attack (Bentz et al. 2004).

Current Conditions in the United States

Mountain pine beetle populations have been increasing in the United States since 1999. In particular, the US Forest Service's Northern Region is currently experiencing an outbreak expansion.

Outbreak Status in the Northern Region

The current outbreak in the Northern Region began to attract attention in 1996. At this time, following a couple of years of slightly increasing infestations, just over 53,300 acres (21,570 ha) were infested. In 1997, the infested area increased to 71,600 acres (28,975 ha), then almost doubled to 114, 700 acres (46,417 ha) in 1998. In 1999, the infested area grew to 144,000 acres (58,275 ha) and in 2000 to 149,200 acres (60,379 ha). In 2001 we experienced a significant increase—to 236,500 acres (95,708 ha). And in 2002, the infested area came close to doubling again, increasing to 517,600 acres (209,465 ha). Data for 2003 infested areas have not been compiled; but in most infested areas, populations and beetle-killed trees are still increasing. In all infested areas, resources are being seriously impacted.

Current (2002) Conditions by State

Table 1 summarizes the infested area, by state, for those states reporting mountain pine beetle-infested areas in 2002.

Table 1. Mountain pine beetle-infested area, by state, 2002.

State	Infested Area (acres) (2002)	Infested Area (ha) (2002)
California	186,800	75,595
Colorado	209,000	84,579
Idaho	339,300	137,310
Montana	249,500	100,969
New Mexico	3,800	1,538
Nevada	2,600	1,052
Oregon	182,300	73,774
South Dakota	102,900	41,642
Utah	26,700	10,805
Washington	173,100	70,051
Wyoming	88,000	35,612

Figure 1 illustrates mountain pine beetle trends for the past 25 years. The peak infestation year of 1981, the decline in the early-1990s, and the resurgence in infested area in the past few years are all clearly seen.

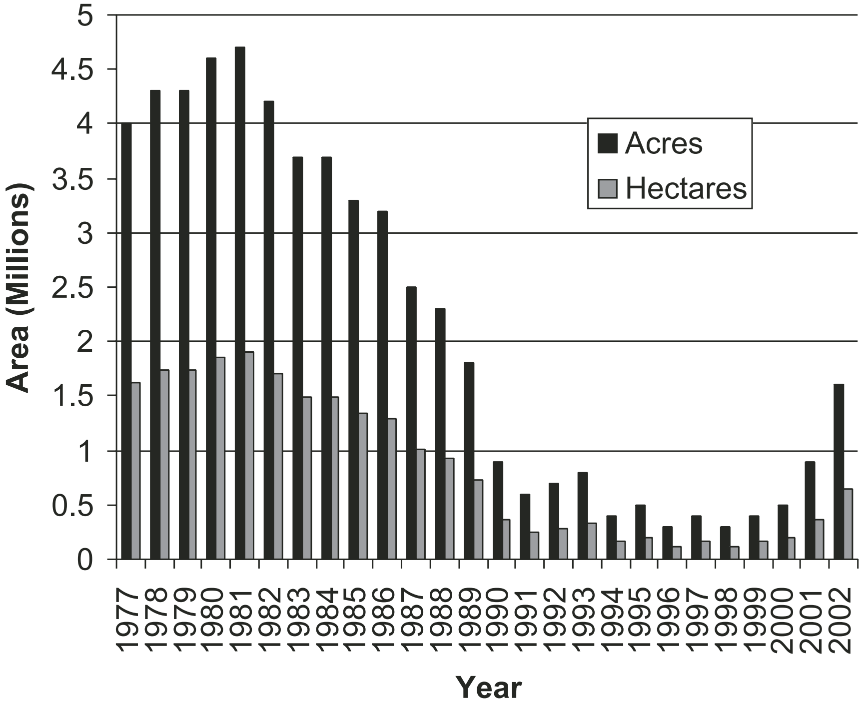

Figure 1. Mountain pine beetle-infested area, western United States, 1977-2002.

Other Affected Species

Although most management efforts to date have dealt with beetle-caused mortality in lodgepole pine stands, and to a lesser extent ponderosa pine, mountain pine beetle depredations in other hosts are significant. Prior to white pine blister rust (*Cronartium ribicola* J.C. Fisch.) devastating western white pine stands, mountain pine beetle outbreaks were regarded as one of western white pine's most damaging pest. With the desire to develop rust resistance in those forest types, the impetus to prevent beetle-caused losses has taken on a new emphasis.

In many parts of the northern Rocky Mountains, limber pine "decline" is a matter of serious concern to resource managers. While there are likely several factors involved in the decline of this most valuable, mid-elevation species, one of the most obvious agents contributing to tree mortality is mountain pine beetle.

Finally, at high elevation sites throughout the Rocky Mountains, whitebark pine is of importance because it is often the only, or major, tree species on those sites and is essential for an array of watershed, wildlife, and recreational amenities. Within the past few years, at least in our region, and I believe this to be the situation elsewhere, mountain pine beetles have killed thousands of trees in these fragile ecosystems. White pine blister rust is also becoming more prevalent. It is imperative that we strive to protect these high-value trees from beetle infestations.

Conclusions

In conclusion, mountain pine beetles, as native inhabitants of pine-dominated ecosystems in North America, were here long before us and will no doubt remain long after we are gone. Still, we must try to reduce tree mortality and realize management objectives. The past 25 years have seen great developments in our understanding of mountain pine beetle population dynamics, host interactions, and how beetle populations may be manipulated to our advantage. Most of the time, we know what we should do, and when we should do it; but often our resolve meshes poorly with those whose philosophies are counter to our own. In the US, we are frequently incapable of conducting management activities that would best serve the needs of the resource. Still, we learn, continue to improve, and develop more effective management strategies. I caution against becoming too self-confident in efforts to "out smart" mountain pine beetles, however. Most of the lessons I've learned in nearly 30 years of trying suggest we have yet to progress that far.

Ken Gibson is an Entomologist in Forest Health Protection, USDA Forest Service.

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The Mountain Pine Beetle: Scope of the Problem and Key Issues in Alberta

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Abstract

Alberta is facing the threat of another mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak. Current infestations in the Bow Valley have spread outside Banff National Park to adjacent provincial land. Almost all lodgepole pine (*Pinus contorta* Douglas var. *latifolia* Engelmann) forests in Alberta are found outside the normal mountain pine beetle distribution range; however, its range has been expanding in Alberta. Pine forests in Alberta are becoming older due to an effective wildfire suppression program. Approximately 60% of eastern slopes pine forests is over 80 years old and is very susceptible to the mountain pine beetle. The current mountain pine beetle infestation spans a variety of jurisdictions. The values and tools used to manage the beetle vary according to their individual land management mandates. Various resource and land management agencies in Alberta and British Columbia are working cooperatively to manage the mountain pine beetle in the Rocky Mountain region along the border between the provinces. Historical climate records in Alberta indicate a warming trend in the last century. If the current warming trend continues, this pest will expand its range in Alberta. Jack pine (*Pinus banksiana* Lamb.) is a potential beetle host in Alberta. In northern Alberta, lodgepole and jack pine overlap in distribution and hybridize. If the mountain pine beetle successfully colonizes hybrid lodgepole-jack pine and pure jack pine forests, Canada will face a major ecological, social and economical disaster.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is the most destructive pest of mature lodgepole pine (*Pinus contorta* Douglas var. *latifolia* Engelmann) forests in Canada. British Columbia (BC) is currently experiencing the largest pest outbreak in Canadian history. Alberta has been fortunate to have experienced only two known outbreaks in recent history: 1940 to 1943 in Banff (Powell 1966) and 1977 to 1985 in the Waterton-Blairmore area (Alberta Forestry, Lands and Wildlife 1986). In both cases, human intervention played a major role in containing the outbreaks, with below normal fall and winter temperatures eventually being responsible for ending the outbreaks. However, Alberta is facing the threat of another mountain

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pine beetle outbreak. The current threat is much greater than that of the previous outbreaks, due to the overwhelming abundance of susceptible pine forests on the eastern slopes of the Rockies.

Alberta has to face three challenges in dealing with mountain pine beetle management: aging forests, multi-jurisdictional mandates, and the potential expansion of the beetle into jack pine (*Pinus banksiana* Lamb.) forests.

Mountain Pine Beetle in Alberta

The current mountain pine beetle infestation in Bow Valley started along Healy Creek in Banff National Park where an infestation was detected in 1997; however, at the time of detection there was evidence of trees killed by the beetle 2-3 years previously. Healy Creek is located approximately 20 km east of the outbreak in Kootenay National Park in British Columbia. At Healy Creek, the first infestation was observed at an approximate elevation of 1700 m in a marginal habitat for the mountain pine beetle; however, this population appeared to have been influenced largely by the Kootenay population and expanded downstream of the creek. Since then, the beetle infestations in Banff National Park have spread eastward through the park and to adjacent provincial land. The number of infested trees has increased exponentially over the last six years.

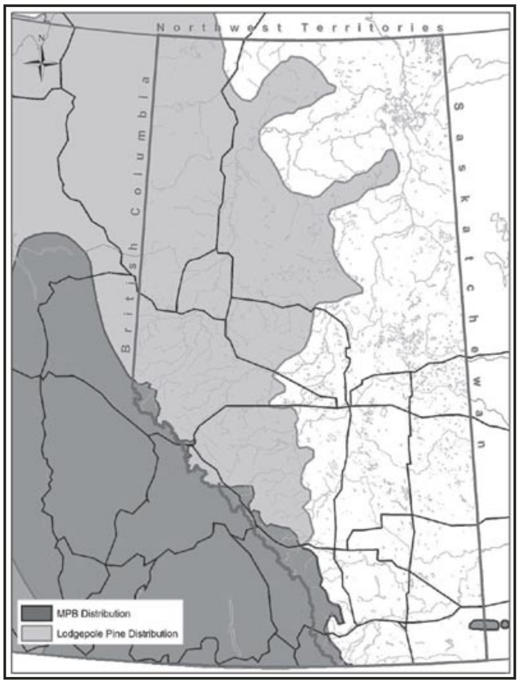

Figure 1. Distribution of lodgepole pine and the current mountain pine beetle distribution range in Alberta based on the historical surveys and pheromone bait monitoring records.

Alberta's present lodgepole pine forest ecosystem has evolved without the presence of the mountain pine beetle.

The mountain pine beetle is a temperate pine forest pest. The eastern edge of the beetle distribution lies along the southern Rockies near the Alberta-BC border where the effect of maritime climate ends. Thus, a large component of lodgepole pine forests in BC and almost all the lodgepole pine forests in Alberta are found outside the normal mountain pine beetle range of distribution (Fig. 1).

The mountain pine beetle range is expanding in Alberta. The mountain pine beetle occasionally invades pine forests in a narrow area along the eastern slopes of the Rockies in southern Alberta when consecutive mild winters and hot, dry summers occur. However, Alberta has recently been experiencing more frequent mild winters. In 1979, the beetle was discovered for the first time in the Cypress Hills in southern Alberta (Chambers 1981). In 1997, the mountain pine beetle was recorded in the Wilmore Wilderness Park (north of Jasper National Park). In 2003, the mountain pine beetle was recorded for the first time at a pheromone-baited monitoring site in the Kakwa Wildland Provincial Park located still further north (54° latitude).

Pine forests in Alberta are generally getting older due to an effective wildfire suppression program. The mountain pine beetle attacks and kills healthy mature lodgepole, limber (*P. flexilis* James) and whitebark (*P. albicaulis* Engelmann) pines in Alberta. The eastern slopes of the Rockies consist of over 3 million ha of naturally occurring, homogeneous lodgepole pine forests that contain approximately 387 million m^3 of timber. For tens of thousands of years, forest fires, mainly due to lightning and burning by aboriginal people, have been the main disturbance of these forests. In fact, most of the eastern slopes pine forests have originated from massive forest fires in the 1880s and early 1900s. However, decades of wildfire suppression have resulted in extensive, 80 to 120+ year-old pine forests. Currently about 60% of eastern slopes pine forests is over 80 years old. Therefore, mountain pine beetle hazard in eastern slopes pine forests is extreme.

Jurisdictions and Land Management Mandates

A healthy forest is able to sustain itself ecologically while providing for society's economic, social, recreational and spiritual needs and values. While all jurisdictions share the same objective of managing for a healthy forest, the values and tools used to manage the beetle vary according to land management mandates. Public support for mountain pine beetle management programs also vary. Forest industry wants an aggressive approach. Environmental non-governmental organizations want natural processes to continue, including the restoration of fire to the ecosystem. However, smoke is an issue for tourism, transportation and local residents.

Mountain pine beetle infestations span a variety of jurisdictions with different land management mandates. The mountain pine beetle is considered to be a naturally occurring species in the mountain national parks. Therefore, the parks have no mandate for controlling the beetle. However, the mountain pine beetle is invasive on adjacent forests in the eastern slopes where the expansion of the beetle populations has serious economic, social and environmental consequences.

Various resource and land management agencies in Alberta and BC are working cooperatively to manage the mountain pine beetle in the Rocky Mountain region along the border between the provinces. The collaboration between Parks Canada and Alberta Provincial Agencies has achieved significant results in reducing the beetle infestations in the Bow Valley corridor. Banff National Park has: rescheduled the prescribed burning to remove large tracts of lodgepole pine stands susceptible to mountain pine beetle attack; implemented single-tree treatment of attacked trees in the area from the Banff town site to the eastern boundary; and harvested trees to create fire guards for prescribed burns.

In the past 12 months the park has burned 4,420 ha of susceptible pine forests (total area burned: 4,968 ha) containing some infested trees, and cut and burned or logged 2725 trees. The park also deployed 524 pheromone baits in Fairholm Range to contain the beetle population for the 2003-04 winter treatment. Banff National Park has implemented an exceptional program to manage the mountain pine beetle, despite limited available tools, and has destroyed approximately 68% of green-attack trees in the beetle treatment zone between the Banff town site and the east park gate along the Bow Valley (Personal Communication, J. Park, Banff National Park, Parks Canada, Banff). In the 2002-03 winter, Alberta Sustainable Resource Development detected and treated a total of 1,009 infested trees (98% treatment) in Alberta Provincial Parks, and the Town of Canmore and private developers treated an additional 303 infested trees. Overall, Banff National Park, Alberta Sustainable Resource Development, the Town of Canmore and private developers controlled approximately 74% of infested trees in the area east from the Town of Banff in the Bow Valley corridor.

A Ministerial Order was issued in 2002 and 2003 prohibiting the movement of pine logs and pine products with bark-on into Alberta from BC, western US and southern Saskatchewan between June 1 and September 30. The BC Ministry of Forests, Saskatchewan Environment and Resource Management, and the Forest Industry in Alberta and BC were notified. A truckload of infested logs is equivalent to a large patch of infestation containing sufficient beetles to potentially infest a few hundred trees. This awareness campaign appears to have been effective in reducing unauthorized log movement from 18 incidents in 2002 to zero incidents in the summer of 2003.

Future Risk of Mountain Pine Beetle in Alberta

Historical climate records in Alberta indicate a warming trend in the last century. It is reasonable to assume this trend will continue for the foreseeable future. The northern and northeastern limits of the beetle's distribution are approximately bounded by the isotherm for −40°C mean minimum winter temperature (Safranyik 1978). Therefore, the current warming trend will allow this pest to expand its range.

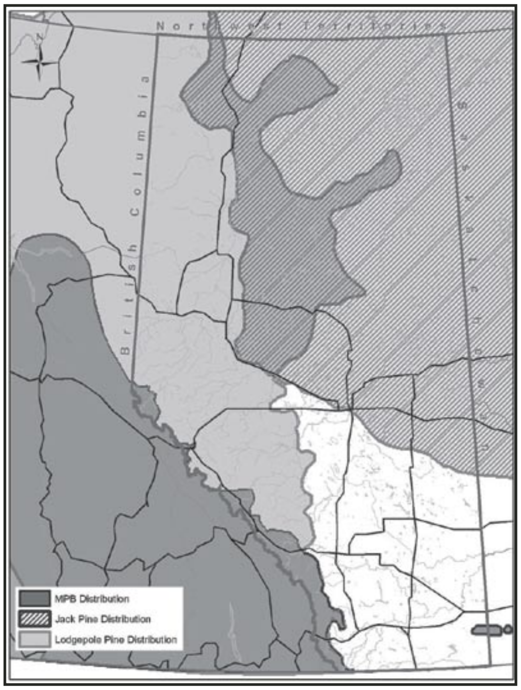

Figure 2. Lodgepole pine and jack pine hybrid zone with the current mountain pine beetle distribution range in Alberta.

Furthermore, jack pine is a potential beetle host in Alberta and Saskatchewan (Cerezke 1995). Lodgepole pine and jack pine overlap their distribution ranges in northern Alberta. This is the only place in North America where western and eastern pine species meet and hybridize (Fig. 2). The mountain pine beetle is an invasive species. If the mountain pine beetle successfully colonizes hybrid lodgepole-jack pine and pure jack pine forests, Canada will face a major ecological, social and economic disaster.

In the past the Alberta shelterbelt program introduced a large number of Scots pine (*Pinus sylvestris* L.) into the prairie farms. The mountain pine beetle successfully attacked some of these Scots pines during the last outbreak in the 1980s. The surviving Scots pines are now 20 years older and more susceptible. These patches of shelterbelt may serve as stepping-stones for the mountain pine beetle to susceptible jack pine forests.

Conclusions

Overall, the mountain pine beetle program in Alberta has been effective in maintaining the beetle population at a steady level. The program in Alberta has been implemented at a landscape level by collaboration among stakeholders including Alberta Departments of Sustainable Resource Development and Community Development, Parks Canada, Canadian Forest Service, Forest Industry and Municipalities and private developers. The successful mountain pine beetle management progrm in Alberta will also prevent the introduction of the beetle to Canada's boreal jack pine forests.

Acknowledgements

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Hideji Ono is Manager, Forest Health Section, with the Alberta Sustainable Resource Development.

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Provincial Bark Beetle Strategy: Technical Implementation Guidelines

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Abstract

This paper outlines the measures undertaken to cope with the largest mountain pine beetle infestation in the recorded history of British Columbia. Rapidly expanding infestations in several areas of the province have made it necessary to develop a provincial strategy with these main objectives: minimize the spread of beetles; minimize the loss of timber value; and minimize the loss of Crown revenue. Based on sound biological and forest management principles, the Province of British Columbia has developed a system for allocating the distribution of resources to affected areas. The Provincial Bark Beetle Strategy is comprised of Technical Implementation Guidelines and their respective components. They summarize the approach being taken to bark beetle management in British Columbia today.

Introduction

British Columbia (BC) is currently dealing with the largest mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestation in the province's recorded history. Mountain pine beetle has affected 9 million ha of mature lodgepole pine (*Pinus contorta*) stands and has killed over 108 million cubic meters of pine to date. The infested area spreads across both the northern and southern interior of BC. As mountain pine beetle continues its expansion, the area and volume impacted are projected to increase significantly, as more than 1 billion cubic meters of mature pine are at risk of infestation in the interior of the province.

The mountain pine beetle infestation has been characterized as a provincial "natural disaster" and is now at risk of spreading to other provinces. The infestation has created a forest management crisis that has serious implications for continued management of our forest asset. Lodgepole pine harvest represents the largest component of the provincial forest inventory in the interior of the province and is the single largest contributor of any species to overall provincial harvest levels. This species is therefore a critical part of our present and future asset base.

Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

The provincial government has recognized that the beetle epidemic warrants a unique focus. The need for a provincial strategy has been emphasized by several factors:

- There are rapidly expanding infestations in several areas of the province;
- There is a clear realization that some areas are no longer appropriate for mitigation actions;
- There are limited management resources (funding and logging capacity);
- There is a need for consistent management across the province; and,
- There is a need for clear, consistent application of a coordinated response.

As a result, the Province has embarked on the development of a provincial strategy with the following objectives: minimize the spread of beetles; minimize the loss of timber value; and, minimize the loss of Crown revenue.

Mountain Pine Beetle in BC

As of 2003, 4.2 million ha of red attack were recorded through aerial overview surveys in the province (Fig.1). This figure has more than doubled since 2002. A close look at the lodgepole pine inventory reveals that the 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. Mountain pine beetle activity appears to be positively correlated with the increase in the amount of susceptible pine (Fig. 2).

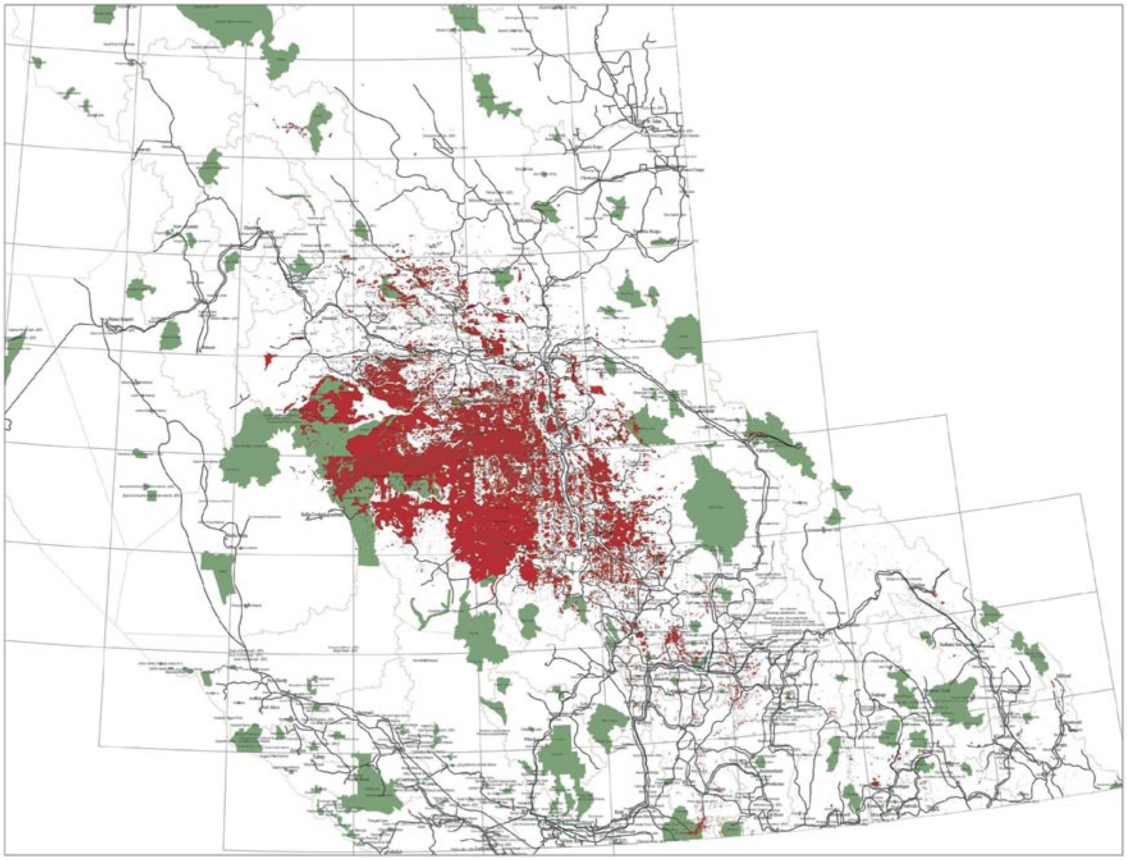

Figure 1. First draft of mountain pine beetle attack in 2003, plotted October 8, 2003 (Northern Interior Forest Region and Southern Interior Forest Region).

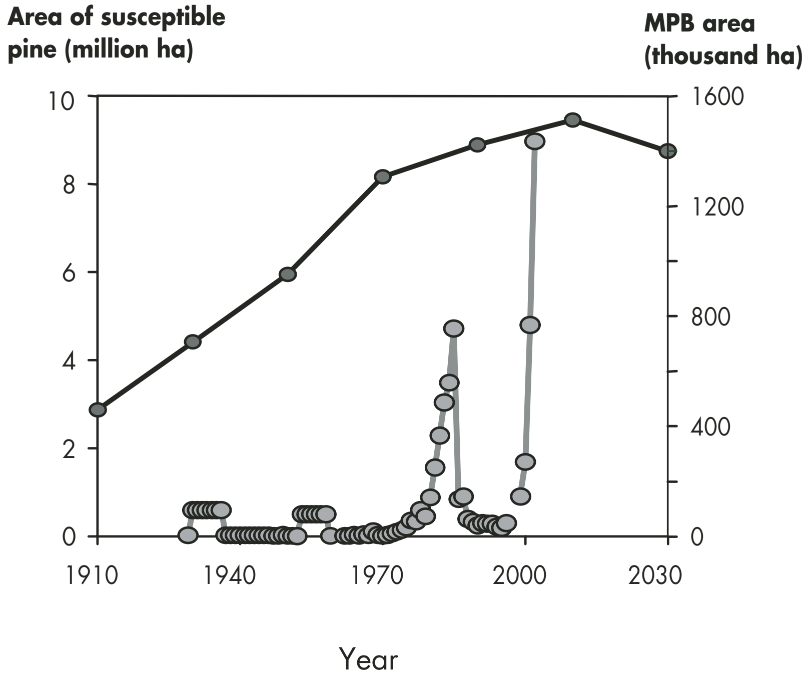

Figure 2. Estimated area of mountain pine beetle-susceptible pine (solid circles - million ha) and of mountain pine beetle (MPB) outbreaks (empty circles - thousand ha) in BC. Gap is a result of no survey conducted in 1996.

Overall Approach

The provincial strategy developed by the Ministry of Forests and the Forest Industry Emergency Bark Beetle Task Force is intended to provide an overall framework to guide forest management and mitigate damage to timber supplies, while minimizing the risk of future catastrophic outbreaks. Its development is a dynamic phenomenon, laid over an already complex mix of land uses, tenures, ecosystems and economic circumstances. It will provide general guidance to government and industry in allocation of resources, development and approval of Defined Forest Area Management (DFAM) Forest Health plans and bark beetle management strategies, and enable the most effective local actions to occur in a provincial context. Research and field experience in mountain pine beetle control indicate that success in suppressing infestations is dependent on the strategies and tactics employed, the effort expended on the control operation, and the point in the outbreak cycle when control is initiated. The key elements of bark beetle management are as follows:

- Rating stands for susceptibility and risk of depletion;
- Annual detection surveys and mapping of infestations;
- Annual assessments of rates of change in infestation levels and spread; and,
- Prompt, appropriate and thorough action on all infestations where suppression or control to some degree is feasible.

Technical Objectives

The main objective is to provide a technical approach for bark beetle management based on the fundamental elements of bark beetle–host interaction and proven tactics to prevent or mitigate losses. The provincial approach is designed to concentrate limited resources where management can have an impact, and identify situations where it is impossible to affect the course of infestations and tree mortality.

Overall, the strategy must be biologically based to a great extent, while recognizing that other resource management objectives and issues must be integrated (Fig. 3).

In the endemic state, beetle populations occur primarily in single trees or small, scattered groups of trees. During the incipient (pre-epidemic) phase, the infested spots grow in size and number, and tend to coalesce into large patches. As the outbreak expands, the patches extend over the landscape and small spots or individual infested trees are found at the leading edge of large outbreaks, or in areas where populations are just beginning to build. Hence, the ratio of infested spots to infested patches at the landscape level can be used as a measure of the stage of an infestation. The following table (Table 1) attempts to illustrate the change in beetle infestation dynamics. These general relationships are the foundation for the broad management zones.

Strategy assignment occurs on two levels: landscape level beetle management units (BMUs) and broad provincial zonations. The overall intent of establishment of BMUs and zonation is to clarify where and when specific management strategies and tactics are appropriate.

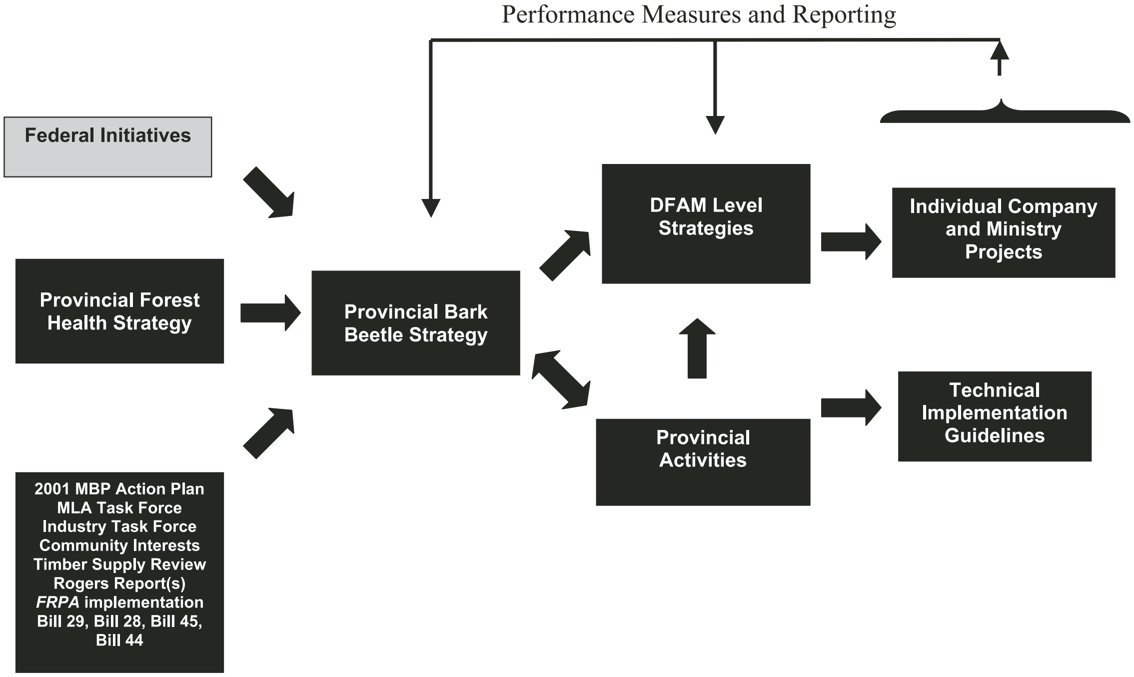

Figure 3. Framework for mountain pine beetle management activities in the province.

Table 1. General infestation dynamics.

% of infestation in patches \ **% of infestation in spots**	Low	Moderate	High
High	Old infestations; high red, high grey; > 4 yrs		
Moderate		Ongoing active infestation; many patches; interspersed spots	
Low			New infestation; “leading edge”; many spots; few patches

BMU Strategies

A BMU is a planning and reporting unit for operational beetle management. Its purpose is to facilitate the implementation of beetle management activities. Resource management objectives should be consistent throughout the unit. Strategies should be evaluated for compatibility with adjacent BMUs.

BMU boundaries are customarily congruent with the boundaries of Landscape Units. The strategy, and, therefore, the recommended treatment options, is selected after consideration of the status of the outbreak in the BMU and the estimated feasibility of achieving specific objectives inherent in the BMU strategies available. Primary considerations include the following:

- Current status of the outbreak;
- Potential for further spread and intensification;
- Access;
- Harvesting/milling capacity; and,
- Availability of other suppression resources.

Figure 4 illustrates the assigned BMUs to the Interior Emergency Bark Beetle Management Area as of 2003.

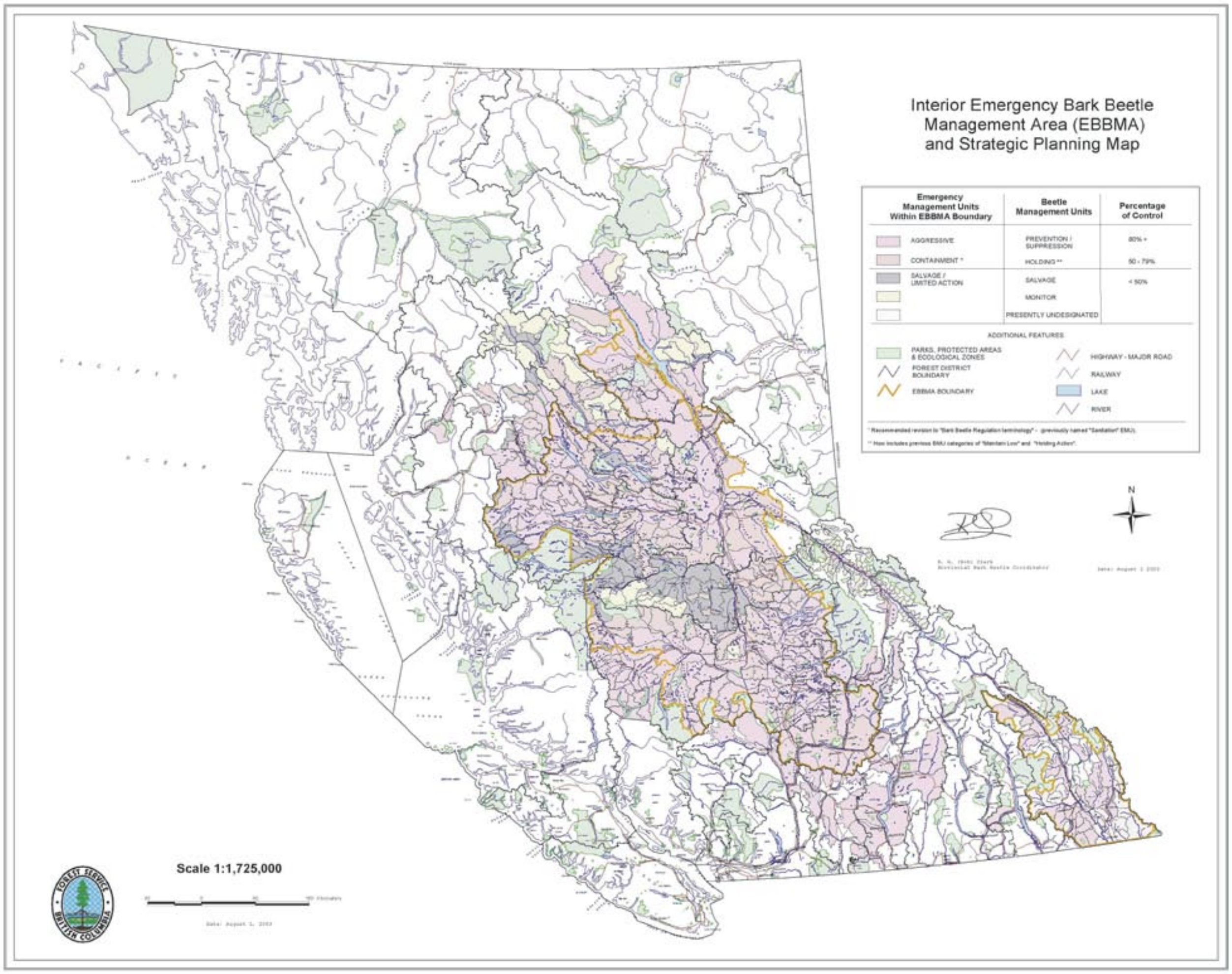

Figure 4. Interior Emergency Bark Beetle Management Area (EBBMA) and Strategic Planning Map.

There are four possible BMU strategies (Table 2). These strategies are selected based on the level of outbreak in an area and the estimated effectiveness of selected treatments in achieving stated objectives.

Suppression/Prevention: This is the most aggressive strategy. It is selected when the infestation status is such that aggressive direct control actions are expected to keep an area at low level of infestation. Areas are not infested or are lightly infested, and resources for direct control or harvesting and milling capacities equal or exceed the amount of infestation. Objectives are to harvest or treat more than 70% of all infested material in any given year. The intent of the strategy is to reduce or keep the outbreak to a size and distribution that can be handled within "normal resource capability".

Holding: The intent of this strategy is to maintain an existing outbreak at a relatively static level. It is a delaying strategy until adequate resources are available or access created that allow for a more aggressive approach, or to reduce overall loss while waiting for a killing climatic event. This is appropriate in areas with chronic beetle infestations that are too large to deal with using single-tree treatments or where access is poorly developed for directed harvesting. The objective is to harvest or treat approximately 50% of currently infested material in any given year.

Salvage: Salvage is applied to areas where management efforts would be ineffective in substantially reducing the beetle populations and subsequent levels of damage. Such areas have extensive outbreaks covering a large proportion of susceptible stands. The objective in this case is to salvage affected stands and minimize value loss. This strategy may also apply to areas containing small volumes of pine or areas where the pine is marginally economic – that is, where control is not worth the effort that would be expended and the objective is to salvage whatever values are there.

Monitor: This strategy is applied to areas where management efforts would be ineffective in substantially reducing the beetle population and subsequent levels of damage, or where there is no short-term (less than 5 years) possibility of salvaging dead timber. This may be due to management constraints such as wilderness area, park or ecological reserve, or because access cannot be put in place before substantial merchantable degradation of the dead material occurs.

Table 2 illustrates general BMU strategy criteria, with the exception of "Monitor".Some criteria for assigning BMU strategies are found in Table 3. Examples of BMU characteristics under the various strategies are found in Table 4.

Table 2.Objectives for beetle population removal for the four BMU strategies.

Strategy	% Current infested area to treat[1].	Comments
Suppression/ Prevention	~80	Address all current attack within two years, stand proofing, other actions. The intent is to "control" the outbreak in that area and stop spread.
Holding	50-70	Address the largest proportion of newly infested material, at least close to the rate of expansion. The intent is to maintain beetle populations at a level that can be dealt with annually without huge expansion.
Salvage	<50	The priority is to salvage timber previously attacked to minimize value loss. Relevant in areas where suppression or holding actions are no longer appropriate or feasible.
Monitor	0	No action is required beyond monitoring and recording. This is most appropriate in parks and ecological reserves and in inoperable areas where the outbreak has peaked, salvage is not possible, and there is no chance for any mitigation of further loss.

[1] Based on estimates from the most current annual aerial overview.

Table 3. General BMU strategy criteria.

Factor	Factor Definition		
	Suppression	Holding	Salvage
Green: red ratio (average for the BMU)	<10: 1	<10: 1 i.e.,- not adjacent to an overwhelming source of beetles.	>10: 1 i.e., indicative that large populations have dispersed in from adjacent BMUs and that populations will expand at a rapid pace.
Harvest/ treatment capacity	≥ estimated green attack	≤ 2X estimated green attack	2-3X estimated green attack (or greater once ground probe information is evaluated).
Infestation distribution	Mostly spots with relatively few patches.	Mix of small spots, small and medium patch infestations.	Small and medium patches with some small spots.

Table 4. Characteristics of four BMU strategies.

Characteristic	Strategy			
	Suppression/ Prevention	Holding	Salvage	Monitor
% Current infestation to treat	~≥80	~50-70	~≤50	0
Hazard rating	All	Mod – High	Mod – High	All
Road access	Required	Need in short term	Short term or planned	Not necessary
Infestation status	Light – low outbreak	Low outbreak to outbreak	Extensive outbreak or collapsed	N/A
Spot: patch	High	High-Moderate	Low	N/A
Estimated chance of controlling beetle	High	Moderate	Nil – Low	N/A

Provincial zones

Provincial bark beetle management zones allow rational allocation of resources to support aggressive actions in areas where management will have the greatest impact. Management zones are based on the consideration of the following factors:

- Host availability and other resource information;
- Provincial status of infestations based on overview survey;
- Infestation trends;
- Existing or potential access; and
- Management objectives and non-timber values and considerations.

Management zones are also identified by the Provincial Bark Beetle Co-ordinator to determine where special operations and regulations are applicable. These broad classifications are useful in high-level allocation of resources. There are three provincial bark beetle management zones reflecting different levels of infestation and management effort.

Aggressive Management

- Majority of BMUs in this zone are suppression;
- Leading edge of large outbreak or contain arising infestations;
- All beetle management strategies and tactics (including detailed aerial surveys and single tree treatments) are applicable in the appropriate situation; and
- High amounts of moderate to high hazard stands remain uninfested.

Containment

- It is biologically feasible to at least hold infestations static with vigorous directed harvesting and limited single-tree treatments. Primary management activity will be directed harvesting (large and small blocks) of currently infested trees.
- Containment baiting would be utilized wherever appropriate; and
- Only limited use of direct control methods such as single-tree treatment would be contemplated.

Salvage/Limited Action

- No suppression or containment of beetle populations;
- Salvage/rehabilitation of stands as possible;
- Minimal impact on beetle population intensification or spread;
- Infestation has outstripped management resources; and
- Little or no single-tree treatments or probing for levels of green attack.

A generalized idea of when the three zones are appropriate (based on the stage of outbreak) is given in Figure 5.

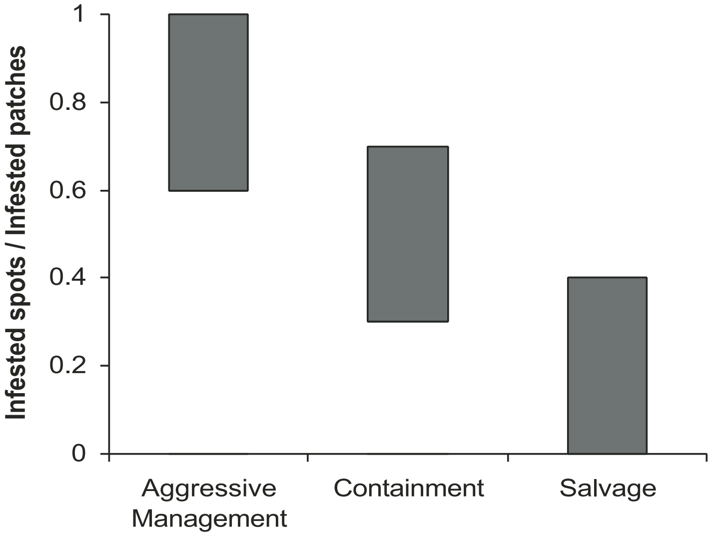

Figure 5. Provincial zone characteristics (based on stage of the outbreak).

Beetle Management in Parks

The objective of insect management in forests outside of parks and protected areas is to minimize losses to resource values. The objective of insect management inside parks and protected areas is to allow natural processes to prevail; however, to maintain protected area values or to prevent cross boundary spread of insects to adjacent crown forests, insect management in parks and protected areas may be required.

Conclusions

This paper summarizes the approach being taken to bark beetle management in BC, and presents guidelines and criteria for determining relevant area-specific strategies and the beetle management unit and zone level of planning. The recommendations arising from these guidelines and criteria are based on biological principles, and should direct resources to areas where an impact on infestations is possible. However, other resource management imperatives, economics or logistics may well overlie these recommendations and modify priorities. The priorities set by the use of this document should serve as a basis of discussion to provide a consistent and rational approach to beetle management across the province.

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Challenges and Solutions – An Industry Perspective

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Abstract

Alex Ferguson is a registered professional forester and holds the positions of Chief Forester, Canadian Forest Products Limited and Chair of the interior forest industry's Mountain Pine Beetle Task Force. In presenting this paper, Mr. Ferguson outlines three challenges facing the forest industry in dealing with the mountain pine beetle epidemic across the interior of BC. He talks about the challenges in dealing with the substantial volume of beetle-killed timber and the problems in finding adequate markets for this dead pine. He also raises the question of the environmental impacts of the epidemic on land use plans, and concludes with community stability implications of the expanding epidemic.

Mr. Ferguson addresses the issue of the possibility of allowable annual cut (ACC) fall-down in the future, due to the increased AAC currently in place to access greater volumes of dead pine. Mr. Ferguson calls upon the provincial and federal governments to initiate mitigation strategies for affected communities. He encourages communities to begin looking at "Life after Beetles" and encourages the Premier's Office to maintain a lead role in the process of developing solutions. He concludes by stating the industry is very much willing to play a major role in finding solutions.

Introduction – "The Challenges"

The information provided in this paper is intended to build upon the presentation that was made earlier in the symposium by the province's Chief Forester, Larry Pedersen, RPF. The Chief Forester provided information concerning a recent government analysis of twelve selected management units in the central interior of British Columbia (BC) and addressed the impacts of the mountain pine beetle epidemic. In summary, Mr. Pedersen stated that significant reductions in allowable annual cut are anticipated due to the considerable reduction in mature live lodgepole pine. The situation is expected to continue to worsen until Mother Nature steps in with much colder weather. This information represents significant challenges for the interior forest industry sector and this paper addresses three specific challenges.

Firstly, the prolonged attack on lodgepole pine has resulted in the accumulation of a large inventory of dead pine. There is now a need to deal with this increasing inventory. To date, management efforts have been focused on the leading edge of the epidemic as a necessary strategy, but they have been unable to keep pace with the rapid expansion of the epidemic. Manufacturing facilities have only a limited capacity to cope with beetle-killed timber even if all facilities operate on a three-shift basis. The

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industry must also find suitable markets in which to sell the extra fiber, especially given the current trade situation with the United States. Most customers in the Pacific Rim prefer non-stained lumber, leaving only those U.S. customers who recognize that the quality and strength of beetle-killed timber have not been compromised. While the industry has focused on timber supply impacts, limited attention has been directed toward the opportunity that may exist with mountain pine beetle damaged fibre. There may be real opportunities to allow new entrants to the industry including First Nations companies to get involved in mitigating the impacts of the increased volumes.

Secondly, the challenge exists for dealing with the environmental impacts of the mountain pine beetle epidemic. During the 1990s, many people in BC participated in land use planning tables, grappling with how land surrounding their communities should be used, and for what purpose. Eventually, there were a series of land use plans adopted by the provincial government to guide resource development. In some areas, these basic plans have been further refined to landscape level plans, identifying visual quality and ecosystem management objectives. There is the need to understand the impacts of the epidemic on these plans. Further, there is a need to understand how mammals, fish, birds and the myriad of other species that live in our interior pine forests are adapting to the changing environment. In addition, other resource users such as guide-outfitters, resort and lodge operators, trapping and backcountry tourism, are being impacted. Answers to these issues are required before solutions can be considered.

Thirdly, the impact on local communities must be considered. This may ultimately be the most important challenge. While the success of the forest industry is directly linked to timber availability and market, and it will live and die by these factors, the communities are "there" irrespective of the market or timber supply situation. The implication of the Chief Forester's earlier message is there could be increased timber supply due to the expanded volume of beetle killed timber and commensurate economic activity over a possible 10- to 15-year period. Although this has positive implications in the short term, the longer-term implications are more crucial.

Discussion – "The Solutions"

From the Chief Foresters' message, it is conceivable that he will further increase annual allowable cuts to maximize the opportunities to salvage as much of the dead pine as possible. The scenario should and could provide a number of positive opportunities for new products and new forest industry players. However, with an increase in allowable annual cut over the short term, comes the possibility of a fall-down over the longer term. For those areas that will experience a fall-down in available timber supply in ten, fifteen or twenty years, now is the time to begin collaborative planning for new directions and new opportunities for our forests and our communities. The communities have "time" on their side.

With help from both the provincial and federal governments and the forest industry, most communities have the knowledge and motivation to plan for and realize minimal impacts from this epidemic. There is time to plan now for the future stability of our forest-dependent communities.

For the environmental impacts of the epidemic, the process for assessing impacts and preparing options to mitigate these impacts must be initiated. Land use groups involving all stakeholders including government, agencies, resource users, as well as First Nations, must determine the impacts of the epidemic on their own specific areas and plans, and develop their own mitigation strategies.

Conclusions

While this paper is not intended to provide a long list of solutions, it is a call to action. There is only one BC and as exhibited in the response to this summer's fires with the province coming together as never before, the same collective action must be taken to deal with the mountain pine beetle epidemic. While the fires have had an immediate outcome with destroyed infrastructure and resources, the mountain pine beetle epidemic may have a more critical effect, with destroyed communities and economies, if long-term strategies are not put in place.

BC's Premier Gordon Campbell has recently announced a mountain pine beetle symposium to be held in Quesnel later this year. It is hoped that he will empower the communities to produce long-term strategies to deal with the upcoming challenges. The solution that may be suitable for Quesnel may not be the solution for Vanderhoof. Conversely, the Vanderhoof solution may be ideal for Kamloops. With continued leadership from the most senior government official in BC, our community leaders can produce plans aimed at mitigating long-term impacts of the mountain pine beetle on their respective communities. It is important to recognize that communities outside the immediate areas of infestation will also feel the impacts; therefore, they too must become involved. Our communities must begin to consider "Life after the Beetles" and the Quesnel process needs to be the catalyst to begin this thinking process. The forest industry is certainly prepared to take an active role in finding solutions.

Acknowledgements

The impetus for this paper comes from the forest industry's Mountain Pine Beetle Task Force, a group that was formed in 1999 to promote communications and action on the epidemic. From the outset, the Task Force has promoted strong interaction between its members and government officials in finding and promoting solutions to deal with mountain pine beetle. Both industry and government officials working on and through this Task Force are to be commended for their foresight.

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Mountain Pine Beetle Management in British Columbia Parks and Protected Areas

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Abstract

British Columbia is currently experiencing a mountain pine beetle epidemic due to natural beetle population cycles, successive mild winters, and an abundance of mature pine forests as a result of fire suppression. Of the 4.2 million ha currently infested provincially, approximately 623,000 ha of forests in over 60 parks and protected areas are being affected. The priorities for management of bark beetle infestations in parks are to prevent spread of beetles across boundaries while maintaining park ecological values. There are two distinct phases of park management associated with the epidemic: short-term infestation management and long-term post-infestation management. Short-term infestation management is focussed on prevention of infestation spread. Long-term post-infestation management is focussed on issues such as hazard tree management, post-epidemic pine deadfall, fuel hazard reduction and wildfire management, maintenance of recreation and habitat values, and management of access caused by forest harvesting adjacent to parks.

Introduction

British Columbia (BC) is currently experiencing a mountain pine beetle (*Dendroctonus ponderosae*) epidemic throughout the range of lodgepole pine (*Pinus contorta*) forests in the province. The epidemic is the result of a number of factors including natural beetle population cycles, successive mild winters, and an abundance of mature pine forests as a result of fire suppression. A discussion of the epidemic origins and spread will be presented in this paper, along with an examination of short-term infestation mangement and long-term post-infestation management in parks.

Outbreak Origins

Mountain pine beetles attack a wide variety of pine species; however, lodgepole pine is BC's most economically valuable and most susceptible pine species. Lodgepole pine may be BC's most predominant tree species due to its wide ecological range (Lotan and Perry 1983) and comprises a large volume component in BC's forests. Lodgepole pine is a fire-maintained sub-climax species that requires heat from

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Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

wildfires to open its serotinous cones (Lotan 1973) and the ecological dependence of lodgepole pine to fire is well understood by forest managers.

While the ecological dependence of lodgepole pine stands to fire is well known, the ecological dependence of lodgepole pine to mountain pine beetle as a disturbance agent is not commonly understood. Some researchers have suggested that mountain pine beetle infestations serve as a critical thinning agent for stagnant lodgepole pine stands and that lodgepole pine has actually ecologically adapted to depend on mountain pine beetle disturbances (Peterman 1978).

The three way ecological relationship between lodgepole pine, mountain pine beetles and fire has been upset by our past fire control efforts, creating the elements necessary to favor an epidemic. Lodgepole pine forests often grow in ecosystems subject to frequent fire return intervals; however, fire control has been practiced throughout much of the range of lodgepole pine forests for many decades. Analysis of the lodgepole pine profile in BC has shown that 65% of the lodgepole pine in forests of BC is mature and susceptible to mountain pine beetle infestations. The current amount of mature lodgepole pine is estimated to be over 20% greater than what would be expected in a natural fire regime (Personal Communication, A. Carroll, Natural Resources Canada, Victoria, BC). It may be stated, in fact, that BC is facing an epidemic of mature lodgepole pine rather then an epidemic of mountain pine beetles.

Mountain pine beetle populations may be reduced by cold winter temperatures (-37ºC), or cold early fall temperatures (-27ºC) (Unger 1993). Areas currently experiencing the mountain pine beetle epidemic have not received these temperatures since the onset of the epidemic in 1994, providing no natural control of the populations. Recent research has shown that this is may be the result of global climate change (Environment Canada 2000). The combination of warm weather and abundant hosts has lead to the rapid expansion of mountain pine beetle populations in many lodgepole pine forests across the province.

Forests in parks largely share the same forest profiles as other BC forests due to past fire control policies which, until the last decade, stipulated that fires must be suppressed in parks (BC Parks 1982). Accordingly, many park forests are facing epidemic mountain pine beetle infestations. These parks share management challenges common to other similarly affected forests, such as a history of fire control, abundant host, and remote location limiting access and treatment. Since parks are relatively unmanaged landscapes, they may act as a natural “canary in the coalmine” for forest ecosystems, by reflecting the latent potential for natural disturbance events which may have become unbalanced by human forest management actions.

Spread of the Mountain Pine Beetle Epidemic

A popular misconception developed that the current provincial mountain pine beetle epidemic began in Tweedsmuir Provincial Park. While there is a very large infestation in Tweedsmuir that has no doubt contributed to the beetle population in some areas of north-western BC, infestation centres in many other lodgepole pine stands across the north central and southern part of the province also developed almost simultaneously with the Tweedsmuir infestation and have rapidly grown beyond control.

This province-wide inception of the epidemic is further confirmed by a 2003 retrospective mapping project done by Ministry of Forests Research Branch to show cumulative provincial levels of mountain pine beetle attack for 1999, 2000, 2001 and 2002 (Personal communication, M. Eng, BC Ministry of Forests, Victoria BC). The mapping shows that, in 1999, incipient mountain pine beetle infestation centers were widely dispersed throughout most of the range of lodgepole pine in the province. As the epidemic progressed through 2000, 2001 and 2002, it is apparent that localized infestations such as the Tweedsmuir infestation spread regionally, however, on a provincial basis, infestations basically filled in between the widely separated infestation centers around the province.

Current Mountain Pine Beetle Situation in British Columbia Parks and Protected Areas

Approximately 4.2 million ha of forest are currently infested in BC, the most extensive mountain pine beetle epidemic in BC's recorded history (British Columbia Ministry of Forests 2003a). Of the total area infested, approximately 623,000 ha of forests in over 60 parks and protected areas are also infested with mountain pine beetle (Personal communication, T. Ebata, BC Ministry of Forests, Victoria BC). The scale of the infestation in parks is variable, however, and while some parks may only contain a few ha of infestation, others such as Tweedsmuir may contain hundreds of thousands of ha of infested forest. This is the largest recorded natural disturbance to ever take place in BC's provincial parks and protected areas.

The level and relative percent infestation can be determined for infested areas within parks and compared to those at the regional and provincial scale. This information is summarized in Table 1.

Table 1. Park forest infestations compared to total Regional and Provincial forest infestations.

Forest Region	Non Park Forest Land Infested (ha)	Park Forest Land Infested (ha)	Total Infested Forest Area (ha)	Park % of Total Infested Forest Area
Cariboo	2,277,201	79,309	2,356,510	3.4%
Prince George	931,186	93,961	1,025,147	9.1%
Prince Rupert	307,708	239,500	547,208	43%
Vancouver	12,571	204,946	217,517	94%
Kamloops	55,162	2,456	57,618	4.2%
Nelson	24,684	2,452	27,136	9.0%
Totals:	3,608,512	622,624	4,231,136	14.7%

The area of "light infestation" in parks (1% – 10% of trees attacked) accounts for 302,017 ha of the total infested area of 622,624 or just under 50% (48.5%) of all infestations in parks. "Moderate infestation" (11% to 29% of trees attacked) accounts for 145,174 ha or 23% of the infested area and "severe" (30% + of trees attacked) accounts for 175,383 ha or 28% of park infestations.

The summary shows that on a provincial basis, park forest infestations account for 14.7% of the total provincial infested area. Since parks account for approximately 12% of the landbase of BC, this infestation rate seems relative to the total park area. When the level of regional infestations is considered, park infestations in the Cariboo, Prince George, Nelson and Kamloops regions account for 9% or less of the infested area in these regions. If an average is taken for these four regions, park infestations average 5.1% of the total infested area.

The regions with the largest relative infestations, Prince Rupert (43%) and Vancouver (94%) are both highly influenced by one park, Tweedsmuir Park, which is the largest park in BC and contains the largest infestation of all BC parks. The Tweedsmuir Park infestation accounts for the largest infestation in the Vancouver region.

Park Forest Management

The management of the mountain pine beetle epidemic in BC's parks and protected areas presents many challenges. Since epidemic levels of infestations in protected areas cannot be managed independently from surrounding landscapes adjacent to parks, BC Parks has worked closely with the BC Ministry of Forests, the forest industry, affected communities, First Nations, and non-government organizations in dealing with this complex park management issue.

While mountain pine beetle infestations are considered part of a natural forest renewal process in parks and protected areas, they are considered destructive in forests allocated for timber production. Since insects do not recognize jurisdictional boundaries, they move unobstructed from protected area forests into crown forests or conversely, from crown forests into protected area forests. BC Parks recognizes that the management of park beetle infestations to prevent spread of beetles across boundaries, while maintaining park ecological values is extremely important for the protection of adjacent forest economic values. Management of mountain pine beetle infestations in protected areas, however, is often more difficult than management in adjacent forests for several reasons:

- beetle management in protected areas may, in some cases, require a higher level of planning to protect unique protected area values;
- infestations in protected areas are often located in remote locations requiring air access; and,
- aerial photography, forest mapping and forest inventories routinely undertaken in adjacent forests often stop at protected area boundaries.

It is recognized by park managers that there will be two distinct phases of park management activities associated with the mountain pine beetle infestation:

- activities that take place in parks to manage the actual infestation – infestation management; and,
- activities that take place in parks to address the ecological changes associated with large areas of dead pine trees after the infestation has abated – post-infestation management.

Infestation Management

Infestation management activities in parks and protected areas are conducted in cooperation with the BC Ministry of Forests in accordance with the Provincial Bark Beetle Management Technical Implementation Guidelines (British Columbia Ministry of Forests 2003b) which divides landscapes into beetle management units irrespective of administrative boundaries. Beetle management units are defined by the level of infestation and associated management actions undertaken in the unit. Units with low levels of infestation which can be comprehensively treated are defined as "control" units. Beetle management units with larger infestations which cannot be comprehensively controlled are called "holding" units if there is a possibility of reducing infestation levels; or, "salvage" or "monitoring" units if infestation levels are overwhelming and no infestation management is possible. Beetle control is generally only undertaken in parks and protected areas which fall into "control" beetle management units. When overwhelming infestation rates occur in parks or protected areas and no control mechanisms are ecologically or economically feasible, the infestation is allowed to progress as a natural process.

Beetle control in parks and protected areas is more complex than beetle management in other forests because park management must balance beetle control activities with maintenance of park values. The most common control treatment used in parks and protected areas in BC is to use pheromone baits to concentrate insect populations and then fall and burn individual trees on site to kill the insect larvae. In the winter of 2001/02, approximately 15,000 trees in 38 parks were treated this way. For the winter of 2003/04 there are plans to undertake mountain pine beetle treatments in 32 parks, although this may be subject to change based on funding limitations and updated mountain pine beetle probing assessments and associated treatment goals.

Where larger infestations occur, prescribed burning is used to kill hundreds or even thousands of ha of infested trees. Prescribed burning was used to control initial infestations in Tweedsmuir Park in 1995 when 600 ha were burned (Safranyik et al. 2001) and again in 1997 when 250 ha were burned. By 1998, however, the infestation had progressed to over 15,000 ha and due to the overwhelming size of the infestation, it was determined that no control was possible and control activities ceased.

Issues associated with managing the epidemic in parks and protected areas include:

- Preventing the spread of beetles from park and protected areas to working forest or private forests where possible;

- Managing increased access and other ecological effects resulting from logging near park boundaries;
- Responding to community and First Nations concerns about social, economic and ecosystem changes associated with beetle infestations, and,
- Responding to non-government and environmental group concerns that beetle management actions may adversely affect natural values in protected areas.

Post-Infestation Management

The long-term impact of mountain pine beetle infestations on park ecosystems and associated wildlife will be highly variable depending on the many factors including both the intensity of infestation and the composition of the park forest species prior to the infestation. From an ecological perspective, pine beetle infestations do not appear to be an "ecological disaster" for parks as they are often described. Mountain pine beetles kill only pine trees and leave all of the surrounding tree species, vegetation and ecological components undisturbed. So, while the pine trees are dying, the rest of the ecosystem is still alive and in some cases other tree species are stimulated to grow faster. For example, many parks affected by the beetle infestations have mixed forest types. Spruce (*Picea* spp) and fir (*Abies* spp) understory will be released as the pines die and in 20 years, where there are now red trees, there will be a green forest with grey tops of dead pines scattered throughout. Preliminary forest sampling conducted in the most severely affected sections of North Tweedsmuir park has shown that immature understory and codominant tree species growing among the beetle-killed pines will form an equivalent forest in the near future (Cichowski 2000).

There are cases, however, where critical habitats may be affected by lodgepole pine mortality. For example, in the Entiako Park and Protected Area, critical caribou winter range is being monitored to determine if deadfall associated with pine mortality will create mobility problems for migrating caribou or, if forest succession following the infestation will alter critical habitat attributes. If mobility or critical habitat attributes are affected, active ecosystem management may be required to maintain habitat values.

As a result of pine mortality, there has been concern expressed that uncontrollable wildfires similar to the Yellowstone fire of 1988 would immediately follow. A massive wildfire associated with the current mountain pine beetle infestation has not happened, however, and the actual wildfire threat may decrease in the short term. Wildfire threat will likely decrease as beetle-killed pines lose their needles and the capacity to support a crown fire. In the long term, however, the potential for high intensity fires due to deadfall in beetle-killed pine forests will increase long after the infestation has collapsed. Three primary periods of increased fire hazard in lodgepole pine stand following mountain pine beetle outbreaks have been identified (Environment Canada 1982):

- Immediately following an outbreak, when needles and small branches are retained on standing dead trees, stand susceptibility to crown fires may be increased. Understory response to the outbreak will also affect stand susceptibility during this period by affecting the potential for ground fire to simultaneously occur.
- An elevated fire risk also occurs about ten years after the outbreak, when tree bark begins to slough off.
- The most extreme risk occurs after beetle-killed trees have fallen, approximately 20 to 50 years after the outbreak, when fuel-loading is at its maximum. Fuel quantity and arrangement may produce extremely high intensity fires.

Most parks affected by the mountain pine beetle epidemic have passed through the first phase of the increased fire hazard, leaving them between phase 1 and 2 and at a relatively low risk for fire hazard. As deadfall begins to take place in the next 20 years, however, parks will begin to experience the second slightly higher risk and the third extreme risk. Park managers are currently planning to reduce fuel accumulations due to pine mortality through the use of prescribed fire and tree removals where required. Likely, there is probably a 15- to 20-year "window of opportunity" to deal with potential future fuel hazard issues. As more trees fall, fuel hazard will increase and may result in wildfires of high intensity, which are extremely difficult to control.

Fire hazard management may be required to create fuel breaks or reduce fuel loading in situations where cross boundary values including facilities, private lands, or the working forest may be at risk from protected area wildfires. This issue will require on-going efforts for many years following infestations, as deadfall rates will accelerate as time progresses.

Post-infestation management activities in parks and protected areas will include:

- Monitoring critical wildlife habitats in beetle-killed forests;
- Initiating research to predict park vegetation response to the infestation;
- Ensuring visitor safety from hazard trees;
- Maintaining recreation values;
- Planning for wildfire control and fuel hazard reduction in community and facility interface areas; and,
- Planning to address potential high intensity fires in areas of high fuel loading.

Research, Planning and Long-term Treatment Projects

Research

Research requirements associated with the mountain pine beetle infestations in protected areas are mainly focused on providing science-based information for ecosystem management actions. Research issues associated with protected areas ecosystem management include the determination of:

- long-term range of variability of park forested ecosystems;
- current forest variance from natural conditions based on long-term natural disturbance intervals;
- wildfire spread rate and intensity in beetle-killed pine stands;
- dead fall rates and fuel loading in beetle-killed pine stands;
- rate and species of natural regeneration of beetle-killed pine stands;
- habitat changes and associated wildlife responses to beetle-killed pine stands;
- increased access and habitat fragmentation associated with logging adjacent to protected areas;
- species composition and habitat use in beetle-killed pine stands;
- rate of regeneration and co-dominant succession in beetle-killed stands; and
- long-term vegetation and ecosystem response to pine mortality.

To address some of these research questions an interagency research program has been proposed by the Canadian Forest Service, the BC Ministry of Forests and the BC Ministry of Water, Land and Air Protection to determine wildfire response in beetle-killed pine stands. The program will assess probability of ignition and wildfire response of beetle-killed pine stands compared to live pine stands. Research results will be used to plan prescribed burns in parks and provide information for wildfire control and threat reduction.

Planning and Management

Planning and management are required to deal with the wide range of issues which will arise from the post-epidemic forests in parks and protected areas. Specialized plans and management actions to deal with thousands of ha of post-infestation beetle-killed pine stands will need to be prepared. Planning and management actions include:

- fuel hazard management plans and fuel reduction treatments;
- prescribed burn prescriptions and prescribed burns to reduce fuels, maintain habitats and support forest diversity; and
- long-term monitoring to determine park ecosystem response to an infestation.

Examples of planning and management actions in BC parks and protected areas include:

- Strategic Wildfire Risk Assessment for Manning Provincial Park – this assessment identifies wildfire risk and associated potential fuel management and wildfire threat reduction activities for the park.
- Ecosystem Management Plan for Mount Robson Provincial Park – this plan identifies the requirement to vary the forest matrix of the park through the use of prescribed burns. Prescribed burning will reduce infestation rates, remove infested hosts, create a fuel break for adjacent facilities and create early seral forests and habitats. A 2,500 ha prescribed burn was planned for the Moose River area of the park, but was postponed due to the wildfire crisis in the southern part of BC in the summer of 2003.
- Fuel Reduction Project for Silver Star Provincial Park – this project is planned to reduce forest fuels and associated wildfire risk associated with dead and dying pine trees as a result of a mountain pine beetle epidemic in Silver Star Park. The project will reduce fuels, remove infested trees and create wildfire control access in the park to help protect park facilities and the adjacent Silver Star Ski resort from wildfires.

Conclusion

The mountain pine beetle epidemic in BC in parks and protected areas crosses many ecological, social, and economic boundaries. The objective of the BC Parks mountain pine beetle management program is to manage beetle infestations to reduce impacts to crown forests where possible, but also to maintain the natural values of parks and protected areas.

Management of the mountain pine beetle epidemic in parks and protected areas goes beyond insect control. Since many park ecosystem and forest management plans call for prescribed burning, there is need for a coordinated burning program. Prescribed fires reduce beetle host and also bring forests back into natural mosaics, create firebreaks and reduce fuel loads. Forest cover inventories for many parks need updating and studies to determine fire hazards, fall down rates and vegetation responses associated with beetle infestations should be initiated.

No one is sure when the mountain pine beetle epidemic in BC will collapse. While the infestation is not considered an ecological disaster for the affected parks, the epidemic will present management challenges in affected protected areas for decades following the actual epidemic collapse. Issues such as: hazard tree management; post epidemic pine deadfall; fuel hazard reduction and wildfire management; maintenance of recreation values; and management of adjacent access will require continuing efforts from protected area managers following infestation collapse.

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Mountain Pine Beetle Management in Canada's Mountain National Parks

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Abstract

Coordinated efforts using an ecosystem-based management approach to forest health have, to date, mitigated the expansion of mountain pine beetle populations in the mountain national parks, resulting in the short-term protection of commercial forests in Alberta. Joint approaches to implementing a regional forest management strategy and incorporating communications in all aspects is gradually building public support for the use of fire as a management tool. Numerous benefits to society include directly reducing the mountain pine beetle populations, reducing beetle habitat, renewing forest health, improving wildlife habitat, reducing susceptibility to wildfire and future insect and disease infestations and providing effective management of public lands for future generations.

Introduction

The mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae), is a native insect in the southern Rocky Mountains and is part of the natural processes of forest disturbance. Measuring only 5 -7 mm or about the size of a grain of rice, it is also the bark beetle that has had the greatest economic impact on the forest industry of western North America. With the mountain pine beetle epidemic devastating the commercial forests of British Columbia (BC), it is not surprising that the Province of Alberta and its forest industry want to stop the beetles at the continental divide that is also the provincial boundary and the location of the mountain national parks.

Historically there have been several outbreaks of mountain pine beetles in the mountain national parks. From 1929 to 1943 in Kootenay National Park of Canada, approximately 65,000 ha of pine forest with 85% mortality was affected. There was a small population expansion in Yoho National Park in the 1930s. In Banff National Park of Canada between 1940 and 1943 approximately 4,000 ha with 1% mortality was affected and between 1979 and 1983 there were 162 trees colonized in the Upper Spray River area. In Waterton Lakes National Park of Canada between 1977 and 1986, there was extensive colonization of the pine forest by mountain pine beetles, resulting in 50% mortality of the pine trees. Wildfire followed the beetles and has limited the potential for mountain pine beetle population growth in the near future. Until 1999 there were no records of mountain pine beetle in Jasper National Park of Canada.

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The current expansion of beetle populations began in the early 1990s, driven by several precursors. The process of fire has been virtually eliminated from the national parks and surrounding landscapes in BC and Alberta through fire suppression for the past 80 years. This has resulted in large areas of pine forest of prime age (80-120+ years old) for hosting mountain pine beetles. There have been successive winters of mild temperatures that have been conducive to mountain pine beetle population growth and reduced over-winter mortality. And there is a large population of mountain pine beetles in the adjacent, upwind areas of the mountain national parks.

Mountain pine beetle green-attack trees were observed in Banff National Park in the Brewster Creek and Healey Creek areas in 1997. The conditions at the Brewster Creek location were not conducive to population growth. However, the Healey Creek population was growing at a rate of 3:1 (3 green-attack trees to each red-attacked tree). The population was noted further east on Mount Norquay in 1998 and further east again on Tunnel Mountain and the Fairholme Bench the following year. By 2001, the mountain pine beetle populations on Tunnel Mountain and the Fairholme Bench were expanding at a rate of 7:1. An estimate of >8000 colonized trees was determined from intensive field surveys resulting from the 2002 flight and >1000 green-attack trees were identified in Canmore, outside the national park in 2002.

In Jasper National Park in 1999, approximately 20-30 trees were attacked in the Smoky River area, with no successful brood development and 6-12 trees were attacked in the Miette River Valley in the area of the Yellowhead Pass. In 2003, <300 trees were identified, cut and burned in the adjacent Wilmore Wilderness area of Alberta and 50 additional green-attack trees were identified in the Yellowhead Pass area.

Policy Background

Parks Canada's "Guiding Principles and Operational Policies" (Section 3.2.3) (Parks Canada 1994) states that: "National park ecosystems will be managed with minimal interference to natural processes. However, active management may be allowed when the structure or function of an ecosystem has been seriously altered and manipulation is the only possible alternative available to restore ecological integrity." Policy (Section 3.2.4) further states that: "Provided that park ecosystems will not be impaired, the manipulation of naturally occurring processes such as fire, insects and disease may take place when no reasonable alternative exists and when monitoring has demonstrated that without limited intervention:

- there will be serious adverse effects on neighbouring lands; or
- major park facilities, public health or safety will be threatened; or
- the objectives of a park management plan prescribing how certain natural features or cultural resources are to be maintained cannot be achieved."

The exclusion of fire for over 80 years has significantly altered the forests and wildlife habitat of the mountain national parks and created conditions that are ripe for mountain pine beetle colonization. Fire suppression has also resulted in a build-up of forest fuels creating desirable conditions for wildfire that could threaten neighbouring communities. In addition, the mountain national parks form the margin between the mountain pine beetle epidemic conditions in BC and the commercial forests in the Province of Alberta. Therefore, the conditions for ecosystem manipulation and active management are met in the mountain national parks.

Parks Canada policy (Section 3.2.5) further states that: "Where manipulation is necessary it will be based on scientific research, use techniques that duplicate natural processes as closely as possible and be carefully monitored." A goal stated in the management plans for all mountain national parks is to restore 50% of the historic fire cycle in order to achieve ecosystem restoration. As fire is the key process that has been disrupted by management practices, the use of fire is the key management tool for restoring ecological integrity. The problem is, therefore, defined as a forest health/old tree problem due to fire suppression. The benefits of correcting the ecological problem include a reduction in mountain pine beetle populations and habitat, a more diverse forest that is more resilient to insect and disease attacks, improved habitat conditions for wildlife, reduced threat of wildfire and potentially increased biodiversity.

Management Approach

Annual monitoring was replaced with aggressive monitoring for mountain pine beetles in 1998, in cooperation with the Canadian Forest Service, the Province of Alberta and Parks Canada. Mountain pine beetle risk and susceptibility mapping was undertaken jointly by Parks Canada and the Province of Alberta with the cooperation of the forest industry in Alberta. Mapping revealed large expanses of prime beetle habitat crossing many land management boundaries and embracing different land management objectives. It was clear that management of the issue needed to occur on a coordinated, regional or ecosystem basis, in partnership with all land managers.

Parks Canada resequenced its proposed prescribed burns to address the increasing concern about the population growth of mountain pine beetles. A "Regional Forest Management Strategy" Environmental Screening for Banff National Park (Parks Canada 2002) was prepared and submitted for public review. The strategy identified an adaptive, ecosystem-based management approach to be undertaken by Parks Canada in cooperation with the Province of Alberta and the Alberta forest industry, with an annual scientific and public review of the results of management actions and proposed next steps.

In addition, a management area east of the town of Banff along the eastern portion of the national park was identified for active management and control of the expanding mountain pine beetle population. In this area, Parks Canada undertakes direct actions to manage the mountain pine beetle, including intensive monitoring, cutting and removal or burning of green-attack trees, pheromone baiting to concentrate beetle flight dispersal to areas where trees can be cut and removed or burned, development of fire guards to safely implement prescribed fires and the use of prescribed fires to reduce beetle populations and habitat. This program is supported by applied research.

West of Banff, the mountain pine beetle population is being intensively monitored and prescribed fire plans will be implemented according to the restoration of the historic fire cycle. Currently, beetle populations are small in size and slow growing. If beetle populations in this area begin to increase rapidly, prescribed fire use may be accelerated to reduce the beetle population and available habitat. The western area, however, is important as a benchmark for scientific research to better understand mountain pine beetle ecology, related ecosystem management processes, the effects of management of actions and public perceptions.

Regionally, Parks Canada is also following a two-pronged approach to addressing forest health and the management of mountain pine beetle populations. First, a proactive approach is being used to reduce the susceptibility of the forest to mountain pine beetle colonization. The Canadian Forest Service SELES-MPB Model (Fall et al. 2004) is being applied to examine probable pathways for the spread of mountain pine beetles. This model has shown that the Yellowhead Pass and the Athabaska River valley are the likely routes through Jasper National Park to the commercial forests of Alberta. In conjunction with this model, the application of an Insolation Model shows that green-attacked trees follow a very narrow band of insolation values (185,000-196,000 watts/m^2). This model has been used in the Bow River valley in and adjacent to Banff National Park to prioritize beetle field survey locations.

Parks Canada's second approach is to apply a "long-term ecosystem states and processes strategy" toward reducing the amount of beetle habitat. This strategy recognizes that the mountain pine beetle problem is primarily an old tree/forest health issue, and that there are many other inter-connected concerns that also must be addressed. Banff National Park is one of the core-protected areas in the Central Rockies Ecosystem. Ecological integrity of the park is inter-dependent with the surrounding areas. Management actions must take into account the bio-physical and human inter-relationships in order to achieve the objectives of preventing or reducing the impacts of current mountain pine beetle colonization and reducing the risk of future population and range expansions. The following ecosystem model (Fig. 1) identifies the linkages that need to be considered in Parks Canada's management approach.

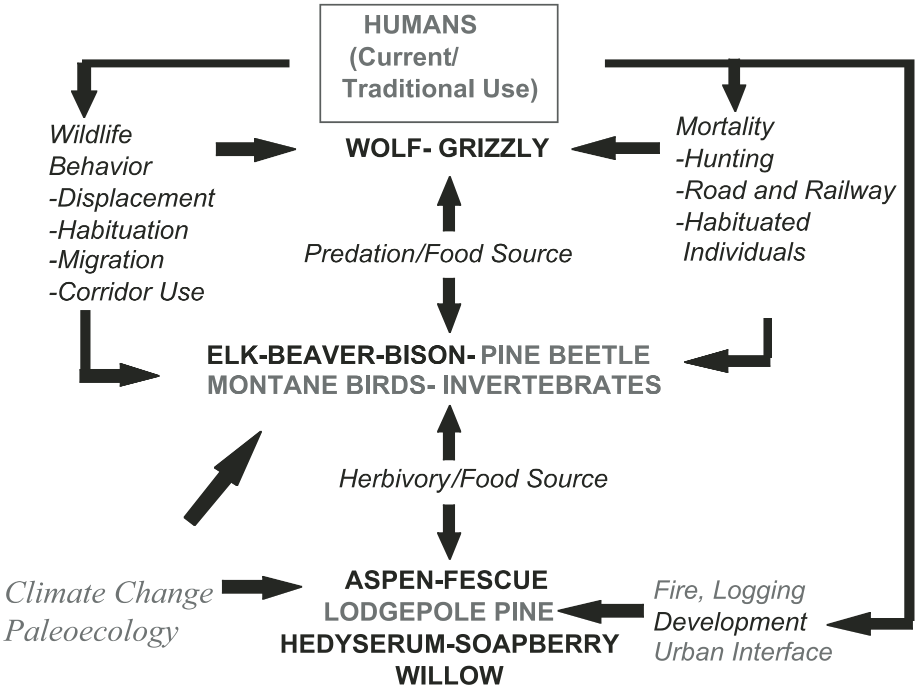

Figure 1. Ecological Indicators for Eastslope Central Rockies Ecosystem.
(Source: 1999-2004 reports from the Montane Ecosystem Science and Stakeholder Workshops
held in Banff National Park, Canmore and Sundre, Alberta.)

For example, along with lodgepole pine and mountain pine beetles, trembling aspen is a primary indicator in this ecosystem model. Objectives identified in the Park Management Plans and in on-going stakeholder reviews require that long-term patterns of wildlife habitat maintenance, including aspen regeneration, occur in areas thinned or burned as part of the mountain pine beetle initiative. However, aspen will only recover after a fire if the density of elk is less than 1 elk per square kilometer (White, 2003). At this density, elk browsing levels will enable aspen suckers to reach the critical height of 2 m to ensure their survival. Through the Banff Elk Management Strategy (Parks Canada 1999) and the establishment of the Fairholme Wolf Pack, unnaturally high levels of elk were reduced to levels that would permit regeneration of aspen, and enable the use of prescribed fire. The predator–prey relationships were dynamic, moving from high prey and low predator numbers in the early 1990s, to high prey and high predator numbers, to low prey and high predator numbers and then as wolves dispersed, to the current situation of low predator and low prey numbers. Thus, wolves are critical to the maintenance of elk population densities that would permit regeneration of aspen after the use of prescribed fire. However, in the on-going situation of low predator and prey numbers, a natural condition, and with the intense level of human activity in the Bow Valley, there are many opportunities for wide ranging wolves to be killed, with the potential of having no wolves in the Bow Valley. If this should occur, it is important that there are other areas where wolves could disperse from, to re-colonize the Bow Valley thus keeping the elk population in check. As a result, the Province of Alberta has expanded their wolf registry system to include all of the areas adjacent to the eastern boundary of Banff National Park and is cooperating with research efforts that will enable the maintenance of predator-prey relationships at the ecosystem scale.

Linking mountain pine beetles with wolves and elk is characteristic of current ecosystem-based management approaches. Many other wildlife species, such as grizzly bears, are also dependent on applying ecosystem-based strategies to address the mountain pine beetle/forest health issue. Currently, carnivore use of forested wildlife corridors near park town sites is a serious constraint to beetle management actions that require thinning, burning and green-attack tree removal. The proactive, ecosystem-based approach links the main management tool of fire with the mountain pine beetle population expansion and related societal benefits of reduced susceptibility to wildfire, improved wildlife habitat and ecosystem restoration, and ensures consultation and communications with all stakeholders, affected communities, interest groups and the public. Fuel thinning and fireguards are essential in order to use prescribed fires safely. The proactive approach creates these safety requirements with a combination of tree harvesting, where possible and cutting and/or burning. Results are monitored and management actions are adapted accordingly, based on scientific and public reviews.

The proactive approach is used in combination with a reactive approach that includes intensive monitoring, consultation and communications, pheromone baiting, removal, or cut and burn of green-attack trees in the management area, and again more communications, which is a key element at all stages of the management approach.

Organization

A senior management level Strategic Direction Council was established to oversee the management of the mountain pine beetle/forest health issue in Alberta. The Council members represent the Canadian Forest Service, Alberta Sustainable Resource Development, Alberta Community Development, the forest industry with adjacent Forest Management Agreements, and Parks Canada. The Council provides broad policy direction and priorities, ensures coordination through over-arching direction on prevention, detection and control, and facilitates communications through development of a common understanding of the approach, ensuring effective communications among agencies and industry, as well as between the strategic and operational committees. A Joint Communications Plan has been developed to coordinate all communications activities around the mountain pine beetle and forest health.

The Mountain Pine Beetle Strategic Direction Council policy states: “Federal and Alberta governments and other land management partners work collaboratively with respect to forest management to protect the economic value of the provincial forest and achieve ecological integrity objectives of the national and provincial parks and protected areas. Actions include an aggressive short-term approach to control mountain pine beetles in areas of high risk, and the development of a long-term strategy to create greater vegetation diversity across the landscape, working cooperatively with industry, interest groups and local communities.”

At the working level, staff participates in the West Yellowhead and the Central-South Operational Coordinating Committees. Additional representation on these committees includes Alberta Fish and Wildlife, communications staff from all groups, First Nations, and the Yellowhead Committee, Mount Robson Provincial Park. The BC Forest Service and the Alberta Fire Operations Unit receive the record of the meetings. Sub-committees for prescribed fire, mountain pine beetles, communications and wildlife also coordinate their efforts around the broader concerns of forest health and ecological integrity.

Current Situation

Banff National Park of Canada: Over-winter mortality in 2002 was high. Of the green-attack trees identified through intensive field surveys, 2725 trees were removed, 5400 ha of mountain pine beetle habitat were burned, 524 pheromone baits were set for the 2003 flight and 945 green-attack trees from the 2003 flight were identified through intensive field surveys in the fall of 2003.

Jasper National Park: There has been generally poor brood development, with an increase from 6 trees to 12 trees attacked in the Miette River valley/Yellowhead Pass area. There was no expansion of the population from the 20-30 trees attacked in the Smoky River area in 2002. Approximately 27,000 ha of prime age lodgepole pine/beetle habitat were burned, providing an effective fireguard on the south side of the Athabaska River valley. The proposed prescribed burn in Mount Robson Provincial Park, BC did not occur due to the extreme fire season in BC.

Yoho National Park: The mountain pine beetle population is increasing, especially in the west side of the park.

Kootenay National Park: Mountain pine beetles are doing well in the south and in some areas are attacking smaller diameter trees. The beetle population is becoming host limited and static. Approximately 15,300 ha of lodgepole pine were burned in the north end of the park in 2003.

Waterton Lakes National Park: Previous mountain pine beetle activity and wildfire have limited host availability in Waterton Lakes National Park. There were no green-attacked trees identified in 2003.

Proposed Actions for 2004

Parks Canada will:

- continue intensive monitoring with the Canadian Forest Service and the Province of Alberta;
- continue to undertake research in support of an integrated, ecosystem-based, adaptive management approach;
- continue fire guard coordination and development;
- continue active management along the east boundary of Banff National Park;
- continue the development and implementation of the communications program;
- continue to work with the provinces of Alberta and BC, industry, stakeholders, interest groups, communities and the public to ensure a coordinated, regional ecosystem-based program to the management of regional forest health.
- continue to work with Mount Robson Provincial Park to mitigate the expansion of mountain pine beetle populations, encourage the use of prescribed fire and increase communications with the public.

Summary

To date, the expansion of mountain pine beetle populations in the mountain national parks of Alberta have been mitigated, resulting in short term protection of the commercial forests in Alberta. In addition, coordinated efforts are resulting in improved opportunities for multi-jurisdictional ecosystem-based management. A joint approach has successfully incorporated communications in all aspects of managing forest health and the mountain pine beetle population expansion leading to increasing awareness and understanding by the public. The careful implementation of prescribed fire and management of wildfire is gradually building public support for the use of fire as a management tool that provides numerous benefits for society, including, directly reducing the mountain pine beetle populations, reducing beetle habitat, renewing forest health, improving wildlife habitat, reducing susceptibility to wildfire and enabling prescribed fire to be used safely.

The program to date has resulted in strengthened inter-agency and industry working relationships and effective management of public lands for future generations. The results to date confirm the theory that dealing with the growth of mountain pine beetle populations early and before the population moves beyond the incipient stage of growth can be effective in preventing epidemics. In national parks where the conditions for active management can be met, ecological integrity objectives can be met along with a wide range of additional public benefits.

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Mountain Pine Beetle Management and Decision Support

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Abstract

Management of mountain pine beetle involves strategies and tactics aimed at keeping beetle populations at endemic levels and maintaining vigorous stands. Tactics aimed at reducing beetle populations are termed “direct control” and those directed at maintaining stand vigour are called “preventative management”. Decision support tools have been developed that provide valuable information so that managers can make informed choices on appropriate tactics and allocation of resources. Susceptibility and risk rating systems and spatial models are amongst the most useful of these decision support systems. A number of key questions that may be addressed through modelling or other research approaches are presented.

Introduction

There are three objectives that we address in this paper. The first is a review of some of the knowledge on the biology and epidemiology of the mountain pine beetle, which was presented by Carroll and Safranyik (2004), and placement of this knowledge in a management context. Our second objective is to provide an introduction to some of the decision support tools available for managing the mountain pine beetle. Some of these decision support tools are further discussed by Riel *et al.* (2004) and Fall *et al*. (2004). Our final objective is to provide a transition to the research component of this symposium by identifying some of the main knowledge gaps that are either being currently addressed or need to be addressed in the near future.

Population Dynamics

The mountain pine beetle is capable of causing devastating losses to mature pine forests, as we are currently witnessing in British Columbia (BC). This beetle is a native insect and is generally present in low numbers throughout its range. Periodically, one or both of two situations will result in the beetle population shifting from endemic to epidemic levels (Fig. 1).

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*Mountain Pine Beetle Symposium: Challenges and Solutions. Octob*er 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

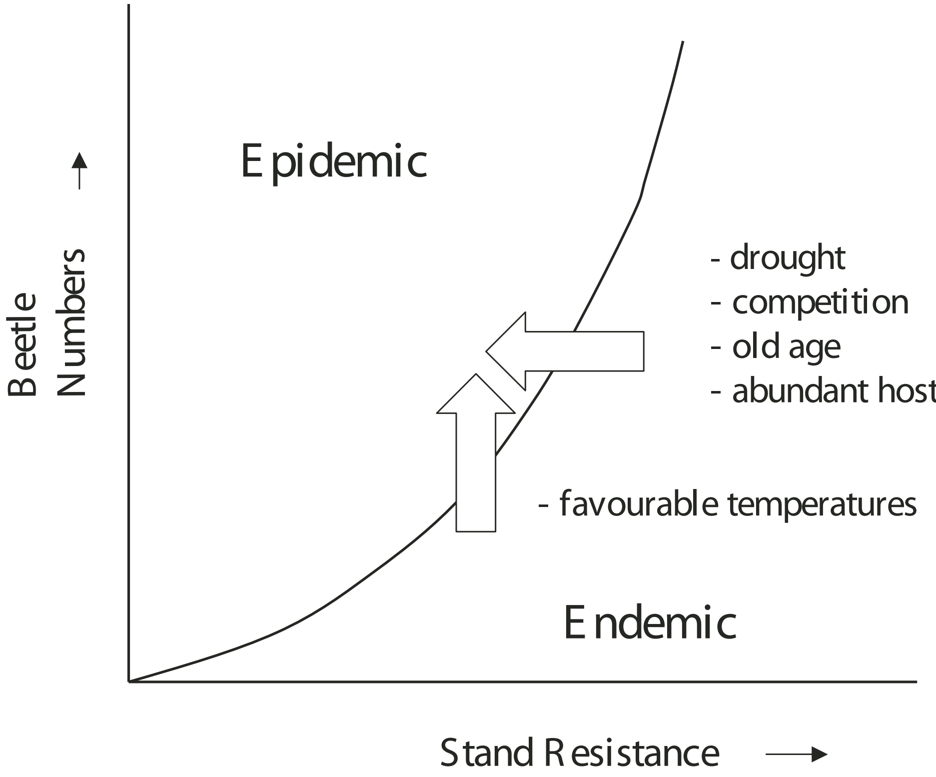

Figure 1. Factors contributing to mountain pine beetle shift from endemic to epidemic populations (after Berryman 1978).

Favourable weather conditions will increase the survival of the beetle during winter and the flight period and will result in a larger beetle population. This larger population is able to overcome the resistance of larger pine trees using their mass-attack behaviour, and thereby produces significantly higher numbers of progeny in these trees. Alternatively, or additionally, tree and stand susceptibility to attack by the beetle can be reduced during periods of drought, or if stands become too dense or old (Fig. 1). Depending on how widespread these optimum conditions are, the mountain pine beetle may be able to quickly increase in population. Once the population is large, there is a snowball effect where tree resistance is of little importance because large numbers of attacking beetles will eventually overcome the resin defenses of even the most vigorous trees. Given abundant host material, the mountain pine beetle will spread across the landscape, with dispersing beetles joining resident populations to achieve the critical mass required to successfully attack the larger trees in which they have the best survival and reproduction.

Management

We can utilize the knowledge that we have gained about the biology and epidemiology of the mountain pine beetle, and its interaction with its host, to aid in making decisions that will reduce losses to this insect. The nature of the decisions we have to make in resource management often depends on the population level of the mountain pine beetle.

To have a mountain pine beetle infestation, both a susceptible stand and a beetle population must be present. From a management point of view, our objective is to keep the beetle population low and to keep our stands vigorous. Treatments aimed at reducing beetle populations are termed “direct control” and those aimed at increasing stand vigour are termed “indirect control” or “preventative management” (Fig 2).

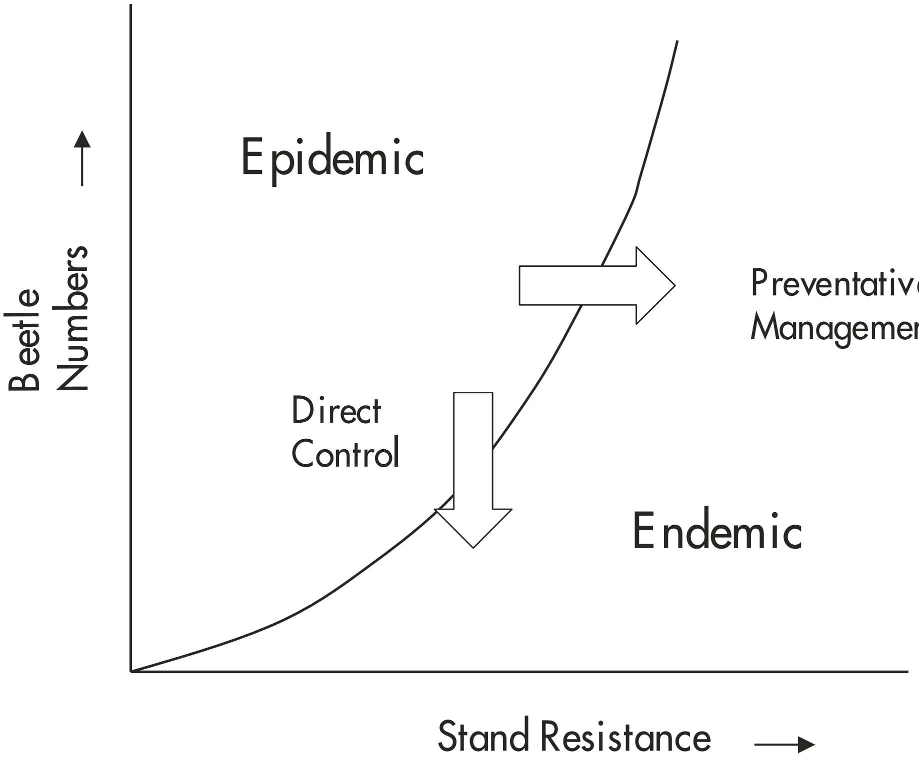

Figure 2. The role of population reduction (direct control) and preventative management in maintaining mountain pine beetle at endemic levels.

Direct control tactics are aimed at killing beetles under the bark of infested trees. The objective is to break the epidemic cycle by returning the population to the endemic phase (Figs. 2, 3). Direct control tactics include single-tree treatments such as removal and processing, felling and burning, de-barking or treatment with monosodium methanearsonate (MSMA). MSMA is a chemical solution squirted into an axe frill around the base of an infested tree within the first 3 or 4 weeks following attack while the tree is still alive. The chemical is drawn up through the conductive tissue of the tree and kills the beetles under the bark. Larger groups of infested trees are usually treated by block harvesting and processing. Pheromone baits may be applied to individual trees or stands to attract and concentrate beetles prior to treatment. Pheromones are naturally occurring attractants produced by members of a species to attract other members of the species. In the case of mountain pine beetle, pheromones are used to create the advantage of mass-attack to overcome the tree's resin defense system. Synthetic pheromones are commercially available and can be used to supplement management tactics.

Preventative management involves treatments aimed at reducing susceptibility at the tree, stand and landscape scales. This is done through increasing tree vigour, altering microclimate and reducing the amount of contiguous host. Thinning and spacing increases tree vigour as indicated by increased growth rates and resin production. It also alters the microclimate within a stand to one less favourable to mountain pine beetle in terms of wind speed, light and temperature (Whitehead et al. 2004). The contiguity of host can be altered through harvesting, fire, and silviculture by working towards the creation of a species-age mosaic on the landscape. This reduces the landscape-level susceptibility to the beetle and makes it more difficult for beetles to spread rapidly.

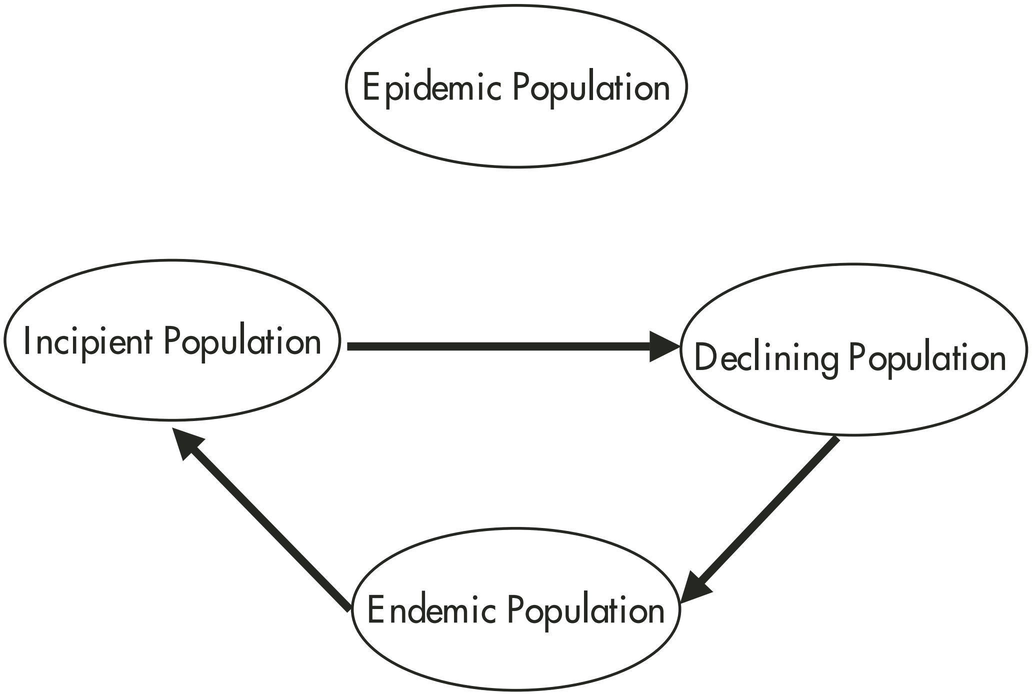

Figure 3. Breaking the cycle of mountain pine beetle epidemiology through direct control (population reduction).

Decision Support Tools for Mountain Pine Beetle Management

Susceptibility and Risk Rating Systems

During the endemic stage it is human nature to forget about the threat from mountain pine beetle and direct our efforts to other problems. This time, however, provides the prime opportunity for preventative management. The primary objective of preventative management is to reduce the susceptibility of trees, stands and landscapes. A stand susceptibility rating system can be used to locate stands with the highest potential for loss to the mountain pine beetle. The Shore and Safranyik (1992) stand susceptibility rating system is based on four main variables: stand age, stand density, stand location (latitude, longitude and elevation), and the percentage of stand basal area composed of larger pine. This decision support tool gives each stand a rating between 0 and 100 and allows resource managers to prioritize their stands for treatments. For preventative management the highest susceptibility stands should be given harvest priority. At a landscape level, susceptibility maps (Fig. 4) can be used to identify contiguous areas of high susceptibility that could be broken up through harvesting or fire.

The Stand Susceptibility Index relates to the eventual basal area killed in the event of a mountain pine beetle infestation (Shore et al. 2000) (Fig 5).

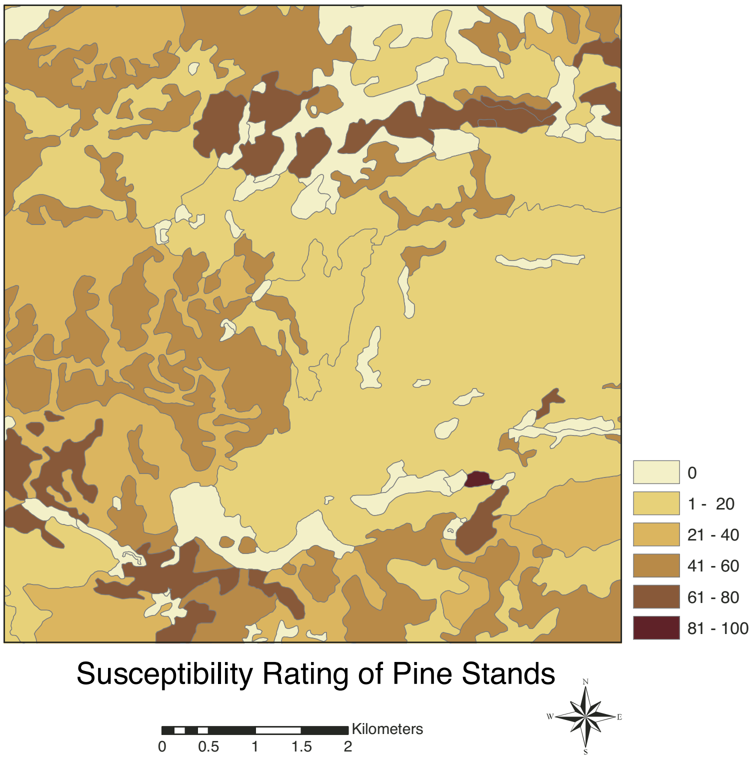

Figure 4. A stand susceptibility map based on Shore and Safranyik (1992) can be used to identify high susceptibility stands and contiguous areas of high susceptibility for setting priorities for treatment.

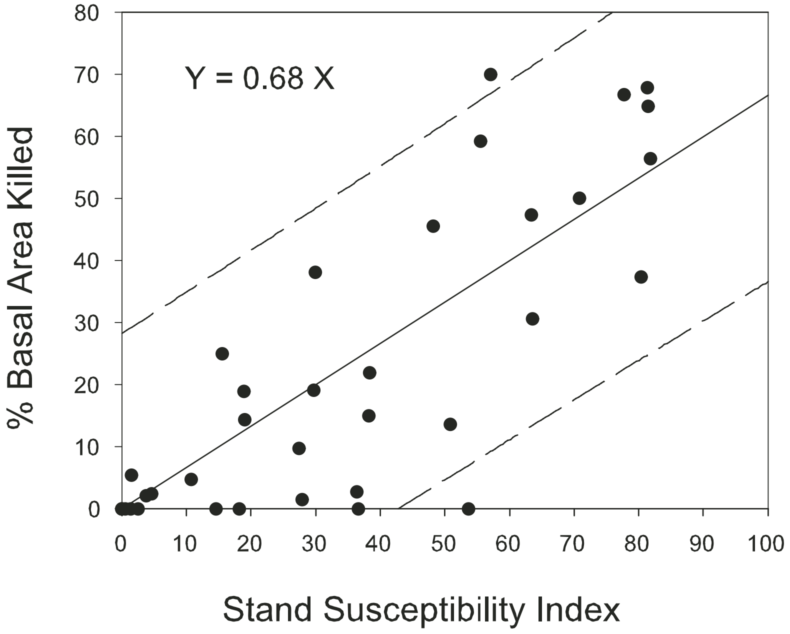

Figure 5. The relationship between the Shore and Safranyik (1992) Stand Susceptibility Index and the percentage of stand basal area killed following a mountain pine beetle infestation can be used for large scale (but not individual stand) predictions of loss (from Shore et al. 2000). Regression is $y = 0.68x$; $r^2 = 0.86$ (outside lines represent 95% prediction level).

The Stand Risk Index (Shore and Safranyik 1992) is an extension of the Stand Susceptibility Index that includes "beetle pressure". Whereas the Stand Susceptibility Index indicates the potential of a stand for damage in the event of an infestation, the Stand Risk Index incorporates the likelihood of that event occurring based on the proximity and magnitude of surrounding beetle populations. The risk index is used to set priorities for direct control during the incipient to epidemic stages of an outbreak.

The shift from the endemic to incipient phase of an outbreak can often be subtle and escape detection. The upper line in Figure 6 illustrates this point. A single infested tree in year 1 can result in 512 infested trees in year 10 if the population doubles each year. Although this shows the rapidity of an exponential increase in population, the infested trees in year 10 would still only represent about 2% of a 20-ha stand, and could be either missed in surveys or dismissed as insignificant. The lower line in Figure 6 illustrates another important point.

Treatment of three out of the eight infested trees in year 4 resulted in 194 fewer infested trees in year 10. The message here is that even partial treatment of infested trees can have some effect. Although this may only be a delaying tactic, it may provide additional time in which a negative weather event will affect the population, or at least it may provide time to mobilize against the epidemic.

During the incipient to epidemic phases, one of the crucial decisions to be made is the number of infested trees that need to be removed in an area to keep the infestation from growing. This information can be utilized to develop or alter strategies for managing mountain pine beetle infestations. If it is determined that the number of trees requiring treatment far exceeds the resources needed to carry out the activity then a decision is required on either increasing resources or shifting from a suppression to a maintenance or salvage strategy [see Hall 2004 for a discussion on beetle management strategies].

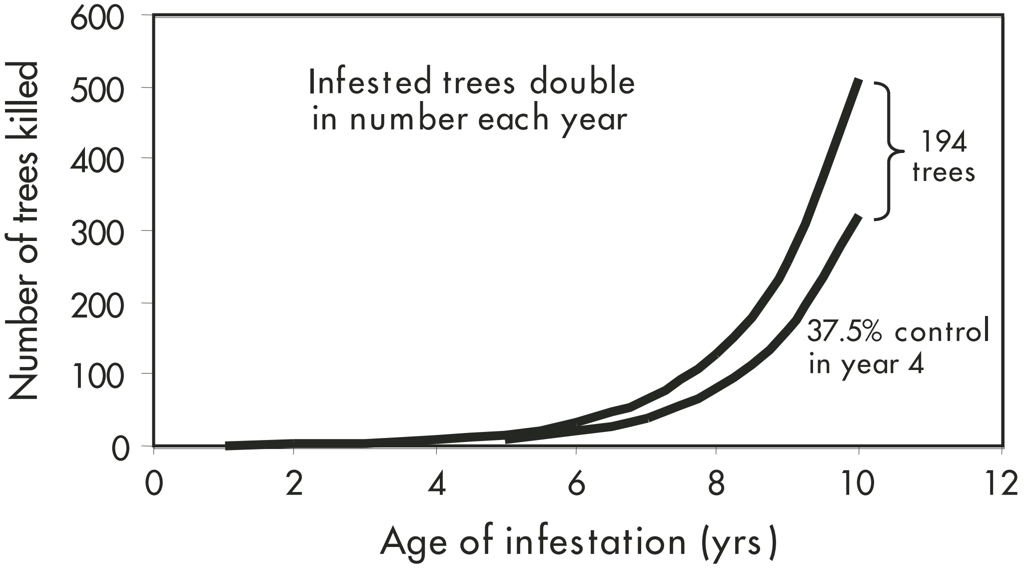

Figure 6. Growth in the number of infested trees over 10 years with and without partial treatment based on a single tree being infested in year one and a growth rate for infested trees equal to 2x. Treatment is three of eight infested trees being removed in year 4.

Rule of Thumb for Determining Number of Infested Trees Requiring Treatment

We have developed a decision aid that we refer to as a “rule of thumb” for determining the number of infested trees requiring treatment (Fig. 7).

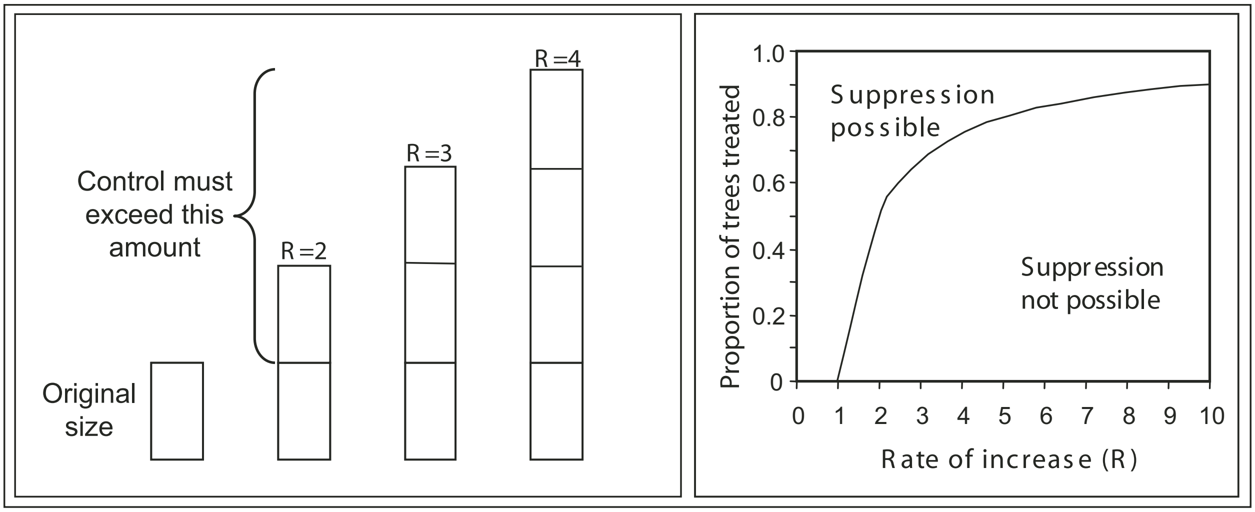

Figure 7. “Rule of thumb” for calculating what proportion of currently infested trees in an area need to be removed to keep the population static (left) and to control the infestation (right).

The diagram on the left is an illustration of the general concept. Here the first bar designates the size of the current infestation, in terms of the numbers of infested trees. The next three bars illustrate the size of the potential infestation next year provided that it doubled, tripled or quadrupled. One-half to three-quarters of the infested trees have to be removed just to keep the infestation from growing. If we want to suppress the infestation we need to remove a higher proportion of the trees. This concept is summarized in the diagram on the right. The situations where suppression of infestations is possible, given specific rates of increase in the number of infested trees, are above the curve. For example, if the average yearly rate of increase were 3, we would need to treat more than two-thirds of the infested trees each year in order to suppress the infestation. The line between suppression possible and not possible defines the number of trees requiring treatment to maintain the infestation at a static level (Fig. 7). It should be noted that use of this approach for decision-making requires good survey estimates of the number of currently infested trees.

Modelling Tools

If an infestation is not controlled at the incipient stage it can quickly accelerate to an epidemic. At this stage scattered single infested trees soon form small groups and eventually the small groups fill in to become a continuous infestation. As an epidemic grows, resource management decision-making becomes more complex. Single-tree treatments become less important and block harvesting directed at removing as many infested trees as possible is the main tactic. Infestations tend to advance in the general direction of the prevailing wind. The epidemic becomes analogous to a slow moving fire and is treated in a similar manner. Harvesting is directed at the moving front of the epidemic where the highest numbers of currently infested trees exist. The objective is to reduce the population, and try to slow the spread of the epidemic. This will buy some time in which it is hoped that unfavorable weather conditions will cause a decrease in the beetle population, or at least provide some time to recover more of the dead trees while the wood is still usable.

A point is reached where there are not enough resources to aggressively treat all of the infested trees. Strategic decisions need to be made on where to focus resources. Some of the important considerations are:

- What is the effect of this epidemic on the future timber supply? (See Pedersen 2004.)
- Where should different beetle management strategies be applied? (See Hall 2004)
- Does altering the cut level provide useful ammunition for reducing the beetle epidemic?
- What are the socio-economic implications of this epidemic?
- At what point do we decide that the fight against the beetle in a particular area is futile and focus on reducing non-recoverable losses? (Shift from suppression to salvage strategy.)
- What is the shelf life of the killed trees and how can harvesting be optimized to minimize non-recoverable losses?
- What are the other resource implications of this epidemic and subsequent harvesting?
- What will become of the stands that have been attacked by mountain pine beetle?
- In suppression strategy areas, where should blocks be placed, and what size should they be to achieve the maximum population reduction?
- How much effort should be put into beetle management, and what are the most effective tactics in different circumstances of topography, stand types, and beetle conditions?
- Would improved detection help the beetle management effort?
- Do any of the policy rules cause difficulties for beetle management?
- What is the effect of climate change on mountain pine beetle epidemiology?
- Can the epidemic spread further into Alberta and into the boreal forest?

We believe the best way to approach this multitude of questions is through modelling. The Canadian Forest Service has been transferring knowledge about the mountain pine beetle into models for the past few decades (e.g., Shore and Safranyik 1992; Safranyik et al. 1999; Riel et al. 2004). More recently, we have developed a spatially explicit, landscape level, mountain pine beetle model (SELES-MPB) in collaboration with Dr. Andrew Fall (Riel et al. 2004; Fall et al. 2004). Using this model, the spread and impact of the mountain pine beetle can be examined under different management and climate scenarios. The model can be set up to address many of the questions listed above, or to output variables that will serve as inputs to other models more specifically designed to answer these questions. This topic will be covered in more depth in Riel et al. (2004) and Fall et al. (2004).

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A Spatio-temporal Simulation of Mountain Pine Beetle Impacts on the Landscape

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Abstract

Two mountain pine beetle simulation models, which operate at distinct spatial and temporal scales, are used in combination to produce a third model: a spatially explicit landscape-scale simulation of mountain pine beetle outbreak activity. This model (known as SELES-MPB) is a stochastic, process-based simulation capable of projecting mountain pine beetle spread and impacts on the landscape through time and space, and can be used to explore and evaluate management strategies. In addition to landscape projections of mountain pine beetle impacts, SELES-MPB can project stand level impacts (e.g., trees and volumes killed by diameter class, resulting stand structure) increasing its utility as a decision support tool.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopk.) is the most destructive insect of mature pine in western North America (Wood 1963). In western Canada, outbreaks have periodically caused catastrophic losses primarily in lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) (Safranyik et al. 1974; Unger 1993) which affect many forest values and disrupts resource management plans. To better understand mountain pine beetle dynamics and to better manage resources in the presence of mountain pine beetle activity, several simulation models have been developed. Three models, which operate at different scales, are briefly described, and the process of integrating two smaller scale models to create a landscape-scale, spatio-temporal model is presented.

Models

There have been several attempts and approaches to modelling mountain pine beetle activity in British Columbia (BC). With improvements in computer technology, more sophisticated modelling approaches have been applied, and it is expected that this trend will continue. When the province of BC faced a major outbreak in the 1970s to early 1980s, an aspatial landscape-scale model was developed to explore the sensitivity of various management treatments on the mountain pine beetle outbreak (Thomson 1991). Around this time, a more detailed and sophisticated mountain pine beetle population dynamics model was developed (Safranyik et al. 1999).

Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Tree and Stand Level – the Safranyik Model

This population dynamics model (here after referred to as the "Safranyik model") is a complex process-based simulation of mountain pine beetle activity on a 1-ha stand of pure lodgepole pine. The model uses a daily time step and simulates the process of host colonization, brood development and survival, predation and parasitism of mountain pine beetle as well as tree mortality (Safranyik et al. 1999).

The Safranyik model is composed of four main components (Safranyik et al. 1999): a mountain pine beetle biology sub-model, a forest sub-model, a management sub-model and a user interface handling inputs and outputs. Figure 1 shows a simplified flow chart, which demonstrates program flow.

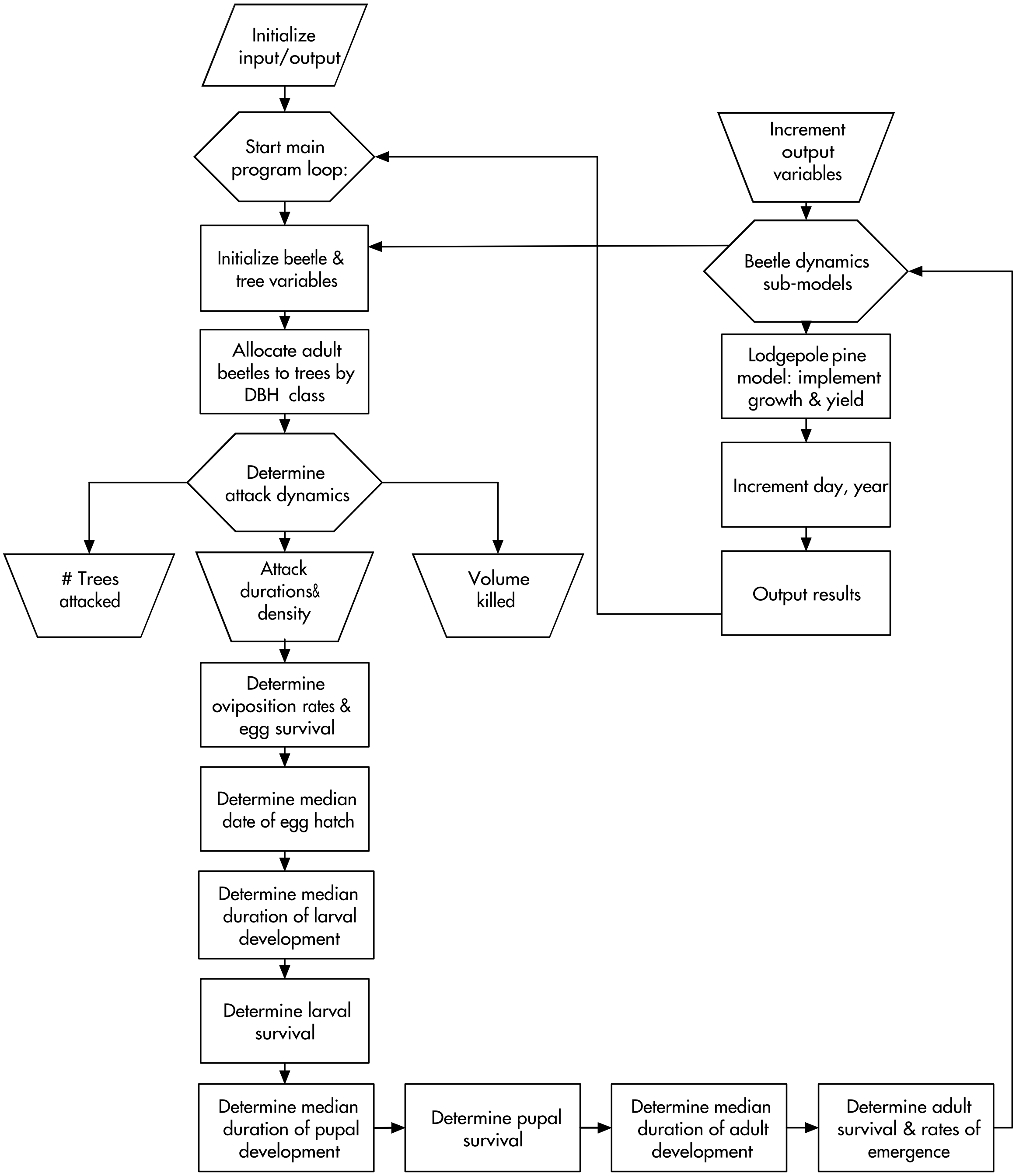

Figure 1. Safranyik model flow diagram (Safranyik et al. 1999).

Stand Level

The Safranyik model represents a sophisticated approach to modelling mountain pine beetle activity and for exploring effects of management intervention at the scale at which it operates. However, the scale of the simulation restricts its utility as a tool for forest managers who must deal with larger stands and stands of mixed tree species. For these reasons, a new simulation called MPBSIM has been developed.

MPBSIM is a stochastic, process based-simulation of mountain pine beetle activity at the stand level. Host stands can be mixed species and can range in size from 1 ha to 50 ha. MPBSIM is a much coarser simulation than the Safranyik model: it simulates host selection, brood development and survival, and beetle emergence and dispersal out of the stand on a yearly time step. Tree mortality is tracked on a year-by-year basis by different diameter at breast height (dbh) classes.

Like the Safranyik model, MPBSIM is composed of four main components: a mountain pine beetle population dynamics sub-model, a stand sub-model, a beetle management sub-model and a graphical user interface for collecting inputs and displaying model outputs.

MPBSIM input requirements include stand parameters and beetle information. Specifically the following inputs are necessary for running the simulation:

- Stand size (in hectares);
- Stand age (in years);
- Stand site index (for lodgepole pine, expressed in metres at 50 years breast height age);
- Percent pine;
- Stand density (stems per hectare); and
- Number of attacking beetles (or, number of currently attacked trees).

The outputs generated by MPBSIM include:

- Projected duration of outbreak (in years);
- The number of trees killed each year;
- The volume of trees killed year by year by diameter class;
- The number of beetles emerging year by year; and
- The number of beetles dispersing out of stand year by year.

Figure 2 shows a highly simplified flow diagram depicting overall program flow in MPBSIM.

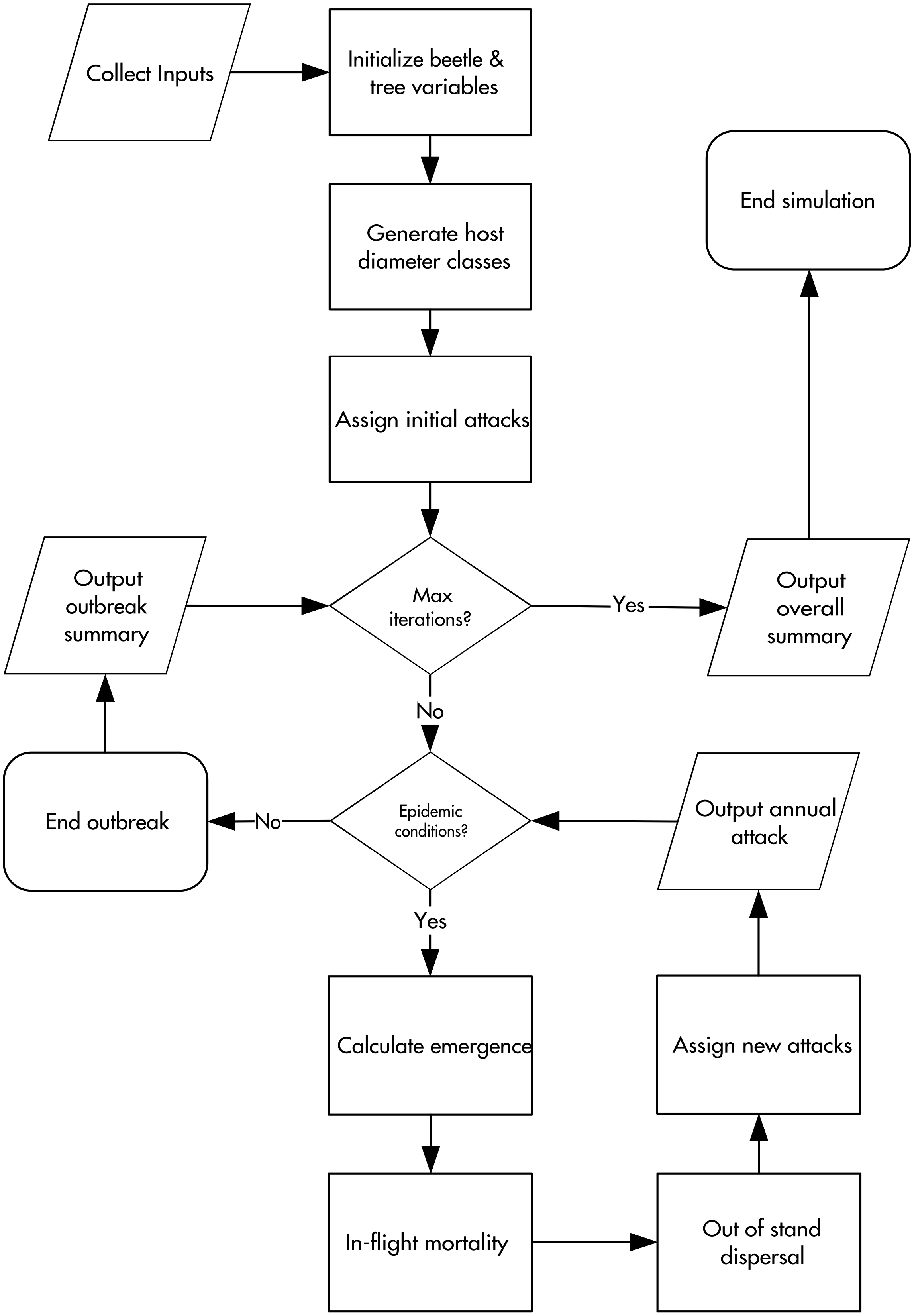

Figure 2. MPBSIM flow diagram.

Landscape Level: SELES-MPB

To effectively simulate a mountain pine beetle epidemic, a landscape scale simulation is important. A spatially explicit simulation allows a better platform for evaluating mountain pine beetle impacts and comparing various management strategies. For these reasons the Spatially Explicit Landscape Event Simulator (SELES) was chosen as a platform to build a spatial landscape scale mountain pine beetle simulation model (Fall and Fall 2001). SELES is not a model, but a raster-based platform in which to build and execute spatially explicit landscape models (Fall and Fall 2001). Every SELES model consists of three components:

1. Raster layers. These are the landscapes on which the simulation is executed. Layers can be base maps, forest inventory, road networks, etc.
2. Global variables. Global variables describe the state of the system.
3. Landscape events. Landscape events are the dynamic models that operate on (sometimes modifying) the landscape (raster layers). Landscape events can communicate indirectly through modifying the landscape.

The spatio-temporal model of mountain pine beetle spread and impact which was developed consists of several landscape events, including a spatially explicit mountain pine beetle spread model, a spatial timber harvesting model, a spatial mountain pine beetle management model and an aspatial mountain pine beetle impact simulation. This model is referred to as SELES-MPB.

Model Integration

To provide a satisfactorily detailed projection of mountain pine beetle impacts and to evaluate management effectiveness, it is preferable to generate stand level details of mountain pine beetle impacts even in a landscape model. For this reason, MPBSIM has been linked with the SELES landscape model as a landscape event. Because the purpose of SELES-MPB is to simulate beetle impacts and management strategies on real landscapes with unique climate and topography, it is important that MPBSIM projects beetle development and survival consistent with those conditions. To do this, MPBSIM is calibrated for the specific landscape using the Safranyik model.

The Safranyik model is capable of utilizing recorded daily temperatures for projecting mountain pine beetle development and survival as influenced by climate. To calibrate MPBSIM, temperature data from several weather stations located within the landscape are collected and adapted as inputs to the Safranyik model. A number of simulations are performed in a variety of stand conditions using these temperature data, and the resulting development and survival rates are used to calibrate MPBSIM.

Once MPBSIM has been calibrated to the local landscape climate, it can now be incorporated into the landscape model using a loose coupling methodology (Chang 2001). This is accomplished by collecting a complete range of inventory data for the landscape in question and pre-running MPBSIM for as many conditions as possible at a large number of different initial beetle attack levels. In practice this can amount to well over one million different combinations. A variety of values and indicators are output and collated in a large table which includes stand information (number of stems per hectare, stand age, percent pine, site index) and beetle and beetle activity information (number of attacking beetles, number of dispersing beetles, number of beetles emerging next year, trees killed and tree volume killed). This table reflects MPBSIM's projection of mountain pine beetle activity for any condition that exists on the landscape (Fig. 3).

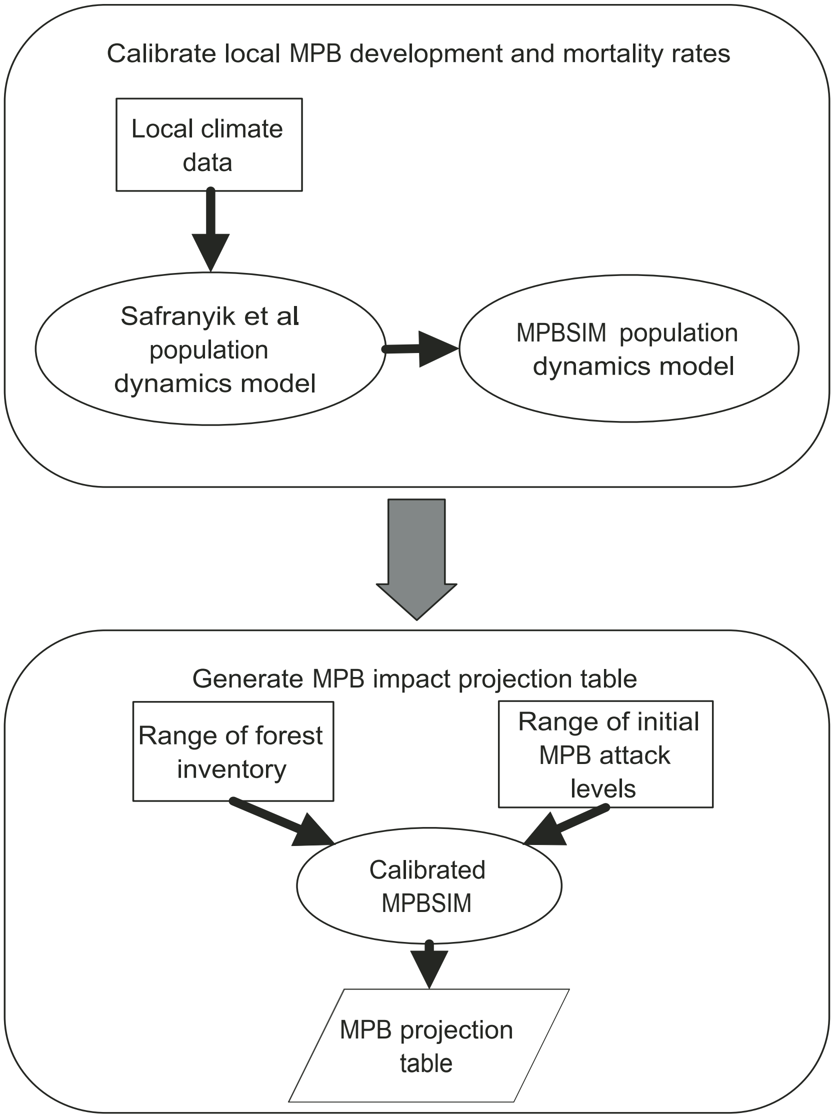

Figure 3. MPBSIM Calibration and table generation for SELES-MPB (MPB = mountain pine beetle).

The MPBSIM generated table is integrated into SELES-MPB as a landscape event, along with the spatial harvesting model and management model (Fig. 4). These landscape events do not directly communicate with each other, but can impact each other by making changes on the landscape (spatial landscape layers).

This modelling approach has been successfully applied in several districts within the provinces of BC and Alberta (Fall et al. 2001; Fall et al. 2002a; Fall et al. 2002b).

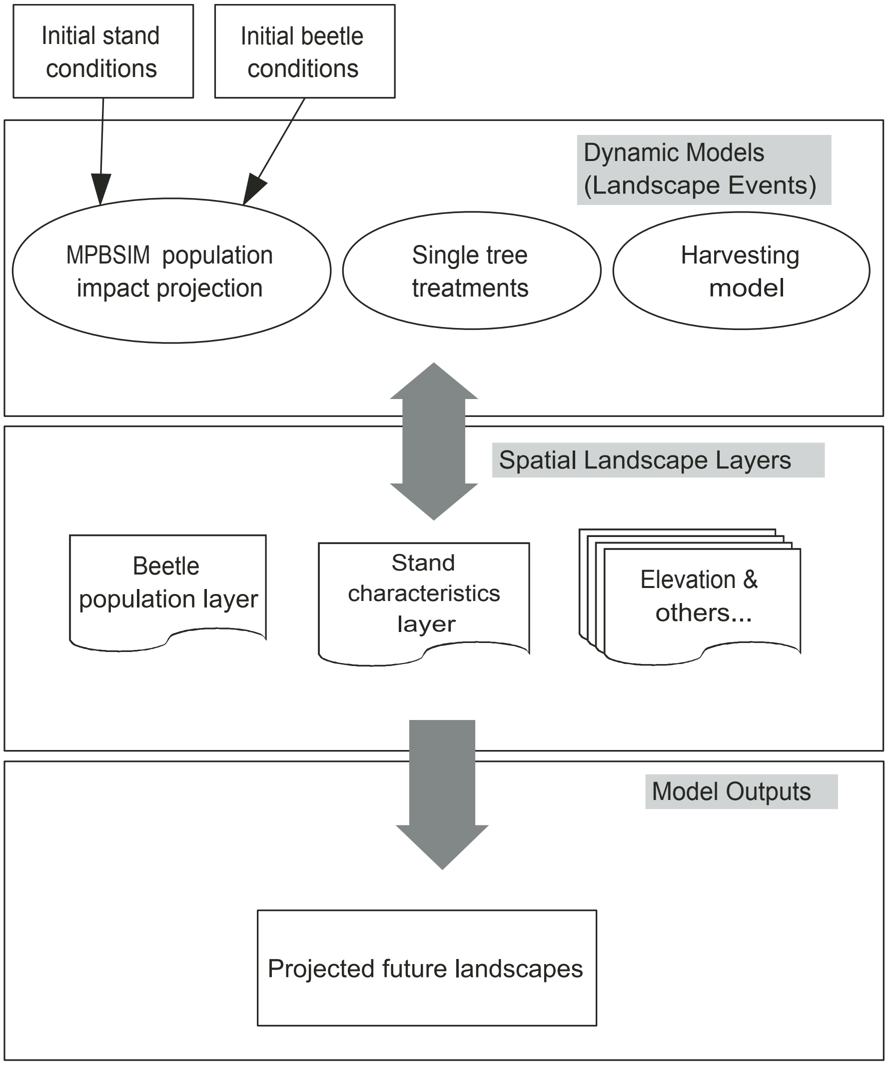

Figure 4. Overview of SELES-MPB.

Conclusions

Modelling mountain pine beetle activity at different scales is important for answering different management questions. Integrating models of different scales allows for a more detailed simulation of impacts and permits evaluation of management at appropriate levels of detail. The loose coupling approach of model integration used in SELES-MPB is a general method that could be used to integrate other models of different scales, whether they are simulations of mountain pine beetle activity or other landscape disturbance agents.

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Integrating Landscape-Scale Mountain Pine Beetle Projection and Spatial Harvesting Models to Assess Management Strategies

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Abstract

A landscape-scale mountain pine beetle population model was developed to assess the impacts of mountain pine beetle outbreaks at spatial scales of over 1,000,000 ha. We integrated this model with spatial timber supply and strategic forest management models in the Lakes, Kamloops and Morice timber supply areas of British Columbia, Canada to analyze the potential spread of the current beetle outbreak under a range of potential management activities in various regions of the province. We analyzed a range of scenarios to contrast management alternatives and beetle conditions. Three main types of effects were assessed: area attacked and volume killed by beetles during the outbreak (over the next 10 years), volume salvaged and non-recovered loss expected during and post-outbreak, and cumulative timber supply impacts. The three study areas provide a gradient across the range of conditions within the overall outbreak area. In general, our analysis highlights the likely effects of applying different beetle management strategies under different conditions. Our results imply that an attack pressure threshold exists, below which fine-scale management can improve potential to control an outbreak, and above which management will likely have little effect on the outbreak.

Introduction

Mountain pine beetle (*Dendroctonus ponderosae* Hopk.) occurs across pine forests in western North America (Wood and Unger 1996). Over the past several years, a major outbreak of mountain pine beetle has been underway across a vast area of the central interior of British Columbia (BC), primarily in lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) stands (Safranyik et al. 1974; Wood and Unger 1996). The magnitude of this outbreak, and the losses faced by the timber industry, is creating havoc with long-term forest planning. It forces the redirection of the allowable cut towards reducing the beetle population and salvaging beetle-killed timber. The cumulative effects of the outbreak and management activities can impact maintenance of other forest values (e.g. caribou migration routes, ungulate winter range, visual quality, etc).

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*Mountain Pine Beetle Symposium: Challenges and Solutions. Octob*er 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

In timber supply areas (TSAs) affected by the current epidemic, resources have been focused towards maximizing impact on the beetle while minimizing impacts on social and forest values. To provide information on expected projections of the outbreak using current best information on the landscape state and beetle and management behaviour, a series of projects to develop a landscape-scale mountain pine beetle and strategic management model that builds in prior work modelling mountain pine beetle dynamics and spatial timber supply was initiated. The main purpose of these studies was to address the question of what would be the likely range of impacts from the current beetle outbreak under a range of alternative beetle management regimes (Anon. 1995) including increased or decreased levels of effort. The core of the landscape model was developed largely with support from the BC Ministry of Forests for projects in Kamloops, Lakes and Morice Forest Districts (Fall et al. 2001; 2002; 2003a), and in a portion of Lignum Ltd.'s Innovative Forest Practices Agreement area near Williams Lake BC (Fall et al. 2003b). The mountain pine beetle model (SELES_MPB) was derived by the authors to scale results from a more detailed stand-level mountain pine beetle population model, MPBSIM developed at Pacific Forestry Centre (Riel et al. 2004).

Our approach was to start with the current conditions, and project likely outcomes and interactions between mountain pine beetles and management, under the various scenarios using spatially explicit stochastic simulation modelling. Input preparation involves assembly of geographic, forest inventory, weather and mountain pine beetle infestation data for each study area. We do not attempt to predict when the outbreak may end, but artificially terminate it after 10 years. We may extend the model time horizon to assess the decay of killed merchantable wood over the following decade and long-term implications on growing stock and other timber supply indicators. Through comparison of various scenarios, the influence of management actions in terms of area infested and volume killed were identified. This information can be used to assess impacts directly, or can serve as input for further analysis of economic, social or ecological costs and benefits. In this paper, we describe the conceptual basis for the management and mountain pine beetle models, and present some key results from the three study areas.

Methods

Overall Landscape Model Design

Our general approach is to integrate the SELES-MPB/MPBSIM Mountain Pine Beetle Landscape Model with the Spatial Timber Supply Model (STSM) (Fall 2002). The design in terms of linkages between model state, landscape processes and output files is shown in Figure 1. For a description of the Spatial Timber Supply Model, which covers details of the harvesting, aging and inventory sub-models see Fall 2002). The Lakes, Kamloops and Morice TSA Landscape Models (called LLM, KLM and MLM, respectively) are specific applications of this framework.

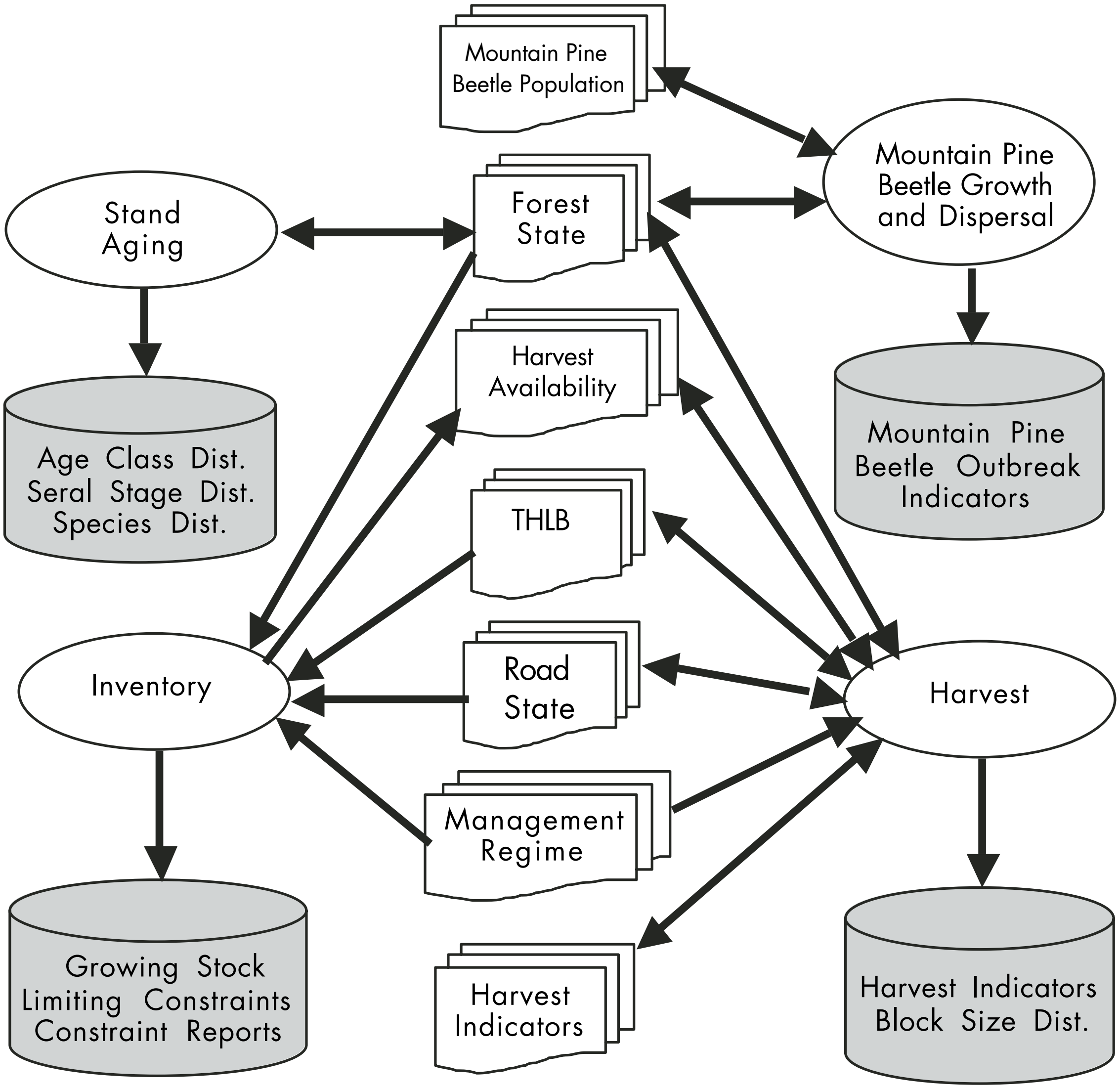

Figure 1. Linkages between primary components of state (shown in the centre), model processes (shown in ovals) and output files (shown as grey drums).

Model State Space

All layers, except where noted, were derived using information from the current forest inventory on each timber supply area.

- Landscape structure: the landscape biogeographical context and the limits of the study area are defined with biogeoclimatic classification (Pojar et al. 1987), by variant (BEC) and elevation in metres.
- Forest state: represented by stand age in years, inventory type group (leading and secondary species), height and volume (derived from growth and yield tables), percent pine (percent of forest in each cell that is pine), stand density (estimate of number of stems per hectare), site index (expected height in metres at 50 years), and analysis unit (represents sites with similar growing conditions, usually based on species, management history and site index).

- Mountain pine beetle population: tracked using mountain pine beetle population (beetles/cell, initiated based on estimates of the initial beetles/cell derived from current infestation data), time since attack (years since last attack in cell), mountain pine beetle susceptibility [computed according to the index developed by Shore and Safranyik (1992)], and mountain pine beetle risk [computed by combining susceptibility with beetle locations but using a different method than in Shore and Safranyik (1992)]. Note that the risk and susceptibility estimated are only used to influence the management models, not the mountain pine beetle population model.
- Harvest availability: potential treatment type (available forest stratified into the type of treatment that would be applied if a block was initiated at that cell; treatments are discussed below), and salvageable volume. This latter variable tracks dead volume that would either be salvaged or become a non-recovered loss in various post-disturbance stages (e.g., green attack, red attack, third year post-attack, etc.). There is no initial state for this information.
- Timber harvesting landbase (THLB): derived from the productive operable forest via a net down process that removes forest for various reasons described in recent timber supply reviews (e.g., British Columbia Ministry of Forests, 2001a, b, c), but applied spatially. The majority of these remove entire cells (e.g., non-merchantable forest), but some may remove only portions of a cell (e.g., roads, riparian zones). Hence, the THLB is represented as a percentage of each cell that is in the THLB.
- Management zones: some management zones are common to all analyses, while others are study-area specific. For example, zones used in the Morice TSA include visual quality objective zones, caribou management zones, integrated resource management zones, resource management zones used to identify community watersheds, landscape units, productive forest (cells classified as productive operable, productive inoperable or non-productive/non-forested), and identified blocks in current forest development plans.
- Management parameters: a range of parameters and tables to set up the harvesting regime, including annual allowable cut (AAC), beetle management unit (BMU) strategies (Maclauchlan and Brooks 1994), minimum harvest age, management constraints, and management preferences.
- Roads: distance to existing roads in metres.

Stand Aging

This event increments stand age with each time step, and updates the age class and seral stage information. It is also responsible for changes to analysis units upon stand regeneration. The model does not capture species shifts.

Inventory

This event performs an inventory analysis for each time step. It tracks the amount of forest above/below the thresholds specified for each constraint within the relevant zones, and determines which cells are available for harvest. For cells that are unavailable, it outputs information to determine which constraints were responsible. For constraints for which recruitment is appropriate, cells are recruited in order of age.

Harvesting

This sub-model is designed so that under conditions with no beetle outbreak, it can be parameterized to match timber supply review (TSR) analysis results, enabled with spatial capability to simulate the allocation of cutblocks across the landscape. Harvest rate (m^3/yr) and volume yield curves for different types and ages of forest were based on recent Timber Supply Review analysis documents (e.g., British Columbia Ministry of Forests 2001a). The AAC and mean volume per hectare determine the area logged and, in part, the number of cutblocks. The following steps are applied to place blocks:

- Cutblocks must fall on eligible land, determined by the timber-harvesting land base, stand age (which must be older than minimum harvest age), access (within 2 km of an existing road), forest cover rules (age class structure in applicable zones allows harvesting), and adjacency rules.
- Eligible cells are classified into potential block types (see below), and cells are processed in this order. Without mountain pine beetle, all cells are classified as "green blocks."
- Within each type, relative preference is assigned to each map cell based on stand age (relative oldest first), potential block type (e.g., salvage opportunity in proportion to salvageable volume), and distance to road (linear decrease with distance). Block start points are selected probabilistically using these preferences to reflect economic and environmental differences among eligible stands.
- Once a harvest block is initiated, a target size is chosen from an input distribution. The default cutblock size was 40-100 ha based on spatial assessments of recent block sizes in the study areas. The cell is then harvested, and the block spreads to adjacent cells until the target size is reached or the adjacent eligible area is exhausted. As only clearcuts were modelled at the scale of the 1-ha cells, harvesting a cell involves setting stand age to zero and updating tracking variables (e.g., annual volume harvested).

Cutblocks were explicitly connected to the main road network by adding a link from the first cell harvested in the block to the nearest existing road. The model then updated a map that stored the distance from each cell to the nearest existing road. This feature permits estimation of the amount of road constructed under a given management regime.

Beetle management was incorporated as strategies to target blocks during the stand selection based on detectable attacked stands, salvage opportunity, mountain pine beetle susceptibility and mountain pine beetle risk. At the start of each year each cell was classified probabilistically (based on detection uncertainty and planning rules) into one of the following cell types:

- Beetle cells: sufficient level of detectable green (year of attack) or red (one year after attack) trees (> 5 detectable trees). The default probability was 1% per detectable tree (i.e., 100% chance for $\geq$ 100 trees), but declined with distance from roads for distances > 1 km.
- Salvage cells: cells that had a sufficient level of salvageable timber ($\geq$ 25 m^3/ha).
- Risk cells: cells that had a sufficiently high-risk index (default: 1% chance per unit of risk, which ranges from 0 to 100%).
- Susceptibility cells: cells that had a sufficiently high susceptibility index (default: 1% chance per unit of susceptibility, which ranges from 0 to 100%).
- Green-tree cells: all other cells.

When selected, a block takes on the type of the cell. In this way, *Beetle blocks* were applied in areas with significant detectable infested trees. *Salvage blocks* were applied in areas with significant detectable standing dead wood. *Risk blocks* were applied in areas with high risk of mountain pine beetle attack. *Susceptibility blocks* were applied in areas with high mountain pine beetle susceptibility. *Green-tree blocks* were placed outside the above areas, and blocks were cut using clear-cuts. Beetle, salvage, risk and susceptibility blocks cannot spread to green-tree cells.

The relative preferences used for cell classification, and the targeted order of harvest based on these types, was based on the beetle management activities carried out by each TSA. Generally, the treatments in a year were placed according to the order given above, but some scenarios placed higher emphasis on salvage or risk blocks. That is, first all beetle blocks were treated; if there was AAC remaining then salvage blocks were treated, etc. The model assumed 90% effectiveness for block treatments in terms of the percent of beetles removed.

Single-Tree Treatments

This sub-model simulated fell and burn and monosodium methanearsonate (MSMA) treatment methods, based on levels provided by each TSA. Fell and burn treatments are generally applied in inaccessible areas or areas with low beetle population levels. These treatments were applied to individual cells, and the volume was not recovered. The model assumed 95% effectiveness of beetles killed in a treated cell.

Mountain Pine Beetle Population Model

Stand-scale models for predicting mountain pine beetle spread and impact have been developed at the Canadian Forest Service (CFS) (Safranyik et al. 1999; Riel et al. 2004). We extended these to the landscape scale using the Spatially Explicit Landscape Event Simulator (SELES) modelling tool (Fall and Fall 2001). The CFS stand-level model MPBSIM projects expected development of a beetle outbreak in a stand of up to several hectares (Riel et al. 2004). Conceptually, our approach involves effectively running MPBSIM in each cell of the landscape with beetles. Since it is not feasible or desirable to do this via a direct link, we first run MPBSIM under a wide range of conditions to produce a table linking conditions to resultant consequences. Conditions include stand attributes (e.g., age, percentage of pine), outbreak status (e.g., number of attacking beetles), etc. (Riel et al. 2004). Consequences refer to the effect of one year of attack under those conditions (e.g., number of dispersers and number of trees killed). The landscape level model uses this table to project mountain pine beetle dynamics in each 1-ha cell containing beetles. The stand table includes stochastic variation in number of emerging beetles, and we control this to capture synchronous annual variation and above-average weather conditions.

Dispersal between cells provides the spatial context for an outbreak, leading to an increased beetle population in cells within a current outbreak, or starting an outbreak in a currently uninfested cell, expanding a current beetle spot or starting a new spot. The flight period, including local and long-distance dispersal and pheromone production and diffusion, is modelled as a spatial process. Long-distance dispersal is largely governed by wind speed and direction used to select distance locations for mountain pine beetle spread, while local dispersal is influenced by wind, susceptibility, pheromones and distance. During attack, beetles kill pine trees, producing red trees (recently killed) and standing dead volume that may be salvaged by the logging sub-model. The model also tracks the loss of salvageable wood resulting from attack. Economic standing dead wood is a subset of ecological standing dead wood, since the latter contains non-merchantable snags. Hence salvageable wood may degrade at a relatively fast rate (e.g., 20% starting 3 years after attack), depending on an input decay rate curve.

Model Outputs

Text output (aspatial annual time series) includes:

(i) age-class distribution of productive forest in 10-year age classes;
(ii) mountain pine beetle outbreak indicators (overall and stratified by beetle management unit), including volume killed, number of trees killed, area attacked and a range of verification indicators (e.g., number of long distance spots);
(iii) growing stock inventory in terms of cubic metres of live forest in various stratifications of the landbase;
(iv) harvest indicators such as annual volume and area harvested, mean age harvested, volume per hectare harvested, harvest species profile, volume of non-recovered loss, volume salvaged, amount of available salvageable wood and area harvested by the various treatment types (i.e., beetle blocks, salvage blocks, etc.); and
(v) amount of spur road constructed. We focus our results on the mountain pine beetle outbreak indicators.

Spatial output

Since multiple replicates of each scenario are run, creating spatial summaries across time and replicates is a challenge. The aspatial indicators summarize information across space and replicates, providing time-series information. We designed several spatial indicators that summarize information across time and replicates:

(i) *TimesAttacked* is the number of runs in which each 1-ha cell was attacked at least once, and can be roughly thought of as the probability that a cell will be attacked at some point in the 10-year horizon;

(ii) *THLBVolumeKilled* is the total volume killed in the THLB over the time horizon of the run, and shows areas likely to have the highest time impacts;

(iii) *PercentPineKilled* is the cumulative percentage of pine killed, and shows areas likely to have the higher ecological impacts; and

(iv) *YearAttacked* is the first year attacked in the run, and shows how the main front of the beetle outbreak is expected to spread across the landscape.

Scenarios Evaluated

A wide range of scenarios was run in all study areas to verify the model prior to making the main "production" scenarios, and led to model improvements and refinements, as well as greater understanding of the model interactions and feedback. We don't describe the results of the verification runs here, and instead focus on scenarios relevant for management. We present selected scenarios from the three study areas to highlight key findings. There are a number of stochastic factors in the model, primarily affecting dispersal due to wind and cells selected by beetles. We ran 10 replicates of each scenario for 10 years (unless otherwise stated) so that we can report means and standard errors.

Calibration Scenarios (Lakes TSA)

Variation in the way historical outbreak information was collected makes it difficult to calibrate and parameterize the dispersal component of the model. Based on the approximate location where the present outbreak in the Lakes TSA was first detected in 1991, and an estimate of the landscape conditions at that time, we designed a set of scenarios to compare model projections with current infestation data. We only present the results of the final calibration scenarios. We estimated the landscape conditions in 1991 by "standing up" cells currently less than 10 years old (by assigning the age and stand density of the nearest unharvested neighbour at the patch boundary). We then created a 1,000-ha "origin" patch outside the TSA in Tweedsmuir Park on the north side of Eutsuk Lake, the purpose of which was to provide a source of long-distance dispersers during flight period (at a rate of 10,000 dispersers per ha in the "origin" patch per year). We ran two scenarios, both for 10 years (1991-2001) and with no beetles in the TSA at the start. In the first (*Origin10)*, external dispersers from the origin patch continue for the entire horizon, and in the second (*Origin5)*, we stop immigration after five years.

Base Scenarios and Broad Management Sensitivity

The base scenarios are designed to address the primary questions regarding the expected impact of beetle management. These differed by study area, based on information obtained by workshops held at the forest district offices. Some common features include application of current forest management policy, operational constraints (e.g., in Morice, amount of pine that can be harvested is constrained by the need to address concurrent outbreaks of western balsam bark beetle (*Dryocoetes confusus*) and spruce beetle (*Dendroctonus rufipennis*)) and focus of effort on beetle areas. Differences included level of fine-scale treatments, harvest level, forest cover constraints, etc. To put the effect of beetle management (*BM* or *Base Run*) on the mountain pine beetle in a broad context, we compared the base scenarios with scenarios of no harvesting (*NoHarv* or *NoMgmt*), and no beetle management (*NoBM)*, and with current beetle management but with forest policy constraints disabled (*BMNoForPol)*.

We also assessed the effects of different levels of AAC with percentages relative to the base run, which applied the AAC level from the last determination (using an estimate for Kamloops TSA, as the study area is only a portion of a timber supply area). The levels assessed differed by study area, and are indicated by the suffix "AAC" followed by the increase over the base AAC (e.g., *AAC x 2* and *BMAAC200* both indicate the base scenario with two times the current AAC). In Morice TSA, we varied AAC from 50% to 500% of current levels.

In addition to the above, we assessed some scenarios specific to each area:

- Morice: The base runs for Morice also include an assessment of immigration from northern Tweedsmuir Provincial Park (indicated with an "*imm*" suffix). As the timber supply review analysis includes some effects of beetle management, we also applied this scenario (called *TSR*). As there is uncertainty regarding the over-winter weather conditions, we ran both "average" weather and "above-average" (*High* or *h* suffix in scenario name) weather.
- Lakes: To assess the effect of the current AAC increase set by the chief forester to deal with the outbreak ("AAC uplift"), we ran the base *BM* and *NoBM* scenarios at two times the current levels of harvest and the BM scenario at 10 times current levels. We also set up variations of the BM scenario with disabled fell and burn (*NoFell&Burn*), and ability to detect green attack (*DetGreenAttk*).
- Kamloops: We additionally assess halving and doubling the AAC (*BM/2* and *BM×2*, respectively), disabling fell and burn (*NoFell&Burn*) and allowing green attack detection (*DetGreenAttk*).

Salvage and Non-Recovered Loss (Lakes TSA)

We contrasted current management with a strategy of focusing on salvage rather than current attack, and assessing non-recovered losses. The difference between the *BM* and *Salvage* scenarios is that the former first targets beetle blocks, while the latter first targets areas with high amounts of salvageable timber.

Green Detection Sensitivity (Morice TSA)

To assess the relative impact of different levels of green attack detection, we varied green attack detection from 0%-100% in 20% increments for the *BM* and *BM + immigration* scenarios, and with average and above average weather. In the base runs, we assumed that only red attack could be detected (i.e,. 0% green detection).

Tweedsmuir Immigration Sensitivity (Morice TSA)

To clarify the debate regarding the role of the infestation in Tweedsmuir Provincial Park in Morice TSA, we ran scenarios with no immigration from Tweedsmuir and with immigration based on overview information. The forest cover information is outdated and of limited use for this analysis. We assumed instead that the areas with outbreak are quite susceptible. We estimated a range of potential immigration pressure based on overview information, and the number of long-distance dispersers likely to be dispersing from Tweedsmuir using the stand table. We varied the proportion of cells generating dispersers from 25% to 100% in 25% increments for the *BM*, *NoMgmt* and *NoBm* scenarios with both normal and above average weather. We used as a base "expected" case the mid-point of this estimated range, which effectively generates dispersers from 50% of the cells mapped as infested. The suffix "*Imm*" indicates that immigration from Tweedsmuir was included at the base 50% level of immigration.

Single-Tree Treatment Sensitivity (Morice TSA)

To assess the effects of different levels of single-tree treatments (fell and burn and tree injection with MSMA), we varied levels of single-tree treatments at 0%, 50% 100%, 150% and 200% of current levels, under the *BM* scenario (with average and above average weather). The base run applied 250 ha/year of fell and burn and 1000 ha/year of MSMA.

Results

All results reported graphically are the mean and standard error of 10 replicate simulations of each scenario.

Calibration Result (Lakes TSA)

Table 1 compares the estimated area of attack and mean volume killed of the calibration experiments with the first year of the main model runs (Initial2001). Although we cannot compare these values statistically, the area attacked seems to be a slight underestimation, but within reasonable limits. The mean growth rate, after two years, for the beetle population in the *Origin10* experiment was 1.75, which is close to an expected growth rate for this area of the province.

Figure 2 illustrates the spatial pattern of the projected outbreak after a decade for the *Origin10* scenario. The left image shows the probability of a cell being attacked (i.e., *TimesAttacked*), and the right one shows the mean proportion of pine killed. Both the area and relative severity of attack correspond reasonably well with the current infestation data used to initialize the main model runs. Attack is concentrated in the southern portion of the Chelaslie landscape unit and Entiako protected area, with moderately high levels of attack in the central area of the landscape unit and some areas of attack across Ootsa Lake. Note that a cell will show as grey if it is attacked at least once in the 10 replicates, so the extent of grey in these images is somewhat larger than is projected by a single run.

Table 1. Comparison of cumulative area and volume killed, and volume killed in final year of run in the two "Origin" experiments compared with the estimates for cumulative area and volume killed used for initial conditions in main model runs.

Scenario	Cumulative Area (ha)	Cumulative Volume Killed (m^3)	Volume Killed (m^3) (final year)
Origin10	181,097	2,539,469	738,788
Origin5	152,687	1,462,039	486,901
Initial2001	192,001	1,070,039	1,070,039

Figure 2. Estimated probability of attack (left) and percent pine killed (right) during the decade 1991-2001 with beetles originating from outside Lakes TSA on the lower left of the study area. Brighter areas indicate higher probability and mortality, with white at or above 50% probability and 80% mortality, respectively.

Base Scenarios and Broad Management Sensitivity

Morice

The four base scenarios simulated current beetle management under average and above-average weather conditions for beetles, and with and without beetle immigration from Tweedsmuir (*BM, BMhigh, BMImm, BMImmh*). All of the base scenarios featuring *BM* resulted in reductions in both the volume killed and total area attacked and formed a cluster at the lower left of Figure 3. The scenarios that had no beetle management or no harvesting at all with average weather conditions formed an intermediate cluster and the same scenarios with above average beetle weather formed a cluster with the highest volume losses and largest area of attack (Fig. 3). These results suggest that the current beetle management employed in the Morice District can significantly reduce both the extent (area attacked) and the intensity (volume killed) of the beetle impact over the next decade even with uncertainties regarding weather and Tweedsmuir immigration. Weather had more of an effect than immigration.

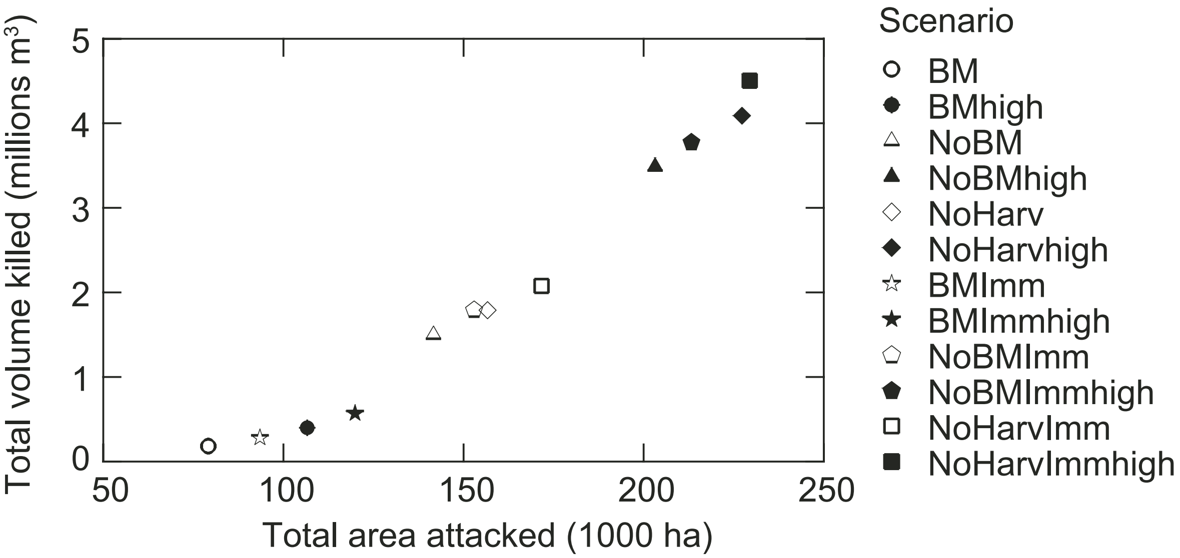

Figure 3. Total volume killed versus area attacked for the base beetle management (BM) scenarios and those with no BM and no harvesting in Morice study area (starting year: 2002).

Disabling forest policy constraints had virtually no impact on beetle damage indicating that these constraints are not limiting current beetle management efforts in the district (Fig. 4). Harvesting under *TSR* rules gave similar results to the *NoBM* scenario. The effect of any harvesting not directly targeted at beetles appeared to be minimal in this landscape with the present beetle population under average weather conditions. At above average beetle weather conditions, the *TSR* and *NoBM* scenarios were slightly more effective than no harvesting, but far less effective than the *BM* scenario (Fig. 4).

Varying the AAC to lower (50%) or to higher (200-500% in 100% increments) levels demonstrated that increases in AAC level above 50% more than the current level had almost no effect on volume losses under any of the four base *BM* scenarios, while reducing the AAC caused increased volume losses (Fig. 5). However, these increased losses need to be put in perspective. Even in the scenario with the highest beetle levels (immigrants and high beetle weather), the volume savings over a decade by increasing the AAC by 50%, are approximately 250,000 m^3. This would require an additional cut of approximately 12,000,000 m^3 to achieve this, so the return is only about 2%.

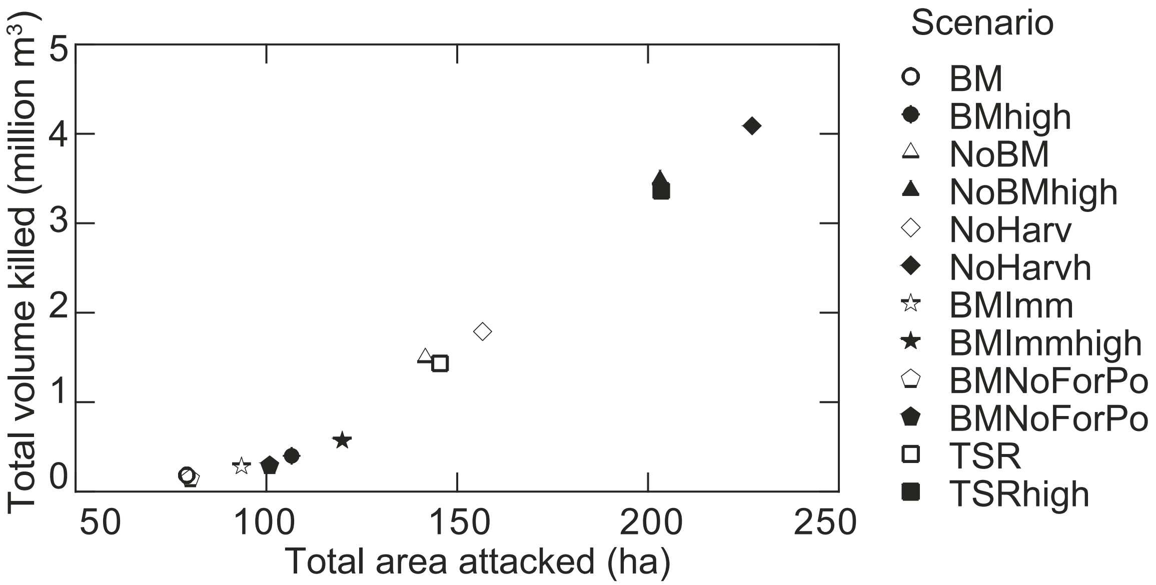

Figure 4. Total volume killed versus area attacked for additional management scenarios in Morice study area (starting year: 2002).

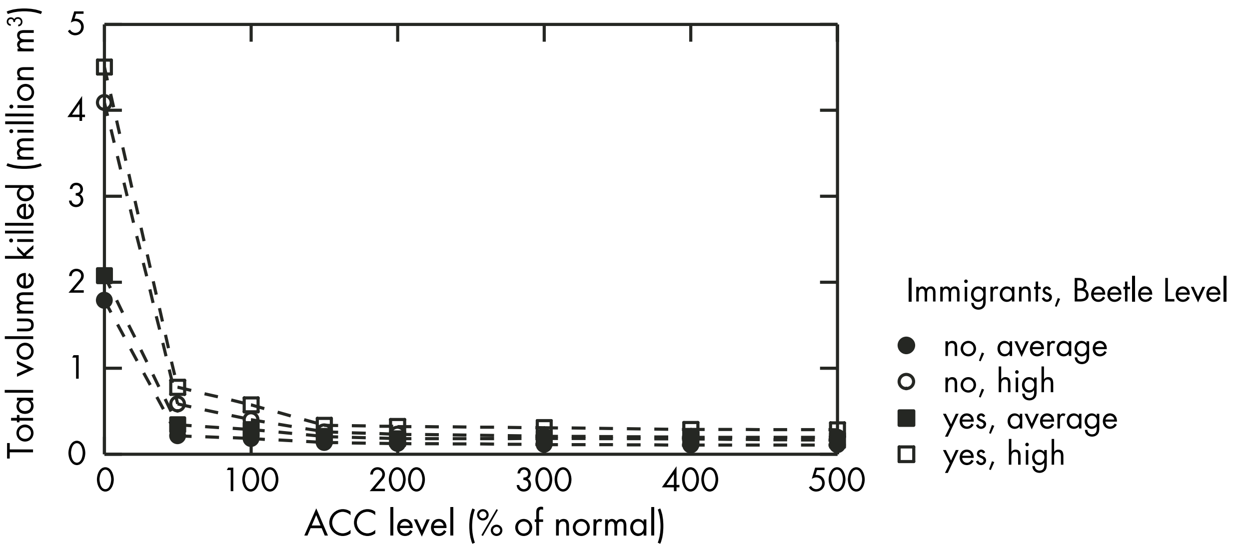

Figure 5. Relationship between volume losses and the AAC level in Morice study area (starting year: 2002).

Lakes

The base *BM* scenario reduced volume losses inside the THLB by approximately 1.5 million m^3 when compared with *NoBM* and about 3 million m^3 over *NoMgmt* during the 10-year simulation period (Fig. 6). Doubling the AAC (*BM_AAC200*) using beetle management treatments significantly reduced volume losses compared to the base BM run. However, the scenario with 10 times the current AAC (*BM_AAC1000*) did not significantly reduce volume losses compared with the *BM_AAC200* scenario. Doubling the AAC under *NoBM* rules resulted in virtually identical volume losses compared to the base *NoBM* scenario. This occurred because the *NoBM* scenarios log stands using the relative oldest first rules and ignore the presence of beetles. The additional cut from doubling the AAC with no beetle management were largely allocated to stands outside of the area of beetle attack and thus had no effect on volume killed.

The scenarios that individually removed various forest policy constraints, turned off fell and burn treatments, ignored BMUs, and increased the probability of green attack detection had no significant effect on predicted volume losses over the simulation period when compared to the base run (Fig. 6). Indeed the only significant decrease in volume losses came from increasing the AAC (Fig. 6). Doubling the AAC decreased volume losses but had no effect on the extent of the outbreak. Only the 10 times AAC scenario significantly reduced both volume losses and the outbreak extent.

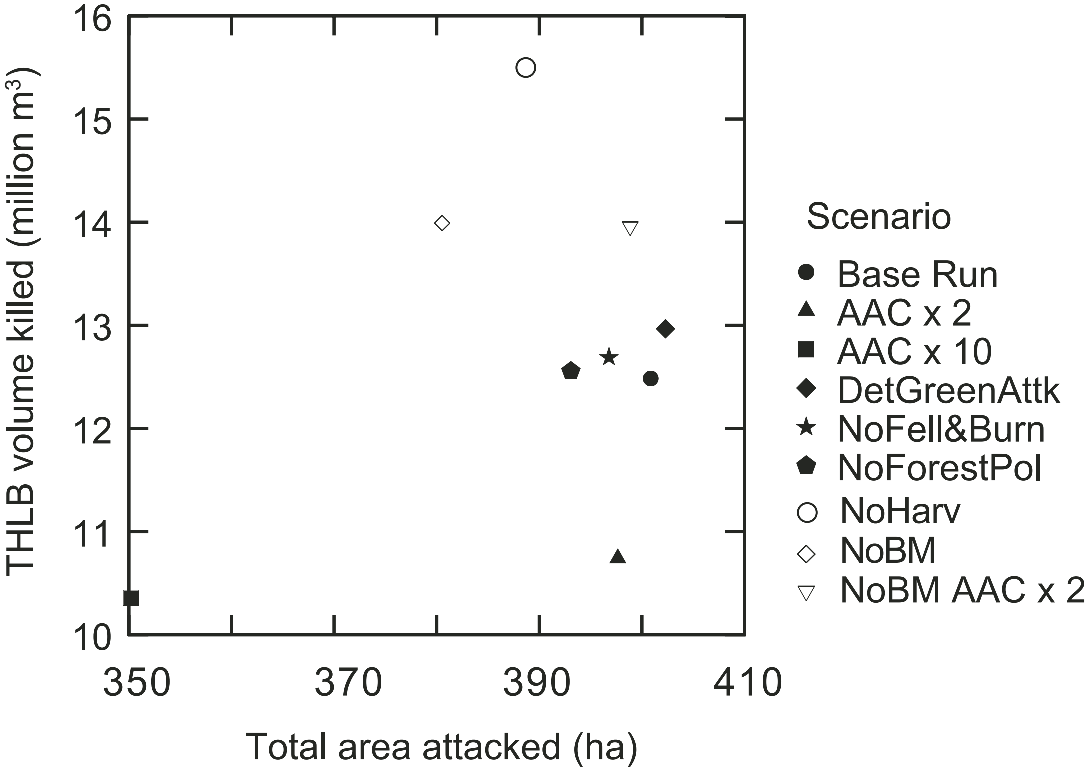

Figure 6. Projected volume losses in Lakes study area plotted against the cumulative area attacked under various management scenarios (starting year: 2001).

Kamloops

The base beetle management scenario (*BM*) reduced volume losses inside the THLB by over 300,000 m^3 compared with *NoBM* and no management scenarios (Fig. 7). The differences between *BM* and increased/decreased levels of beetle management are not nearly as much as the difference between beetle management and no beetle management. The cumulative area attacked over the 10-year period highlights the effect of increasing beetle management effort on reducing the area attacked.

Changing management policy had varying effects on projected volume losses (Fig. 7) compared to the base *BM* run. Disabling fell and burn led to a minor increase in volume killed, indicating that single-tree treatments may be important in this area. Increasing detection of green attack led to a large decrease in area attacked. This reduction is even higher than with a doubling of the AAC. These two scenarios indicate the importance of applying treatments as close as possible to beetle activity centres in this landscape. The scenarios that varied the AAC show the coarse-scale effect of "treatment budget" (total potential effort available in terms of area that can be treated). Decreasing the AAC has a larger relative effect than increasing it, with a 25% increase in volume killed at a 50% AAC reduction compared with 12% decrease for a 50% AAC increase, and 21% increase for a 100% AAC increase.

Figure 8 shows the projected severity of the attack spatially under the *BM* scenario. This image shows the areas that the KLM projects will receive higher levels of mortality during the outbreak. Bonaparte Plateau and Louis Creek seem to be areas of highest concern. Since we do not model incoming beetles from outside the TSA, we may be underestimating attack in some areas, particularly along the western and northern boundaries. Nonetheless, these images highlight some areas that at least warrant monitoring.

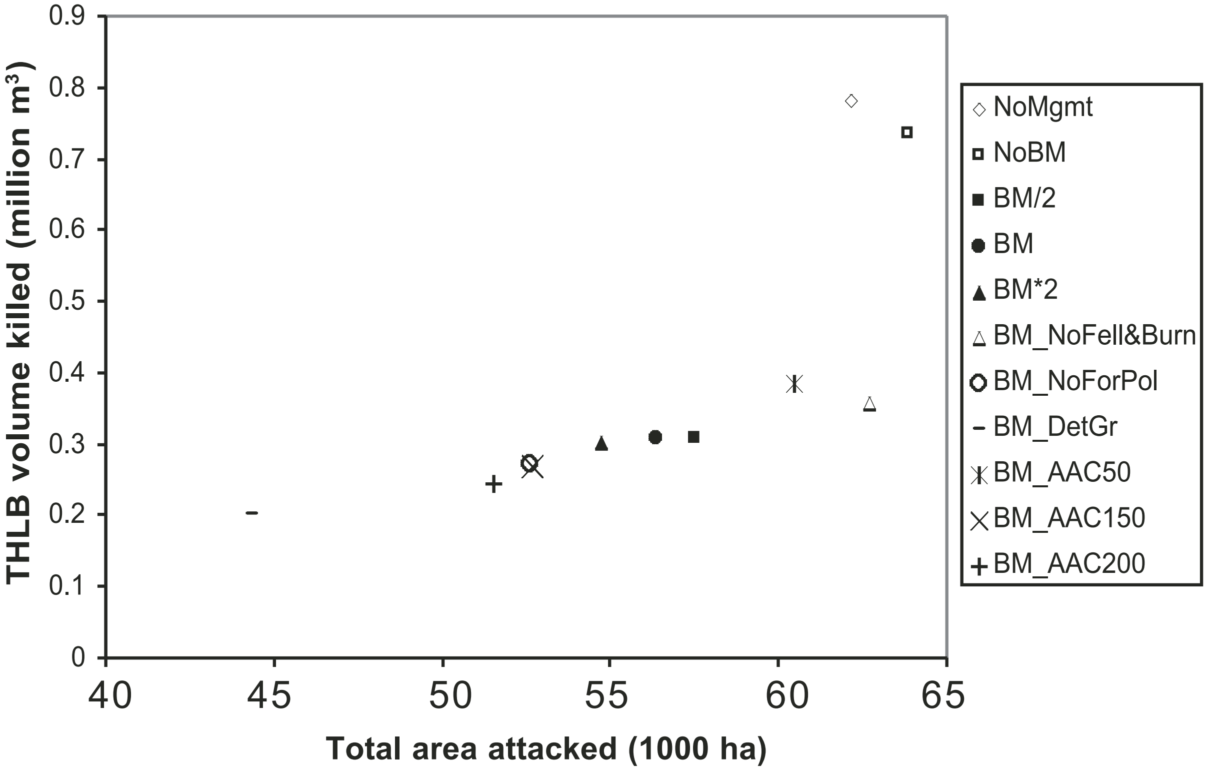

Figure 7. Projected volume losses in Kamloops study area plotted against the cumulative area attacked under various management scenarios (starting year: 1998).

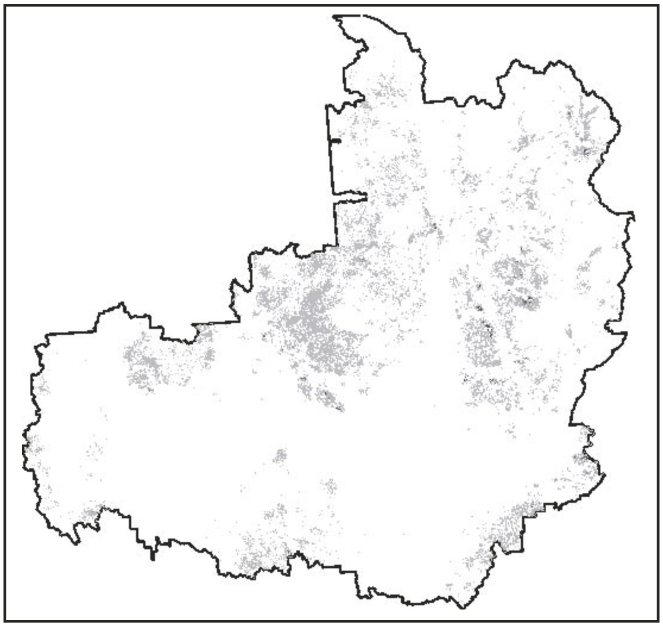

Figure 8. Estimated percent pine killed for the BM (current management) scenario in Kamloops study area. Darker areas indicate higher mortality, with black at or above 75% mortality (starting year: 1998).

Salvage and Non-Recovered Loss (Lakes)

The salvage scenarios resulted in slightly larger volume losses than the beetle management scenarios at current and double AAC levels (Fig. 9). This is not surprising given that beetle management scenarios primarily cut beetle blocks which are targeted at infested stands as soon as they can be detected, and salvage blocks target stands after they are attacked and a significant amount of salvageable volume is available for logging. Non-recoverable loss was reduced by both the beetle management and salvage scenarios compared with no management, with the salvage scenario slightly out-competing *BM* (Fig. 10). Hence, although the salvage scenarios tend to result in more volume impacts, they also recover more salvage volume than the beetle management scenarios at both AAC levels.

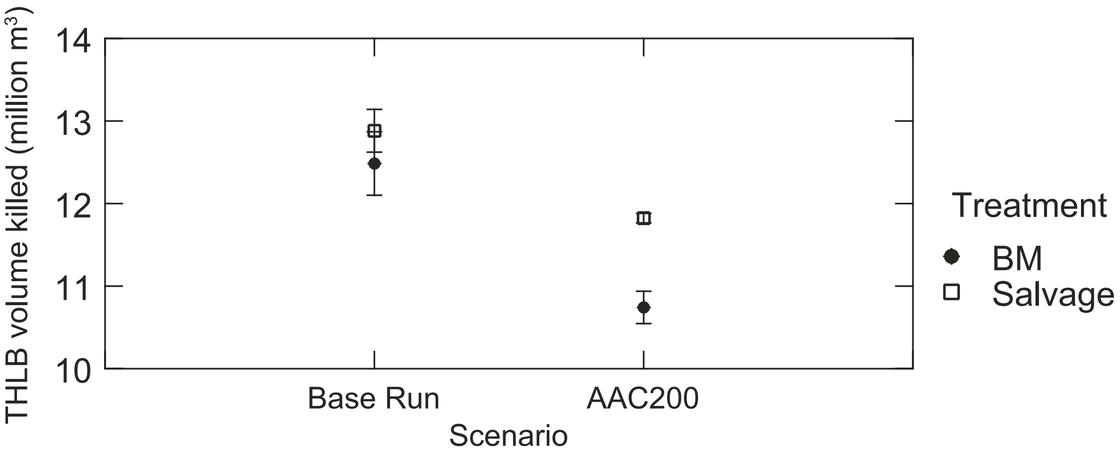

Figure 9. Comparison of predicted volume losses in the THLB using the standard beetle management scenario and a salvage only scenario at two levels of AAC in Lakes study area (starting year: 2001).

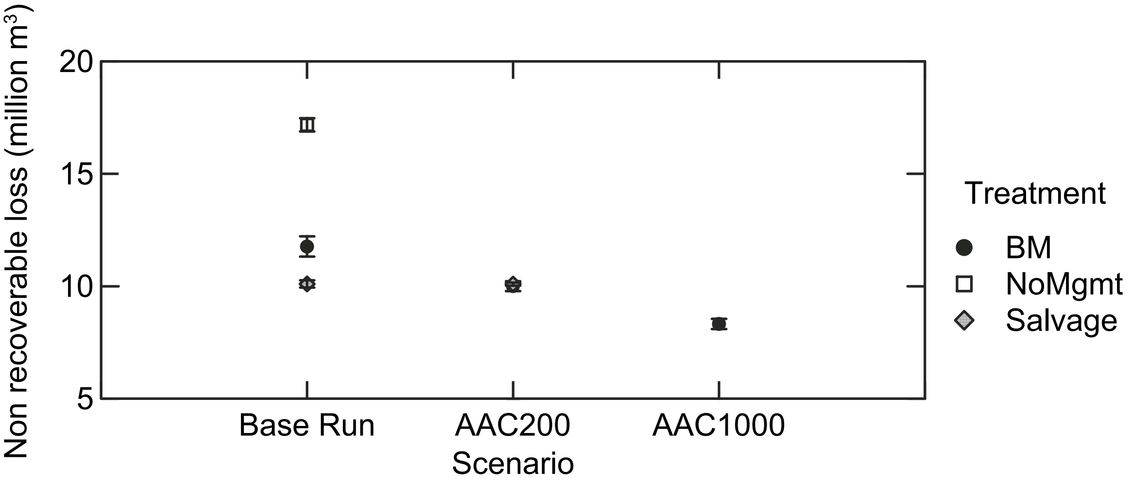

Figure 10. Cumulative predicted non-recoverable loss under no management, beetle management, and salvage preference scenarios at three levels of AAC in Lakes study area (starting year: 2001).

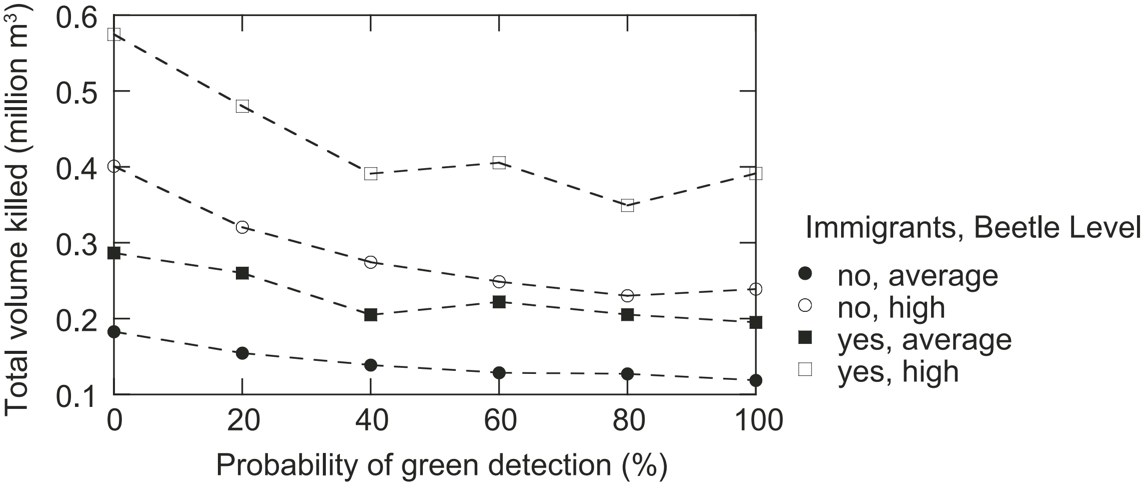

Figure 11. Effect of increasing probability of green attack detection on total volume killed under the BM scenario with and without immigrant beetles under average and above average beetle weather conditions in Morice study area (starting year: 2002).

Green Detection Sensitivity (Morice TSA)

Figure 11 shows that increasing green detection capacity in Morice TSA can improve management somewhat, in particular under increased beetle pressure, and for improved detection at the lower end of the scale. Above 40%, improved detection has less effect.

Tweedsmuir Immigration Sensitivity (Morice TSA)

Increasing the percentage of external long distance immigration pressure caused a slight increase in the volume killed due to a larger beetle population, although the increase was very small (Fig. 12). The *BM* runs used a value of 50%. Volume losses were far more sensitive to weather conditions and management (*BM* vs. *NoBM* and no harvesting; Fig. 3).

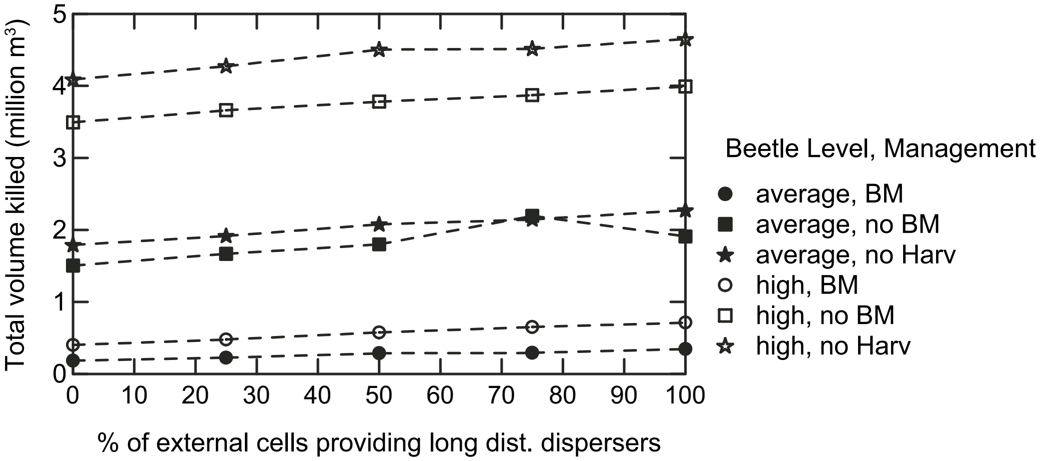

Figure 12. The relationship between volume losses and the percentage of external cells (in Tweedsmuir) that provide long distance dispersers in Morice study area (starting year: 2002).

Single-Tree Treatment Sensitivity (Morice TSA)

Reducing the number of hectares treated annually with single-tree treatments caused an increase in volume losses in above-average beetle weather conditions (Fig. 13). There was almost no effect under average beetle weather except when single-tree treatments were eliminated. Increasing single-tree efforts above current levels had no effect in this landscape under either weather condition. There were no scenarios run at single-tree levels between 0 and 50% of current levels; therefore, it is unknown whether the response between these points is linear. However, the experiment suggests that the modelled levels of treatment are having a significant impact on the outbreak.

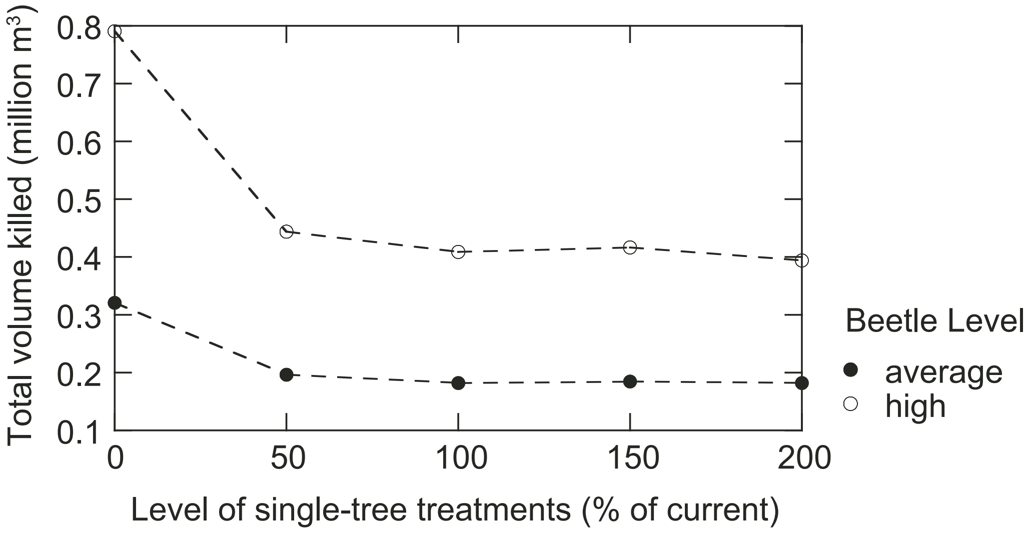

Figure 13. Effect of the level of single-tree treatments on volume killed at average and above-average beetle weather conditions in Morice study area (starting year: 2002).

Discussion

Our analysis of the current mountain pine beetle outbreak in the Morice and Kamloops TSAs, as well as another study in Williams Lake (Fall et al. 2003b), suggest that these outbreaks are of a moderate scale and management efforts can have a significant impact in reducing losses. That is, applying fine-scale beetle management, including small-scale blocks and single-tree treatments, and accurate treatment of spot loci are important in areas with small to medium scale outbreaks, but are less important in situations with many beetles.

Conversely, our analysis in Lakes TSA suggests that this outbreak is of such a large scale that management efforts can only expect to slow down, but not stop its progression. Nonetheless, by slowing its spread, management can buy some time to reduce the non-recovered losses caused by the outbreak until it terminates, either due to extreme weather or by population collapse after hosts are no longer available. Doubling the AAC had the effect of reducing volume killed by approximately 15% (2 million m^3). Although this is significant, it represents a saving of approximately 15% of the total increase in harvesting over the 10 years. However, increasing the AAC had a somewhat larger relative effect in reducing non-recovered losses (approx. 20%).

Uncertainty in model predictions arises from several sources. First, inventory and mountain pine beetle overview input data are not 100% accurate. Some layers such as the percentage of pine and total stand density per hectare were derived from the inventory data and regression (for unmapped areas). A second level of uncertainty involved the structure of the model itself. Like any model, the one we described is simply an approximation of reality and ongoing refinement and improvement will continue through sensitivity analysis and examination of the model projections. However, the results we presented are based on the best available current information and models. These results are best used to weigh the relative merits of management scenarios and are not intended as predictions of exact harvest results or beetle patterns.

Conclusions

These three study areas provided insight into the potential effects of various management strategies in a cross-section of outbreak conditions. The overall message is that there is a threshold of attack, below which fine scale treatments (intensive detection, fell and burn, small blocks, etc.) are warranted and above which overall focus on mitigating impacts may be better. That isn't to say that fine scale management should be completely abandoned, but rather that such management should be targeted at specific areas (e.g., woodlots). We can draw some general conclusions from the analyses we have performed:

- Beetle management can be effective to manage an outbreak provided the outbreak is below a critical threshold (e.g., Kamloops and Morice). Above this threshold (e.g., Lakes), the potential for the outbreak to expand exceeds resource capacity.
- Treatment efficacy is critical for single-tree treatments, but less so for mid-to-large clearcut blocks. Although we didn't assess partial harvesting, we expect that the underlying process is largely related to distance of residual beetles to potential hosts, and the dilution effect of increasing distance (i.e., area increases with the square of distance). Hence, the closer susceptible hosts are to a treatment, the more important it is to have a high degree of treatment efficacy.
- Increased detection capacity is only helpful in cases where detection is a limiting factor. For example, where the number of infested trees far exceeds the resources available, increased detection capacity is not helpful.
- External sources of immigration (e.g., immigration from Tweedsmuir to Lakes and Morice TSAs) are only a major factor in the early stages of an outbreak. Once established, weather factors and dynamics within management units dominate.
- Early attack (as is applied in fire suppression management) is a key approach in reducing the risk of an outbreak growing beyond containment resources.

- AAC uplift is not in itself effective at reducing mountain pine beetle populations, but can be effective at reducing non-recovered losses. That is, at relatively low outbreak levels, finer scale management (focused blocks, single-tree treatments, increased detection) is more effective. At relatively high outbreak levels, management has little potential to stop an outbreak regardless of AAC level.
- Salvage-focused management is a key tool to reduce non-recovered losses, especially in areas with relatively high outbreak levels. In such situations, management is unlikely to be able to stop an outbreak, but may have more opportunities to reduce losses.
- Forest policy (e.g., forest practices code policies) does not appear to hinder the overall efficacy of mountain pine beetle management activities.
- High quality overview mapping surveys are crucial to applying spatial modelling as a decision-support tool. The ability to project with any degree of certainty rests largely on inventory mapping and outbreak mapping.
- Weather and climate are key drivers in outbreak growth rates. In these analyses, we only assessed historic mean *vs.* above average (more current) weather conditions. Further work is ongoing to link mountain pine beetle outbreak assessments with climate change research as part of the CFS Mountain Pine Beetle Initiative.
- Applying and extending these results to other areas can be done in three ways. The simplest is to assess if an area is similar to one of the study areas presented and consider the general recommendations and trends. The most complex would be to adapt and refine this modelling methodology to a new study area. A third option is part of two other CFS Mountain Pine Beetle Initiative projects. At a finer landscape unit scale, we are developing methods to assess likely impacts and interactions of mountain pine beetle and management under a range of potential host and outbreak conditions. This will produce a key that can be accessed using a given landscape unit. At a broader scale, work is currently being done to make a projection of the current outbreak at the scale of the entire province.

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Andrew Fall is the Principal of Gowlland Technologies Ltd. and an adjunct professor at Simon Fraser University.

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Modelling of Mountain Pine Beetle Transport and Dispersion using Atmospheric Models

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Abstract

The mountain pine beetle population in the British Columbia central interior has reached epidemic proportions. Mountain pine beetles move actively through flight over a few kilometers within a stand, and passively through advection by the wind, within and above a forest canopy. Passive dispersal is likely responsible for between-stand and landscape-scale spread of the population. A strategy for the testing and use of atmospheric numerical models to predict the passive movement of mountain pine beetles is described. Preliminary synoptic climatology results indicate that typical weather patterns associated with weather conducive to mountain pine beetle flight are similar to average summertime conditions, except the surface high pressure ridge influencing the weather over BC is stronger than normal. An atmospheric simulation of a situation conducive to mountain pine beetle emergence and flight showed that the above canopy winds and temperatures had considerable spatial and temporal variability, indicating that treating the atmosphere simplistically as a "constant" in mountain pine beetle population models may not lead to satisfactory results.

Introduction

The mountain pine beetle, *Dendroctonus ponderosae*, Hopkins is the most important bark beetle in western North America. Currently, the mountain pine beetle has reached epidemic proportions in five Forest Districts in central British Columbia (BC) (Vanderhoof, Nadina, Quesnel, Central Cariboo, and Fort St. James), with approximately four million hectares and 108 million m^3 of timber affected. The mountain pine beetle issue will remain important given that large tracts of land in central and southern BC are occupied by its principal host, lodgepole pine, *Pinus contorta* var. *latifolia*. The mountain pine beetle's range has been limited climatically to minimum annual temperatures warmer than -40 ˚C; however, the range may be expanding due climate change which has occurred and will continue (Safranyik et al. 1975; Thomson and Shrimpton 1984; Carroll et al. 2004)

Newly hatched mountain pine beetles emerge from host trees in mid to late summer when air temperatures reach 18°C with a peak of flight activity at 25°C (Anhold and Jenkins 1987), and seek new hosts. The onset of emergence and flight is generally preceded by warm, dry weather with the emergence in a region normally occurring over a 7 to 10 day period (Safranyik et al. 1999). It has been suggested

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Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

(Furniss and Furniss 1972; Safranyik et al. 1989) that convection during fair weather conditions typical of emergence and flight may carry some beetles above the forest canopy to be carried over long distances. In an experiment using unbaited traps at various heights within the canopy, Safranyik et al. (1992) inferred that 2.4% of the beetles were above the canopy. Gray et al. (1972) suggest that a fraction of the population may either be incapable of responding to secondary attractants or require flight exercise before responding, so may act as pioneers by dispersing to more distant areas. Thus, mountain pine beetle spread to new hosts in two ways: actively by flight within a stand or between stands over distances less than 2 km; and passively by advection due to the mean wind field above the forest canopy and turbulent eddies, which may transport beetles over longer distances (perhaps up to 100 km assuming a 25 km/h wind and a four hour flight period). In both dispersal modes, for the mountain pine beetle to successfully attack a host tree and therefore spread the epidemic, they must attack at densities sufficient to overcome tree resistance, which is about 35 beetles per m^2 of bark surface (Raffa and Berryman 1983).

As an outbreak becomes an epidemic, the increase in mountain pine beetle population levels leads to more competition for suitable hosts within a stand; thus, a greater number of beetles dispersing passively above the canopy. This acts as a positive feedback mechanism, allowing rapid spread of mountain pine beetle over great distances from one year to the next. During passive transport, spatial and temporal variability in both the mean wind field and in turbulent eddies are critically important in determining both where the mountain pine beetle will move and how they are dispersed. Since mountain pine beetles typically fly during periods of high temperature that tend to occur under slack synoptic conditions, it is hypothesized that terrain-induced thermal circulations (i.e., mountain/valley circulations, anabatic and katabatic flows), as well as steering of the synoptic wind by terrain features, will be important. Terrain features and their interaction with atmospheric circulations and habitat should determine mountain pine beetle fallout zones. The successful establishment of beetles in a fallout zone would then depend on the presence of susceptible hosts, and whether or not there is sufficient density of the beetles to kill the new hosts.

This project focuses on modelling the passive transport of mountain pine beetles by wind at the landscape scale. In the past, several modelling or analysis approaches have been used to study mountain pine beetle spread based on stand susceptibility (e.g., Raffa and Berryman 1986; Mitchell and Priesler 1991; Logan and Bentz 1999; Safranyik et al. 1999; Byers 2000; Shore et al. 2000; Fall et al. 2004), none of which have incorporated a realistic representation of the atmosphere. The approach here uses well-tested atmospheric numerical models in an application that has been used for similar phenomena: for example, to study the spread of *Peronospora tabacina* spores (Yao et al. 1997), and to study movement and dispersion of air pollutants (numerous studies). This paper will provide an overview of the project and a summary of the early results from six months into the three-year research program.

Objectives

The overall research is organized around four sequential sub-projects, each with a defining objective:

1) Identify synoptic weather patterns (i.e., large-scale weather patterns) present during periods of mountain pine beetle dispersal;
2) Identify fundamental relationships between terrain features, atmospheric flows, host species and mountain pine beetle fallout zones;
3) Assess the value-added potential for physics-based meteorological and dispersion models to estimate mountain pine beetle dispersal between one year and the next; and
4) Assess the use of high-resolution real-time meteorological and particle dispersion models to provide improved estimates of current and future mountain pine beetle dispersal.

Methods

The synoptic weather pattern determines the atmospheric background conditions in which mountain pine beetles emerge and move. It is useful to define the weather patterns associated with typical mountain pine beetle episodes before modelling or further work is undertaken. In order to do this, the standard synoptic climatology technique of compositing is employed. This essentially involves finding average weather map patterns (and their standard deviations) associated with different periods in the mountain pine beetle outbreak based on historical information on when mountain pine beetles emerged and the period over which they are in flight. Since these data are not readily available, we have instead used a "Heating Cycle" as a surrogate. We define a "Heating Cycle" as at least four consecutive days in which the maximum temperature is over 20 °C but less than 30 °C, focussing on July and August, since these conditions represent environmental conditions conducive to emergence and flight. We used day three of the sequence for the synoptic climatology.

Weather data for this work comes from the NCAR/NCEP Reanalysis Project (Kalnay et al. 1996) that provides archived gridded meteorological fields every 6 hours on the standard pressure levels at 2.5-degree horizontal resolution from 1948 until the present time.

We hypothesize that fundamental relationships determining where mountain pine beetles move passively and fallout are governed by the interaction of the atmosphere with terrain features (in combination with forest conditions and mountain pine beetle behaviour). The atmosphere is known to exhibit complex interactions with terrain, especially in hot weather, e.g., mountain/valley circulations, anabatic/katabatic flows (up-slope/down-slope winds), lake/land breezes, all of which are flow circulations that reverse between day and night. In addition, during the summer, the planetary boundary layer above the forest canopy evolves considerably during a day – increasing turbulence and growing in depth from only tens of meters overnight up to 2 km or so in depth by late afternoon. Wind speeds increase and directions normally turn clockwise with increasing height above the surface, and this is affected dramatically by the diurnal evolution of the planetary boundary layer that also influences stability and turbulent eddies above the forest canopy. In order to explore these relationships, a mesoscale atmospheric modelling approach using the CSU RAMS (Pielke et al. 1992, http://www.atmet.com) model for meteorological prediction, and the HYPACT lagrangian particle dispersion model (Turner and Hurst 2001; http://www.atmet.com) that uses the RAMS mean wind fields to advect and disperse particles, will be used. RAMS is a mesoscale atmospheric numerical model that is very flexible and is able to use a variety of numerical, boundary condition and parameterization schemes. It can run with nested grids in order to achieve high spatial resolution (e.g., 25 m vertical, 500 m horizontal resolution in the atmosphere) for research applications. RAMS is a finite difference model that solves the partial differential equations governing fluid flow and thermodynamics on a 3-D grid. As such, it is a state-of-the-art, physics-based approach to modelling weather at high spatial resolution. In this first stage of the modelling work, the models will be used in an idealized mode, with simplified terrain of various types (i.e., a domain with a hill, a domain with a valley, combination of hill/valley, large lake, etc.) and idealized meteorological conditions (based on the results from the first study). Mountain pine beetles will be treated as passive tracers and advected/dispersed using RAMS/HYPACT to discover the pattern of their dispersion under different idealized landscapes. This will result in generalized conclusions concerning the nature of the interaction between the atmosphere during typical periods of mountain pine beetle dispersion, and terrain features, leading to different patterns of mountain pine beetle attack at the landscape scale.

In order to assess the value-added potential for physics-based meteorological and dispersion models to estimate mountain pine beetle dispersal between one year and the next, RAMS/HYPACT will be used in a realistic hindcast mode in several case-studies of past mountain pine beetle spread. The idea is to utilize the database of known mountain pine beetle infestations (e.g., http://www.pfc.forestry.ca/entomology/mpb/historical/index_e.html) and use RAMS/HYPACT to simulate a number of those years in order to see whether the approach can successfully simulate past dispersion. Meteorological information needed to initialize and nudge RAMS will be obtained from the NCEP Reanalysis Project for the time of mountain pine beetle emergence and flight. Validation data will come from the various reports documenting the current mountain pine beetle epidemic (e.g., web site above and Wood and Unger 1996; and the detailed maps produced by BC Ministry of Forests). Statistical and graphical comparisons will be made between the modelled and observed pattern of mountain pine beetle spread in order to assess the success of the method.

If it can be demonstrated that the approach can be used successfully to simulate past mountain pine beetle dispersal, then an assessment and recommendations will be made on the use of these models to provide improved estimates of current and future mountain pine beetle dispersal.

Early Results and Discussion

Synoptic Climatology

As a surrogate for mountain pine beetle emergence and flight dates, we have defined a "heating cycle" as at least four consecutive days with the daily maximum temperature between 20° and 30°C. We use day three of the sequence for the synoptic climatology. The annual distribution of heating cycles by month, is given in Figure 1, while Figure 2 shows the distribution of heating cycle lengths for Prince George, BC.

It can be seen that most heating cycles occur in July and August, but can occur as early as April and as late as October (Fig. 1). Most are less than 6 days in length, but can last as long as 24 days (Fig. 2). Since mountain pine beetle are not biologically capable of emergence and flight (depending on the year) until the end of June (Thomson and Shrimpton 1984), and most flight activity typically occurs during July and August (Thomson and Shrimpton 1984), we focus on these two months.

The normal climatology of mean sea level pressure (MSLP) for all days in July and August from 1968-1996 is shown in Figure 3.

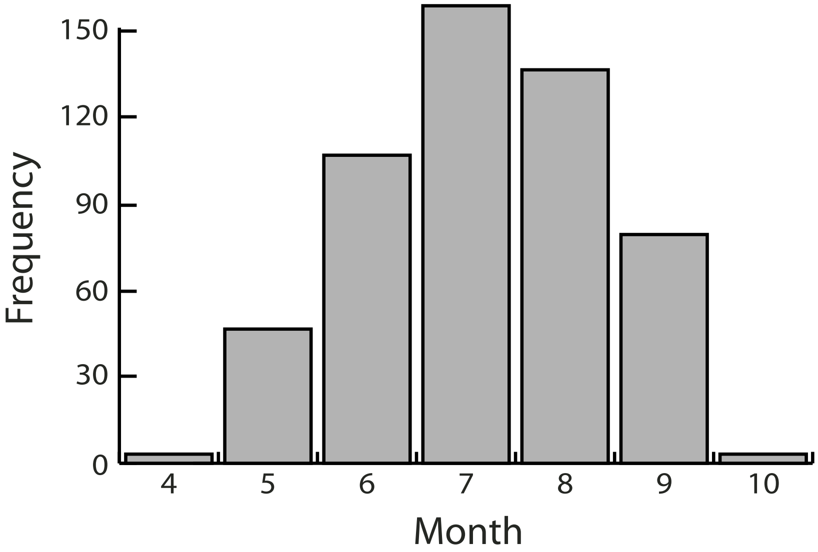

Figure 1. Distribution of heating cycles by month for Prince George between 1943 and 2002. There are an average of 8.9 cycles per year.

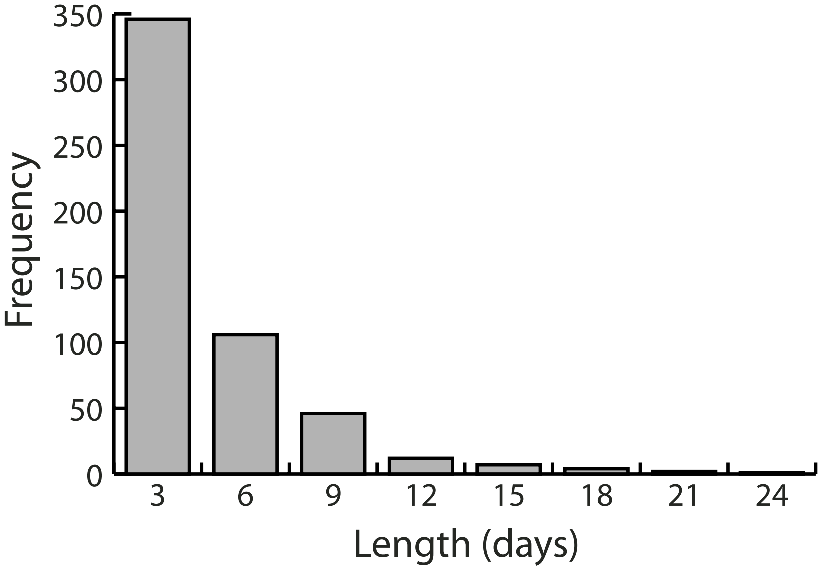

Figure 2. Distribution of heating cycle length for Prince George between 1943 and 2002. The average length is 5.6 days.

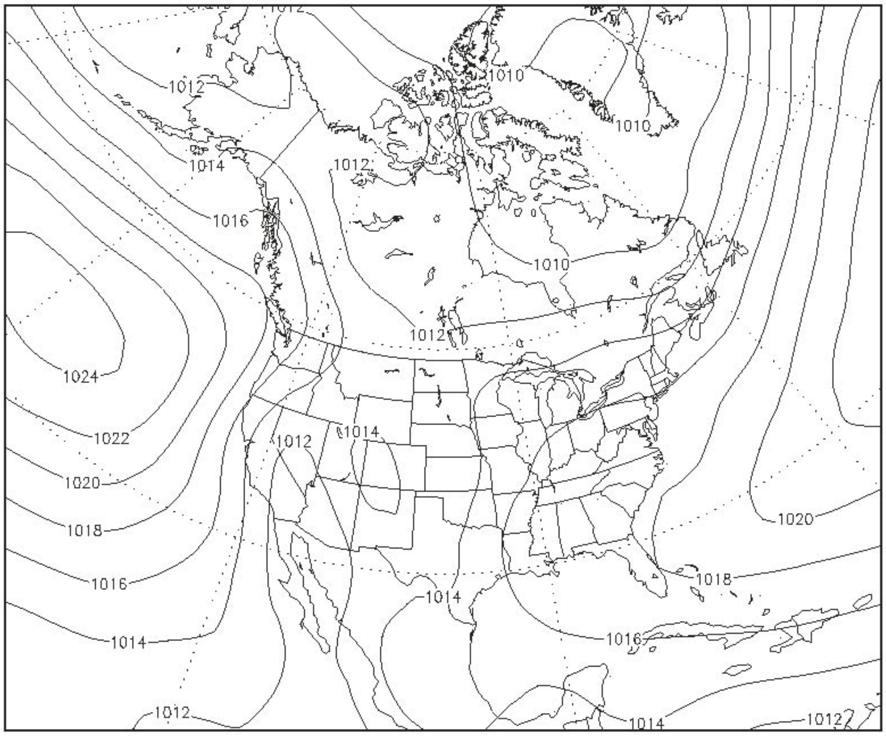

Figure 3. July-August Mean Sea Level Pressure Climatology (1968-1996) based on 1978 days of data. Contours are in hPa.

The weather pattern is characterized by a "Pacific High" pressure center dominating the northeast Pacific, with a ridge of high pressure extending eastward from the High across southern BC. The orientation of the isobars implies a westerly regional wind at the surface over much of central BC. The windrose diagram for all days in July shown in Figure 4, which depicts the wind frequency by speed class and direction, shows that winds frequently come from the west, but southerlies are most common due to steering of the flow by the mountains that flank the central interior plateau.

The average MSLP pattern during day 3 of the 105 heating cycles that occured between 1968 and 1996 (Fig. 5) shows a somewhat similar pattern as the average over all days, with the difference between the two patterns shown in Figure 6.

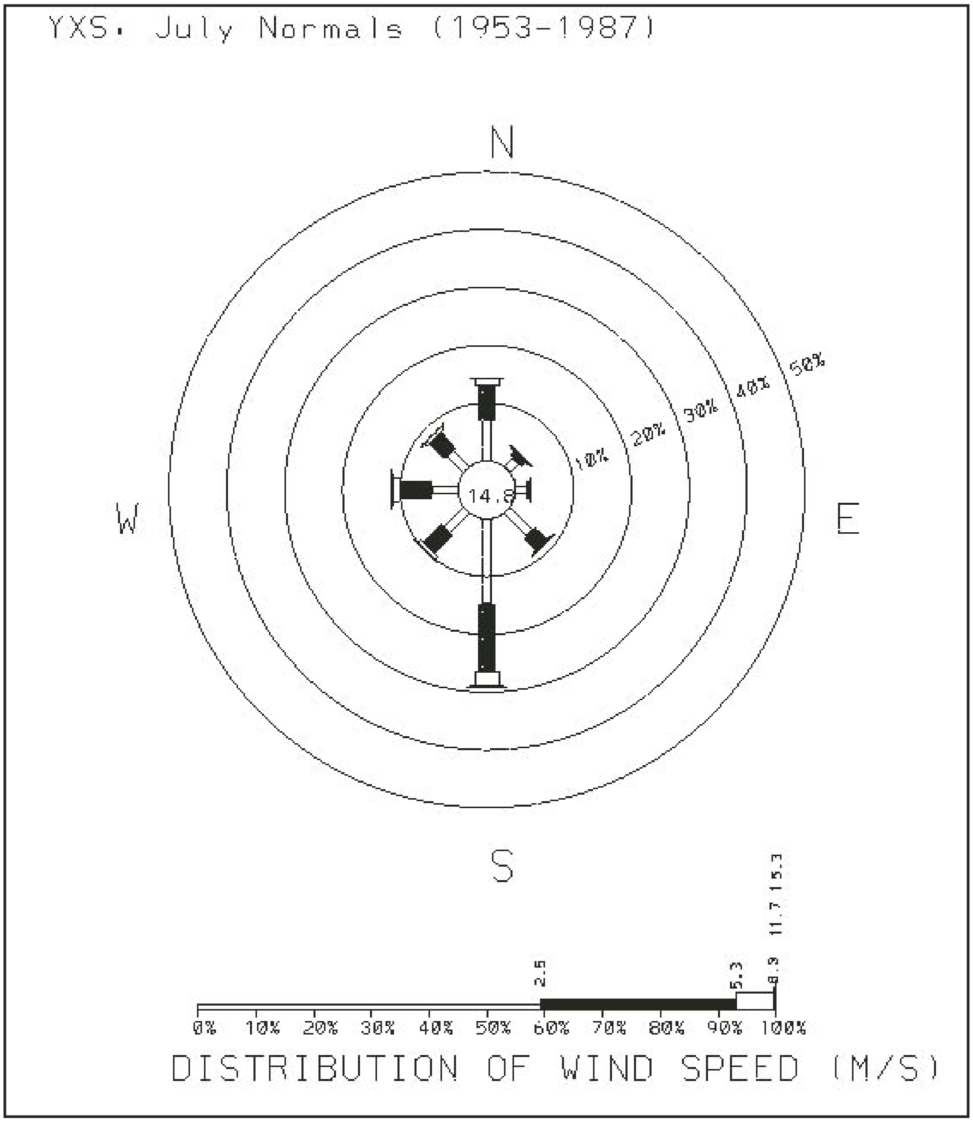

Figure 4. Windrose diagram for Prince George in July, based on data from 1953 - 1987. The direction is that from which the wind is blowing, the radial distance represents the frequency, and the variable width rose arms represent different speed classes (from .3 to 2.5 m/s, from 2.6 to 5.3 m/s, etc.).

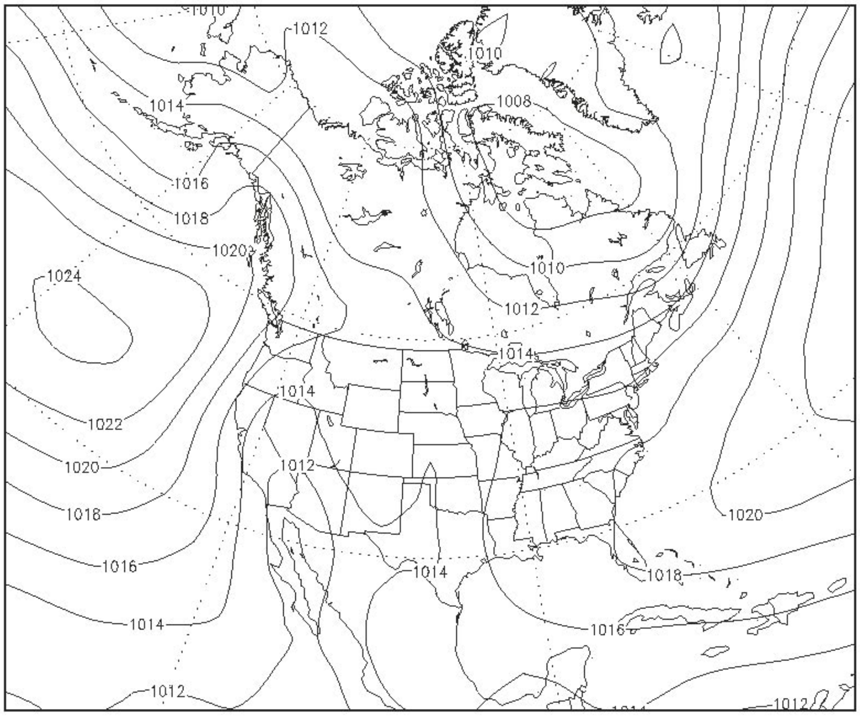

Figure 5. July-August heating cycle Mean Sea Level Pressure Climatology (1968-1996) based on 105 days. Contours are in hPa.

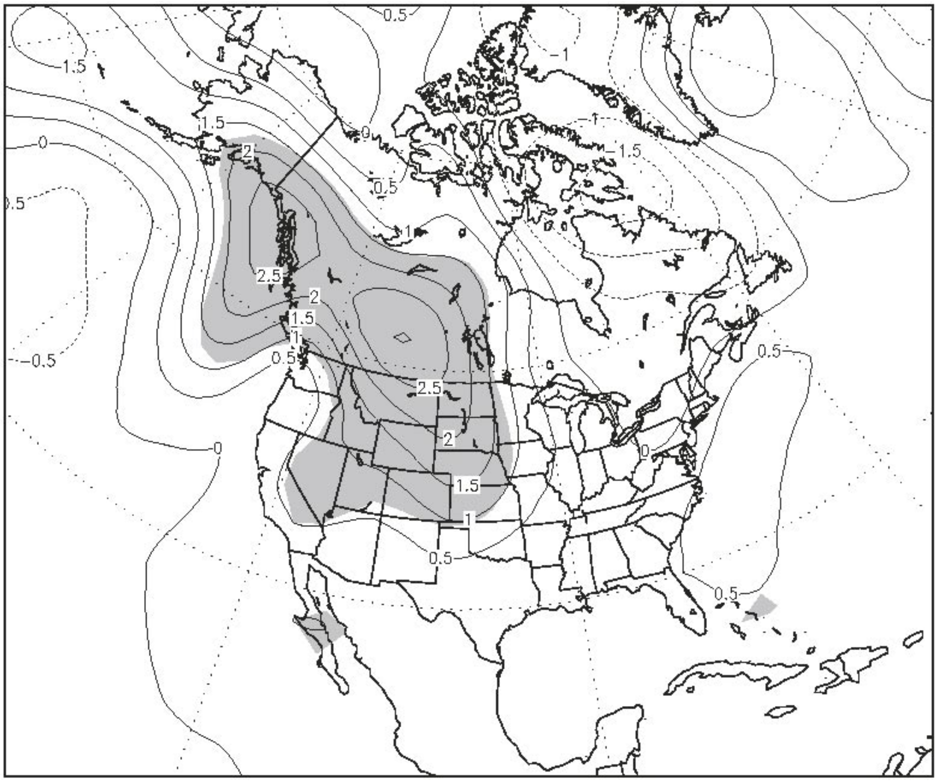

Figure 6. July-August heating cycle Mean Sea Level Pressure anomaly (i.e., Figure 4 minus Figure 5). Areas of statistically significant differences at the 99% level are shaded. Contours are in hPa.

While the pattern and orientation of the isobars over BC on heating cycle days is quite similar to the mean pattern during those months, the MSLP is on average in excess of 2 hPa higher on heating cycle days than it is on all days combined. This indicates stronger surface ridging during the heating cycle days that would contribute to the higher temperatures.

A diurnal variation in windspeed during the above heating cycle days is evident in Figure 7.

As solar radiation heats the surface, this destabilizes the lower atmosphere by warming the air near the ground (Fig. 8). This creates rising plumes of warm air that mix the stronger winds aloft down to near the surface. Since the maximum air temperatures are reached in the late afternoon (Fig. 8) this accounts for the increase in wind speeds at this time.

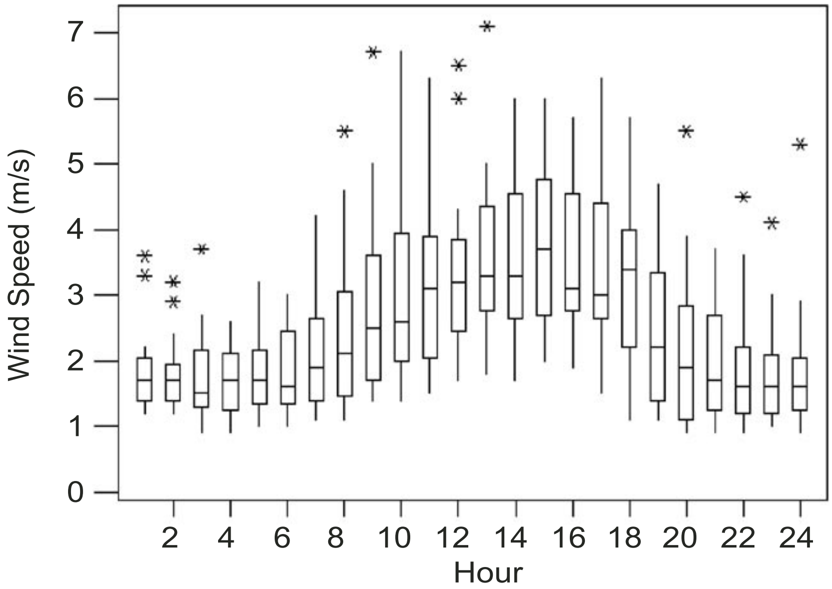

Figure 7. Box and whisker plot showing the distribution of wind speed by hour at Prince George during day 3 of 105 heating cycles. The box indicates the interquartile range, the line in the center of the box is the median, the "whisker" extends from the upper and lower quartile to the highest and lowest value, unless there are outliers that are indicated by asterisks.

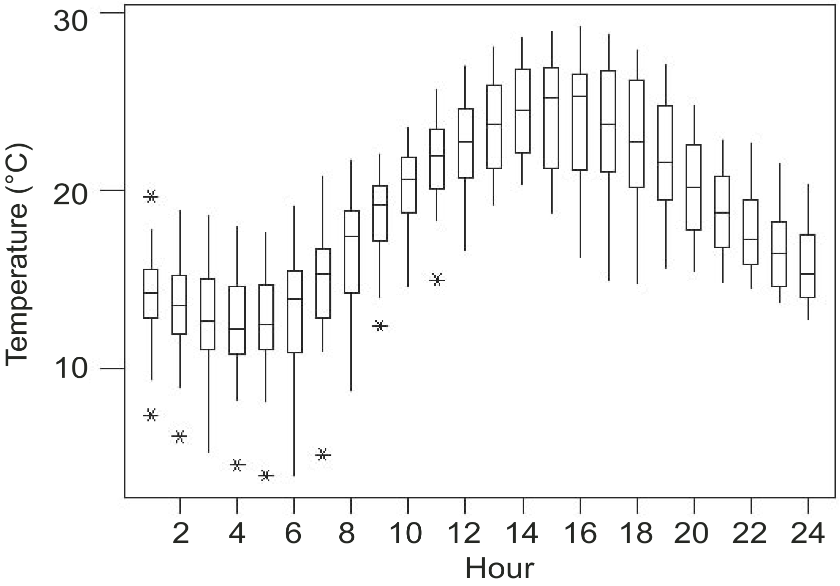

Figure 8. Box and whisker plot showing the distribution of temperature by hour at Prince George during day 3 of 105 heating cycles.

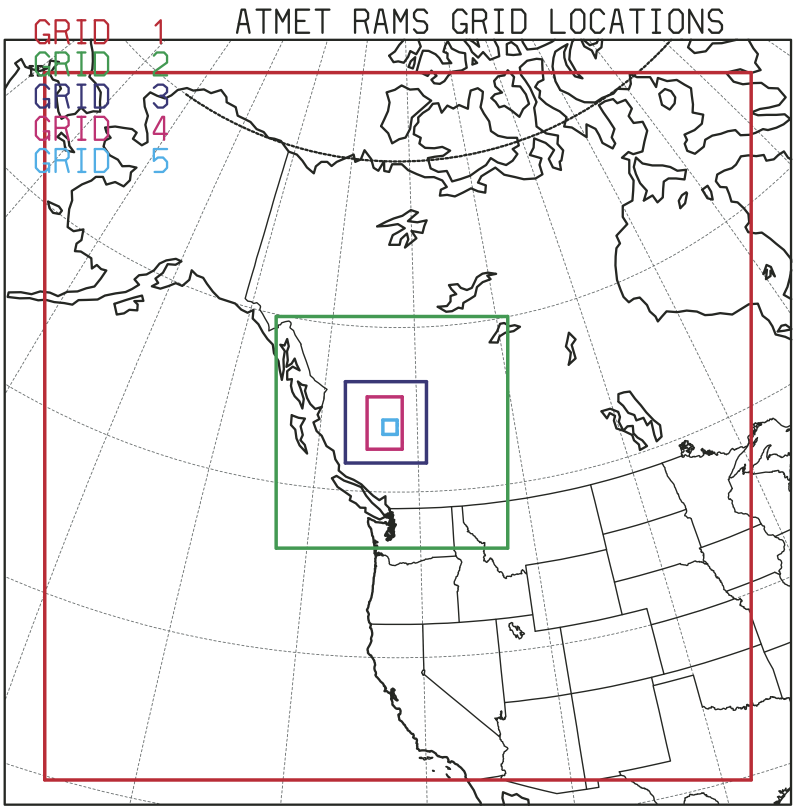

Figure 9. RAMS nested grid locations. Grid 1 (largest) has horizontal grid points 81 km apart. Grids 2, 3, 4 and 5 have horizontal grid points 27, 9, 3 and 1 km apart respectively. All grids have 30 levels in the vertical with 25 m resolution near the surface, stretching to 1000 m resolution in the upper atmosphere.

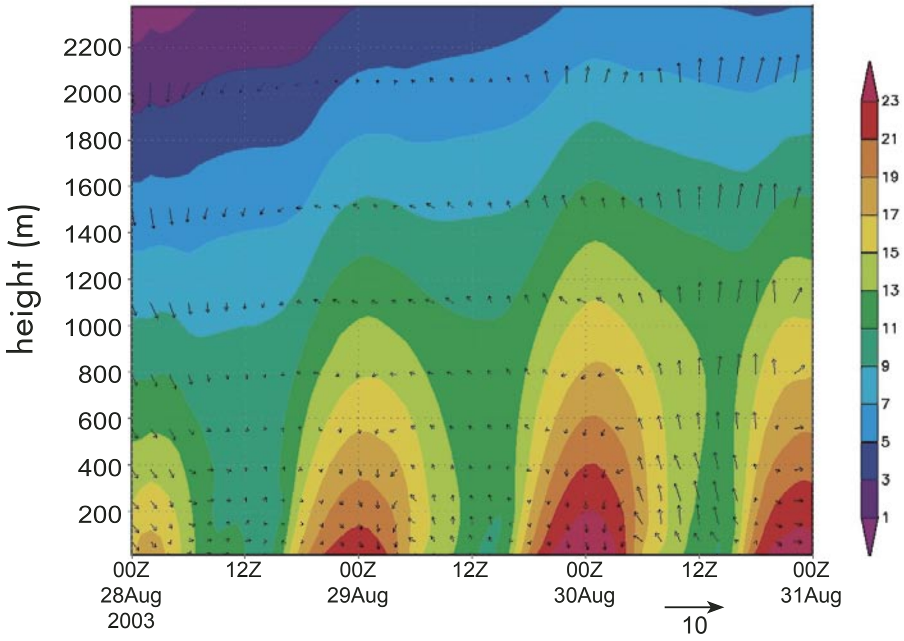

Figure 10. RAMS simulated height - time cross section from 17:00 PDT August 27 to 17:00 PDT August 30, 2003. Temperature (C) is displayed in colour fill, and horizontal wind is shown as vectors. Time on the x-axis is in UTC (UTC is 7 hours ahead of PDT).

Modelling Example

As a first step in modelling mountain pine beetle dispersion, we have conducted an atmospheric simulation, using RAMS of a heating cycle that occured between 17:00 PDT August 27, 2003 and 17:00 PDT August 30, 2003. In configuring the model, we have used five nested horizontal grids (at 81, 27, 9, 3, and 1 km horizontal spacing) as shown in Figure 9. All horizontal grids used the same 30 vertical levels that were spaced 25 m apart near the ground, gradually stretching to 1000 m in the upper atmosphere. The model was initialized and nudged using model output from the NCAR/NCEP Reanalysis 2.5 degree gridded model output to represent the weather processes occuring at scales larger than the domain of grid 1 (Fig. 9).

The results showed great spatial and temporal variability in the wind and temperature fields, especially within the lowest 2 km of the atmosphere over the time of the simulation. Figure 10, showing a height-time cross-section of simulated winds and temperatures for this time period over Prince George, indicates the range of temperature and wind conditions which mountain pine beetles are exposed to during a typical flight period. The 19°C isotherm may delineate the time during the day and maximum altitude of potential mountain pine beetle flight during this time period.

Figure 11 shows a comparison of observed and simulated temperatures at Prince George for this time period. The model generally over-predicts the temperature by a few degrees, although the timing of the maximum and minimum is quite good.

Figure 12 shows the observed and simulated wind speeds at Prince George for the three days. While RAMS increases the wind speed in the late afternoon, it under-predicts the increase compared with the observations. As we make further simulations, we will be refining our modelling strategy to better represent the low-level wind fields.

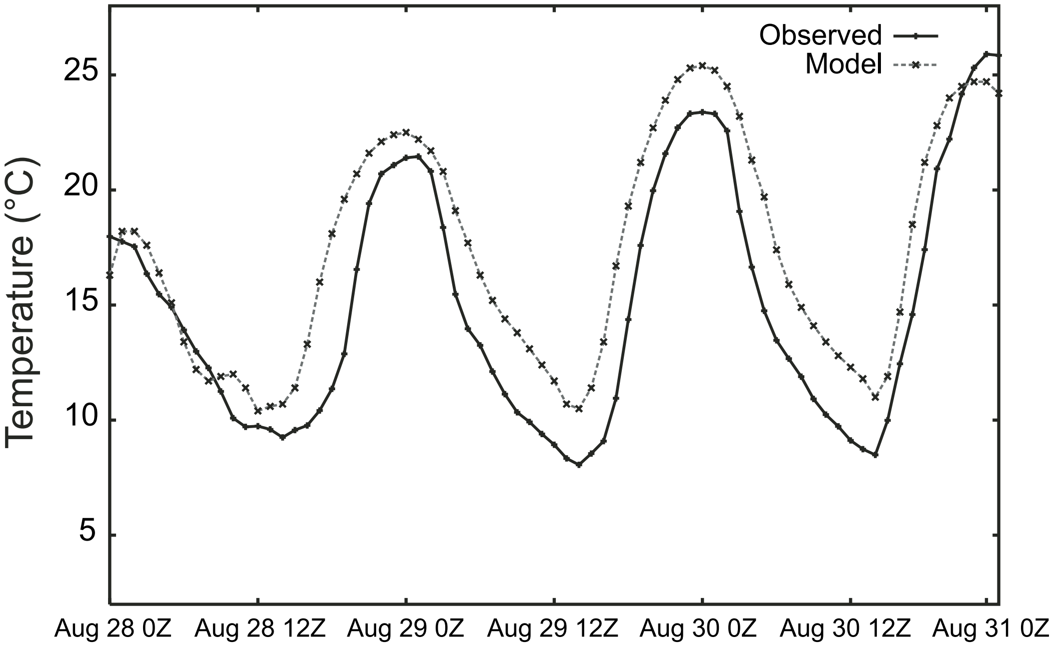

Figure 11. RAMS simulated and observed temperatures at Prince George from 17:00 PDT August 27 to 17:00 PDT August 30, 2003.

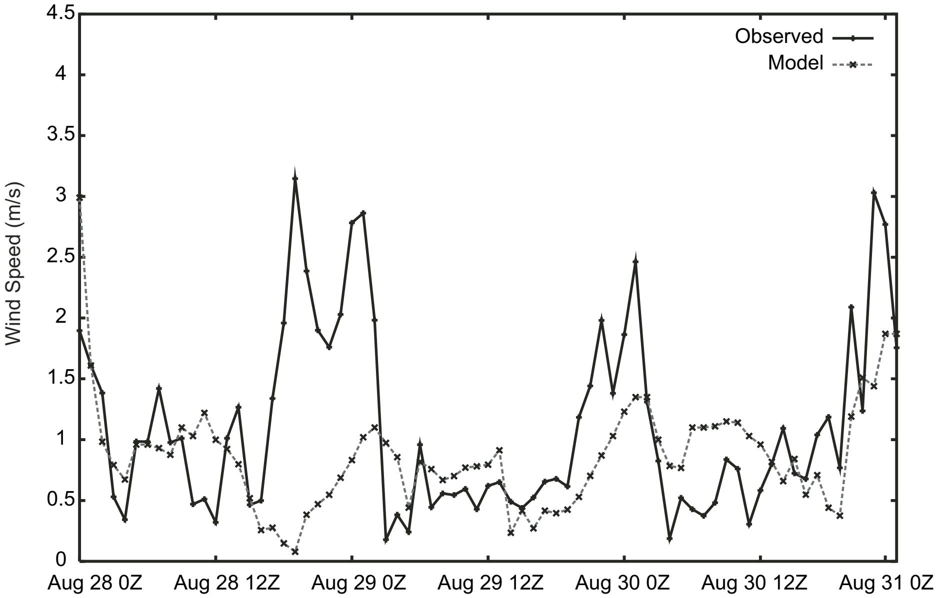

Figure 12. RAMS simulated and observed wind speed at Prince George from 17:00 PDT August 27 to 17:00 PDT August 30, 2003.

Summary and Conclusions

A strategy to model the passive transport of mountain pine beetles by the atmosphere at the landscape scale is described. The strategy involves four steps:

- i) identifying typical weather patterns associated with mountain pine beetle flight and dispersal;
- ii) finding fundamental relationships between terrain features, atmospheric flows, host species and mountain pine beetle fallout zones;
- iii) evaluating the potential and efficacy of atmospheric models to estimate mountain pine beetle dispersal between one year and the next; and
- iv) assessing whether use of these techniques in real-time is useful and practical. Early results from step i) (typical weather patterns) and step iii) (atmospheric modelling of a mountain pine beetle dispersal scenario) are presented.

We define a heating cycle as representing temperature conditions in which mountain pine beetles have been observed to emerge and fly. Using this definition we develop a synoptic climatology, based on day 3 of the heating cycle that shows the typical weather pattern associated with atmospheric conditions conducive to mountain pine beetle flight are quite similar to average summertime conditions, except the surface ridge of high pressure is significantly stronger than normal on the heating cycle days. An atmospheric simulation nested to 1 km horizontal resolution over a three day heating cycle in August 2003 showed considerable spatial and temporal variability in the above canopy windfield. A preliminary comparison with observed temperature and wind speeds at Prince George indicates that the model can simulate the temperature reasonably well, although the wind speed taken directly from the model is not as close to observed and will need to be improved in subsequent simulations. A more detailed and comprehensive verification of the wind and temperature fields, as well as atmospheric transport will be conducted in future work. Nevertheless, the considerable spatial and temporal variability in the above canopy wind and temperature fields shown in the RAMS simulation indicates that passive atmospheric transport of mountain pine beetle is complex and probably cannot be well treated simplistically. One implication of this is that treating the atmosphere as a "constant" in mountain pine beetle population models may not lead to the best results.

Acknowledgements

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Peter L. Jackson is an Associate Professor at the University of Northern British Columbia.

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Remote Sensing Technologies For Mountain Pine Beetle Surveys

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Abstract

Surveys for mountain pine beetle are undertaken across a range of scales to provide forest managers with up-to-date information regarding the location, extent, and numbers of infested trees. Remote sensing provides new opportunities to detect and map mountain pine beetle damage to inform management and mitigation decisions. The key to using remotely sensed data is to identify how this new information can be integrated with traditional datasets. In this communication, we present the survey information needs for mountain pine beetle management, then match those needs with the potential and limits of remote sensing. Some examples of how remotely sensed data have been used for mapping mountain pine beetle impact are then presented.

Introduction

Management information needs associated with a mountain pine beetle infestation, and the potential of remote sensing to address these information needs were summarized during a stakeholder workshop in June, 2003 (Wiart 2003).

The goals of the workshop, supported by the Mountain Pine Beetle Initiative, were stated as:

- To provide a forum for discussion on the detection and mapping of mountain pine beetle;
- To aid in the reviewing of mountain pine beetle survey and mapping with remotely sensed data;
- To assist in providing direction to Canadian Forest Service (CFS) and British Columbia (BC) Ministry of Forests research managers regarding mountain pine beetle survey and mapping with remotely sensed data.

To meet these goals, there were talks presented by federal and provincial program managers, scientists (federal, provincial, and academic), and industry. The industrial participants represented both the forest management and consulting sectors. The workshop presentations enabled a clear description of the magnitude of the mountain pine beetle outbreak in BC and current management and mitigation activities. The information needs of the provincial and industrial management agencies were discussed and refined into clear business drivers. The key business drivers for mountain pine beetle detection and mapping were identified as:

Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

- Detection and mapping of provincial level red attack;
- Operational mapping of red attack for layout and sanitation;
- Green attack detection for sanitation; and
- Technology transfer.

The scientists and consultants presented research and operational survey activities. Potential gaps between user needs and research activities were then identified.

Each business driver was evaluated against current remote sensing technologies and relevancy for funding from the CFS Mountain Pine Beetle Initiative. Detection and mapping of provincial level red attack was generally considered to be an issue of provincial concern. Additionally, since there exists no identifiable remote sensing approach that is capable of replicating the cost and utility of the existing provincial aerial overview survey information, this business driver was given a low priority. Operational mapping of red attack for layout and sanitation was identified as a research area that has potential for short- and long-term research, with focus on operational techniques. Operational applications include strategic planning for one party (i.e., province) and tactical planning for others (i.e., timber manager). The priority for research and development for red attack mapping was high, with a recommended focus on incipient level of mountain pine beetles. Green attack detection for sanitation at incipient levels was important, but considered a low priority for federal research funding. Green attack detection at endemic or epidemic attack levels was also considered low priority for remote sensing research. A range of issues regarding timing of beetle impacts, data collection, processing, image extent, costs, and required turn-around time were issues identified that limited potential application of green-attack detection. Technology transfer, while not an information need per se, was identified as a desired outcome of research programs, to ensure that agencies involved with mountain pine beetle management have the required information to make informed decisions on detection and mapping activities. Both written documentation and workshops were seen as important forums for communicating methods and results.

Based upon the results of this workshop and the identified operational information needs, our research has focused upon red attack mapping:

- Testing existing red attack mapping techniques at the incipient and endemic level of mountain pine beetle;
- Developing new methods for red attack detection at the stand and landscape scales;
- Improving estimates of the magnitude of forest damage at the landscape scale; and
- Technology transfer.

With remotely sensed data, red attack mapping has been demonstrated with a range of techniques, including with single date imagery (Franklin et al. 2003), multi date imagery (Skakun et al. 2003), and through data integration (Wulder et al. *in press*). Further investigation of models, data integration procedures, high spatial resolution, and high spectral resolution imagery show potential. Long term goals of a remote sensing program in support of red attack mapping would be to develop low-cost techniques for integrating stand and landscape scale information. The transfer of technology from research to operational management communities is also an important objective of current and future research activities.

Background

Mountain Pine Beetle

In BC, an outbreak of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) has reached epidemic proportions. The primary host, lodgepole pine (*Pinus contorta*), experiences extensive mortality when susceptibility to attack is high, particularly during sustained periods of warm, dry weather over several years, and when abundant reserves of host trees are accessible (Carroll and Safranyik 2004; Safranyik 2004). Symptoms of mountain pine beetle attack are evident by the colouration of crown foliage. The first change in foliage colour occurs during the fall or early winter of the year following an attack when foliage of infested trees gradually changes from bright to dull green, referred to as green attack. By the spring, damage is visually apparent, as foliage becomes yellow (i.e., chlorotic), then bright red. Trees that have been dead for more than a year and have lost most or all of their foliage are referred to as grey-attack (Unger 1993).

The impacts of a severe infestation include economic, environmental and social losses. Economic losses occur primarily through the direct loss of timber volume and through indirect means, including the disruption of forest management plans and tourism. Environmental losses include wildlife habitat and increased fire hazard. Furthermore, social disruption occurs as a consequence of job losses.

Remote Detection and Mapping

Changes in foliage characteristics are detectable with remote sensing instruments. Pigments, the structure of leaf tissues, and leaf moisture content have characteristic patterns of absorption or reflectance of electromagnetic energy (Wiegand et al. 1972). Knowledge of these patterns allows for the development of algorithms to detect changes in foliage characteristics using remotely sensed data. Additional opportunities conferred by remote sensing of forest insect disturbances include efficiency over ground surveys, repeatability, and wide-area coverage.

Users of remotely sensed data must find a match between image information content and the resolution characteristics of available imagery (Lefsky and Cohen 2003). The spatial resolution of the imagery will dictate the information content of a given pixel (e.g., tree or stand level characteristics). The spectral resolution will define the types of characteristics that may be discerned. For instance, changes in leaf vigour are evident earlier in infrared wavelengths than in the visible wavelengths. The discernable forest characteristics may be limited by field conditions including: atmospheric conditions, influence of surrounding objects, angle between the light source and the surface, angle between the surface and the point of observation (Wiegand et al. 1972). Temporal resolution considerations include what time (day, year, etc.) an image is collected. The revisit cycle of a particular sensor also influences the types of analysis options available. Radiometric resolution of a given sensor will influence the precision with which attributes may be defined.

As noted in Lefsky and Cohen (2003) image resolution characteristics combine to result in unique information content (Table 1). For instance, a Landsat pixel will relate a range of characteristics. In a mountain pine beetle context, the digital number of a given Landsat pixel will be based upon factors such as the number of trees, the stand structure (age, stratum, crown closure), species mixture, attack state and understory composition. As a result, the range of spectral characteristics that define a disturbed pixel may overlap with those of a healthy stand. Figure 1 illustrates the relationship between image spatial and spectral resolution and resultant information content.

Table 1. Image data requirements for red attack detection at three levels of mountain pine beetle populations.

Mountain pine beetle population	Forest damage characteristics	Spatial resolution requirements	Spectral resolution requirements
Endemic Level	Single or small groups of trees	High	High
Incipient Level	Small groups of trees	High or medium	High or moderate
Epidemic Level	Large groups of trees over large areas	Medium	Moderate

Figure 1. Illustration of information content of three common image spatial resolutions of 30 x 30 m, 4 x 4 m, and 1 x 1 m. Larger pixels tend to amalgamate a greater variety of stand elements.

The three frames in figure 1 simulate three different pixel sizes, placed upon the digital photo of an area undergoing mountain pine beetle attack. The larger frame represents a 30 x 30 m pixel (e.g., Landsat multispectral), the mid-size frame represents a 4 x 4 m pixel (e.g., IKONOS multispectral) and the smallest frame represents a 1 x 1 m pixel (e.g., IKONOS panchromatic). Within the large frame, red attack trees, faders and green trees can be visually interpreted. Also present are shadows, understory, and other elements of a typical pine stand. The spectral response for that particular pixel is an amalgam of all the elements present. This amalgamation would not result in a effective signal for the mapping of red attack in this particular pixel. Higher spatial resolution multispectral data, in this example illustrated by the mid-sized frame, contains fewer elements, therefore, would be capable of higher accuracy in red attack mapping. The trade-off for the higher resolution is smaller image extent. For example, a Landsat TM image covers 185 x 185 km whereas a IKONOS image has a minimum order size of 10 x 10 km. The high spatial resolution panchromatic example, represented by the smallest frame, begins to capture stand conditions that are not entirely based upon mixtures. The small pixel may capture a single stand element, such as a portion of a sunlit tree crown. For algorithm development it is preferable that groups of pixels capture the distinct signal rather than single pixels. The compromise with the panchromatic data is that the broad spectral range is inferior to detection capabilities of narrower spectral bands captured with multispectral sensors. Research has demonstrated that across this range of spatial resolutions, not withstanding the above limitations, red attack has been successfully mapped using satellite and airborne systems (Franklin et al. 2003; Skakun et al. 2003; Bentz and Endreson, In Press; White et al. In Press). While the pixels are mixtures of various stand elements and characteristics, image-processing techniques can be applied to capitalize upon the image information present.

Research Summary

In this following section, the results of completed research projects will be summarized, and indications of future research directions will be presented. The research and related discussion is focused on the red attack stage of mountain pine beetle attack from satellite imagery. There are a range of spatial data sources available to aid satellite based red attack mapping, including sketch maps, GPS survey data, forest inventory, and ancillary data sources such as digital elevation data.

Single satellite image mapping

The identification and classification of mountain pine beetle red attack damage patterns was accomplished using 1999 Landsat TM satellite imagery, a 1999 mountain pine beetle field and aerial point dataset, and GIS forest inventory data (Franklin et al. 2003). This study took place in a mature lodgepole pine forest located in the Fort St. James Forest District, BC. Variance in the satellite imagery that was unrelated to mountain pine beetle damage was reduced – primarily by stratifying the image using forest inventory data and removal of other factors uncharacteristic of red attack damage. Locations of known mountain pine beetle infestation were used to train a maximum likelihood algorithm. Overall classification accuracy was 73%, based on an assessment of 360 independent validation points. The classification accuracy achieved in this project was higher than that obtained in earlier research with Landsat data and forest damage classes because spectral differences between non-attacked and red attack areas were enhanced through stratification. The final classification map showed small pockets of infestation – individual pixels within forest stands – which were likely the locations of mountain pine beetle red attack damage.

Multiple satellite image mapping

Forest disturbances, by definition, have a temporal aspect. This characteristic can be capitalized on to detect change. Disturbances can be difficult to find with single date imagery, where analysis is based upon contrast and variation of spectral signal from expected values. The use of multitemporal Landsat-7 Enhanced Thematic Mapper Plus imagery was examined to determine the potential for red attack mapping. The image data were acquired in 1999, 2000, and 2001, and were geometrically and atmospherically corrected and processed using the Tasseled Cap Transformation to obtain wetness indices. These steps were followed by a new enhancement called the enhanced wetness difference index (EWDI). The final processing steps of the EWDI include pixel subtraction, enhancement, and thresholding of the wetness index differences. The EWDI was designed to improve visual identification of canopy changes over time, and was used in this study to help isolate small clusters or pixels that represent groups of red attack tree crowns that were otherwise difficult to discern. A helicopter-based red attack survey dataset was used to identify stands with red attack in 2001. A forest inventory dataset was also used to stratify the image data; visual interpretation and classification results indicated that classes with red attack trees were different from non-attacked forest stands. The resulting EWDI discriminated classes of 10-29 red attack trees, 30-50 red attack trees, and healthy forest. Classification accuracy of red attack damage based on the EWDI ranged from 67% to 78% correct (Skakun et al. 2003).

Polygon Decomposition

Polygon decomposition was developed as a tool to integrate different data layers, such as satellite image classifications, with existing GIS data to provide timely and accurate estimates of forest change (Wulder and Franklin 2001). A forest inventory database requires maintenance over time or the data can become quickly outdated. Polygon decomposition, following an insect infestation, can document the changes which have occurred to polygon attributes which otherwise may not be represented until a complete update procedure has been conducted. Timely observation and mapping of mountain pine beetle red attack stands are important information requirements if infestations are to be understood and managed.

Polygon decomposition may be applied to improve the understanding of the extent and characteristics of mountain pine beetle attack as depicted in maps from a variety of sources. Differing map products, such as sketch maps, attack locations recorded using a Global Positioning System, and EWDI results, may be compared. These differing data sources may be "decomposed" using the existing forest inventory, into estimates of the proportion (in percent) and area (in hectares) of mountain pine beetle red attack damage (Figure 2).

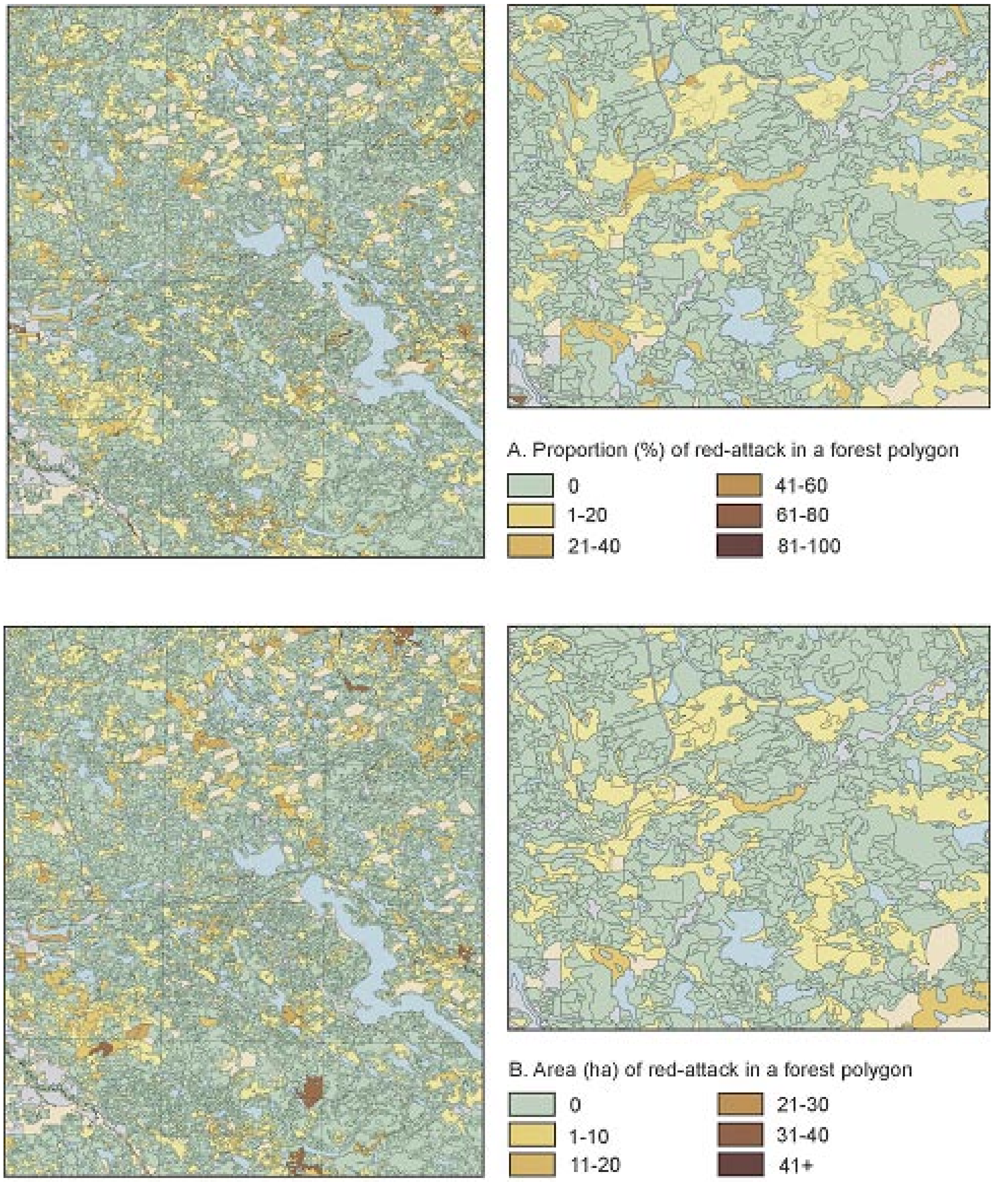

Figure 2. Example 1:20,000 provincial inventory map sheets populated with the results of a change detection procedure applied to Landsat satellite imagery. The pixel based change detection results can be integrated with the forest inventory data following a polygon decomposition approach to create new attributes indicative of mapped mountain pine beetle impacts. In this example, new attributes of proportion and area attacked are shown.

Large differences were observed in the area of the infestations as represented in the three different maps, but the red attack stands had similar forest characteristics. Stands with a high pine component in the age category 121 to 140 years, with diameter breast height over 25 cm and crown closures from 66% to 75% were identified as most susceptible to beetle attack. A stand-by-stand interpretation of red attack developed using polygon decomposition provides more detail than could be obtained by considering each of these data layers seperately. In the future, it is expected that polygon decomposition could be used in assessing non-attacked forest stands for susceptibility or perhaps predicting beetle movement patterns (Wulder et al. in press).

Conclusions

When surveying the red attack stage of a mountain pine beetle infestation, as in all studies using remotely sensed data, the information needs must dictate image data choices. To aid in the image data selection, the information need should also be constrained by area of coverage desired, costs, and timing. Regarding mountain pine beetle disturbances, remotely sensed data may be used to map large areas of forest at the red attack stage, or to detect smaller areas that may have red attacked trees. The methods for these two examples differ, as do the management questions that will be addressed.

Red attack mapping is possible with a range of methods and data sources. The data sources may be considered as an information hierarchy, where small-scale (i.e., Landsat) characterizations may be used to determine where large-scale data are collected (i.e., IKONOS. Spatial data from a variety of sources can improve mapping accuracy from remotely sensed data. Methods for large area characterization of red attack are appropriate for some operational applications. Data integration with forest inventory data, through polygon decomposition, enables forest managers to access required information in a timely and familiar format.

Future research with high spatial and spectral resolution imagery will test if red attack mapping can also be successful under endemic and incipient conditions. Development of models that combine knowledge of mountain pine beetle biology with spatial data characterization of local and current conditions will improve our ability to plan for and mitigate mountain pine beetle impacts.

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Evaluating Satellite Imagery for Estimating Mountain Pine Beetle-Caused Lodgepole Pine Mortality: Current Status

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Abstract

Spatial accuracy in the detection and monitoring of mountain pine beetle populations is an important aspect of both forest research and management. Using ground-collected data, classification models to predict mountain pine beetle-caused lodgepole pine mortality were developed for Landsat TM, ETM+, and IKONOS imagery. Our results suggest that low-resolution imagery such as Landsat TM (30 m) is not suitable for detection of endemic level populations of mountain pine beetle. However, good results were obtained for pixels with groups of red beetle-killed lodgepole pine (> 25 trees killed per 30-m pixel), implying that Landsat imagery is most suited to detection of populations at the building or epidemic phase. Preliminary results using high resolution IKONOS imagery (4 m) suggest that detection of individual or small groups of red beetle-killed lodgepole pine can be accomplished with a relatively high accuracy.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins Coleoptera: Scolytidae) is one of the most important drivers of vegetation change in lodgepole pine (*Pinus contorta*) forests. Outbreaks of these insects can be truly impressive events, with annual losses that are often greater than fire or any other natural disturbance. Mountain pine beetle populations can erupt rapidly, resulting in large increases in tree mortality within a few years. Timely forest management is contingent upon population monitoring and detection of beetle-caused tree mortality. Mountain pine beetle populations persist at endemic levels in single attacked trees scattered across a landscape. Population monitoring at this level can be difficult. Given appropriate weather and stand conditions, beetle success increases and groups of trees begin to be attacked. At the outbreak level, thousands of hectares with up to 70% mortality can occur. One promising avenue for detection of tree mortality caused by mountain pine beetles at various population levels is the use of remotely sensed data.

Remotely sensed data can be used for detecting visual, and through the near infrared bands, non-visual physiological changes in vegetation. Numerous studies have investigated the use of satellite-based digital remote sensing for the characterization of forest ecosystems and changes that occur within

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Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

these systems [see Lunetta and Elvidge (1998) and Cohen and Fiorella (1998) for reviews]. Pixel-wise transformations of spectral values are often used to enhance particular vegetative qualities. Ratios of spectral bands and the Normalized Difference Vegetation Index, which are based on known spectral interactions in green vegetation canopies, are examples of techniques that result in vegetation indices. Derived vegetation indices generally have a stronger relationship to the phenomena of interest in the scene than do any single spectral band. The tasseled-cap transformation, originally developed using Landsat Multispectral Scanner (80 m resolution) data (Crist and Cicone 1984), is another technique which can be used to extract physical/biological characteristics from the spectral features to develop more sensitive vegetation indices. The tasseled-cap procedure produces an orthogonal transformation of the original six-channel data to a new, three-dimensional space that creates axes that describe scene brightness, greenness, and wetness. This technique was adapted to Landsat 5 Thematic Mapper data (TM) (30 m resolution) (Crist and Cicone 1984) and Landsat 7 Enhanced Thematic Mapper data (ETM+) (30 m resolution) (Huang et al. 2002) providing an invariant transformation for comparing both TM and ETM+ scenes.

The tasseled-cap technique has proven useful in many situations as an indicator of forest vegetation change (Cohen and Fiorella 1998; Price and Jakubauskas 1998), including predictions of bark beetle-caused mortality in California (Collins and Woodcock 1996; Macomber and Woodcock 1994). Using change detection techniques and percent basal area killed per multi-pixel stand over a 3-year period as the basis for analysis, up to 73% accuracy was obtained for stands with a 20% mean change (N=50) that was attributed to bark beetle-caused mortality (Collins and Woodcock 1995; 1996). Similarly, an earlier study suggested groups of infested trees needed to be large, at least 1.5 ha (17 pixels) in size, to be detected using TM data (Renez and Nemeth 1985). In a recent Canadian study using Landsat TM imagery and a combination of helicopter and ground crew collected data, Franklin et al. (2003) predicted pixel-wise presence/absence of mountain pine beetle-killed lodgepole pine with an overall accuracy of 73%. Stratification of the image prior to classification is one technique used by Franklin et al. (2003) to increase the per pixel accuracy of detecting red-attacked versus green trees. We define red-attacked trees as trees that were attacked and killed by bark beetles the flight season prior to the current year. Lodgepole pine foliage typically turns red approximately 10 months after the initial mass attack.

In addition to the low resolution TM data, several recently launched satellites collect data at a higher resolution of 4 m and 1 m. Little work on detecting red beetle-killed trees has been conducted with these data. Our main objective of this paper is to relate the status of research aimed at evaluating Landsat TM, ETM+ and IKONOS (4 m) satellite data for detecting levels of red mountain pine beetle-killed trees in lodgepole pine stands in the United States.

Methods

Study Site and Ground Data Collection

Landsat

The study area was located in a mountainous region of the Lolo National Forest in central Montana (Fig. 1).

Elevation within the study area ranged from 940 m to 1524 m. Forest conditions were mixed conifer, although all ground plots were taken in areas with predominantly lodgepole pine (*Pinus contorta*). Other species included subalpine fir (*Abies lasiocarpa*), mountain hemlock (*Tsuga mertensiana*), western hemlock (*Tsuga heterophylla*), larch (*Larix occidentalis*), grand fir (*A. grandis*) and Douglas-fir (*Pseudotsuga menziesii*). Based on aerial detection survey (ADS) information (USDA Forest Service, Forest Health Protection, Region 1) mountain pine beetle populations were active within the study area beginning in 1994.

Ground data was collected from August through September in 2000, 2001 and 2002. In 2000, data were collected using variable radius plots (20 Basal Area Factor) on a 3 x 3 grid, with plot centers every

30 m. A 30 m plot size was used to correlate with the area covered by a TM pixel. In 2001, each site consisted of nine plots, again in a 3 x 3 grid pattern, but a 100% survey was taken within each 30 m x 30 m plot (0.09 ha) instead of variable radius plots as in 2000. In 2002, sampling intensity at each site was reduced to facilitate an increase in the number of sites across the study area. The grid size of plots at each site was reduced to 2 x 2 (4 total plots) with a 100% survey taken within each 30 m x 30 m plot. In addition, plots on the ground were oriented in a north-south direction to more closely align with the Landsat image pixels. At each plot, all years, diameter at breast height (dbh) was measured for all trees, and each tree was assigned a species and attack code: 1) live and not currently infested, 2) current mountain pine beetle attack, 3) mountain pine beetle-attacked the previous year, 4) mountain pine beetle-attacked two years previous, or 5) mountain pine beetle-attacked more than two years previous. At each site, GPS positions were acquired to relate the survey sites to the digital imagery. Points were taken in the center of each plot in 2000 and in the four corners and center of each site in 2001 and 2002. A total of 58 sites and 380 plots were surveyed from 2000-2002: 15 sites and 143 plots in 2000, 13 sites and 117 plots in 2001, and 30 sites and 120 plots in 2002. To increase the sample size of live, non-beetle infested trees, areas of green lodgepole pine were located on aerial photos of the study area taken in 2000. These areas where then overlaid on the 2000 ETM+ image to extract spectral digital values for green lodgepole pine.

IKONOS

The Sawtooth National Recreation Area (SNRA) is located in central Idaho (Fig. 1). Elevation at the valley floor is approximately 2000 m. Forest conditions within the study area were mostly pure lodgepole pine, with transition areas of Douglas-fir and subalpine fir as elevation increased on the valley slopes. Mountain pine beetle populations began building in the northern section of the SNRA in 1997, and by 2002 were at outbreak levels throughout the valley (USDA Forest Service, Forest Health Protection, Region 4, ADS). Ground data collection for classification of IKONOS imagery was conducted in September 2002 and

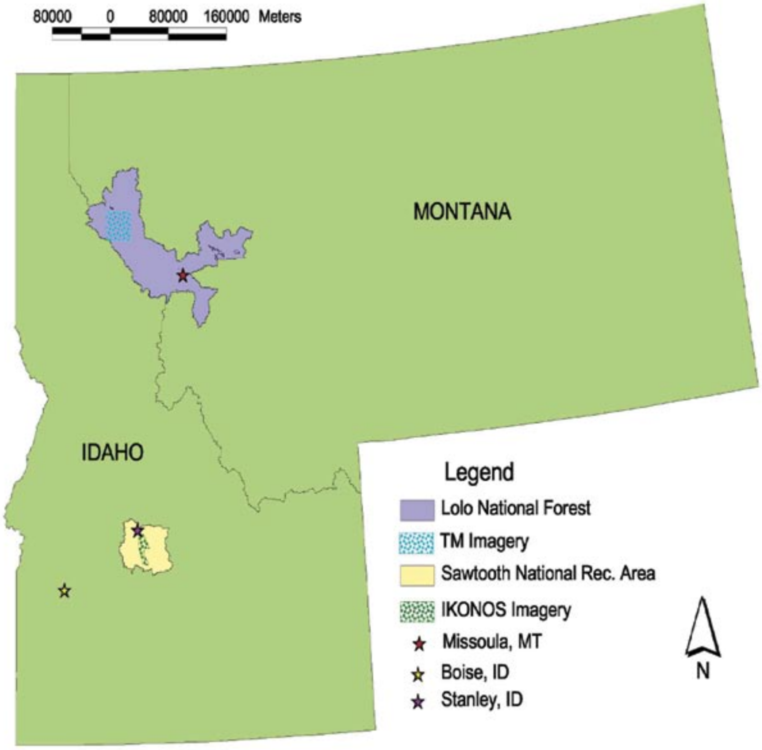

Figure 1. Study locations within Montana (Landsat) and Idaho (IKONOS).

consisted of identifying individual trees and assigning a trees species and attack code: 1) live and not currently infested, 2) current mountain pine beetle attack, 3) mountain pine beetle-attacked the previous year, or 4) mountain pine beetle-attacked two years previous. The geographic location of each tree was recorded with a GPS. Other classes including water, roads, dirt, agriculture, and sagebrush were identified from the IKONOS image. The training data contained 699 observations in 10 classes (Table 1).

Table 1. Number of observations in each class of the training data used for developing classification models for the 2001 IKONOS image.

Vegetation Class	Number of Points	Vegetation Class	Number of Points
Agriculture	106	Red trees	68
Dirt	53	Road	68
Douglas-fir	66	Sagebrush	29
Grass	15	Shadow	84
Green lodgepole pine	55	Water	155

Image Acquisition and Processing

Landsat

Landsat imagery (Path 42, Row 27) was acquired for the following dates: October 4, 1993; August 31, 1998; August 26, 1999; August 28, 2000; August 15, 2001; and August 18, 2002. The 1993 and 1998 images were from the Landsat 5 Thematic Mapper (TM) sensor, and the 1999-2002 images were from the Landsat 7 Enhanced Thematic Mapper (ETM+) sensor. All five images were re-projected to UTM coordinates, Zone 11N, and NAD27 datums, and geo-rectified to the 1993 image. The images were cropped to focus on the area in which ground data were collected. After preliminary processing, several corrections and enhancements were performed on all images including dark pixel atmospheric correction (Chavez 1975), and calibration to radiance values and conversion to reflectance values (NASA Landsat 7 Science Users Handbook http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html; Canada Centre for Remote Sensing Calibration/Validation, http://www.ccrs.nrcan.gc.ca). After a specific correction procedure, a tasseled cap transformation was performed using a 6 x 6 matrix of coefficients, specific for each sensor (Tables 2 and 3). This value was then multiplied by 1023 to increase the range of digital values.

Table 2. Tasseled-cap coefficients for the TM sensor (Crist and Cicone 1984).

Index	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
Brightness	0.3037	0.2793	0.4743	0.5585	0.5082	0.1863
Greenness	-0.2848	-0.2435	-0.5436	0.7243	0.0840	-0.1800
Wetness	0.1509	0.1973	0.3279	0.3406	-0.7112	-0.4572
Fourth	-0.8242	0.0849	0.4392	-0.0580	0.2012	-0.2768
Fifth	-0.3280	0.0549	0.1075	0.1855	-0.4357	0.8085
Sixth	0.1084	-0.9022	0.4120	0.0573	-0.0251	0.0238

Table 3. Tasseled-cap coefficients for the ETM+ sensor (Huang et al. 2002)

Index	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
Brightness	0.3561	0.3972	0.3904	0.6966	0.2286	0.1596
Greenness	-0.3344	-0.3544	-0.4556	0.6966	-0.0242	-0.2630
Wetness	0.2626	0.2141	0.0926	0.0656	-0.7629	-0.5388
Fourth	0.0805	-0.0498	0.1950	-0.1372	0.5752	-0.7775
Fifth	-0.7252	-0.0202	0.6683	0.0631	-0.1494	-0.0274
Sixth	0.4000	-0.8172	0.3832	0.0602	-0.1095	0.0985

Stand survey data within a GIS database (USFS, Timber Management Control Handbook Region 1 Amendment 2409.21e-96-1) were used to stratify the landscape by creating a mask layer that was applied to each image. Included in the mask layer were stands in which lodgepole pine comprised the plurality of the stocking and was also the primary species of the stand component based on plurality of basal area stocking. In addition, only stands that had not been harvested within the past 50 years were included. Following image enhancements and transformations, spectral values for each survey plot within each site were assigned using area of interest layers. Using the GPS points collected in the field, ground-collected plot data from each site were overlaid on each transformed image. Area of interest layers were created surrounding all pixels encompassed in each plot and any adjoining pixels that could influence the overall mean spectral value of a plot. A mean digital value was calculated for each band, within each area of interest. The spectral digital values were combined with the ground data (describing the amount of mountain pine beetle activity in the plot) into a database for statistical analysis.

IKONOS

IKONOS satellite imagery was acquired for 26 August 2001 and 3 September 2001 for the 299-km^2 study area within the SNRA. The IKONOS multi-spectral imagery has four bands: blue (0.45 μm—0.52 μm), green (0.52 μm—0.60 μm), red (0.63 μm—0.70 μm), and near infrared (0.76 μm—0.85 μm) at a resolution of 4 m. The imagery was purchased ortho-rectified with eight bits per pixel, and geo-referenced to metadata layers obtained from the Sawtooth National Recreation Area and ground control points (e.g., major road intersections) obtained with a GPS.

Statistical Analyses

Landsat

Ground data collected in 2001 and 2002 were used to develop a model for classifying the TM and ETM+ images. Because trees that were beetle-killed the previous year and two years previous had a very similar foliage color, these trees were merged into one category identified as Red. Trees beetle-killed more than two years before the date of the image were placed into a separate category identified as Grey. All live trees (all species) and trees beetle-infested the year of the image date were merged into one category identified as Green. A variety of metrics were calculated for each plot to test appropriate measures for correlating vegetative ground data with the pixel spectral value on Landsat images. These included trees per acre Red, trees per acre Green, trees per acre Grey, basal area Red, basal area Green, basal area Grey, number of trees Red, number of trees Green, and number of trees Grey. Ground data were also summarized, per plot, into one of three classes: 0-9 trees Red, 10-24 trees Red, and > 25 trees Red.

To develop a model for classifying the amount of beetle-caused tree mortality within Landsat image pixels, the relationship between 254 ground points and the corresponding spectral value of the image was analyzed using a variety of statistical algorithms including regression trees, linear discriminant analysis, quadratic discriminant analysis, and k's Nearest Neighbor (SAS Institute, Splus®). A 10-fold cross-validation estimate of the error rate was computed, and one thousand random permutations of the data were generated. Each permutation was then split into two pieces, with the first 90% of the observations being assigned to be a training data set and the remaining observations comprising a test data set. The four classifiers were then fit to the training data, evaluated on the test data, and the predictive error rates averaged over all 1000 samples. Using the derived model, all images were classified. The 2001 and 2002 image classifications were assessed using ground data collected for those years and site-specific error was assessed using a confusion matrix and a weighted kappa statistic (Campbell 1996). Model-predicted classified images were also compared to polygons of mountain pine beetle-killed trees developed from digitized aerial detection surveys (USFS, Forest Health Protection Region 1; McConnell et al. 2000).

IKONOS

Training data collected on the ground (Table 1) were combined with the associated pixel spectral values on the image. The same four statistical classification algorithms used to develop models for Landsat imagery were tested with the IKONOS multi-spectral data for classification model development. A 10-fold cross-validation estimate of the error rate was computed using each method, and one thousand random permutations of the data were generated. Each permutation was then split into two pieces, with the first 90% of the observations being assigned to be a training data set and the remaining observations comprising a test data set. The four classifiers were then fit to the training data, evaluated on the test data, and the predictive error rates averaged over all 1000 samples. Using the derived model, all pixels of the IKONOS image were classified and assessed using the same training data set.

Results and Discussion

Of the four models tested, cross-validation revealed that the lowest overall misclassification rate (37.67%) for Landsat imagery was achieved using the linear discriminant analysis-derived model and non-transformed values of tree counts. Class 2 had the highest misclassification rate (62.02%), while classes 1 and 3 had lower rates (21.14% and 33.70%, respectively). The addition of Green and Grey tree counts per pixel did not significantly increase the power of the model. The linear discriminant model resulted in the following equations that can be used to create a classified Landsat image based on 3 classes of mountain pine beetle-killed trees (Class 1: 0-9 trees Red, Class 2: 10-24 trees Red, and Class 3: > 25 trees Red):

$$\text{CLASS 1} = -83.45386 + (B1\times -1.03769) + (B2\times 1.65584) + (B3\times -0.90812) + (B4\times 3.27962) + (B5\times -2.19315) + (B6\times 2.08431)$$

$$\text{CLASS 2} = -85.12807 + (B1\times -1.05044) + (B2\times 1.62908) + (B3\times -0.94684) + (B4\times 3.38405) + (B5\times -1.86218) + (B6\times 1.95214)$$

$$\text{CLASS 3} = -84.82084 + (B1\times -1.13747) + (B2\times 1.64929) + (B3\times -1.07066) + (B4\times 3.31968) + (B5\times -1.45134) + (B6\times 2.42476)$$

The Bn values are the individual bands of the tasseled-cap transformed TM image for a given pixel. The equation that generates the largest value is coded to its respective class value. This model was applied to all images, then masked with two layers to remove areas of bare ground, water, non-lodgepole pine stands, and stands that had been harvested. The classification accuracy assessment using 2001 and 2002 ground data revealed an overall accuracy of 59% with a weighted kappa of 45.6% (Table 4).

Class 3 had the greatest predicted classification accuracy when compared to ground data (79%).

Cross-validation revealed that the lowest overall misclassification rate (11.68%) for the IKONOS image was achieved using quadratic discriminant analysis. Over 95% of the mountain pine beetle-killed trees (Red trees) were correctly classified (Table 5).

Green lodgepole pine and Red trees were misclassified less than 0.01%. Misclassification of Douglas-fir as green lodgepole pine and vice versa accounted for the largest amount of error. Transformation of spectral values using tasseled-cap or the Normalized Difference Vegetation Index did not increase the power of the model.

When applied to the 1993 Landsat TM image, taken prior to the start of the mountain pine beetle outbreak within the study area, the Landsat TM model predicts more areas of beetle-caused mortality than are shown in the Aerial Detection survey for that year (Fig. 2).

These predictions are somewhat expected based on the poor accuracy of vegetation Classes 1 and 2 (Table 4). At endemic population levels, mountain pine beetle-caused tree mortality most likely will not cover an entire 30 m pixel. However, model predictions of the 2002 ETM+ image, during the peak of the mountain pine beetle outbreak in the study area, correlate well with the mortality estimated by Aerial Detection Surveys for that year (Fig. 3).

Although we have not yet quantified differences in IKONOS model predictions and observed mortality in the Sawtooth National Recreation Area, patterns of mortality in a small area of the image are consistent with our ground observations (B. Bentz unpublished data) (Fig. 4). Validation data collection in the Sawtooth National Recreation Area is ongoing.

Table 4. Error matrix of 2001 and 2002 ground data and predictions based on 2001 and 2002 ETM+ Landsat images. Red trees are trees killed by mountain pine beetle 1 and 2 years prior to the image date.

	0-9 Red trees	10-24 Red trees	>25 Red trees	Total
Class 1				
Frequency	74	22	4	100
Percent	58%	25%	9.5%	
Class 2				
Frequency	47	44	5	96
Percent	37%	52%	12%	
Class 3				
Frequency	6	19	33	58
Percent	0.05%	22%	79%	
Total	**127**	**85**	**42**	**254 (59%)**

Table 5. Partial error matrix for vegetation classes predicted on the 2001 IKONOS image.

	Grass	Green lodgepole pine	Douglas-fir	Red trees	All other classes
Grass	27.6%	0.3%	6.1%	4.8%	61.2%
Green lodgepole pine	3.9%	56.1%	40.0%	0.0%	0.0%
Douglas-fir	1.4%	23.8%	74.8%	0.0%	0.0%
Red trees	1.3%	0.01%	0.0%	95.8%	2.9%
All other classes	0.4%	0.2%	0.2%	0.6%	98.6%

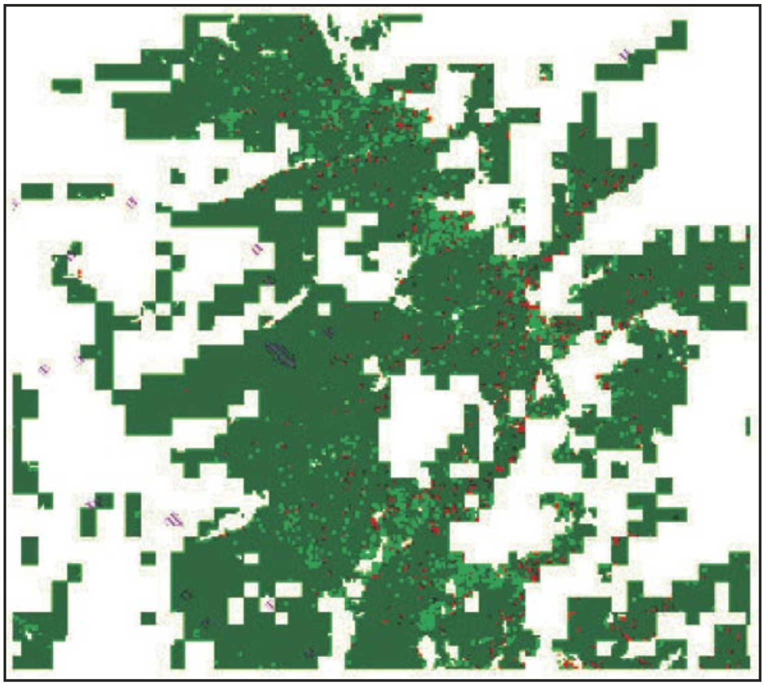

Figure 2. Model predictions of mountain pine beetle-killed lodgepole pine in 1992 (prior to the mountain pine beetle outbreak) on the Lolo National Forest using 1993 Landsat TM imagery. Red pixels are predicted to have > 25 beetle-killed trees per 30-m pixel, light green pixels are predicted to have 10-24 beetle-killed trees per 30-m pixel and dark green pixels indicate 0-9 beetle-killed trees per 30-m pixel. White areas are non-lodgepole pine dominated stands. Purple cross-hatched polygons are areas predicted to have beetle-killed trees based on 1993 Aerial Detection Surveys.

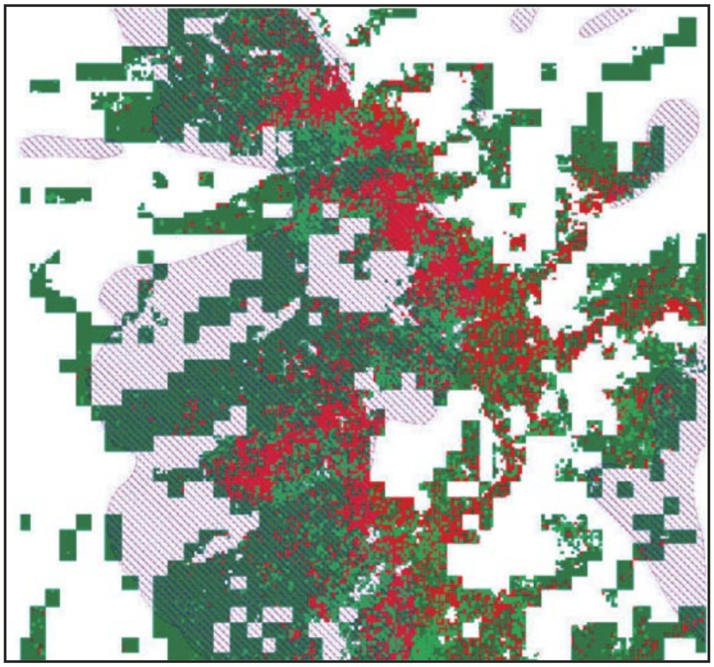

Figure 3. Model predictions of mountain pine beetle-killed lodgepole pine in 2001 (at the peak of the mountain pine beetle outbreak) on the Lolo National Forest using 2002 Landsat ETM+ imagery. Red pixels are predicted to have > 25 beetle-killed trees per 30-m pixel, light green pixels are predicted to have 10-24 beetle-killed trees per 30-m pixel and dark green pixels indicate 0-9 beetle-killed trees per 30-m pixel. White areas are non-lodgepole pine dominated stands. Purple cross-hatched polygons are areas predicted to have beetle-killed trees in 2001 based on 2002 Aerial Detection Surveys.

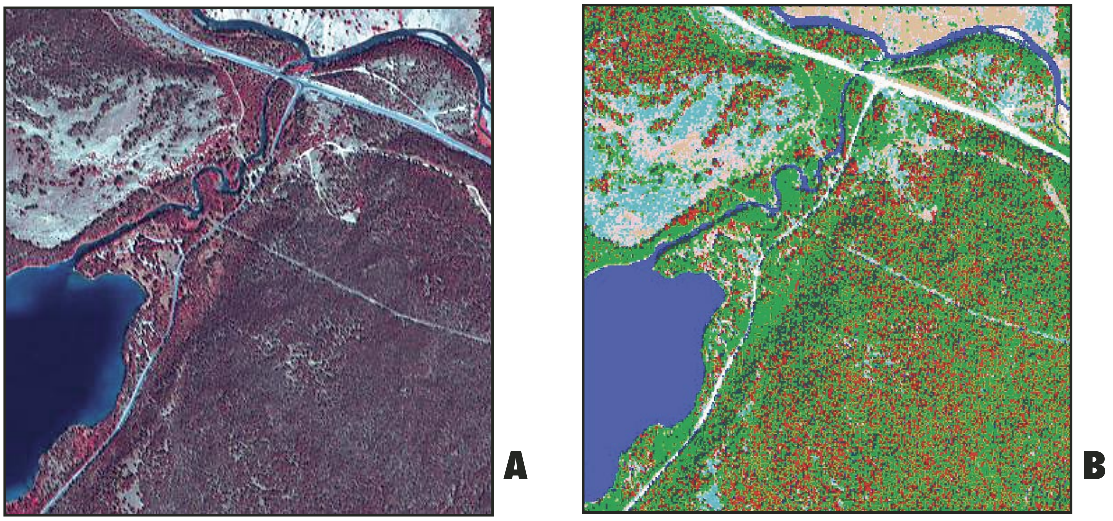

Figure 4. A portion of the 2001 IKONOS image from the Sawtooth National Recreation Area (A), and the image classified using quadratic discriminant analysis (B). Red pixels represent mountain pine beetle-killed trees, light green pixels are live lodgepole pine and dark green pixels are Douglas-fir trees. Cyan, pink, blue and white are predictions of grass, sagebrush, water, and roads, respectively.

Conclusions

Discriminant analysis algorithms provided the best overall statistical fit between mountain pine beetle-killed trees identified on the ground and both Landsat TM, ETM+, and IKONOS pixel spectral values. One of the largest sources of error in model development was correlating the spatial location of ground data (e.g., individual trees or stands of trees) with the correct pixel spectral signal of the images. Our results from the Lolo National Forest suggest that Landsat TM and EMT+ data may be better suited to detection of beetle-killed trees after the population has expanded to killing groups of trees that will dominant the spectral signal of a 30 m pixel. The spectral signal of individual or small patches of red beetle-killed trees, which are indicative of endemic populations, will be difficult to identify with the low-resolution imagery. However, when populations reach the building or outbreak level, models developed for Landsat TM and ETM+ data can provide increased spatial accuracy of groups of red beetle-killed trees compared to current methodology including Aerial Detection Surveys. A more accurate spatial representation of mountain pine beetle infested trees will facilitate both management and research aimed at landscape-scale disturbance processes. Preliminary results in the Sawtooth National Recreation Area suggest that high-resolution imagery, such as IKONOS, show promise for detection of small groups of trees or individual trees killed by the mountain pine beetle. Remotely sensed imagery can be a valuable tool for forest managers, although the specific product to use should correspond with the appropriate beetle population level and specific land management objectives and budget.

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Spatial-Temporal Analysis of Mountain Pine Beetle Infestations to Characterize Pattern, Risk, and Spread at the Landscape Level

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Abstract

An understanding of spatial processes is necessary when modelling and predicting mountain pine beetle (*Dendroctonus ponderosae* Hopkins) behaviour. The recent availability of large area, mountain pine beetle data sets enables new approaches to studying spatial processes of infestations. Our goal is to explore observed, landscape level, spatial and spatial-temporal patterns of mountain pine beetle infestations using data collected by the Morice Forest District. A better understanding of mountain pine beetle spatial behaviour will be obtained by: investigating the nature of error and information content of the data and improving data visualization; exploring spatial and spatial-temporal patterns in observed data; comparing observed spatial patterns with modelled expectations to identify areas with unexpected patterns; and exploring the landscape characteristics of areas that are statistically different from our expectation of mountain pine beetle behaviour. We provide an introduction to our project by presenting the objectives, methods, and some preliminary results.

Introduction

The increasing number of spatially explicit mountain pine beetle studies attest to the importance of incorporating spatial processes when modelling or predicting insect activity (e.g., Bentz et al. 1993; Powell and Rose 1997; Logan et al. 1998; Fall et al.2004). Spatial studies of bark beetles can be carried out at many different scales. For example, at a fine scale, the spatial patterns of individual insects within a gallery have been studied (Byers 1984), while at a coarser scale, the spatial pattern of tree mortality within a stand has also been analyzed (Mitchell and Preisler 1991; Preisler and Mitchell 1993). Landscape scale studies have been more limited due to a lack of large area data sets, with most using simulation of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) processes, both spatial and aspatial, to better understand mountain pine beetle behaviour (e.g., Powell et al. 1996; Logan et al. 1998; Riel et al. 2004; Fall et al. 2004).

An influx of monitoring programs, combined with new technology and data acquisition methods, has generated large area, multi-temporal, mountain pine beetle data sets. For instance, point data on

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infestations has been collected for the Morice Forest District (1.5 million ha) since 1995. Using these data, we can explore observed spatial patterns in mountain pine beetle infestations. Pattern-based analysis can be used to better understand the spatial processes associated with mountain pine beetle infestations and may enable refinement of process-based models.

Our research goal is to explore landscape scale, spatial and spatial-temporal patterns in mountain pine beetle infestations by applying spatial statistical analysis tools to infestation data from the Morice Forest District. In this document, we outline our study objectives and provide an introduction to our research by describing research questions and methods, and presenting some preliminary results. We begin this discussion by describing data attributes and characteristics relevant to this study.

Study Area and Data

The Morice Forest District, near Houston, British Columbia (BC) (see Fig. 1), is currently experiencing epidemic numbers of mountain pine beetles. Bordered on the west by the Cascade Mountains and on the south by Tweedsmuir Provincial Park, the topography is gentle in the north and east, and mountainous in the southwest. Covering an area of approximately 1.5 million ha, the Morice Forest District is dominated by lodgepole pine (*Pinus contorta*) and spruce (*Picea*).

While the central and northern portions of the Morice Forest District were infested in the early and mid 1990s, the southern portion was infested later. Since there are many differences in mountain pine beetle activity, the northern, central, and southern areas of Morice are considered separately where appropriate in our analysis.

The Morice Forest District has used aerial surveys to monitor mountain pine beetle infestations since 1995. From helicopters, surveyors identify clusters of dying or infested trees and a global positioning system is used to record the location of the cluster centroids. For each cluster, the number of infested trees is estimated and the species of infestation is recorded. The maximum area associated with a location point is a circle with a radius of 100 m. However, points may represent smaller areas and variations are unknown.

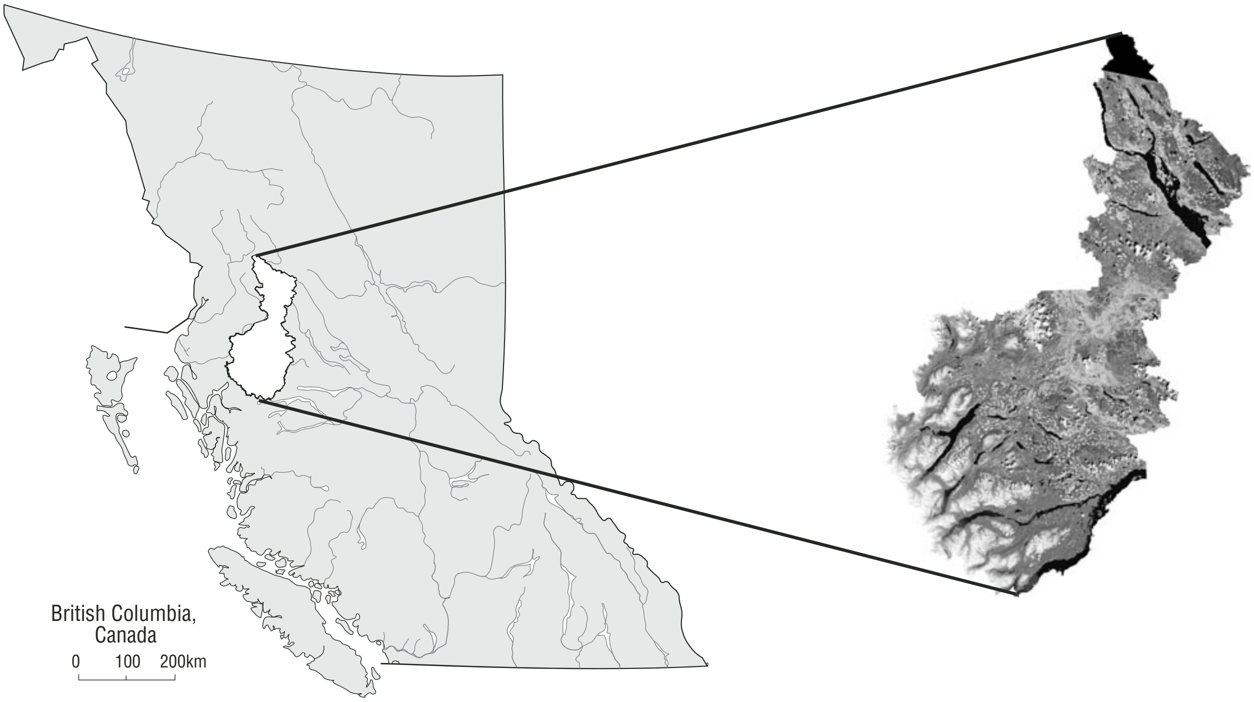


Figure 1. The Morice Forest District is centered in Houston, BC, Canada.

Field data associated with aerial surveys are available from 1999 to 2002. For 2001 and 2002, field visits were made for approximately 75% of aerial survey locations. However, field data from 1999 and 2000 are sparse. During field data collection, ground crews locate the infestation clusters that were recorded during aerial surveys and determine the cause of lodgepole pine mortality. If there are trees killed by mountain pine beetles, crews record the number of green trees currently under attack, the number of trees attacked the previous year, the number of trees attacked two years previously, and the number of trees attacked which are now grey. Later, field sites may be treated in an effort to reduce the impact of the mountain pine beetle, in which case the type of treatment is recorded.

Research Objectives

Our research objectives are grouped into four categories. The first category is the improvement of our understanding of the data by quantifying the information content of point-based, aerial surveys of mountain pine beetle infestations and demonstrating appropriate techniques for visualizing infestation data while considering data uncertainty. The second category is exploratory spatial analysis, including investigations of spatial and spatial-temporal trends in landscape level, mountain pine beetle activity. The third category involves the comparison of observed mountain pine beetle data to expectations conditioned on forest risk. Here we consider how to incorporate data uncertainty when generating a model of forest risk and we use statistical comparison of observed and modelled spatial patterns to identify interesting areas (hot spots) where unexpected patterns occur. The fourth category involves investigation of these hot spots. By analyzing the physical characteristics of areas underlying hot spots, relationships between site conditions and mountain pine beetle infestations can be determined. Such relationships will allow us to better understand model output and may be useful in identifying spatial parameters important for generating mountain pine beetle models.

Understanding the Data

As with all large area data sets, aerial surveys are prone to uncertainty. Therefore, when undertaking spatial analysis, a thorough investigation of data accuracy and information content is necessary to ensure confidence in results. Our comparisons of field and aerial data show that aerial data are useful for mapping the location and magnitude of infestations that occurred more than one year previously. In aerial point data, the majority of attribute values are small, as is the error associated with most individual survey locations. The cumulative impact of error, however, is considerable, as only 28% of survey points have the correct attributes. Although both errors of omission and commission occur, commission errors account for almost twice the uncertainty, and overall the distribution of errors approximates a gamma distribution.

The information available from point-based, aerial surveys is often difficult to visualize. Since aerial surveys are used to monitor large areas, data sets tend to be sizeable and difficult to represent. Simple cartographic techniques generally provide insufficient improvements (Fig. 2) and visualization is complicated by data uncertainty. Data visualization can be improved by converting point data to surfaces using kernel density estimators. As well, using a Monte Carlo approach and estimates of attribute error, kernel density estimators can be used to incorporate uncertainty into data visualization.

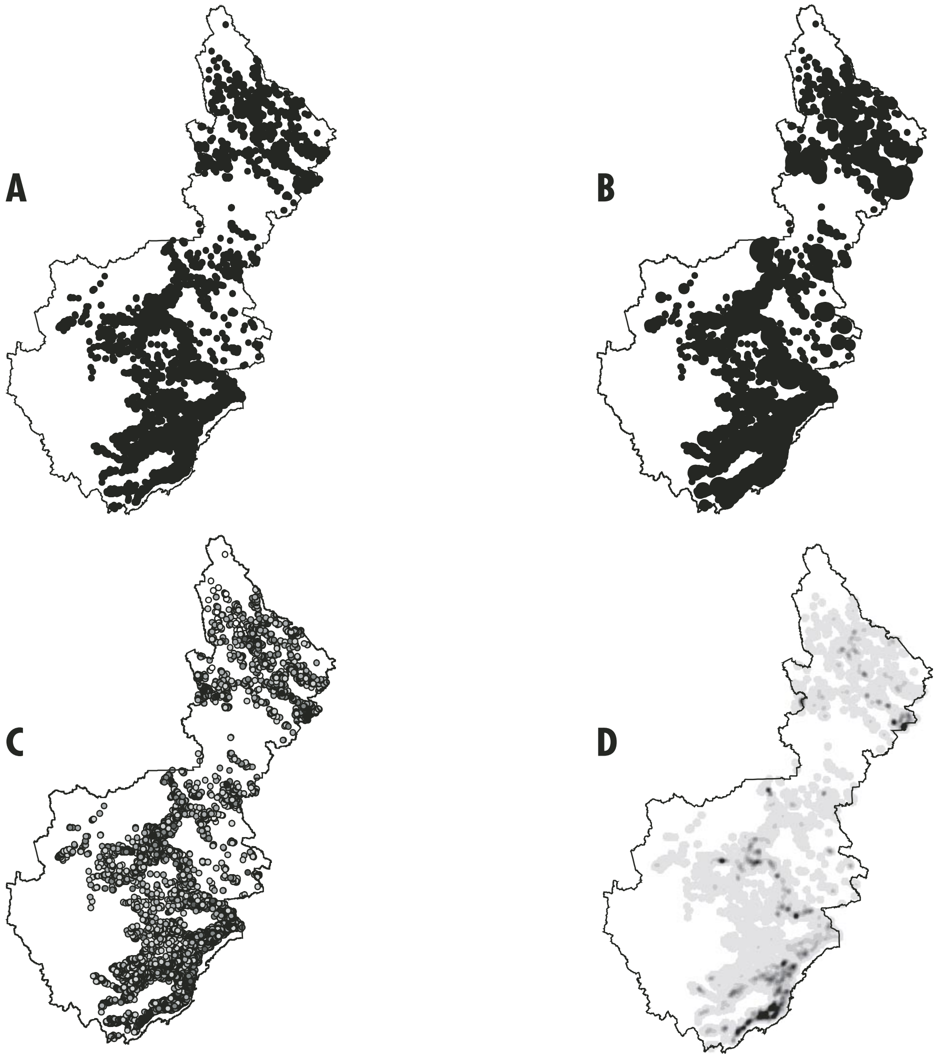


Figure 2. Comparison of data visualization techniques: A) Aerial survey points with no enhancements. B) Aerial survey point attributes represented as proportional symbols. C) Aerial survey point attributes represented as proportional colours. D) Aerial survey point attributes represented using a kernel density estimator. (darker locations have higher infestation).

For details on kernel density estimators we refer the reader to Silverman (1986) and Bailey and Gatrell (1995). Essentially, kernel density estimators can be used to visualize the intensity of events over space. Conceptually, the intensity $\lambda(z)$ at a particular location $\boldsymbol{z}$ in a study area A can be estimated by the naïve kernel density estimator

$$\hat{\lambda}(z) = \frac{\text{the number of events in a disk centred on } z}{\text{area of the disk}}$$

A more precise estimate, $\hat{\lambda}_\tau(\boldsymbol{z})$ is defined by

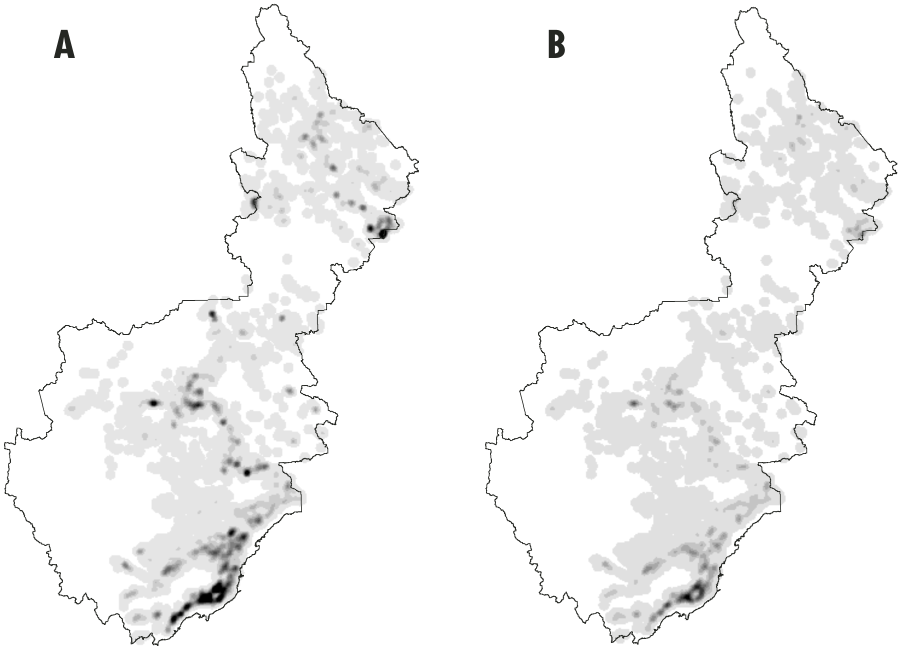
$$\hat{\lambda}_\tau(z) = \frac{1}{p_\tau(z)}\left\{\sum_{i=1}^{n}\frac{1}{\tau^2}k\left(\frac{(z-z_i)}{\tau}\right)y_i\right\} \quad z \in A$$

where $\boldsymbol{z}$ and A are defined as above, τ is the radius of a disk centered on $\boldsymbol{z}$, $k(\,)$ is the kernel or a probability density function which is symmetric around about the origin, $\boldsymbol{z}_i$ ($i = 1, \ldots, n$), are locations of

n observed events, and y_i is the attribute value at $\boldsymbol{z}_i$. The term $p_\tau(z) = \int_A k[(z - \boldsymbol{u}) / \hat{o}] d\boldsymbol{u}$ is an edge correction equivalent to the volume under the scaled kernel centred on $\boldsymbol{z}$, which lies inside of A (Diggle 1985). The disk radius τ is the most important parameter to consider when generating kernel density surfaces as it controls the amount of data smoothing. For this research, τ was set equal to 2 km, optimizing improvements to data visualization while retaining detail. Also this value is sufficiently large to be relatively robust with respect to any errors in the locations of the points (approximately 25 m maximum). Further, given the size of the kernel relative to the study area, the impact of edge effects was considered negligible and no edge correction was applied.

In brief, the method for incorporating uncertainty in kernel-estimated density surfaces is as follows. Possible realizations of point locations and attribute values are generated by randomly drawing values from a gamma distribution, whose parameters were estimated by fitting a distribution to the field data using a maximum likelihood estimator. Spatial uncertainty is incorporated by randomly drawing values for both the x and y coordinates from a normal distribution with a mean of 0 and standard deviation of 1. These values are scaled to ±25 m, which is the spatial uncertainty estimated by field crews. One hundred point realizations are generated and a kernel density surface is produced for each realization. The 100 kernel density surfaces are summed and averaged to generate a final kernel density surface incorporating uncertainty. Most often, aerial survey attributes are overestimated; therefore, when kernel density surfaces are corrected, attribute values generally decrease (Fig. 3 and Fig. 4).

Figure 3. Kernel density surfaces estimated from aerial points and attributes.



A) Kernel density surface without consideration of data uncertainty.
B) Kernel density surface including data uncertainty. Darker tones are higher values.

Exploratory Spatial and Spatial-Temporal Analysis

Kernel-estimated density surfaces are useful for investigating spatial patterns in a single time period and may be used to relate landscape characteristics to variations in infestation magnitude. Using the corrected kernel-estimated density surfaces, infestations were categorized as intense or non-intense, where intense infestations are defined as values in the 90th percentile of the kernel density surface frequency distribution (Fig. 5). The 90% threshold identifies areas with landscape characteristics that were distinctive relative to less infested and non-infested areas. The spatial distributions of intense and non-intense infestations were compared with landscape characteristics such as pine age, percent of pine in a stand, elevation, aspect, and slope in the northern, central and southern portions of the study area. The relationship between infestation intensity and forest age is demonstrated in Figure 6. Forest age classes were determined using the forest inventory data representative of forest characteristics in 1999. Forest age classes were as follows: 1 (1-20 years); 2 (21-40 years); 3 (41-60 years); 4 (61-80 years); 5 (81-100 years); 6 (101-120 years); 7 (121-140 years); 8 (141-250 years); and 9 (> 250 years).

In the northern sub-area, the pine age classes underlying both intense and non-intense infestations approximately follow the distribution of age classes in the area. While age class 8 (141-250 years) is most heavily infested, it is not attacked more often than anticipated if the mountain pine beetle randomly selected host trees. This is likely related to the infestation history. The mountain pine beetle infestations in the north were intense in 1996 and 1997. By 2001 there was little mature pine remaining as most has been infested or harvested. However, the forest age data is based on conditions in 1999; thus, there appears to be more mature pine than would actually be available in 2001 and 2002.

In the central sub-area, mountain pine beetle preferred age class 7 (121-140 years) when the infestation was intense and age class 8 when the infestation was non-intense. In this area, stands of age class 7 have a higher percentage of pine (mode = 70% pine) than stands with age class 8 (mode = 30% pine). As a result, most age class 8 stands have relatively few trees available for infestation, so the most intense infestations are found elsewhere.

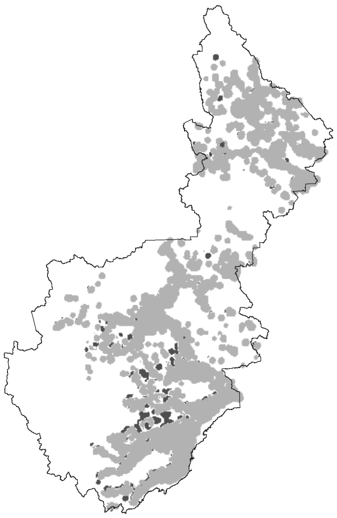


Figure 4. Difference in kernel densities calculated with and without corrections. Gray represents areas where the correction resulted in a decrease in infestation values and black represents locations where the correction generated an increase.

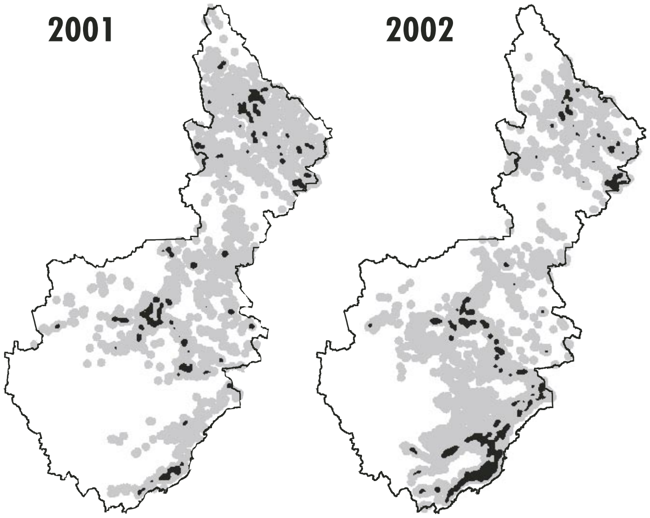


Figure 5. Variation in infestation intensity in 2001 and 2002. Black represents intense infestations, grey represents non-intense infestations, and white represents no infestation.

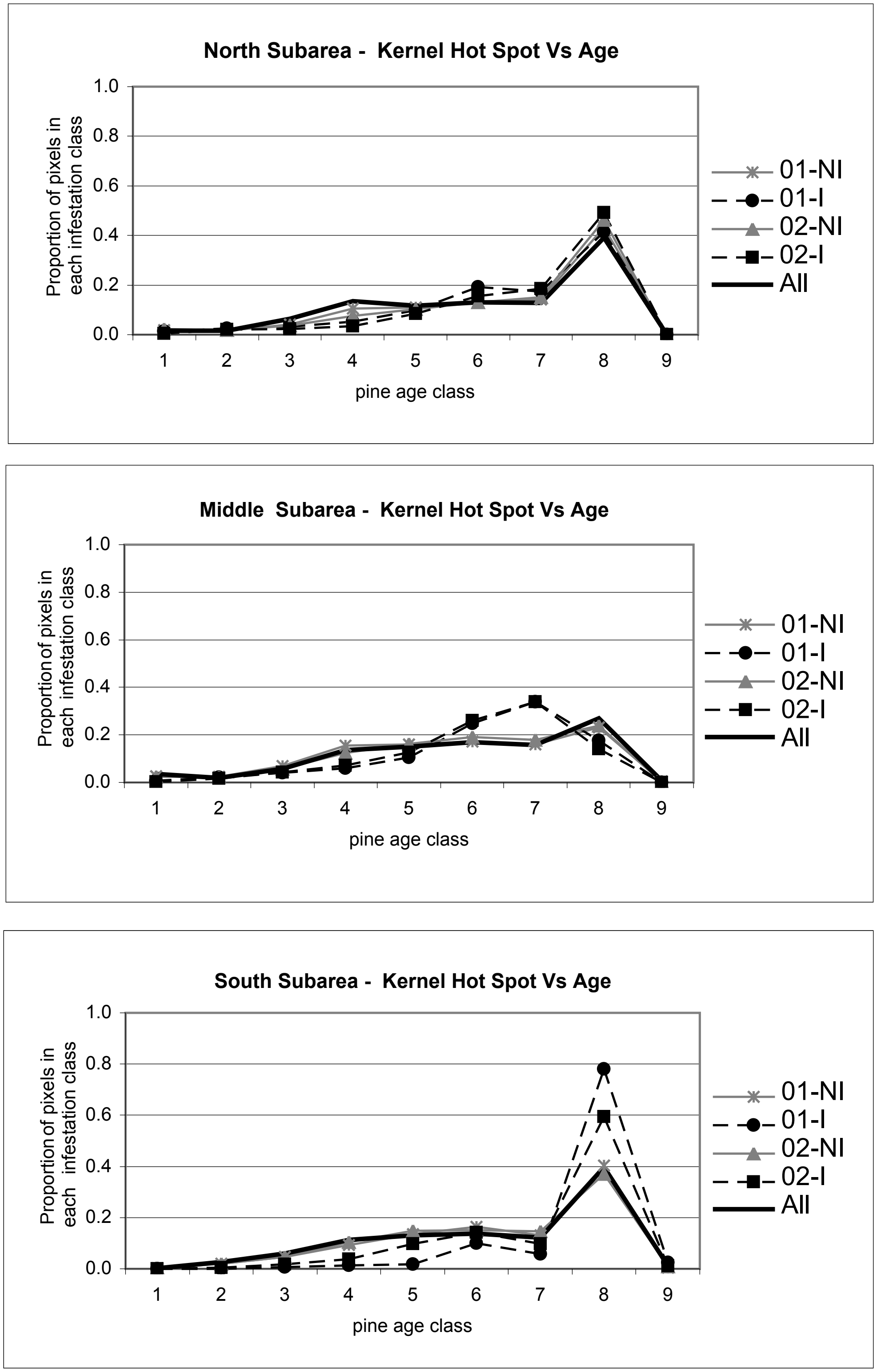


Figure 6. Comparison of pine age classes underlying intense and non-intense infestations in 2001 (01) and 2002 (02). I = intense infestations, NI = Non-intense infestations, and All = the distribution of all pine locations within the study area.

In the southern sub-area, age classes associated with non-intense infestations have a similar distribution to the overall distribution of forest age. However, the intense infestations rarely occur when trees are young and are most frequently associated with age class 8. Clearly, host age selection is not random. In 2001, almost all intense infestations occurred in age class 8. In 2002, most intense infestations were associated with age class 8 forests, although intense infestations were increasingly found in younger forest age classes. In the south, mountain pine beetles first appeared in large quantities in 2000. Therefore, in 2001 many age class 8 trees, which are the hosts preferred by mountain pine beetle, were available. By 2002, fewer age class 8 trees were available, so the mountain pine beetle began infesting younger age classes.

Kernel-estimated density surfaces can also be used to explore spatial-temporal patterns in mountain pine beetle infestations. By differencing surfaces, we can represent temporal change in the spatial pattern of mountain pine beetle infestations and investigate methods of defining meaningful change. Here we define meaningful change in mountain pine beetle infestations using the 5% tails of the distribution of a surface of change (e.g., surface 2002 – surface 2001). An example is shown in Figure 7 where change is represented between 2001 and 2002. While this definition allows the threshold for significant or meaningful change to vary depending on mountain pine beetle activity in the whole area, 10% of the infested area is always considered to have changed meaningfully. From the perspective of forest monitoring, this method is useful as it is flexible enough to identify areas of change relative to resources available for mitigation. For instance, if resources are available to treat 25% of the affected Forest District, the thresholds can be changed to identify the most impacted 25%. To better understand why change varies over space, change will be compared with landscape characteristics and methods of treating mountain pine beetle infestations.

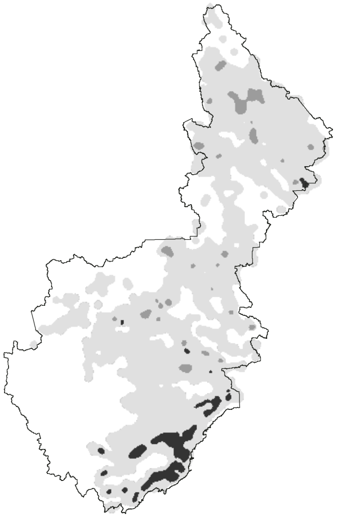


Figure 7. Change between 2001 and 2002. Significant change is defined as values in the 5% tails of the distribution of a surface of change. Black areas represent locations where mountain pine beetle activity has increased significantly, dark gray areas represent a significant decrease, and light gray areas represent locations of change that are not significant.

Comparing Observed Data with Mountain Pine Beetle Model Expectations

Quantitative analysis of spatial patterns generally involves the comparison of an observed spatial pattern to some expected pattern. Most often, the expected pattern is generated assuming a process of complete spatial randomness (Upton and Fingleton 1985). However, due to aggregative behaviour and mountain pine beetles' need of lodgepole pine, it is unlikely that the spatial pattern of infested trees is random. Thus, comparing observed patterns in infestation data to a random expectation seems inappropriate.

A more suitable expectation of spatial pattern may be generated based on the present understanding of mountain pine beetle behaviour. For example, we know that the location of trees infested by mountain pine beetles in the current year is not random, but rather related to the site of infested trees in the previous year. An expectation that incorporates knowledge of mountain pine beetle behaviour will allow statistical significance to be used to identify hot spots or locations where the pattern is unexpected based on the current understanding.

The Shore and Safranyik forest risk model (Shore and Safranyik 1992; Shore et al. 2000) calculates the probability that forests will be infested based on forest characteristics, beetle location, and population size. The probability of risk derived from this model may be used to condition the randomization of attributes within a specific time period, thereby allocating more infestations to locations with a higher likelihood of risk. Based on this model, we can identify hot spots, or locations where the spatial pattern of mountain pine beetle infestations is unexpected.

As hot spots will be detected using randomizations conditioned on the forest risk model, the value of our quantitative analysis is directly related to the quality of the forest risk model, which, in turn, is impacted by the quality of the input data. Inputs to the forest risk model include forest inventory data and mountain pine beetle aerial survey data, both of which are prone to error. Consequently, it will be useful to investigate methods to incorporate data uncertainty when modelling forest risk.

There are two sources of uncertainty that are of concern when working with forest inventory data. First, the attribute values attached to different forest characteristics tend to be uncertain. Secondly, in some instances, the input parameters required for modelling forest risk are not provided in the forest inventory data. As no other data source exists, surrogate input parameters available from the forest inventory data must be used and the impact of this should be investigated. There are also two important considerations regarding error in the mountain pine beetle data. The first is the spatial and attribute error discussed above. The second issue is that some areas are treated to mitigate mountain pine beetle populations, while others are not. Two mountain pine beetle populations of similar size, one treated and the other not, will likely have different impacts on forest risk. How to deal with these sources of uncertainty when modelling forest risk will be considered.

Investigating Hot Spots

Hot spots represent areas that are poorly predicted, based on our present understanding of mountain pine beetles. Therefore, investigations into the characteristics underlying hot spots may provide new insights as to why mountain pine beetle activity in some areas is poorly predicted. Landscape characteristics of particular interest include elevation, aspect, slope, forest age, and stand species compositions.

Conclusion

Understanding landscape-scale spatial and spatial-temporal processes of mountain pine beetle infestations is important when modelling and predicting mountain pine beetle behaviour. New, large area data sets provide a vehicle for understanding spatial processes through the exploration of observed spatial patterns. Knowledge of the error and information content of aerial survey data is essential when using such data for spatial pattern analysis. Improved visualization, which includes the incorporation of data uncertainty, allows examination of spatial and spatial-temporal patterns. Quantitative analysis undertaken by comparing observed spatial patterns to those expected, based on our current understanding of mountain pine beetle behaviour, allow hot spots, or areas where the spatial pattern does not meet our expectation, to be identified. By investigating the landscape characteristics underlying hot spots we hope to generate new insights that can be meaningfully combined with ongoing mountain pine beetle modelling.

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Phytosanitary Risks Associated with Mountain Pine Beetle-killed Trees

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Abstract

The risks associated with transporting mountain pine beetle-killed trees outside of the infestation area are being determined. Concerns regarding log movement within Canada focus on the mountain pine beetle, *Dendroctonus ponderosae* (Hopkins) and its potential for establishment in other parts of Canada. Other secondary pests that may be associated with trees killed by mountain pine beetle, including insects, fungi and nematodes, are being identified and evaluated for their potential to be of phytosanitary concern in international trade.

Introduction

Trees killed by *Dendroctonus ponderosae* (Hopkins) and the fungi associated with the beetle will, over time, become host to a variety of organisms including insects, fungi and nematodes. Organisms found in beetle-killed trees will include both those that were present prior to beetle kill (nematodes, stain and decay fungi, yeasts, bark and wood boring beetle species including mountain pine beetle) and those that infest trees after tree death. Some of these organisms may pose a threat to forests outside of the province of British Columbia (BC) and their inadvertent movement through domestic or international trade of logs, lumber or other wood products could result in damage to forests in other areas and provoke phytosanitary controls that jeopardize market access of BC wood products. Through current industry practices and market expectations, most lodgepole pine harvested in central BC is milled into lumber and kiln-dried. Some wood is exported as material for log home building or as raw logs to offshore markets. For example, more than 300,000 m^3 of logs (species unspecified) were exported to Korea in 2002 (BC Ministry of Forests, unpublished statistics). However, as the large volume of mountain pine beetle-killed timber enters the system, there are expected to be shifts in processing methods and wood marketing, resulting in untreated wood of potentially high phytosanitary risk leaving the province. It is critical that wood destined for international markets be free of potentially damaging agents. The results of this study will provide the

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first data available to support market access for wood products derived from mountain pine beetle-killed timber for current and future outbreaks.

Domestic Risk Assessment

The objective of the domestic risk assessment is to assess the risks associated with the movement of mountain pine beetle-killed wood to markets within Canada. Currently, two Canadian provinces, Alberta and Saskatchewan, have enacted legislation to prevent the movement of lodgepole pine logs with bark-on from BC. The concerns raised by these provinces are largely based on the recognition that jack pine (*Pinus banksiana* Lamb.), a host of *D. ponderosae*, is a major component of the boreal forest east of the Rockies and overlaps in distribution with lodgepole pine in Alberta. Based on historical records, mountain pine beetle outbreaks have been observed west of the Rockies (with one outbreak in the Cyprus Hills in southeastern Alberta, southwestern Saskatchewan and some activity in the foothills of western Alberta). The eastward restriction of the beetle's distribution is thought to be a function of climate; however, there is speculation that with changes in climate, the beetle could move further east into the jack pine forest.

Methods

The risk analysis is currently underway and will follow the protocol used by the Canadian Food Inspection Agency, which includes identifying high risk pathways, likelihood of establishment in new ecosystems (under current and modified climate change scenarios), predicted economic and ecological consequences of establishment, and potential domestic and international trade implications. The risk assessment will conform to international standards (IPPC 2003) and will be defensible in international law.

International Risk Assessment

The objective of the international risk assessment is to determine population levels of insects, fungi and nematodes in beetle-killed timber and to provide advice to the BC forestry export sector regarding the risks of incorporating untreated wood in international trade.

Methods

Secondary pest populations are being determined by isolating organisms from wood samples collected from within the beetle-infested area. Trees are sampled from three mountain pine beetle attack categories: green, red, and grey attack. The green and red attack trees cover the range of ages that timber is expected to be salvaged from and thence enter the production stream. At each sample location, 10 trees in each of the sample categories are felled. From each tree, 1 m bolts are taken from the base and upper stem (below crown) and returned to Canadian Forest Service, Pacific Forestry Centre for insect rearing. Middle and upper stem samples for both insects and fungi are being taken in order to determine secondary organisms associated with mountain pine beetle-killed trees; their incidence, and hence quarantine significance. Additionally, 30 cm bolts immediately adjoining the 1 m bolts are cut for fungal isolation and returned to the University of BC. Moisture and pinewood nematode (*Bursaphelenchus xylophilus*) samples will be obtained from three 5-cm discs cut from the base, middle and upper stem.

Log bolts are placed in rearing cages constructed for insect emergence and held for up to one year. Insects isolated from sampled trees are identified using the laboratory rearing facilities and insect collection at Pacific Forestry Centre in Victoria.

Decay and blue stain fungi are being isolated and identified using both morphological and molecular identification methods. A minimum of three blue stain isolations are cultured from each bolt and maintained at the University of BC. Morphological identifications based on cultural characteristics are verified using DNA sequence information (beta-tubulin gene, ITS-1). Decay fungi are isolated and identified using similar techniques.

Nematodes are extracted from both wood (three 5-cm discs/tree for a total of 90 extractions/site) and insects (*Monochamus* spp.) emerging from sample wood using a modified Baermann funnel technique. DNA was obtained from extracts using reversible adsorption of DNA to paramagnetic beads. The initial approach was to use a species-specific probe (Abad 2000). However, this probe was found to cross-hybridize with DNA from lodgepole pine. Therefore, a new approach was adopted using polymerase chain reaction techniques (PCR). We designed PCR primers for a microsatellite sequence specific to *Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickle (pinewood nematode). PCR amplification of this sequence was used to screen samples for the presence of *B. xylophilus*. The PCR approach was successful in amplifying *B. xylophilus* DNA, but not lodgepole pine DNA. Preliminary experiments were conducted to determine the efficacy of the PCR amplification in varying mixtures of *B. xylophilus* and a related nematode, *B. mucronatus*. Mamiya and Enda DNA from *B. xylophilus* cultures was used as a control in all experiments and in extraction identifications to confirm the presence of *B. xylophilus*. Preliminary results indicate that this method can be used to detect a single individual nematode in a wood sample. Extractions of live nematodes from wood positive for *Bursaphelenchus xylophilus* will be used to determine the population dynamics of nematodes in trees killed by mountain pine beetle.

Conclusions

This project is in its first year of establishment. Log bolts have been collected from five sites throughout the infestation area including: Princeton, Cranbrook, Radium, Riske Creek and Little Fort.

Eric Allen is a research scientist with the Canadian Forest Service, Pacific Forestry Centre.

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Impact of Mountain Pine Beetle on Stand Dynamics in British Columbia

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Abstract

A three-year research project was established in 2001 to examine the impact of mountain pine beetle on stand dynamics in British Columbia and southern Alberta. The project had three components: assessments of the effects of mountain pine beetle on stand dynamics; projection of mountain pine beetle impacts on stand and fuel dynamics with Prognosis^{BC} and the Fire and Fuels Extension; and estimation of mountain pine beetle outbreak and fire return intervals.

Permanent sample plots were re-measured after 10-19 years since establishment in 31 mountain pine beetle-affected stands in the Chilcotin Plateau, Kamloops and Nelson Forest Regions, and Kootenay and Waterton Lake National Parks. New permanent plots were established in 15 currently affected stands in Manning Provincial Park and Entiako Protected Area.

In total, 1631 lodgepole pine and non-host tree species cores were used to determine growth-release periods. In total, 272 tree cross-sections were examined and cross-dated for mountain pine beetle scars with 127 identified. This paper provides a summary of the project results.

Introduction

Lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) dominated stands comprise some 14 million ha of forestland in British Columbia (BC), roughly 25% of the provincial timber supply (British Columbia Ministry of Forests 1995). Between 1959 and 2002 a cumulative area of approximately 4.7 million ha of pine-leading stands have been affected by mountain pine beetle (*Dendroctonus ponderosae* Hopk.) (Taylor and Carroll 2004). The current outbreak was estimated to cover 4.2 million ha in 2003 (Ebata 2004).

A variety of silvicultural tools and management strategies can be used to reduce the risk of timber losses to mountain pine beetle before and during an infestation. Following infestation, salvage logging

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has been the main practice to recover some residual value from affected stands. Prescribed burning has also been attempted on a limited scale to renew lodgepole pine stands in protected areas. Because the amount of timber killed in the present outbreak is beyond the industrial capacity to extract and process, and because a large proportion of affected stands occur in protected areas such as Tweedsmuir Provincial Park, a significant proportion of affected stands will not be salvage logged in the short term.

An understanding of the impact of mountain pine beetle outbreaks on the growth and yield of surviving trees in residual stands, regeneration, woody debris dynamics and fire potential is needed for managers to make better decisions regarding management of residual mountain pine beetle affected stands.

Disturbance and Stand Structure

Lodgepole pine is a seral species in many ecosystems, but can be a self-perpetuating climax species where climate, disturbance, and edaphic factors limit the regeneration of other species (Agee 1993). Although lodgepole pine produces both serotinous and non-serotinous cones, permitting successful regeneration in either the presence or absence of fire, it is considered to be a fire dependent species (Lotan et al. 1985). The landscape level age-class structure of lodgepole pine can be described as a mosaic of even-aged and uneven-aged patches intermingling in space and time (Agee 1993). Whether a given patch or stand is even-aged or uneven-aged depends upon the disturbance history of the site: in the absence of fire, consecutive mountain pine beetle attacks in the stand contribute to the conversion of an even-aged stand to an uneven-aged stand (Roe and Amman 1970). Non-stand-replacement fires (i.e., surface fires) also lead to the creation of uneven-aged stands (Agee 1993), whereas high-intensity stand-replacement fires create even-aged stands. Lundquist and Negron (2000) developed a conceptual model of stand development in ponderosa pine that classified disturbance agents into two basic ecological functions. Firstly, new stands developed as a result of fire, wind, and epidemic populations of mountain pine beetle killing trees over large areas. Secondly, small-scale canopy gaps influenced stand development and structure due to a wide variety of factors killing small numbers of trees.

Impacts of Mountain Pine Beetle on Stand Dynamics

Forest stand dynamics are the processes of mortality, regeneration and growth. Heath and Alfaro (1990) examined a mixed Douglas-fir/lodgepole pine stand near Williams Lake, BC, where mountain pine beetle killed 76% of the pine in the early 1970s. In response to this natural thinning treatment (Peterman 1978), the radial growth rate of residual Douglas-fir was enhanced for 14 years after mountain pine beetle attack, suggesting the possibility that stand volume lost by the mortality in lodgepole pine might be compensated for by increased Douglas-fir growth by the time harvest rotation was reached. Release of remnant Douglas-fir and spruce post-epidemic was also observed in Wyoming and Idaho by Cole and Amman (1980). It is unknown whether there is release of surviving lodgepole pine in stands attacked by mountain pine beetle.

It is evident that the mortality imposed on lodgepole pine forest stands by mountain pine beetle attacks should influence fire behaviour: mountain pine beetle kills trees, changing both the quantity and spatial distribution of fuels in the forest. What is lacking is a link between the mortality rate of trees in lodgepole pine forests under attack by mountain pine beetle and the subsequent fuel loading of the stand over time. Mitchell and Preisler (1998) found that in unthinned lodgepole pine stands in southern Oregon, mountain pine beetle-killed trees began to fall to the forest floor after 5 years, with 50% of trees falling within 9 years, and 90% fallen by 14 years post-attack. Johnson and Greene (1991) found that it is possible to make reasonable post-fire disturbance estimates of tree-fall rates by examining trees already on the ground using equations of decomposition rates. Given the mass density of downed trees, rough estimates of the actual time of fall could be determined. They did not examine mortality due to mountain pine beetle attack. Using a retrospective approach, Turner et al. (1999) found that high severity mountain pine beetle attacks (>50% of trees killed) increased crown fire probability, but intermediate or light levels of mountain pine beetle severity reduced crown fire probability during the wildfires of 1988 in Yellowstone National Park.

Stuart et al. (1989) and Mitchell and Preisler (1998) noted that the structure of lodgepole pine forests in central and southern Oregon were uneven-aged, with distinct episodic pulses of regeneration strongly correlated to mountain pine beetle outbreaks and fire. The magnitude of the regeneration pulse was a function of disturbance intensity. Delong and Kessler (2000) investigated the ecological characteristics of mature forest remnants left by wildfire in Sub-Boreal landscapes near Prince George, BC, and found some remnants had an uneven-aged, episodic pattern of lodgepole pine regeneration. Stuart et al. (1989) found that mountain pine beetle outbreaks were preceded by a decrease in the mean annual increment of the stand.

Projecting Mountain Pine Beetle Impacts on Stand Structure and Dynamics

Mountain pine beetle infestations result in variable mortality and create uneven-sized and mixed species stands across a broad ecological range in BC. Models are needed to project long-term impacts of mountain pine beetle on forest stand dynamics; fuels succession, and fire behavior potential. Models could help determine if release of other tree species maintained stand productivity through to scheduled harvest, the time course of fall down of mountain pine beetle-killed trees, and the structure and volume of the final harvest stand.

Taylor et al. (1998) used Prognosis^{BC} (Snowdon 1997) and the Fire and Fuels Extension (Beukema et al. 1997, 2000; Reinhardt and Crookston 2003) to project changes in fine and coarse woody fuels and potential fire behavior in relation to stand development for five locations in the dry forests of southern BC interior. Prognosis^{BC} (version 3.0) has been calibrated for much of southern BC interior (Zumrawi et al. 2002) and linked to the most recent version of the Fire and Fuels Extension may provide a useful framework for the modelling ecosystem development following mountain pine beetle attack.

In 2001, we began a project to determine the impact of mountain pine beetle on stand dynamics. This paper provides a summary of the project results.

Objectives

The mountain pine beetle stand dynamics project had three main objectives:

- Determine the effects of mountain pine beetle on stand dynamics (i.e., mortality, growth, structure, composition, regeneration, and fine and coarse woody debris accumulation rates) across a range of biogeoclimatic zones, stand conditions, fire regimes, mountain pine beetle outbreak frequency;
- Determine fire and mountain pine beetle outbreak recurrence; and
- Demonstrate/test the Prognosis^{BC} and Fire and Fuels Extension module to project stand dynamics (including fine and coarse woody debris), stand mountain pine beetle susceptibility, and potential fire behavior.

Methods

Impact of Mountain Pine Beetle on Stand Dynamics

Several researchers established plots to examine the initial impact of mountain pine beetle on stand structure during past outbreaks at a number of locations in BC and Alberta:

- Between 1935 and 1942, George Hopping (Vernon Entomology Laboratory) established 10 plots (seven 1 acre and three ¼ to 1 acre plots) in an infestation in Kootenay National Park. In 1993, Malcolm Shrimpton sampled four plots in the general area of some of the 1935 and 1942 plots.

- In 1980, Ben Moody (Canadian Forest Service, Northern Forestry Centre) established 25 plots in five stands in Waterton Lakes National Park.
- In 1987, Terry Shore (Canadian Forest Service), established 10 plots in each of 30 stands in the Chilcotin, five stands in the Kamloops Region and six stands in the Nelson Forest Region.
- In 1993, Terry Shore also established 10 plots in six stands in Kootenay National Park after an outbreak in the late 1980s and early 1990s.

In this component of the project we relocated, and if possible, re-measured these sample plots. In addition, we established new permanent sample plots in the current mountain pine beetle outbreak in order to extend the geographic and ecological range of the study (Fig. 1). The numbers of plots and characteristics are given in Table 1. We were able to relocate and re-measure all of the plots established by Moody and Shore in Waterton Lakes and Kootenay National Parks, respectively. We also relocated and re-measured 15 stands in the Chilcotin Plateau, four stands in the Kamloops Forest Region and one in the Nelson Forest Region; 21 of the original stands were heavily disturbed by logging or wildfire and could not be re-assessed. We did not re-measure the stands assessed by Hopping because they had been extensively disturbed and because we did not have the original field records. One stand in Kootenay National Park was not relocated.

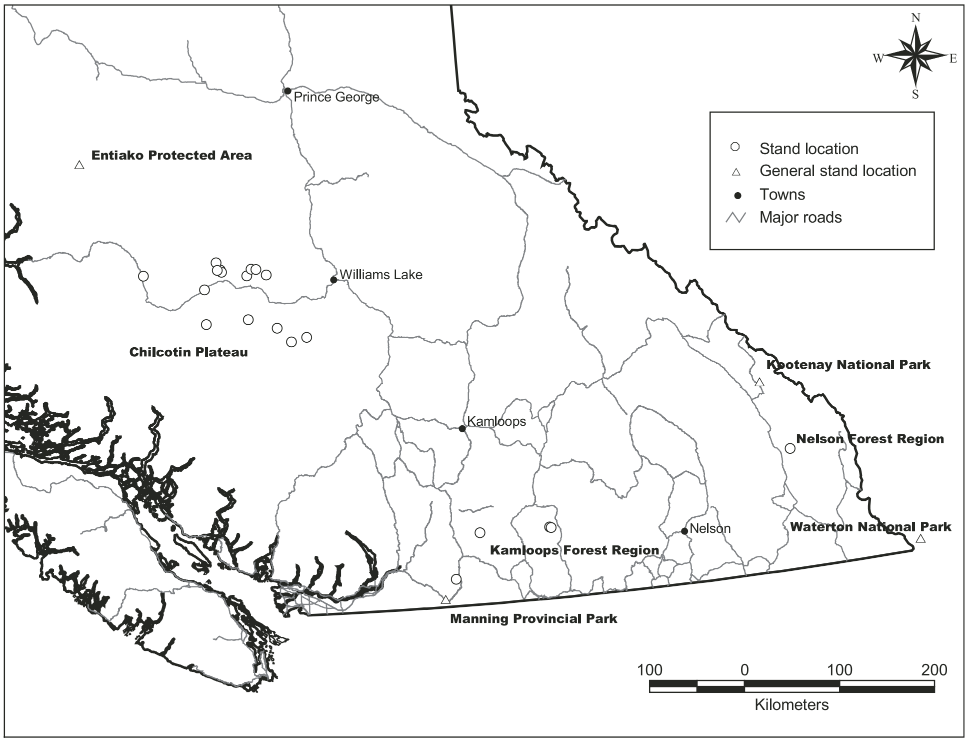

Figure 1. Location of mountain pine beetle stand dynamics project stands in BC sampled from 2001 to 2003.

In general, field data collection methods necessarily followed those used in the original studies. Prism plots were used to determine mountain pine beetle impacts on the dominant and co-dominant trees, while fixed area plots were used to sample pole-sized trees and regeneration.

Pre-outbreak standing live volume cannot be estimated simply by adding average standing dead volume in 1987, killed by mountain pine beetle, to the standing live volume. It is important to note that estimates of the impact of the beetle on stand density and volume in this study are snapshots in time.

We can state with accuracy what proportion of trees standing at the end of the outbreak were killed by mountain pine beetle, but this is a different estimate than if we want to relate mortality to initial stand conditions at the time the outbreak began. All stands were sampled using prism plots. Each tree represents a different sized plot, whose size is directly proportional to its diameter at breast height (DBH) included in the sample. A dendrochronological study will be providing data to determine the year each beetle-killed tree, sampled in 1987, died. This information will assist in knowing the time the epidemic began and the time period surviving trees grew before being sampled in 1987. For example, the potential error for pre-outbreak basal area could range from 10% to 21%, assuming most trees were killed in 1984 and over a 10 year period starting in 1977, respectively (Stockdale et al. 2004). In addition, if the surviving trees have grown prior to sampling in 1987, they would have occupied a smaller plot than they do today (Stockdale et al. 2004). A certain proportion of these trees, therefore, would have been too small to be included in a sample taken at the beginning of the outbreak. Without knowing the distance each tree is from the plot centre, we cannot determine precisely which of these trees in each sample should be removed from the sample pool. By not removing these trees from the sample pool, any estimates of pre-outbreak stand conditions would be overestimated in terms of density, basal area and volume, as we would be including too many trees in the analysis. Therefore, we will not provide estimates of pre-outbreak stand basal areas, volumes and densities in this paper.

In addition, coarse woody debris (>7 cm diameter) and fine fuels (≤7 cm diameter) were sampled along a 30 m randomly oriented transect in each plot. For coarse woody debris, the diameter and species of each piece, intersected by the transect tape, was recorded. Each piece was assigned to one of five classes of decomposition. Fine fuels were tallied along the first 25 m of the transect line using the method by Trowbridge et al. (1986).

In addition to the stand measurements, five pole-sized host and five non-host (if available) trees were cut at ground level in each of two DBH classes (0 - 3.9 cm and 3.9 - 7.5 cm). In the laboratory, 217 cross-sections (at ground level and 1.3 m - DBH) were sanded and examined for evidence of growth release. A release was defined as a period where tree rings showed an abrupt and sustained change in width, as judged by an experienced observer.

In 2002, ten study plots were established in each of five stands in Manning Provincial Park and eight study plots in each of ten stands in the Entiako Protected Area and Tweedsmuir Park. Protected areas were chosen so there would be a higher chance they could be re-measured in the future. Study stands were located in areas having recently experienced severe levels of mountain pine beetle activity.

Estimating Past Fire and Mountain Pine Beetle Outbreak Recurrence

The occurrence of past fire and mountain pine beetle outbreaks was inferred from release periods evident in tree ring cores and supplemented where possible with direct evidence from fire and mountain pine beetle scars in tree sections.

Increment cores were collected from lodgepole pine on all plots sampled, as well as from non-hosts (tree species not normally attacked by mountain pine beetle), if available. The cores (one per tree) were extracted at DBH with an increment borer parallel to the slope contour. The total number of cores collected in 68 stands was 1,337 lodgepole pine and 365 non-host tree species (Table 1).

Table 1. Number of mountain pine beetle stands established and re-measured and lodgepole pine and non-host species increment cores collected in BC and Alberta.

		Established		Re-measured		No. of cores	
Sample Location	Biogeoclimatic Sub-Zone	Year	No. of stands	Year	No. of stands	Lodgepole pine	Non-host species
Chilcotin Plateau	SBPSxc IDFdk4 MSxv	1987	30	2001	15	623 (1987) 258 (2001)	8 (1987) 30 (2001)
Kamloops and Nelson Forest Regions	MSdk IDFdk2 IDFdm1 MSdm1	1987	11	2001	5	38	49
Waterton Lakes National Park	Not available	1980-3	5	2002	5	38	43
Entiako Protected Area	SBSdk	2002	10			152	42
Manning Provincial Park	ESSFmw IDFdk2	2002	5			95	67
Kootenay National Park	Not available	1993	6	2003	5	94	94
Bull Mountain	IDFdk3	1975 1985	1	2002	1	39 (2002)	32 (2002)
Total			68		31	1337	365

Increment cores were collected in 2002 from lodgepole pine and Douglas-fir trees on Bull Mountain, near Williams Lake. The BC Ministry of Forests had surveyed this area in 1975 and 1985 to establish the amount and condition (alive or dead) of the overstory and understory. Cores were also collected from a nearby site that had not been affected by mountain pine beetle to confirm that any growth release detected was due to a thinning effect and not to a coincident period of abnormally favourable weather (Heath and Alfaro 1990).

Ring-width measurement was conducted using a Windendro® tree-ring measuring system and a Measu-Chron incremental measuring system. Chronologies were constructed using cross-dated ring-width series that were standardized using methods by Eisenhart and Veblen (2000). The standardized ring-width series were used to identify canopy disturbances (Veblen et al. 1991a). Each chronology was visually inspected for growth release that might indicate a mountain pine beetle outbreak. A growth release was called a mountain pine beetle release if it was abrupt and sustained over several years. The onset of a growth release was a year that exhibited a 50% increase with respect to the mean ring width of the previous five years. The end of a release was defined by the year when rings returned to pre-release levels. Thus, the start and end of the release was compared only with the tree-ring indices that directly preceded the release and not to the whole chronology. Releases that lasted less than 5 years were not used based on a similar method for detecting release in Engelmann spruce (*Picea engelmannii* (Parry) Engelm.) trees following spruce bark beetle outbreaks in Colorado (Veblen et al. 1991a, b).

Overall, but especially in the Chilcotin Plateau, it was difficult to find sufficient non-host trees to build reliable chronologies for species other than lodgepole pine. Four non-host chronologies were built for the Chilcotin Plateau and Kamloops and Nelson Forest Region samples. Non-host chronologies for other sampling locations are currently being completed. Non-host chronologies were examined to determine if periods of release in non-host species were synchronous with periods of release in lodgepole pine.

Recurrence of Mountain Pine Beetle and Fire Using Scar Dates

Both low intensity surface fire and mountain pine beetle strip attacks, which don't kill trees, leave scars which can be used to determine the year of disturbance. The characteristics we used to distinguish fire from mountain pine beetle scars are presented in Table 2. These were based on differences between fire and mountain pine beetle scars reported in Mitchell et al. (1983) and Stuart et al. (1983) supplemented with our own field experience.

A number of cross-sections were collected when the permanent sample plots were established in the Chilcotin. In addition, we examined a number of cross-sections that other researchers collected in the Chilcotin for evidence of mountain pine beetle attack (Fig. 2).

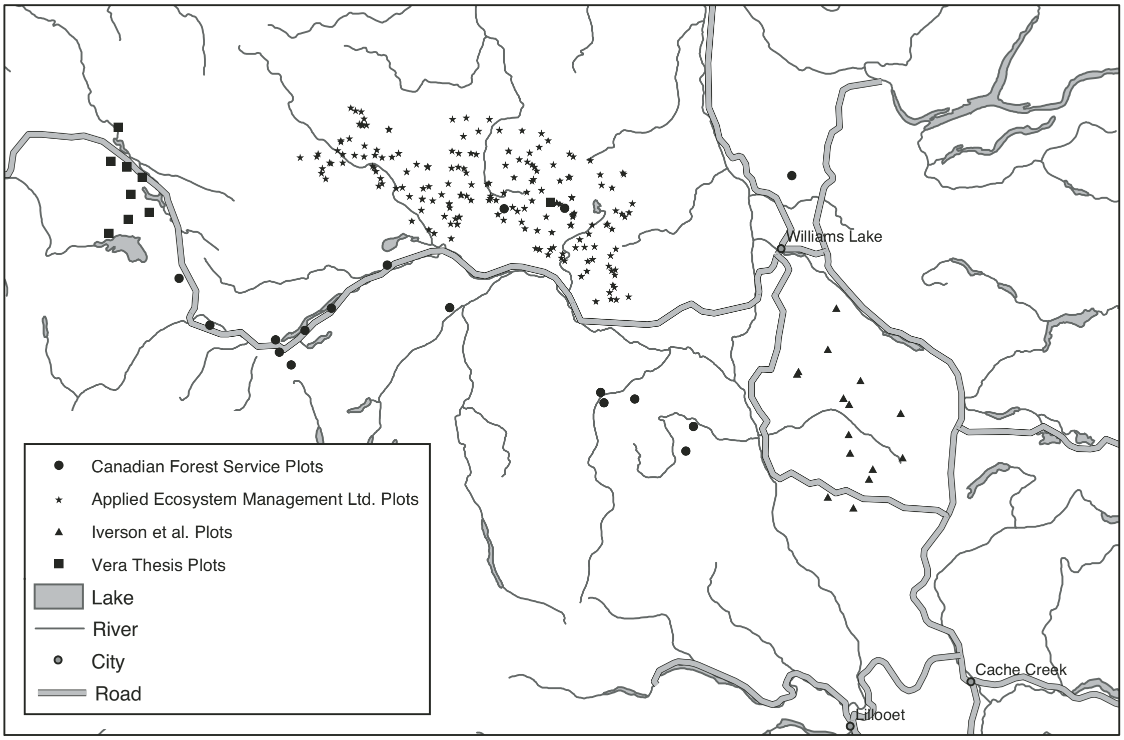

Figure 2. Sample location of fire and mountain pine beetle scarred discs and agency or individual that collected the samples.

The fire and mountain pine beetle disturbance dates determined from scarring allowed some limited analysis of the potential interactions of fire and mountain pine beetle in the Chilcotin Plateau. No cross-sections were available for the other sample areas. The number of scars and locations are given in Table 3. Canadian Forest Service cross-sections were cross-dated using the plot (or plot closest to) master chronologies completed in 2001 to 2002. Cross-sections from the Applied Ecosystem Management Ltd. project (2002) and Paula Vera's master's thesis (2001) were statistically cross-dated using a revised master chronology developed from the thesis. Marker years from these two projects were consistent with each other. Visibly narrow rings almost always present on each sample were dated at 1869, 1922, 1931 and 1951. Cross-sections from the Iverson et al. (2002) project were cross-dated using a master chronology already developed for that project.

In total, 272 cross-sections were examined and cross-dated for mountain pine beetle scars (Table 3). A total of 127 mountain pine beetle scars were identified from these cross-sections.

Table 2. Characteristics used to distinguish mountain pine beetle scars from fire scars.

Fire Scar	Mountain Pine Beetle Scar
Catface on bottom of tree without bark	Strip kill often has bark remaining on face
No blue stain fungus	Boring dust and vertical resin on scar face
Subsequent fires after the first one tend to be on the same side of the tree, even with different spread directions on flat ground	Mountain pine beetle galleries visible on dead section of tree
Usually no bark present on older scars, if present, lacking exit holes (Mitchell et al. 1983)	Can be several scars around tree perimeter in same annual ring
Usually only one scar in the same annual ring	Visible entry points (if bark still on) and blue stain fungus in dead cambium area
Generally scars do not occur in consecutive years	No charcoal on tree
	Can have scars in consecutive years

Table 3. Number of cross-sections examined.

Source	Biogeoclimatic Sub-Zone	Number of cross-section examined
Canadian Forest Service (this project)	SBPSxc IDFdk4 MSxv MSdk IDFdk2 IDFdm1 MSdm1	67
Applied Ecosystem Management Ltd. (2002)	SBPSxc IDFdk4 SBPSdc SBPSmk	83
Iverson et al. (2002)	IDFdk3	26
Vera (2001)	SBPSxc	96
Total		**272**

Prognosis^{BC} and Fire Fuels Extension Module Projections

A total of 90 simulations using Prognosis^{BC} 3.0 and the Fire and Fuels Extension are being conducted to project the changes in stand structure, fuel loading and fire behavior for 15 stands in the Chilcotin Plateau, 10 in the Entiako Protected area, and 5 in Manning Provincial Park. As previously described, measurements for the Chilcotin Plateau stands were taken in both 1987 and 2001, resulting in two sets of stand data for this area. Each of the stands (including both data sets for the Chilcotin Plateau) is projected for two different scenarios: with mountain pine beetle mortality included and assuming no mountain pine beetle mortality. Simulations are done using 5-year time steps for 30-year projections.

The stand visualization system (McGaughey 1997) was also used to generate graphic images of each stand to depict stand conditions which is represented by a list of individual stand components, e.g., trees, shrubs, and down material. In addition, the mountain pine beetle susceptibility rating developed by Shore and Safranyik (1992) is being calculated for the sample stands, prior and post mountain pine beetle attack, to determine how stand susceptibility to mountain pine beetle attack changes with stand succession.

Results

Impact of Mountain Pine Beetle on Stand Dynamics

Stand dynamics results available to date are summarized in Table 4a, 4b, and 4c.

Table 4a. Post-outbreak and re-measured live tree volume and density by study area.

	Live tree volume (m^3/ha) > 7 cm DBH				Live tree density (stems/ha) > 7 cm DBH			
Study area	Post Outbreak	n	Re-measured	n	Post Outbreak	n	Re-measured	n
Kamloops	193.1 (24.2)	5			555 (28)	5		
	218.2 (29.9)*	4	150.1 (24.5)	4	588 (51)*	4	377 (84)	4
Nelson	203.9 (18.9)	6			780 (152)	6		
	159.3 (-)*	1	163.9 (-)	1	441 (-)*	1	349 (-)	1
Chilcotin	88.7 (8.5)	30			758 (52)	30		
	87.2 (11.3)*	15	68.1 (8.2)	15	857 (84)*	15	546 (57)	15
Manning	195.5 (34.0)	5	-		616 (60)	5	-	
Entiako	63.7 (11.0)	10	-		645 (125)	10	-	

*1987 estimates for post-outbreak stands that were re-measured 2001.
( ) Standard error of the estimate.
n Number of stands.

Table 4b. Post-outbreak and re-measured standing dead volume and density by study area.

	Standing dead volume (m^3/ha)				Standing dead density[1] (stems/ha)			
Study area	Post Outbreak	n	Re-measured	n	Post Outbreak	n	Re-measured	n
Kamloops	167.0 (16.9)	5			393 (58)	5		
	171.1 (21.0)*	4	96.7 (28.1)	4	370 (66)*	4	273 (72)	4
Nelson	91.8 (16.6)	6			316 (83)	6		
	64.4 (-)*	1	12.1 (-)	1	291 (-)*	1	120 (-)	1
Chilcotin	62.7 (5.9)	30			318 (31)	30		
	52.6 (6.6)*	15	17.4 (3.4)	15	289 (34)*	15	140 (26)	15
Manning	256.8 (33.1)	5	-		528 (136)	5	-	
Entiako	182.8 (24.4)	10	-		791 (114)	10	-	

[1] Includes mountain pine beetle green attack at sampling time.
*1987 estimates for post-outbreak stands that were re-measured 2001.
( ) Standard error of the estimate.
n Number of stands.

Table 4c. Post-outbreak and re-measured pole-sized tree and regeneration density by study area.

	Live tree density (stems/ha[1]) <7 cm DBH >1.5 m height				Regeneration (stems/ha) ≤ 1.5 m height			
Study area	Post Outbreak	n	Re-measured	n	Post Outbreak	n	Re-measured	n
Kamloops	-		570 (126)	4	-		2111 (788)	4
Nelson	-		385 (-)	1	-		8344 (-)	1
Chilcotin	652 (88)[1]	15	1422 (192)	15	4970 (540) 4687 (857) *	30 15	4538 (972)	15
Manning	658 (195)	5	-		1364 (274)	5	-	
Entiako	944 (390)	10	-		777 (204)	10	-	

[1] 1987 estimate for pole-sized tree density based on 2001 sampled trees that were aged at DBH to determine if they met the criteria for pole-sized trees in 1987.

*1987 estimates for post-outbreak stands that were re-measured 2001.

( ) Standard error of the estimate.

n Number of stands.

Chilcotin Plateau

Lodgepole pine is the most common tree species. A unique multi-age and size stand structure exists as a result of lodgepole pine being able to regenerate under its own canopy, and past multiple mountain pine beetle outbreaks and surface fires (Fig. 3).

Figure 3. Photograph of Stand 125; plot 2 in the Chilcotin Plateau illustrating the multi-sized lodgepole pine stand structure. A time period of 16 years has elapsed since the 1970s/1980s mountain pine beetle outbreak collapsed in the winter of 1985.

From 1987 to 2001, post-outbreak standing live tree volume and density was reduced, for the 15 stands re-measured in 2001, by 22% and 36% respectively, although there was significant variation due to differences in stand structure (Table 4a). Despite an increase in growth rates in smaller diameter residual trees, there still was a reduction in standing live volume and tree density from 1987 to 2001. This reduction in standing live tree volume was mainly the result of additional mountain pine and *Ips* beetle mortality that occurred from 1987 to 2001. Standing dead tree volume (caused by mountain pine beetle and other causes) was reduced on average by 67% and tree density by 52% due to fall down (Table 4b). Mountain pine beetle-induced mortality occurred mainly in the larger diameter trees.

In 2001, pole-sized tree density was two times higher than in 1987, based on a 1987 tree density estimate using 2001 sampled trees that were aged at DBH to determine if they met the criteria for pole-sized trees in 1987 (Table 4c). Lodgepole pine and aspen were the most common pole-sized tree species. Pole-sized trees varied in their response to a reduction in canopy closure by DBH class, stand location, species, and time since the last mountain pine beetle outbreak. Data analysis has not been completed to determine if mountain pine beetle-induced mortality levels among stands is related to pole-sized tree release, as well as, the pole-sized tree age.

Pole-sized lodgepole pine averaged 48 years old, ranging from 13 to 162 years. The time to reach DBH averaged 30 years in the Chilcotin Plateau. In the 0 - 3.9 cm size class, 21.2% of discs show a response during the 1990s. The 3.9 – 7.5 cm size class showed a lower release rate of 9.2%. Between the late 1970s and 2001, 96.6% of the pole-sized trees had demonstrated a release in growth.

Three historical periods of response in the pole-sized trees sampled in the Chilcotin Plateau were identified. These responses were related to known mountain pine beetle outbreaks in the 1970s, 1980s and 1990s. The first commenced in the early 1970s, lasting long enough to see a response in the tree ring widths in the middle 1980s. A second mountain pine beetle outbreak in the early 1980s resulted in a response in the early 1990s. The most striking response to the outbreak was the release of previously suppressed individuals of all species.

Lodgepole pine seedling density was recorded at the second highest density of all study areas and had similar densities in 1987 and 2001 (Table 4c). There was a minor amount of Douglas-fir, spruce, and sub-alpine fir in 1987. In 2001, Douglas-fir and spruce seedlings were still present in small numbers, sub-alpine fir seedlings had disappeared, and two new species, trembling aspen and willow, had appeared. Of these two new species, trembling aspen was the most abundant.

Mountain pine beetle influence on forest stand dynamics is similar to that of defoliating insects, which are known to improve the growing environment of surviving trees following an epidemic attack (Mattson and Addy 1975; Wickman 1978). In younger stands it is the veteran large-diameter trees that are targets for mountain pine beetle attack. When the older trees die, smaller, younger trees in the stand may respond to the increase in resources available for growth. The mortality of lodgepole pine after a mountain pine beetle outbreak permits the accelerated growth of small Douglas-fir and spruce pole-sized trees or seedlings. This results in a shift towards shade-tolerant species over a longer period of time than if these tree species were part of co-dominant or dominant tree layers. This pattern of disturbance-mediated acceleration of succession also occurs following windthrow of lodgepole pine-dominated stands (Peet 1981; Veblen et al. 1991b).

The importance of accelerated growth as opposed to new seedling establishment following a mountain pine beetle outbreak is a major contrast to what is usually observed following high intensity fires where few trees survive (Veblen 1986; Aplet et al. 1988; Veblen et al. 1991a, b). Stand replacement fires favour regeneration of lodgepole pine and other shade intolerant species that regenerate quickly. However, ecosystem responses following a mountain pine beetle outbreak may be less rapid, because surviving trees may be old and unable to respond and because mountain pine beetle-killed trees do not immediately drop their foliage (Waring and Pitman 1985). This would partially explain the release of pole-sized trees in the Chilcotin Plateau stands occurring throughout the last thirty years.

Fine and coarse woody fuel volume and loading results are presented in Table 5.

Table 5. Fine and coarse woody fuel volume and loading by study area.

Study Area	No. of Stands	Fine Woody Fuel < 7 cm (m^3/ha)	Coarse Woody Fuel > 7 cm (m^3/ha)	Fine Woody Fuel < 7 cm (t/ha)	Coarse Woody Fuel > 7 cm (t/ha)
Kamloops	4	16.8 (4.5)	222 (71)	6.9 (1.8)	91 (29)
Nelson	1	16.4 (-)	70 (-)	6.7 (-)	31 (-)
Chilcotin	15	12.9 (1.3)	66.9 (7.7)	5.3 (0.5)	27.4 (3.2)
Manning	5	10.3 (3.0)	117 (24)	4.3 (1.2)	45 (8.7)
Entiako	10	13.2 (2.1)	57 (14.3)	5.6 (0.9)	23.4 (5.8)
Waterton	4	16.1 (2.0)	103 (37)	6.8 (0.8)	42 (15.0)

( ) Standard error of the estimate.

In 2001, fine and coarse woody fuel loading in the Chilcotin Plateau was the second lowest found in all study areas because of relatively low stand volumes (prior to the 1970s/1980s mountain pine beetle outbreak), growth rates, and tree mortality levels (Table 5). Snag attrition between 1987 and 2001 (caused by mountain pine beetle and other causes) made up most of the coarse woody debris sampled in 2001. If coarse woody debris had been measured in 1987, it would have been much lower than in 2001 since the previous mountain pine beetle outbreak to 1987 was from the 1930s to 1940s. Very few of the fallen trees from the 1930s to 1940s outbreak would have contributed significantly to coarse woody debris in 1987, due to 40-50 years of decomposition time.

Southern British Columbia

Kamloops Forest Region had four out of the five original 1987 sampled stands available for re-measurement in 2001, while the Nelson Forest Region only had one out of the six original 1987 sampled stands. Stand dynamics results for Nelson region stands are therefore limited to one stand, and cannot be used to project results for other areas in the Nelson Forest Region. Mountain pine beetle control and salvage activities accounted for the loss of six stands for potential sampling in 2001.

Although lodgepole pine was still the most common tree species in the stands sampled in the Kamloops and Nelson Forest Regions, many other tree species were present. Douglas-fir and spruce were the most common non-host tree species, especially in the larger DBH size classes, in the Kamloops Forest Region stands. Douglas-fir and western larch were the most common non-host tree species, especially in the larger DBH size classes in the Nelson Forest Region one remaining stand. An occasional fire scar provided some evidence of surface fires in the sampled stands in both regions; stands seem to have most often originated from stand replacement fires (i.e., crown fires). More even-aged multi-species stand structure existed in these regions as compared to the unique multi-age and size stand structure dominated by lodgepole pine in the Chilcotin Plateau.

In the Kamloops Forest Region, standing live tree volume in 1987 was twice as much as in the Chilcotin due to higher site productivity and tree growth in the southern BC interior (Table 4a). Although growth occurred in non-host large diameter species like Douglas-fir and spruce from 1987 to 2001, live volume decreased on average by 31% and tree density by 36%. The reduction in live volume was due to additional mortality that occurred from 1987 to 2001, especially by mountain pine beetle and *Ips* beetles. Standing dead volume (mountain pine beetle) was reduced on average by 44% and tree density by 26% due to snag attrition (Table 4b). The volume and density results by DBH size class indicated that mountain pine beetle mortality occurred mainly in the larger diameter lodgepole pine.

In the Nelson Forest Region, lodgepole pine, by volume, did not dominate species composition as much as in the Kamloops Forest Region. Standing live volume, for the one re-measured stand, increased slightly from 1987 to 2001. Standing dead volume (mountain pine beetle) and tree density was reduced on average by twice as much as in the Kamloops stands (Table 4b). This may indicate a higher fall down rate in the Nelson Forest Region stand than in the Kamloops Forest Region stands although only one stand was used in the Nelson Forest region for this comparison. Douglas-fir and western larch volume, in the 25-30 cm DBH class, was over twice that of lodgepole pine in the Nelson Forest Region stand. This seems to indicate that a shift in species composition away from lodgepole pine in the co-dominant and dominant tree layers has occurred from 1987 to 2001, although there is only one stand to show this shift in species composition.

In 2001, pole-sized tree density in the Kamloops and Nelson Forest Regions was two to three times lower than in the Chilcotin Plateau stands but similar to Manning Provincial Park and the 1987 estimate for the Chilcotin (Table 4c). This pole-sized tree density difference was in spite of a higher tree density (> 7 cm DBH) in the Chilcotin Plateau stands (Table 4a). The pole-sized tree density in Kamloops and Nelson Forest Regions was half that found in the Entiako Protected area (Table 4c), even though the southern interior stands have less crown closure due to mountain pine beetle-induced mortality.

Seedling density in the one Nelson Forest Region stand was the highest recorded for all study areas, 2 times the seedling density in the Chilcotin Plateau (Table 4c). Seedling density in the Kamloops Forest Region was less than half that in the Chilcotin Plateau stands, but was greater than any other study area except the Nelson Forest Region.

In 2001, for both Kamloops and Nelson Forest Region stands re-measured, fine woody fuel loading was similar. Coarse woody debris was three times as high in the Kamloops Forest Region stands than in the one re-measured Nelson Forest Region stand (Table 5). This was mainly because two of the four stands in the Kamloops Forest Region were located in riparian leave strips that were surrounded by recent harvest openings, creating ideal conditions for windthrow of living lodgepole pine and other associated species. The coarse woody fuel loading in the Kamloops Forest Region stands was three times as high as those were in the Chilcotin Plateau because of the larger average lodgepole pine DBH in the southern interior and the windthrow that had occurred in the riparian leave strips. If coarse woody fuel loading would have been measured in 1987 in the Kamloops Forest Region, it would have been lower than that estimated for 2001 since the previous mountain pine beetle outbreak to 1987 was from the 1930s to 1940s in the southern interior. Very few of the fallen dead trees from those decades would have remained on the forest floor surface due to 40-50 years of decomposition. As well, the decomposition would have been more rapid in the southern interior stands since they have a wetter and warmer climate compared to the Chilcotin Plateau.

Manning Provincial Park

Although lodgepole pine was still the most common tree species in the stands sampled in Manning Park, Douglas-fir, interior spruce, sub-alpine fir, and western hemlock were present. Douglas-fir and spruce were the most common non-host tree species in terms of volume, especially in the larger DBH size classes. An occasional fire scar provided some evidence of surface fires in some sampled stands; most stands originated from stand replacement fires (i.e., crown fires). More even-aged multi-species stand structure exists as compared to the unique multi-age and size stand structure dominated by lodgepole pine in the Chilcotin Plateau.

In 2002, the standing live volume in Manning Provincial Park was over twice that in the Chilcotin Plateau in 1987 and Entiako Protected Area in 2002, but similar to Kamloops and Nelson Forest Region stands in 1987 (Table 4a). The higher standing live volume in Manning Provincial Park compared to the Chilcotin Plateau was due to higher site productivity and growth rates in the southern BC interior. Higher volume was found in Manning Provincial Park stands even though there was less mountain pine beetle mortality in the Chilcotin Plateau stands. More potential volume loss exists for Manning Provincial Park stands; since mountain pine beetle had attacked 19% of remaining standing live lodgepole pine in 2002. At the time of sampling, these trees were still alive. In 2002, standing dead tree volume in Manning Park was the highest of all the study areas, while dead tree density was the second highest (a third less than Entiako Protected Area) (Table 4b). The volume and density results by DBH size class indicated that mountain pine beetle mortality occurred mainly in the larger diameter lodgepole pine.

In 2002, pole-sized tree density was the second highest in all study areas, with only Chilcotin Plateau stands having a higher density in 2001 (Table 4c). Douglas-fir, spruce, lodgepole pine, sub-alpine fir, and *Salix* spp. were the most common tree species in descending order of density. In the 3.9-7.5 cm-size class, Douglas-fir and spruce were the most common pole size tree.

Seedling density was the second lowest with the lowest density in the Entiako Protected Area (Table 4c). Douglas-fir, spruce, sub-alpine fir and lodgepole pine were the most common tree seedling species in descending order of density.

Fine woody fuel loading was the lowest of all the study areas (Table 5). The coarse woody fuel loading was twice that measured in the Chilcotin Plateau and half that measured in Kamloops Forest Region. Manning Provincial Park has larger diameter lodgepole pine than in the Chilcotin Plateau and a limited number of dead trees that have fallen down, as compared to stands in the Kamloops and Nelson Forest Regions. This would indicate that the sampled stands in Manning Provincial Park had a lot of natural thinning, blowdown, and coarse woody debris remaining from the previous stand that was disturbed by fire and gave rise to the present stands.

Entiako Protected Area

Lodgepole pine was the most common tree species in the stands sampled in Entiako Protected Area. Spruce, aspen, and *Salix* spp. were also present. Spruce was the most common non-host tree species in terms of volume, especially in the larger DBH size classes. An occasional fire scar provided some evidence of surface fires in some sampled stands; most stands originated from stand replacement fires (i.e., crown fires). Even-aged and sized lodgepole pine (with a minor component of spruce) stand structure existed as compared to the unique multi-age and size stand structure dominated by lodgepole pine in the Chilcotin Plateau.

In 2002, the standing live volume in Entiako Protected Area was the lowest of all study areas (Table 4a). In 2002, standing live tree density was similar to Manning Provincial Park but higher than the re-measured stands in the Chilcotin Plateau and Kamloops Forest Region (Table 4a). The low standing live volume in the Entiako Protected Area was the result of high mortality levels from mountain pine beetle and lower site productivity compared to Manning Provincial Park and the Kamloops and Nelson Forest Regions. There is only a small potential future volume loss in Entiako Protected Area stands from mountain pine beetle attack in 2002 since only 4.3% of the remaining standing live lodgepole pine had current attack. In 2002, standing dead tree volume was the second highest of all the study areas, while dead tree density was the highest (Table 4b). The high standing dead volume and tree density was the result of lodgepole pine dominating species composition, high pre-outbreak tree density of susceptible pine, and smaller diameter pine being killed due to high mountain pine beetle populations. The volume and density results by DBH size class indicated that mountain pine beetle mortality occurred mainly in the larger diameter lodgepole pine.

In 2002, pole-sized tree density was the second highest of all study areas, second only to the Chilcotin Plateau (Table 4c). Spruce, lodgepole pine, and trembling aspen were the most common species in descending order of density. In both pole-sized size classes, spruce and lodgepole pine were most common tree species. In 2002, seedling density was the lowest of all the study areas (Table 4c). Lodgepole pine, spruce, trembling aspen, and *Salix* spp. were the most common tree seedling species in descending order of density. The lack of living lodgepole pine in the overstory and relatively low numbers of non-host species of pole-sized trees and regeneration in the understory will result in slower stand succession than in southern BC interior stands. This is because in southern BC interior sampled stands, non-host tree species are more common in the co-dominant and dominant canopy layers than in the Entiako Protected Area stands.

Fine woody fuel loading was the third lowest of all the study areas but similar to the Chilcotin Plateau stands (Table 5). The coarse woody fuel loading was the lowest of all the study areas. Entiako Protected

Area has larger diameter lodgepole pine than in the Chilcotin Plateau but a limited number of dead trees have fallen down. When the high stand dead tree volume falls down, then coarse woody fuel loading will increase dramatically in the Entiako Protected Area. One compensating factor in reducing coarse woody fuel loading over time is that decomposition will probably be higher in the Entiako than the Chilcotin Plateau due to higher annual rainfall and temperatures in the Entiako Protected Area.

Mountain Pine Beetle Outbreak Recurrence

For the Chilcotin Plateau, 240 lodgepole pine cores were successfully cross-dated and included in the tree-ring analysis. The oldest core dated to 1758, while most dated back to the late 1880s (Alfaro et al. 2004). In all sampled stands there seemed to be fairly synchronous release periods, indicating possible mountain pine beetle outbreaks in the 1890s/early 1900s, 1930s/40s, and 1970s/80s. The latter outbreaks are consistent with Forest Insect and Disease Survey reports and other historical records (Wood and Unger 1996)

The period in the 1890s also had low intensity surface fires as indicated by fire-scarred lodgepole pine found in the Chilcotin Plateau. These surface fires would also have caused some growth release in stands such that the 1890s to early 1900s period cannot be confirmed as the result of only a mountain pine beetle outbreak. The standardized ring-width chronologies for the Chilcotin Plateau indicated a preliminary estimate for the duration of tree-growth release of one to two decades, while the time period between tree releases was roughly 40 to 50 years. Non-host species responded to canopy disturbance approximately at the same time as lodgepole pine.

Because not all lodgepole pine is killed in an outbreak and residual pine trees have been found to exhibit growth release, these trees could eventually become of susceptible size for attack by mountain pine beetle. At least three mountain pine beetle outbreaks during the 1900s and the ability of lodgepole pine to regenerate under the forest canopy, has led to a multi-age and size stand structure. In 2003, mountain pine beetle Ministry of Forests surveys showed light-severity mortality occurring in the Chilcotin Plateau. The growth release of lodgepole pine that started in the late 1970s and has continued to at least 2001, when stands were re-measured, seems to have been enough to increase mountain pine beetle susceptibility to a point where the stands are currently supporting a light severity mountain pine beetle attack.

Standardized ring-width chronologies from Douglas-fir trees on the Bull Mountain site showed a period of release after the last beetle outbreak in the 1970s. Heath and Alfaro (1990) documented this 1970s growth release. The Douglas-fir chronologies showed periods of growth release after periods of suppression that were inferred to be outbreaks by mountain pine beetle. Periods of growth release occurred approximately in 1760s, 1780s, 1860s, 1900s and 1920s. Standardized ring-width chronologies from surviving lodgepole pine trees showed possible mountain pine beetle outbreaks in the 1860s and late 1930s. Douglas-fir displayed a mean radial growth increase of 68% (0.55 mm) after the outbreak of mountain pine beetle in the 1970s. Lodgepole pine trees showed an increase of 58% (0.51 mm) in mean radial growth from the same time period. Fifty-two percent of Douglas-fir trees show a growth response in the five years after the mountain pine beetle outbreak in the 1970s as compared to 70% of the remaining lodgepole pine.

The most striking response to the mountain pine beetle outbreaks was the release of previously suppressed Douglas-fir and surviving lodgepole pine. Following the 1970s outbreak, growth rates for both species remained high for more than 20 years. The results from Bull Mountain indicate that in mixed Douglas-fir and lodgepole pine stands, if there is a significant amount of Douglas-fir in the stand, volume losses from mountain pine beetle-induced mortality in lodgepole pine could partially be offset by the increased growth of the remaining Douglas-fir.

Mountain pine beetle scars can be used in the same manner as fire scars for determining disturbance history. Mountain pine beetle and fire scars can occur on the same cross-section (Fig. 4).

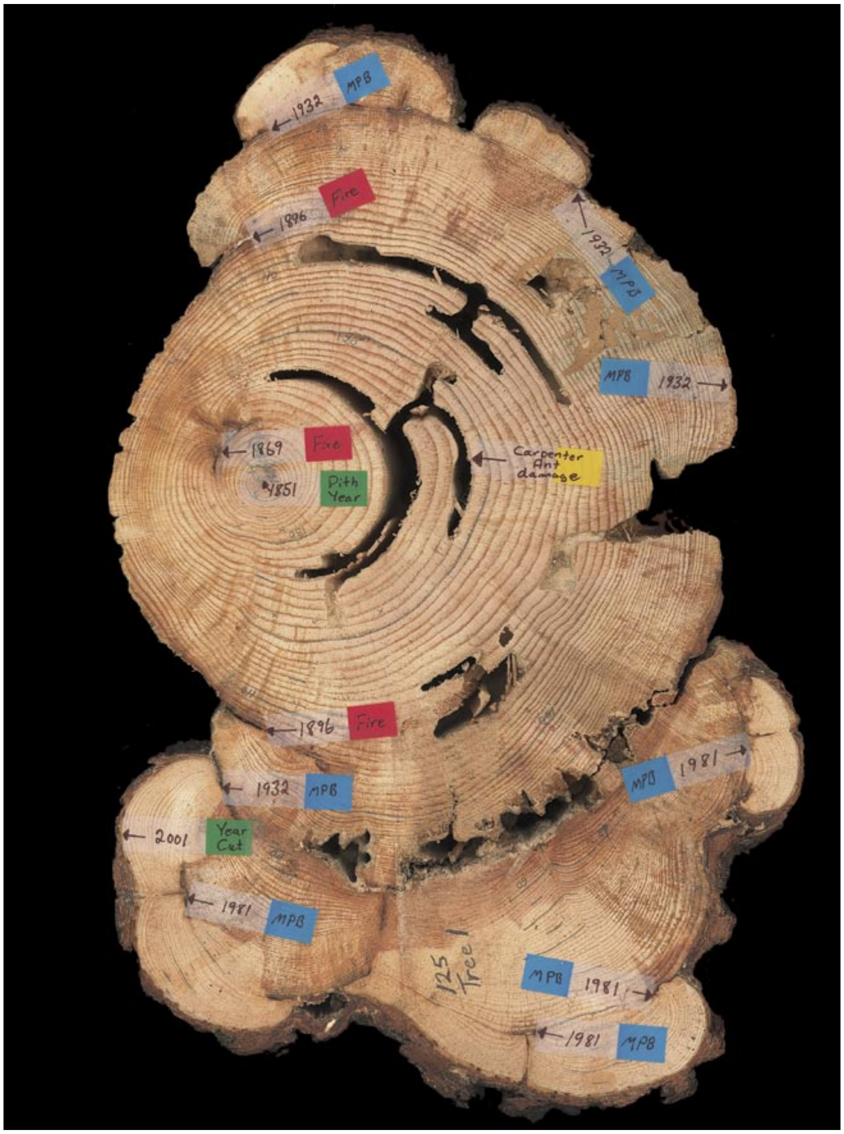

Figure 4. Mountain pine beetle (blue), fire scars (red), and carpenter ant damage (yellow) on lodgepole pine tree disc from the Chilcotin Plateau; stand 125.

In examining 272 fire-scarred tree sections, 127 were found to have one or more mountain pine beetle scars (Table 3 and Fig. 5). The number of mountain pine beetle scars in any year ranged from 1 to 22 (1984) (Fig. 5). On the tree discs with mountain pine beetle scars, a total of 83 fire years were identified (Fig. 5). The number of fire scars in any year ranged from 1 to 32 (1922) (Fig. 5). Fire years identified with 10 or more fire scars were in 1839, 1869, 1896, 1904, 1905, 1911, 1922, and 1926.

The number of mountain pine beetle and fire scars showed some interesting patterns over time (Fig. 5). Prior to 1905, only one mountain pine beetle scar was available to date a mountain pine beetle scar year and prior to 1839, less than 10 fire scars were found (Fig. 5). The reduction in the number of mountain pine beetle and fire scars over time was because very few lodgepole pines have been able to survive multiple fire and mountain pine beetle disturbances. The incidence of fire scarring appears to have declined since the early 1900s. Less than 10 fire scars were found after 1926 and no fire scars were found after 1982. This suggests that the incidence of surface fires has declined in these forests. The reasons for the lack of fire could include early efforts at fire prevention, introduction of fire control laws in the early 1900s, lack of aboriginal burning, fire suppression activities, and changing land use practices (e.g., grazing by large numbers of cattle and horses reducing grass fuels).

Fire and mountain pine beetle scar dates were superimposed on the growth-release diagram that was used to determine mountain pine beetle outbreak periods (Alfaro et al. 2004) (Fig. 6). Growth-release periods identified in each stand were found to be generally consistent with mountain pine beetle scar dates.

Alfaro et al. (2004) noted that the 1890s growth-release period could not be confirmed as being caused by mountain pine beetle-induced mortality. In some stands there are mountain pine beetle scars that do not coincide with a release period from the tree-ring chronologies (Fig. 6). The scarring could have occurred because of endemic conditions for mountain pine beetle. Several of the stands showed a release that was not related to mountain pine beetle or fire scars (Fig. 6). This could be attributed to the fact that generally only two to three cross-section samples were collected from each stand. It is unlikely that every tree or sample collected would be scarred by each disturbance event.

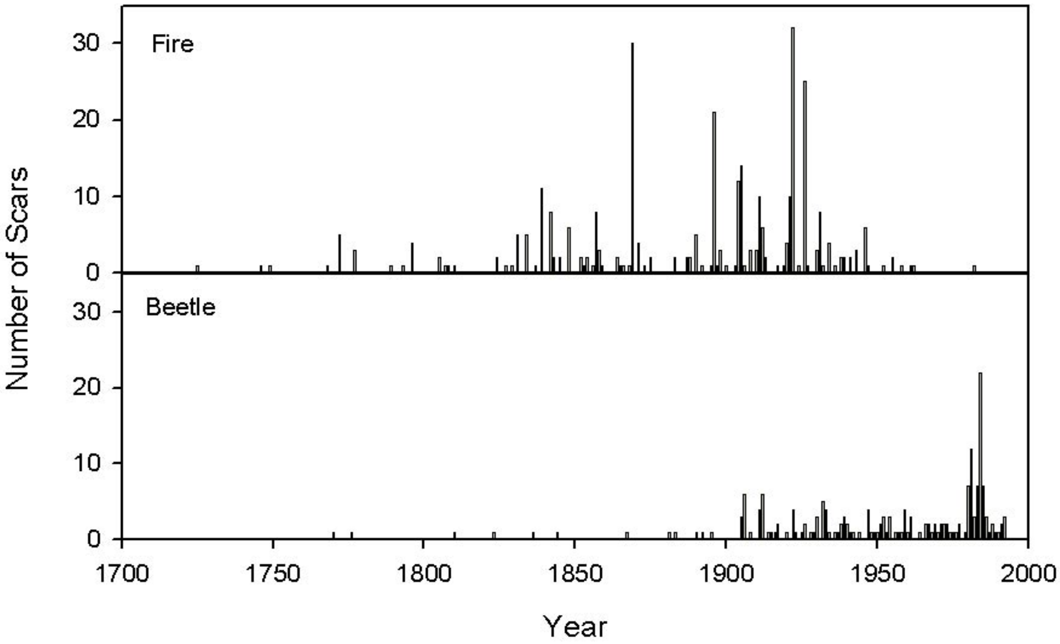

Figure 5. Number of mountain pine beetle and fire scars found on lodgepole pine tree discs by year in the Chilcotin Plateau.

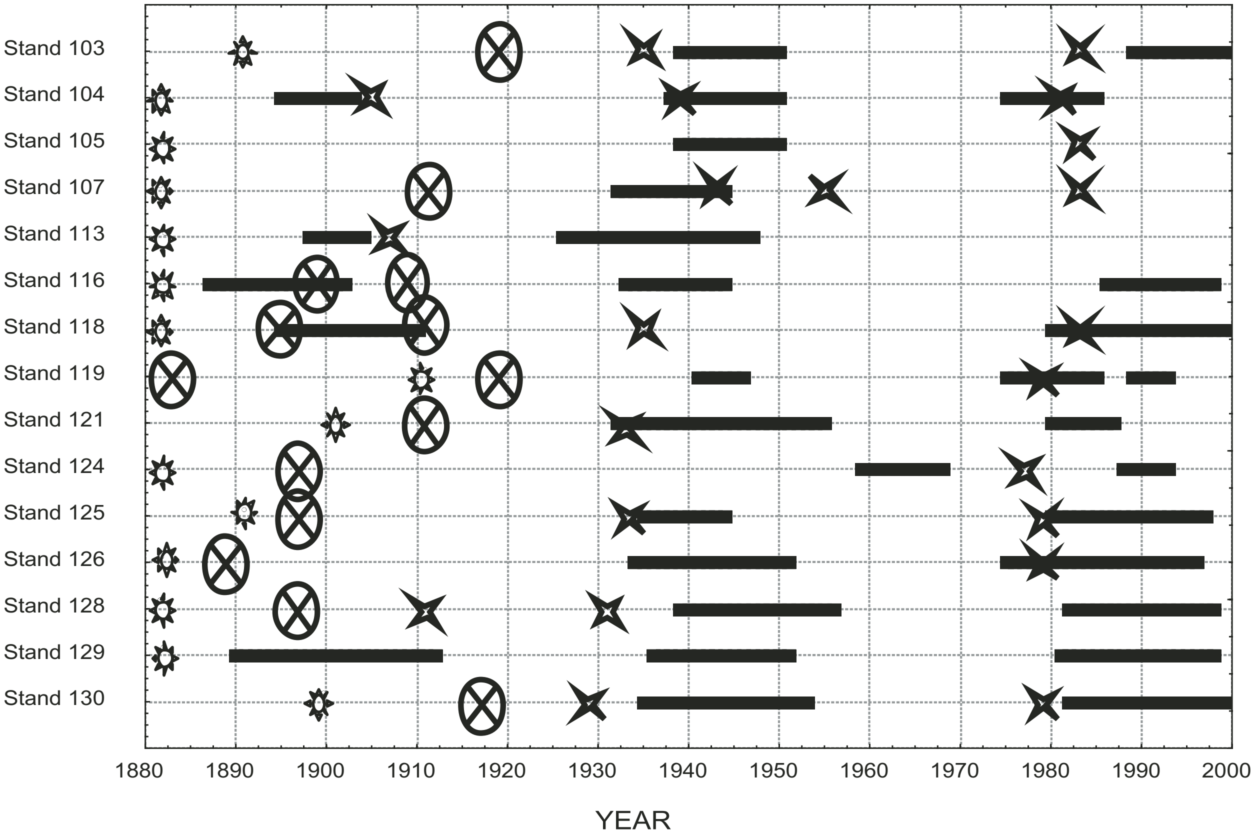

Figure 6. Release periods attributable to mountain pine beetle outbreaks in Chilcotin Plateau, BC, inferred from growth-release periods using tree-ring chronologies (from Alfaro et al. 2004). Fire (circle with cross in middle) and mountain pine beetle (star shaped symbol) scar dates are given for each stand. Asterisk indicates start year for the tree-ring chronology.

One of the limitations of using these data from stands sampled in the Chilcotin Plateau after the 1970s to 1985 outbreak is that the results are mainly applicable to the SBPSxc and IDFdk4 biogeoclimatic subzones, in mixed-severity fire regimes, and in lodgepole stands with multi-age and size structure. The current mountain pine beetle outbreak in BC is occurring in more northern and wetter biogeoclimatic zones that experience crown fires at relatively long intervals and have more even-age and size stands. The plots established in the current outbreak area in Manning Provincial Park and Entiako Protected Area have expanded the project into other biogeoclimatic zones, but will not provide stand dynamics data for many years into the future. These plots have already provided mountain pine beetle impact information and are permanent plots that can be re-measured in future years.

Conclusions

The project results have made a significant contribution to our understanding of the impact of mountain pine beetle outbreaks on stand dynamics, re-occurrence rates for mountain pine beetle and fire, and woody debris dynamics. When modelling efforts are complete, there will be additional knowledge of woody fuel dynamics and fire behaviour potential. This type of information is needed for forest and fire managers to make better decisions regarding management of residual mountain pine beetle affected stands.

A number of conclusions can be made based on the stand dynamics results:

- The volume and density results by DBH size class for all study areas indicated that mountain pine beetle mortality occurred mainly in the larger diameter lodgepole pine.
- Lodgepole pine is the most common tree species in the Chilcotin Plateau study area. A unique multi-age and size stand structure exists as a result of lodgepole pine being able to regenerate under its own canopy, and past multiple mountain pine beetle outbreaks and surface fires.
- Despite an increase in growth rates in smaller diameter residual trees in the Chilcotin Plateau stands, there still was a reduction in standing live tree volume and density from 1987 to 2001 due to additional mountain pine and *Ips* beetle mortality that occurred from 1987 to 2001.
- In the Chilcotin Plateau stands, from the late 1970s to 2001, 96.6% of the pole-sized trees demonstrated a release in growth. Pole-sized lodgepole pine averaged 48 years old, ranging from 13 to 162 years with the time to reach DBH averaging 30 years.
- Seedling density in the Chilcotin Plateau stands had the second highest density of all study areas in 1987 and 2001. In 2001, lodgepole pine was the most common seedling, and two new tree species were recorded, trembling aspen and willow, of which trembling aspen was the most abundant.
- The importance of accelerated growth as opposed to new seedling establishment following a mountain pine beetle outbreak is a major contrast to what is usually observed following high intensity fires where few trees survive.
- Lodgepole pine was the most common tree species in the Kamloops and Nelson Forest Regions and Manning Provincial Park stands; although Douglas-fir, spruce, and western larch (Nelson) were present, especially in the larger DBH size classes. A more even-aged multi-species stand structure existed in these study areas due to stand replacement fires being more common than surface fires. Post outbreak standing live tree volume, in these southern BC interior stands, was twice as great as in the Chilcotin Plateau stands due to higher site productivity in the southern BC interior.
- Pole-sized tree density in the Kamloops and Nelson Forest Regions and Manning Provincial Park stands was two to three times lower than in the Chilcotin Plateau stands. The pole-sized tree density in Kamloops and Nelson Forest Regions was half that found in the Entiako Protected area, even though southern interior stands had less crown closure due to mountain pine beetle-induced mortality.
- Seedling density in the Kamloops Forest Region was less than half that in the Chilcotin Plateau stands, however it was greater than in any other study area except for the one stand re-measured in the Nelson Forest Region.
- There is still more potential volume loss in Manning Provincial Park stands since mountain pine beetle attacked 19% of the remaining standing live lodgepole pine in 2002. These trees were not dead at the time of sampling. In 2002, standing dead tree volume in Manning Park was the highest of all the study areas. When the standing dead trees fall over, coarse woody fuel loading will increase dramatically.

- Lodgepole pine was the most common tree species in the stands sampled in Entiako Protected Area, while spruce was the most common non-host tree species, especially in the larger DBH size classes. An even-aged and sized lodgepole pine stand structure exists due to stand replacement fires being more common than surface fires.
- In 2002, the standing live tree volume in Entiako Protected Area was the lowest of all study areas, due to high mountain pine beetle-induced mortality and lower site productivity compared to the southern BC interior stands. There is only a small potential future volume loss in Entiako Protected Area stands from mountain pine beetle attack since only 4.3% of the remaining standing live lodgepole pine had current attack in 2002. Standing dead tree volume was the second highest of all the study areas, while dead tree density was the highest. The high standing dead volume and tree density was the result of lodgepole pine dominating species composition, high pre-outbreak tree density of susceptible pine, and smaller diameter pine being killed due to high mountain pine beetle populations.
- The results from Bull Mountain indicate that in mixed Douglas-fir and lodgepole pine stands, if there is a significant amount of Douglas-fir in the stand, volume losses from mountain pine beetle-induced mortality in lodgepole pine could partially be offset by the increased growth of the remaining Douglas-fir.
- Fine woody fuel loading was similar in all study areas, while coarse woody fuel loading was the highest in the Kamloops Forest Region stands, due to two of the sampled stands being located in riparian strips that experienced significant blowdown of living large diameter trees of all species present. In 2001, coarse woody fuel loading in the Chilcotin Plateau stands was the second lowest found in all study areas because of the relatively low stand volumes, growth rates, and tree mortality levels.

A number of conclusions can be made based on the mountain pine beetle and fire re-occurrence and scar results:

- For the Chilcotin Plateau, all sampled stands seemed to have fairly synchronous release periods, indicating possible mountain pine beetle outbreaks in the 1890s/early 1900s, 1930s/40s, and 1970s/80s. The fire scar record indicated that the period in the 1890s had low intensity surface fires that might have also caused growth release in the larger diameter trees. The 1890s release period cannot therefore be confirmed as the result of only a mountain pine beetle outbreak.
- Mountain pine beetle scars can be used in the same manner as fire scars for determining disturbance history.
- On the tree discs with mountain pine beetle scars, a total of 83 fire years were identified. Fire years identified with 10 or more fire scars were in 1839, 1869, 1896, 1904, 1905, 1911, 1922, and 1926.
- The number of mountain pine beetle scars in any year ranged from 1 to 22 (1984).
- When mountain pine beetle scar dates were superimposed on the growth-release diagram, growth-release periods identified in each stand were found to be generally consistent with mountain pine beetle scar dates.
- The reduction in the number of mountain pine beetle and fire scars over time was because very few lodgepole pines have been able to survive multiple fire and mountain pine beetle disturbances.
- The incidence of fire scarring appears to have declined since the early 1900s suggesting that the incidence of surface fires has declined in these forests in the 20th century. The reasons for the lack of fire could include early efforts at fire prevention, introduction of fire control laws in the early 1900s, lack of aboriginal burning, fire suppression activities, and changing land use practices (e.g., grazing by large numbers of cattle and horses reducing grass fuels).

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Incorporating Mountain Pine Beetle Impacts on Stand Dynamics in Stand and Landscape Models: A Problem Analysis

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Abstract

Due to numerous operational, legal and ecological constraints, a large portion of the millions of ha of lodgepole pine affected by the current mountain pine beetle outbreak will not be salvage logged. Understanding how unsalvaged stands and landscapes will develop is critical for assessing the socio-economic and ecological impacts of the outbreak. Most modelling work in British Columbia has been of mountain pine beetle population development, outbreak spread, and interaction with management treatments. Further work is needed to project impacts on stand and forest development. Data obtained from our companion study have some implications for stand modelling. In the Chilcotin outbreak, surviving trees in all diameter classes continued to grow well during the course of the outbreak. Many more small diameter trees are killed in an outbreak than mountain pine beetle population models predict. There was extensive mortality due to *Ips* spp. after the collapse of the mountain pine beetle outbreak. Surviving pine and non-host species responded well to release from overstory competition. This project will identify pathways to include mountain pine beetle impacts in stand and forest growth models focussing primarily on Prognosis^{BC} and its extensions, the Fuels and Fire Effects Model, and the Westwide Pine Beetle Model.

Introduction

During a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak, managers need to forecast pine beetle population development and spread to assist in planning harvesting and other control measures to reduce populations and mitigate impacts. Most mountain pine beetle modelling efforts have been focussed on this problem. Where mountain pine beetle populations are beyond control, or an outbreak has collapsed, there is a need to schedule harvesting to maximize value-recovery of dead timber and to assess the long term impacts on annual allowable cuts (AAC) and other resource values. This requires an assessment of the immediate mortality, the shelf-life of standing dead trees, the impact on growth, and regeneration of residual stands.

Our understanding of the long-term effects of mountain pine beetle epidemics is limited. Lodgepole-dominated stands comprise some 14 million ha of forest land in British Columbia (BC) (British Columbia

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Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Ministry of Forests, 1994). Analysis of the cumulative mountain pine beetle outbreak area from the Canadian Forest Service's Forest Insect and Disease Survey annual aerial records shows that a cumulative area of approximately 4.7 million ha of pine-dominant stands were affected between 1959 and 2002 (Canadian Forest Service, unpublished data). The long-term effects of these past epidemics are largely unknown.

The current mountain pine beetle outbreak has affected an estimated area of 4.1 million ha in 2003 alone (Ebata 2004). Due to numerous operational, legal, and ecological constraints, a large portion of this affected landscape will not be salvage-logged. A comprehensive suite of methods or models is needed to improve our understanding of the effects of this outbreak on the growth and future condition of residual stands, long-term impacts on harvest levels, and habitat supply and other forest characteristics. This paper will briefly review the biological and ecological processes that underly the management questions and the models that are presently available that represent these processes.

Mountain pine beetle effects on stand dynamics

The dynamics of both live and dead trees during and following a mountain pine beetle infestation are important to answering questions of stand volume, value, composition, and future conditions. Live tree processes include mortality of host trees, growth of residual host and non-host trees, and regeneration of host and non-host trees. Dead tree processes that are important are breakage, falldown, and decomposition rates, which affect wood quality and value.

The project outlined by Hawkes et al. (2004), is a companion study, and, among other things, is assessing tree mortality, growth, and regeneration of residual stands following mountain pine beetle outbreak in permanent sample plots located in the Southern Interior Region (former Cariboo, Kamloops and Nelson Forest Regions), Waterton National Park (from the epidemic of 1977-1985), Kootenay National Park (epidemic in 1990's), Tweedsmuir Provincial Park/Entiako Protected Area and Manning Provincial Park (current epidemic). Hawkes et al. (2004) is the most comprehensive study to date in BC investigating both immediate impacts of mountain pine beetle epidemics and the long-term changes in forest structure over wide temporal and spatial scales. Combined with other research on the impacts of mountain pine beetle on lodgepole pine stand dynamics, we know the following:

Mountain pine beetle induced mortality

Mortality caused by primary mountain pine beetle infestation is highly variable, and is dependent upon stand structure and species composition. In general, a higher proportion of larger trees are killed by mountain pine beetle, as evidenced in the Cariboo Forest Region outbreak of 1977-1985 (Fig. 1). As population pressure increases, smaller trees are attacked, which is seen clearly in the Tweedsmuir Park/Entiako Protected Area (Fig. 2), which is in the epicentre of the current epidemic. Variable and uneven levels of mortality can create uneven sized and mixed species stands.

Preliminary data analysis in the companion study on stand dynamics has shown that small-tree (dbh<17.5 cm) mortality over the course of a beetle epidemic is considerably greater than that predicted by current scenarios run with MPB-SELES. MPB-SELES does not fix a lower-size limit on which trees will be killed by beetles, but for the purposes of modelling short-term spread of beetles and impacts on timber volume, these parameters have been set so that they limit mortality of small diameter trees (B. Riel, personal communication). Small diameter trees have limited impact on timber volume, and tend towards being beetle-sinks as opposed to beetle sources. For the purpose of modelling long-term impacts of the beetle epidemic on stand structure and development, however, it is important to set model parameters for tree mortality as accurately as possible.

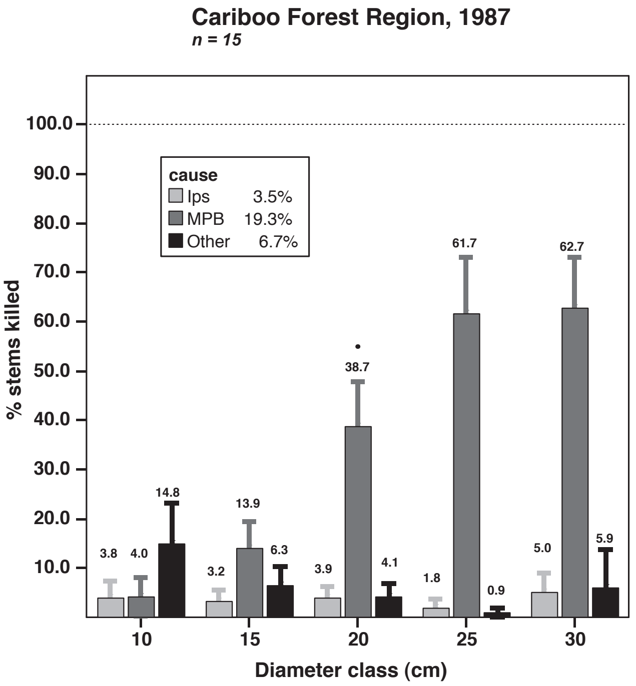

Figure 1. Mortality by diameter class in the Cariboo Forest Region's mountain pine beetle epidemic of 1977-1985. Mortality by mountain pine beetle is significantly skewed to larger diameter trees.

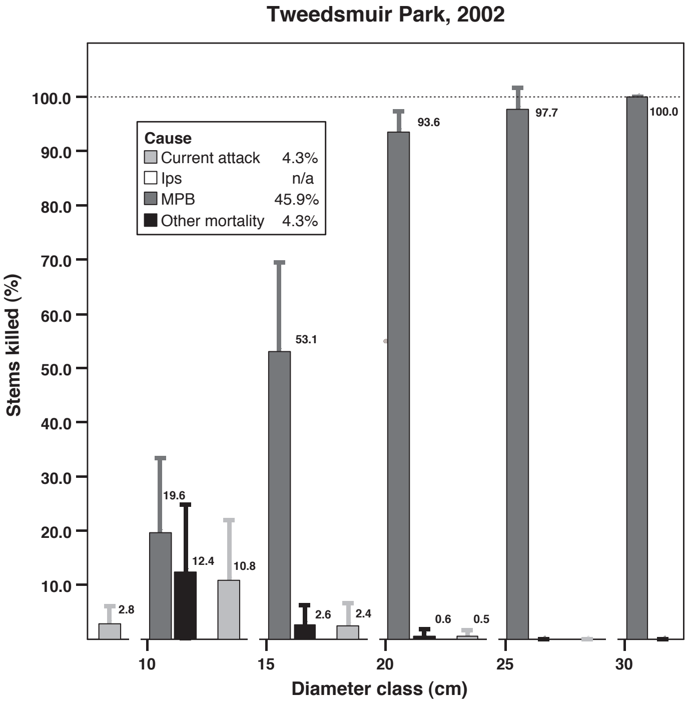

Figure 2. Mortality by diameter class in the current epidemic in Tweedsmuir Provincial Park/Entiako Protected Area. Mortality by mountain pine beetle has affected many more smaller diameter trees than in the Cariboo Forest Region. There is significant current attack taking place in these smaller trees.

Considerable variation in small tree mortality has been observed in past epidemics (Table 1) and in the current epidemic (Table 2). The stands located in the Tweedsmuir/Entiako area show the highest levels of small tree mortality, likely due to being in the epicentre of the current outbreak. Beetles have been active in this region at extreme population levels for several years.

Table 1. Mortality of small diameter trees in three regions affected by the 1977-1985 mountain pine beetle epidemic. Figures expressed in percentage of stems killed.

		Source of mortality		
Diameter class	Region	Mountain pine beetle	*Ips* spp.	Other mortality
7.0 cm-12.4 cm	Cariboo	4.0%	3.8%	14.8%
	Nelson	0	0	13.1%
	Kamloops	0	0	58.3%
12.5 cm–17.4 cm	Cariboo	13.9%	3.2%	6.3%
	Nelson	33.3%	0	16.3%
	Kamloops	18.4%	0	34.2%

Table 2. Mortality of small diameter trees in current mountain pine beetle epidemic (MPB). Figures expressed in percentage of stems killed. Current attack describes trees under attack at time of sampling (September, 2002 in Tweedsmuir/Entiako, August, 2002 for Manning Park). Most trees under current attack are likely dead now.

		Source of mortality		
Diameter class	Region	Mountain pine beetle	Current MPB attack	Other mortality
7.0 cm-12.4 cm	Tweedsmuir/Entiako	19.6%	2.8%	12.4%
	Manning Park	2.3%	3.7%	64.8%
12.5 cm-17.4 cm	Tweedsmuir/Entiako	53.1%	10.8%	2.6%
	Manning Park	13.1%	6.0%	10.0%

Ips spp. induced mortality

In addition to mountain pine beetle induced mortality (primary mortality), preliminary analysis of the stand dynamics companion study (Hawkes et al., these proceedings) has shown that significant secondary mortality may occur as *Ips* spp. populations build up in dead trees to levels where they begin attacking live trees. Furthermore, the mortality caused by these two insect species opens the stand canopy, which in turn may facilitate tertiary mortality in the stand (increased vulnerability to windthrow and other pathogens). Evidence of the extent of secondary and tertiary stand mortality after the collapse of the primary outbreak on trees of all sizes in the Chilcotin Plateau is presented in Figure 3. It is difficult in practice to determine the principal cause of mortality, as dead trees often show evidence of attack from both mountain pine beetle and *Ips*. However, taken together, the mortality between 1987 and 2001 from bark beetles killed a third of the trees that survived the initial mountain pine beetle outbreak between 1977-85.

Tree growth rates

Tree growth rates have been observed to increase during and after the course of an epidemic (Heath and Alfaro 1990). The degree of response is likely variable, depending upon the amount of canopy opening (mortality level) and residual stand structure. Mortality may occur over a period of several years within a stand, as not all trees are killed in the same year. We need to better understand the time course of mortality during the outbreak and how growth processes are affected during an infestation that can last for years, often more than a decade. Data currently available from our companion study indicates that during the epidemic of 1977-1985 in the IDFdk4 and SBPSxc biogeoclimatic subzones on the Chilcotin Plateau, surviving lodgepole pine trees grew an average of 10% in diameter-at-breast-height (dbh) across all diameter classes from 7 cm-30+cm (Fig. 4) between 1977, the year the epidemic began, to 1987 (year of sampling), two years after the epidemic collapsed due to winter cold. When converted to basal area, the increase is 21.8% (Fig. 5). This increase in basal area applies to 81% of the trees in these stands, as only 19% of trees were killed in the epidemic. We are currently cross-dating increment cores from the dead trees to identify when mortality occurred.

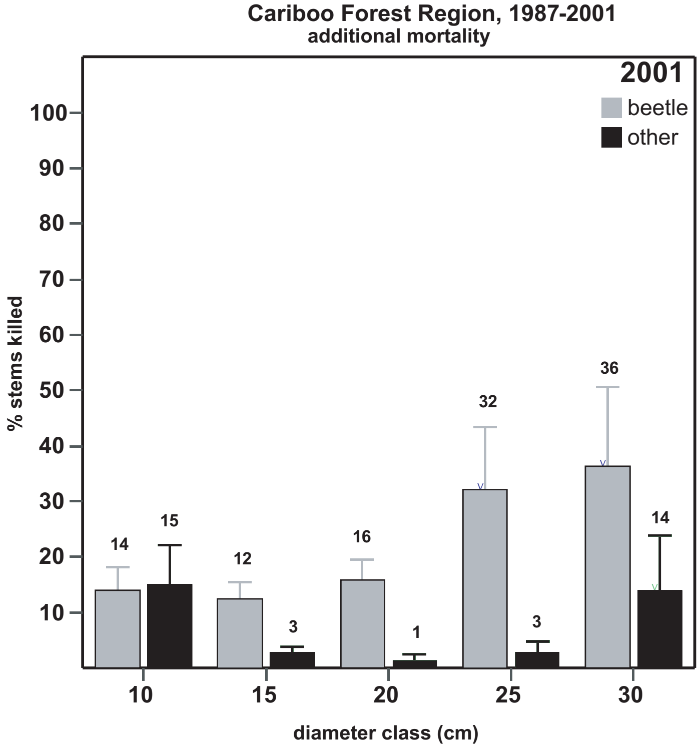

Figure 3: Post-epidemic mortality of lodgepole pine in the Cariboo Forest Region from 1987 to 2001. Figures are expressed as percentage of stems killed that were living in 1987, two years after the end of the MPB epidemic. The two causes indicated in the figure are beetle (MPB and *Ips* spp. combined) and all other mortality sources (other).

Falldown and regeneration rates

In order to assess salvage and forest fire behaviour potential following a mountain pine beetle infestation, we need to determine the falldown rate of beetle-killed trees and their decomposition rates. As epidemics progress and canopy disturbances increase light available to the forest floor, we also need to determine how regeneration of host and non- host trees will be affected in order to predict the future condition and growth of stands on the landscape.

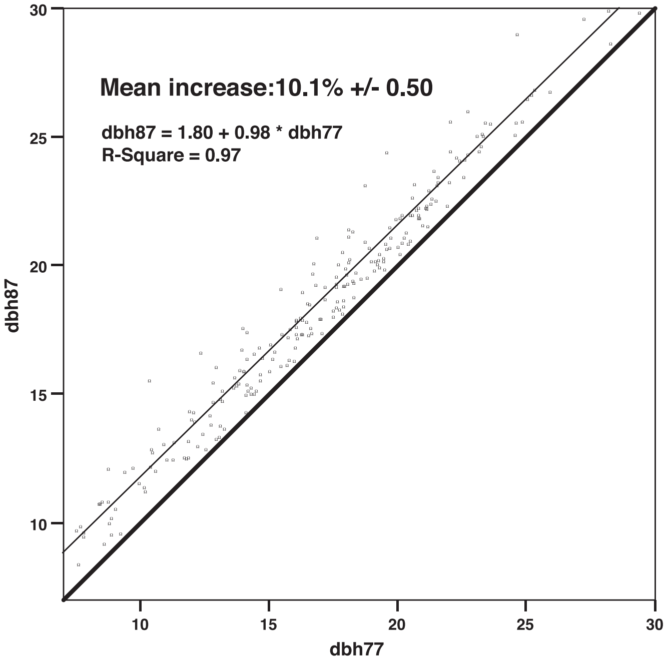

Figure 3. Surviving host-tree diameter growth through the course of the mountain pine beetle epidemic in the Chilcotin Plateau. Bold line indicates line of zero-growth (no change in DBH), lighter line is best-fit line of linear regression of initial DBH in 1977 (dbh77) versus DBH at time of measurement, two years post-epidemic in 1987 (dbh87).

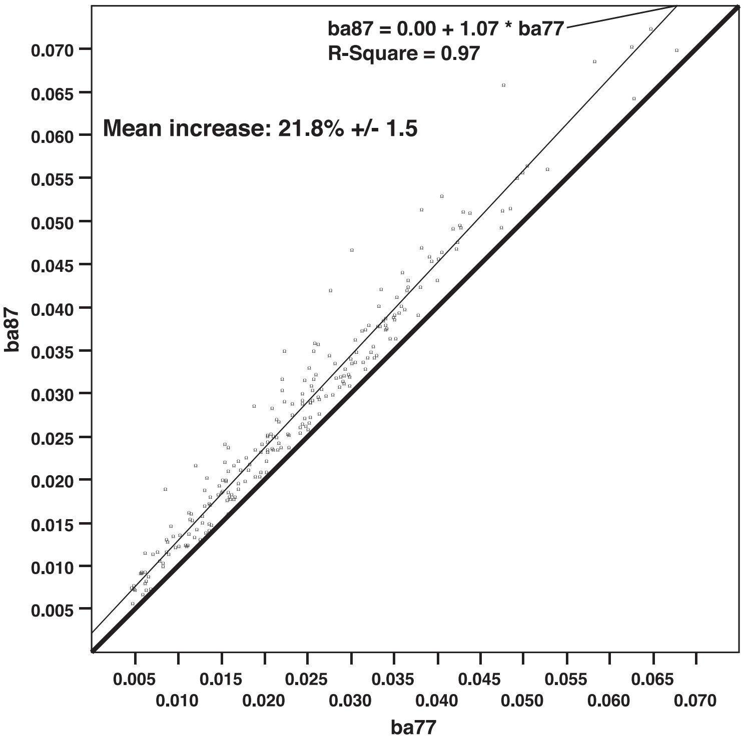

Figure 5. Surviving host-tree basal area growth through the course of the mountain pine beetle epidemic in the Chilcotin Plateau. Bold line indicates line of zero-growth (no change in basal area), lighter line is best-fit line of linear regression of initial basal area in 1977 (ba77) versus basal area at time of measurement, two years post-epidemic in 1987 (ba87).

Modelling framework

A variety of models that represent the processes of beetle mortality, woody debris falldown, growth and regeneration of stands oriented to stands or forest/landscapes, are presently used or can be easily adapted for use in BC. These include, but are not limited to, MPBSIM (Riel et al. 2004), SELES-MPB (Riel et al. 2004; Fall et al. 2004, 2002a, b), Prognosis^{BC} (Zumrawi et al. 2002), the Prognosis Westwide Pine Beetle (Beukema et al. 1997) and Fire Models (Beukema et al. 1996), Woodstock and Stanley (http://www.remsoft.com/forest/index.html). As well as representing different processes, the models are at different temporal and spatial scales: 1) mountain pine beetle population dynamics and spread (immediate impact); 2) stand growth and yield (immediate and long term impacts); and 3) forest/landscape models (longer term, larger spatial scales). The components of a modelling framework will be briefly reviewed from the process point of view.

Mortality

Mountain pine beetle population dynamics and spread models and resulting mortality have been well developed by the Canadian Forest Service, and are represented by MPBSIM (Riel et al. 2004; http://www.pfc.forestry.ca/entomology/mpb/tools/dss_e.html), which is based on a detailed, process-based population model by Safranyik et al. (1999). By itself, MPBSIM is a stand-level model, but when coupled with the Spatially Explicit Landscape Event Simulator (SELES) (Fall and Fall 2001; Fall et al. 2001, 2002a, b) as SELES-MPB, it successfully scales the short-term impacts of mountain pine beetle across the landscape. Some issues with this modelling system are that it does not kill small trees in the numbers seen in plots in our companion study (Hawkes et al. 2004); although this can be addressed by parameterizing the model accordingly (Riel, W.G., Canadian Forest Service, Victoria, BC, personal communication), it does not include secondary mortality agents (*Ips* spp.), and tree growth is too simplistic for modelling long-term forest conditions.

Mortality due to both mountain pine beetle and *Ips* has been represented in the Westwide Pine Beetle Model (WWPB) extension to the US Forest Service Forest Vegetation Simulator (FVS) (Beukema et al. 1994, 1997). The WWPB model has been designed to run with the Parallel Processing Extension (PPE) (Crookston and Stage 1991), which scales FVS from the stand to landscape level. We have recently (October 2003) had the WWPB and PPE models metrified by ESSA Technologies and linked to Prognosis^{BC} V3.0. Both Prognosis^{BC} and FVS have numerous extensions designed for modelling of woody debris fuel loading, forest cover and other issues regarding the projection of future forest conditions. We plan to run the model to test *Ips* mortality prediction.

Impacts on growth

Existing growth and yield (GY) models may be adaptable to capture post-outbreak stand development. The primary GY models in use by the BC Ministry of Forests are TASS and Prognosis^{BC}. Prognosis^{BC} may be the most suitable stand model for this purpose as the BC Ministry of Forests uses it for modelling uneven size class and mixed species stands. Prognosis^{BC} v3.0 (the latest release) has been calibrated for several biogeoclimatic units, is freely available, and has a well-developed graphical user interface. Prognosis^{BC} is the metrified version of the US Forest Service Forest Vegetation Simulator (FVS) model, which has been in use since the late 1970s.

In this and a companion study, we are investigating/demonstrating the use of Prognosis^{BC} to project growth of residual stands following mountain pine beetle outbreak. Residual stand growth following mountain pine beetle attack has not been previously modeled in BC. However, it is implicitly included in the Westwide Pine Beetle model extension to Prognosis^{BC}. Prognosis^{BC} is widely used for projecting the effects of stand treatments and uneven age stand development in southern and central interior BC.

In operational practice, the impacts of other pests of young pine on stand growth have been accounted for by applying operational adjustment factors (OAFs) in TASS (Woods et al. 2000) to modify yield curves. These yield curves can then be included in forest or landscape models (e.g., FSSim, Woodstock, Stanley, SELES-MPB). While TASS may not be suitable for projecting the impact of mountain pine beetle, Prognosis might be used to develop OAFs or new yield curves for mountain pine beetle impacted stands.

Shelf-life and regeneration

The Prognosis^{BC} model includes a natural regeneration submodel which may be able to be calibrated to mountain pine beetle affected stands. The Fire Model extension to Prognosis projects woody debris dynamics (breakage, falldown, and decay rates), but not degradation in wood quality. It has recently (April, 2004) been linked to Prognosis^{BC} v3.0.

Forest landscape models are used to scale up stand-level impacts and projections to address questions of timber supply, habitat quality/availability and other issues of forest health and condition. Most of these models require input of yield curves for some functions (i.e., growth of residual stands, decomposition of timber). Woodstock uses generalized growth curves, and can handle large data sets. However, it is an aspatial model. In order to project the impact of an epidemic it would be necessary to take the real or projected impact at the end of the outbreak and summarize by analysis unit.

SELES-MPB and Stanley are both spatial models, and allow for simulating spatial harvesting rules. SELES-MPB has been applied at very large spatial scales (Timber Supply Area), and model runs have shown that it accurately predicts the spatial location and extent of the epidemic, but tends to under-predict small tree mortality within stands (Riel, W.G., Canadian Forest Service, Victoria, BC, personal communication). In the absence of a tree growth model component, both SELES-MPB and Stanley would have to depend upon generalized growth curves to project forest stand conditions into the future.

The Westwide Pine Beetle Model, in conjunction with the Parallel Processing Extension and Prognosis^{BC} can maintain individual stand dynamics for up to 10,000 stands, which very loosely translates to 1000 km^2. The benefits of greater detail at the stand level is gained by making a tradeoff in the spatial area that can be handled by the model, which is well under the Timber Supply Area scale. Another significant restricting factor for the use of the Westwide model is the requirement of tree lists for each stand, which exceeds the detail available in our current forest inventory records. Numerous imputation procedures are available, such as Most Similar Neighbour analysis, which can fill in empty cells on the landscape, but a certain number of real-data plots are necessary to make this type of procedure robust. There may also be limitations in harvest scheduling, particularly spatial constraints.

Conclusions

It is unrealistic to hope that a single large model will be able to answer all types of questions regarding the effects of mountain pine beetle epidemics on the landscape and how to best manage the epidemic, schedule harvesting, salvage and assess long term impacts.

The Westwide Pine Beetle Model is being examined in some detail in this study because it incorporates all the biological processes including *Ips* mortality, and has not been previously tested in BC.

It may be more appropriate to link specific models into a larger framework. There are considerable scaling challenges to linking these models (Fig. 6).

We need to scale mountain pine beetle impacts on mortality occurring over a period of years, on stand growth for over a period of decades across a landscape of thousands of square kilometers. Additional work is needed to validate components of a framework and demonstrate their use in an integrated fashion in a pilot study area.

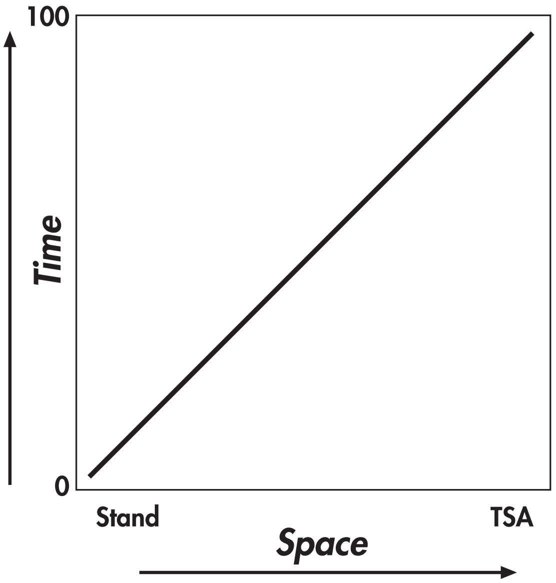

Figure 6. Hypothesized modelling framework: for projecting future forest conditions, we need to be able to examine a stand at time = 0 (bottom left corner) and project it into the future and across a large landscape (TSA = timber supply area) (top right corner).

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Modelling Mountain Pine Beetle Phenological Response to Temperature

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Abstract

Maintaining an adaptive seasonality, with life cycle events occurring at appropriate times of year and in synchrony with ephemeral resources, is a basic ecological requisite. For poikilothermic organisms, phenology is largely determined through adaptive evolution with the prevailing climate, and in particular, annual temperature cycles. In addition to the direct effect of temperature, most temperate region insects have physiological mechanisms (e.g., diapause) that help to maintain an adaptive seasonality. The mountain pine beetle (*Dendroctonus ponderosae* Hopkins), however, exhibits no obvious manifestations of diapause. This has led to the ecologically important question: How is an appropriate seasonality maintained in the mountain pine beetle without the synchronizing influence of diapause? In answer to this basic question, we briefly review the mathematical relationship between environmental temperatures and developmental timing and discuss the consequences of viewing these models as *circle maps* from the cycle of oviposition dates and temperatures of one year to oviposition dates for subsequent generations. Univoltinism, associated with reproductive success for the mountain pine beetle, is related to stable fixed points of the developmental circle map. Univoltine fixed points are stable and robust in broad temperature bands, but lose stability suddenly to maladaptive cycles at the edges of these bands. This leads to the obvious observation that temperatures (weather) can be too cold for the mountain pine beetle to thrive, as well as the less obvious implication that it can also be too warm.

These results are placed in an ecological and management context by relating adaptive seasonality to outbreak potential. The relationship between outbreak potential and temperature is further considered in view of climate change (i.e., global warming). We briefly note the potential for global warming to intensify outbreak characteristics in the current range of mountain pine beetle, as well as promote invasion into new habitats, such as the high elevation pines and northern range expansion into Canadian jack pine.

Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Introduction

Maintaining an adaptive seasonality is a basic ecological requirement for all organisms. Critical life history events must be keyed to appropriate seasonal cycles in order to avoid lethal temperatures or other environmental extremes, provide for coincident timing of reproductive cycles, avoid predation through simultaneous mass emergence, and a multitude of other requirements for maintaining ecological and biological viability. Seasonality and phenology are essentially synonymous terms that have been used to describe these seasonally predictable events, although seasonality is a more general term referring to both periodic changes in the physical environment and the biological response to these changes. Phenology is more specifically used to describe the seasonal progression of a series of biological stages or life history events. At any rate, phenology is central to seasonality and the response of organisms to the climate in which they are embedded.

Climate has long been recognized as an important constraint on mountain pine beetle (*Dendroctonus ponderosae* Hopkins) population dynamics, providing both the limitation on distribution and localized outbreak (including regional) potential (Amman 1973; Safranyik 1978). The aspects of mountain pine beetle biology and life history that are particularly important in view of adaptive seasonality are: (1) The mountain pine beetle is one of a handful of "aggressive" bark beetles that regularly reach outbreak conditions in which large numbers of apparently healthy trees are killed. In fact, successful reproduction by the beetle typically requires killing the host in order to overcome its substantial chemical defenses[1]. (2) The beetle and the host have co-evolved, or at least adapted to one another, over countless millennia, each incorporating the other in their respective survival strategies (Roe and Amman 1970; Peterman 1978). In response to host tree defenses, the beetle has evolved a "mass attack" strategy that overwhelms tree defenses by sheer number of attacking beetles. (3) The mass attack strategy requires essentially simultaneous emergence of adult beetles to provide the large numbers required for a successful attack. (4) In spite of the strong selection pressure for simultaneous adult emergence, existence of diapause or any other physiological timing mechanism has not been observed for the mountain pine beetle. The synchronization of life-history events without a controlling physiological mechanism has been termed "direct" control of seasonality (Danks 1987).

The combination of these four key life-history traits has resulted in an interesting question: How can the prolonged ovipositional period, lasting several months, be focused into an essentially simultaneous emergence period? This question has been the focus for a sustained research effort dating back to the early 1980s (Logan and Amman 1986). Our past work (Bentz et al. 1991; Logan and Bentz 1999; Powell et al. 2000; Jenkins et al. 2001; Logan and Powell 2001) has demonstrated that quiescence and differing developmental thresholds are sufficient for synchronizing adult emergence. The mathematical tools we have developed to analyze phenology and predict seasonality in the mountain pine beetle provide a general framework for any plant or animal with phenology under direct temperature control. In this article, we explore the quantitative analysis of direct temperature control and how these models shed light on adaptive seasonality in the mountain pine beetle. We first set the mathematical framework for modelling seasonality; we then describe analytical tools that result from this framework; and finally, we examine the current unprecedented outbreaks of this insect in light of the quantitative framework for seasonality analysis.

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[1] Host trees can be partially killed, or strip attacked with successful brood production in the killed tissue. This is more common in endemic or incipient populations. After an outbreak is initiated, there are generally enough beetles present that defenses of even healthy trees are overwhelmed.

Methods and Materials

Temperature dependent models

Relating temperature to the development of insects requires differentiating between *age* and *stage*. Although both are related to time, age is chronological in nature and may not be directly observable. Stage, on the other hand, is a developmental concept usually defined by distinct morphological characteristics and a moult for transition from one stage to the next. Another concept, *developmental rate*, is the speed of temporal progression through an instar or stage and is dependent on temperature in a predictable fashion. Assuming that it is the same function throughout a stage, the developmental rate, $r(T)$, at a constant temperature, T, is the inverse ($1/t$) of the time required to complete that life stage. The developmental index, a_j, (or physiological age) in stage j, is then the fraction of the j^{th} life stage completed at any particular time by the median individual in the population, and is not directly observable. It is related to the developmental rate by a differential equation:

$$\frac{d}{dt}a_j(t) = r[T(t)];\;\; a_j\,(t=t_{j-1})=0;\;\; a_j(t)=\int_{t_{j-1}}^{t} r_j[T(t)]\,dt;\;\; a_j(t=t_j)=1 \qquad (1)$$

Life stage j begins at time t_{j-1}, which is the time of completion of the previous life stage (t_{j-1}, as indicated by the initial condition of the differential equation above), and finishes at time, t_j, at which $a_j=1$. What is observable are the developmental milestones, or the times at which one life stage terminates and another begins.

These relationships underlie almost all models of insect phenology (see Logan and Powell 2001). Once the mathematical relationship between temperature, time, and physiological age is defined, there remains the issue of finding an appropriate functional relationship between temperature, T, and the developmental rate, $r(T)$. The rate curves for the eight life-stages of the mountain pine beetle are shown in Figure 1.

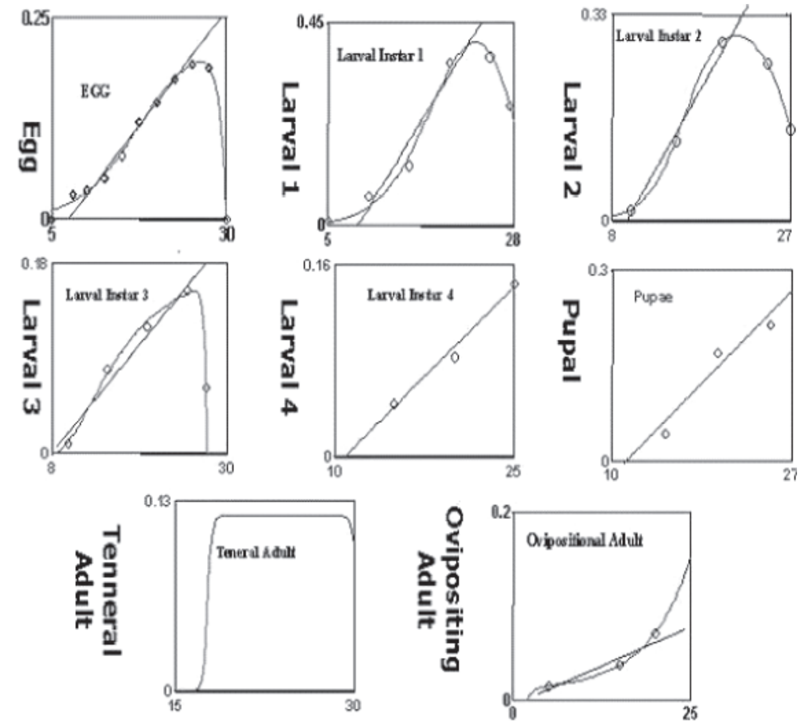

Figure 1. Rate curves for the mountain pine beetle. In all curves, the vertical axis is measured in development/day and the horizontal axis is temperature in centigrade. Data points determined by rearing at controlled temperatures are depicted as open circles.

Parameters for the functional relationships in Figure 1 can be found in Logan and Amman (1986), and Bentz et al. (1991), and a detailed description of the mountain pine beetle model in Logan et al. (1995).

Determining ovipositional dates from year to year

When developmental rate curves are determined for all stages of an insect's life cycle, the question becomes: How should they be used to make predictions regarding adaptive seasonality? Returning to equation [1], solutions can be written by direct integration:

$$a_j(t) = \int_{t_{j-1}}^{t} r_j\big(T(s)\big)ds.$$

Unlike traditional differential equations, where the aim is to investigate the structure of the solution, in this case we wish to determine when the solution reaches $a_j=1$, corresponding to the termination of the j^{th} life phase. This time, t_j, is defined implicitly using the solution to the differential equation [1] and the condition $a_j(t_j) = 1$,

$$1 = a_j(t_j) = \int_{t_{j-1}}^{t_j} r_j\big(T(s)\big)ds.$$

In general, it is not possible to calculate this integral analytically and even less possible to find an explicit expression for t_j, and we resort to numerical solution. The time at which the numerical integral exceeds one is the computational approximation to t_j.

Given a sufficiently long series of temperature measurements and a set of rate curves parameterized for all N stages of an organism, we have outlined a mathematical approach to calculating the sequence of times of developmental milestones, $t_0, t_1, t_2, \ldots, t_N$; corresponding to the date of oviposition (t_0), hatching of the eggs (t_1), progression through larval instars and whatever other life history stages occur, culminating in the emergence of the reproductive adult and oviposition (t_N). The reproductive input from adults of one generation is the initial condition for the egg stage of development in the next generation; we therefore introduce the notation t_0^n to indicate the median date of oviposition in the n^{th} generation, and connect with the sequence of dates of developmental milestones,

$$t_0^n = t_0, t_1, t_2, \ldots, t_{N-1}, t_N = t_0^{n+1}. \tag{2}$$

This sequencing mathematically captures the essential circularity of life history, in which egg begets egg through the intermediaries of adults and the other life stages, as shown in Figure 2.

Model iteration and bifurcation

An initial application of the modelling framework of Equations (1) and (2) can be found in Logan and Bentz (1999). They used observed annual phloem temperature from several ecologically interesting sites to investigate the dynamical properties of the model. The model was initialized for the broadest temporal ovipositional distribution possible, i.e., an egg initiated on each day of the year. Adult emergence dates from one generation was used as the ovipositional distribution for the next, and this procedure was followed for twenty generations using the identical annual temperature cycle. It was observed that the original distribution of 365 days converged to either a fixed point (the initial 365 day ovipositional distribution converged to a single emergence date) or a complex cycle of oviposition and subsequent emergence dates. A bifurcation analysis (in which the same iterative procedure is followed for an incremental sequence of annual temperature cycles, each of which is obtained by adding a small amount to the original 8760 hourly temperatures) further indicated that regimes of stable points were separated by regimes of complex cycles (Fig. 3).

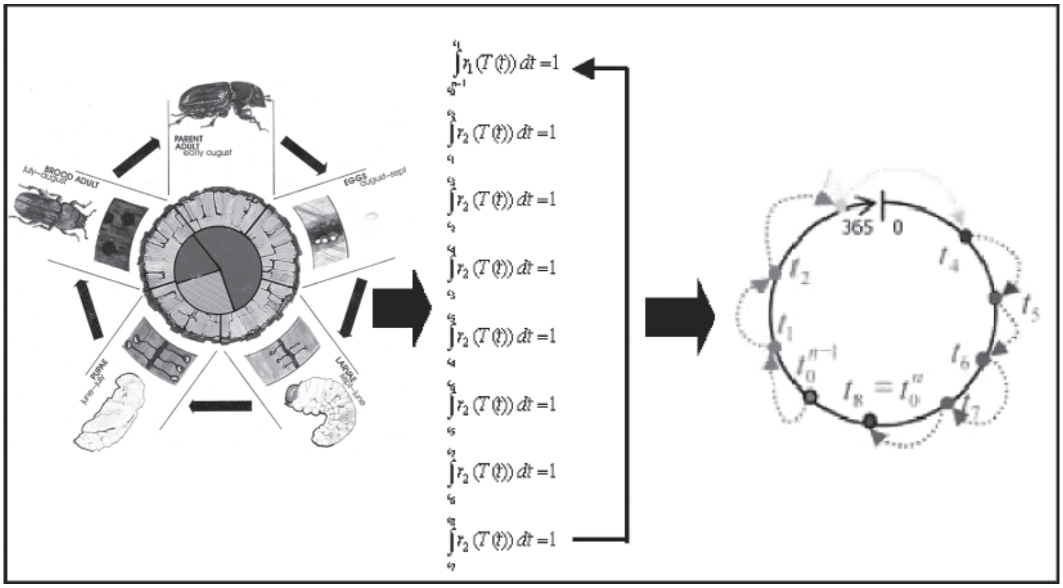

Figure 2. Schematic diagram of the mountain pine beetle model. Development for each life stage is accumulated according to the stage specific development rate curves in Fig. 1. Completion of the final life stage signals the initiation of the first life stage in the next generation. This process is mathematically represented as a circle map, analogous to the cycles of the natural world.

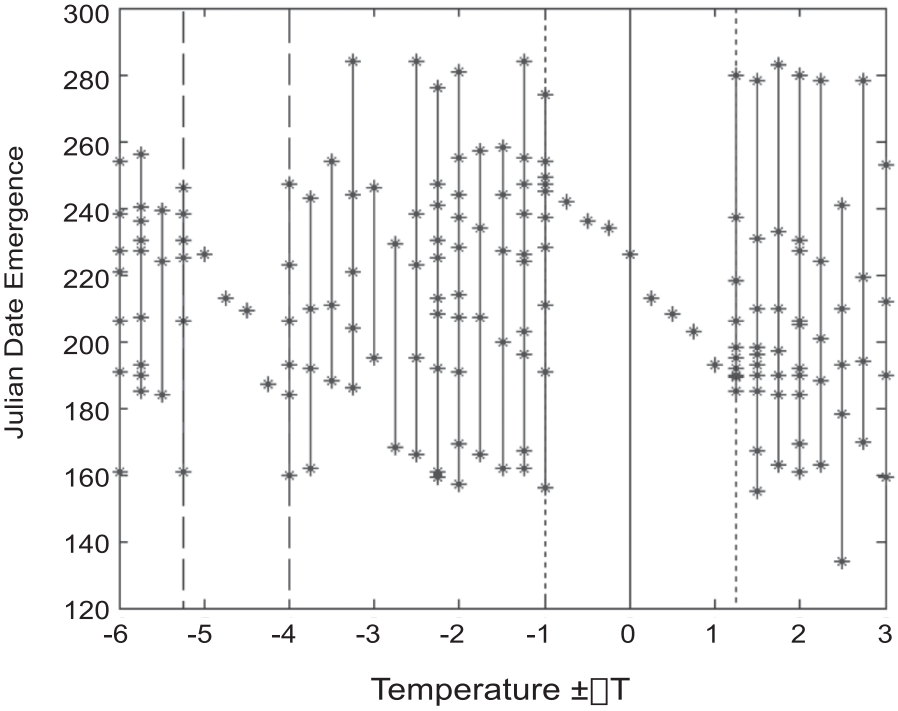

Figure 3. Bifurcation plot of 1995 temperatures for the Ranch site, Stanley, ID, USA. An amount ΔT was added (subtracted) to each hourly temperature in the annual cycle; the model was then initiated and allowed to run for many (20) generations. The last 10 adult emergence dates were then plotted. Plotting of a single point indicates synchrony (good for the mountain pine beetle) while plotting of several points indicates a cycle of emergence dates (bad for the mountain pine beetle). The dashed lines bound the temperature region of synchronous, semi-voltine emergence; the temperature region of synchronous, univoltine emergence is bounded by the dotted lines.

The reader is referred to Logan and Bentz (1999) for details and ecological interpretation of these results. In order to understand how stable, univoltine emergence dates could suddenly bifurcate into multi-date orbits of emergence dates, it is necessary to view phenology as a dynamical system mapping the yearly cycle of possible oviposition dates back to the same yearly cycle (Powell et al. 2000; Jenkins et al. 2001; Logan and Powell 2001).

Defining the *G* function

There is an inherent circularity in the progression of seasons and the rotation of Julian dates from 0 to 365 and back again. Temperature is also, in broad strokes, a periodic function of the time of year. If we assume periodicity in the temperature cycle from year to year, and interpret the sequence of ovipositional dates modulo 365 according to the Julian calendar, we have constructed a mathematical circle map (see Fig. 4).

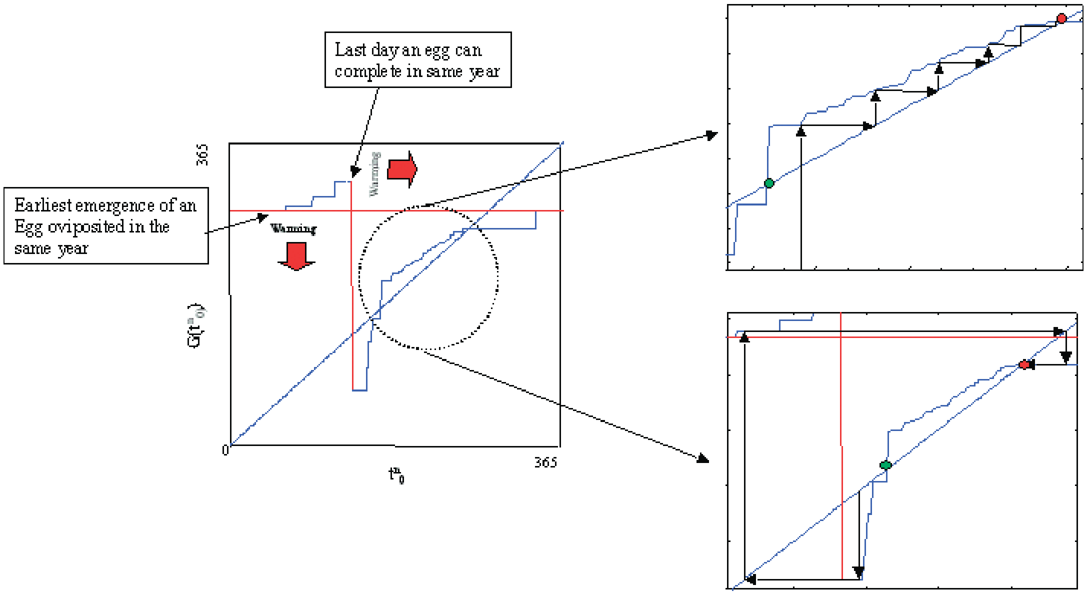

Figure 4. G-function characteristics. The upper intersection of the G-function with the fixed-point line is a stable attractor, as shown by the two trajectories in the two right-hand plots.

By this we mean that, for a given periodic temperature signal, the output oviposition date, t_0^{n+1}, depends directly and uniquely on the oviposition date for the previous generation,

$$t_0^{n+1} = G\left(t_0^n\right), \tag{3}$$

where both t_0^n and t_0^{n+1} are Julian dates (not interpreted modulo 365). This function mapping generation to generation, or "$G-$function" will be the basis for the mathematical analysis of phenology and seasonality. It generates a circle-map if both t_0^n and t_0^{n+1} are interpreted modulo 365, that is, with respect only to *time* of year, but not year.

When the *G* function has a fixed point, that is, if there is a day in the year, t^*, for which

$$t^* + 365 = G\left(t^*\right), \tag{4}$$

then the population must have a fixed number of generations per year. Perhaps more importantly, when this fixed point is stable (that is, when nearby oviposition dates converge to the fixed point as the map is iterated from year to year), the result is that the entire population will tend to synchronize on an oviposition date near the fixed point, thus satisfying the basic requirement of synchronous emergence for the mountain pine beetle's successful mass-attack strategy. Appropriate timing of adult emergence can be evaluated by determining if a stable, univoltine fixed point falls within a window of allowable dates. The stability of the intersection of a *G*-function can be determined by the nature of its intersection with the 45° fixed-point line,

$$t_0^{n+1} = t_0^n . \tag{5}$$

If the slope of the *G*-function at the crossing with the fixed-point line is smaller than one, the fixed point is stable, attracting nearby solutions. Conversely, if the slope at intersection is greater than one, nearby solutions will diverge.

If there is no intersection of the G-function with the fixed-point line, potentially complex cycles result. These cycles violate the definition of adaptive seasonality for two reasons. First, cycles imply asynchronous emergence. Although the resulting cycles may be stable in the sense that they attract and entrain nearby oviposition dates, eggs deposited on different dates will be attracted to different points on the cycle, destroying synchrony. Secondly, these cycles typically involve at least some emergence dates at unacceptable times of the year (i.e., either too late or too early), resulting in increased mortality for some portion of the population.

A graphical interpretation of *G*-function dynamics is provided in Figure 4. A bifurcation by gradually warming a temperature cycle will result in the downward movement of the horizontal asymptote of Figure 4, and the simultaneous rightward migration of the vertical asymptote. Thus, the *G*-function will appear to move as a wave from upper left to lower right as temperatures warm. This will first create and then destroy intersections with the fixed-point line. The range of temperatures for which an intersection occurs correspond to the observed regime of attracting (synchronous) emergence dates in Figure 3, while the range of temperatures lacking an intersection corresponds to the region of complex cycles.

Winding number

In the discussion so far we have focused on univoltinism and fixed points of the *G* function interpreted modulo 365, since the timing and synchrony of one generation per year is important for so many organisms in temperate environments. However, other adaptive seasonalities are possible. Many other important bark beetles go through two or more generations per year (bi-, tri-voltinism, etc.), all of which must be timed with host phenology and resource availability. On the other hand, many important forest insects (for e.g., high elevation populations of mountain pine beetle and spruce beetle) exhibit an endemic state in which a single generation completes every two years (semivoltinism). These voltinisms are also natural, structurally stable consequences of phenological circle maps, as we will discuss below.

An elementary dynamical property of order-preserving circle maps is the *rotation number*. The rotation number is the average number of rotations proscribed by points iterated under the circle map. Given the phenology mapping, $t_0^{n+1} = G\left(t_0^n\right)$, for a periodic temperature series and times *not* interpreted modulo 365 (so that the range and domain of *G* are unbounded), the rotation (or winding) number, *W*, is defined mathematically by

$$W = \lim_{n\to\infty}\left[\frac{G^n(t_0)}{365\,n}\right]. \tag{6}$$

Here $G^n(t_0)$ denotes the n^{th} iterate of G, or the oviposition date in the n^{th} generation, starting with an initial oviposition date of t_0. As n grows larger and larger, the fraction G^n/n approaches the mean slope of the n^{th} generation oviposition curve, giving an average value in terms of number of days per generation. Dividing by 365 gives average number of years per generation, corresponding to the average number of rotations proscribed by oviposition mappings each year. In the limit, this defines one over the net "winding" of the mapped oviposition dates around the circle.

The winding number is particularly important in the context of insect development because it corresponds directly to the voltinism. Thus, a univoltine life cycle corresponds to a winding number of one, a bivoltine life cycle (two generations per year) to a winding number of one half, and a semivoltine life cycle (a two year life cycle) to a winding number of two.

Results and Discussion

The results from the previous section provide criteria for determining an adaptive seasonality for the mountain pine beetle, namely:

(1) The *G*-function has an intersection with the fixed-point line;
(2) The *G*-function intersection is at an appropriate time of year;
(3) The slope of the *G*-function intersection is less than unity; and
(4) The winding number equals one.

These four criteria provide a rapid algorithm for evaluating any weather pattern or temperature regime. If all four criteria are satisfied, then the habitat is thermally adaptive for the mountain pine beetle; if not, then it is maladaptive. A MATLAB® program designed to determine adaptive seasonality for the mountain pine beetle can be obtained by contacting Jesse Logan. See Logan and Powell (2001) for an example application of this tool for climate analysis of mountain pine beetle outbreak potential.

The entire issue of mountain pine beetle climate interaction gains increased importance in the face of global warming. We will briefly describe one application of the *G*-function theory in the Stanley Basin in Central Idaho where we have maintained intensive research on mountain pine beetle population dynamics for almost 15 consecutive years. This area is well within the geographic distribution of the beetle and contains ample forests of lodgepole pine, but for meso-climatic reasons, the historic thermal habitat is only marginally suited for mountain pine beetles. This has two important results: first, instead of the dramatic boom-and-bust outbreak cycles of more benign climates, historical populations tend to be maintained at sub-outbreak levels for prolonged periods. This has allowed for detailed population dynamics research at one site for a prolonged time. Second, climate marginality means that slight variation in annual weather patterns result in immediate and measurable population responses. See Logan and Bentz (1999) for a more detailed description of the Stanley Basin in relation to mountain pine beetle ecology. In spite of the historic marginality of the climate from the mountain pine beetle perspective, the last eight years (1995-2003) have seen an outbreak of major proportions developing in this location.

As an indication of the sensitivity of the mountain pine beetle population response to weather in the Stanley Basin, consider the annual attack densities from the USDA-FS annual Aerial Detection Survey[2] (ADS) data (Fig. 5).

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[2] Aerial Detection Survey (ADS) data is obtained by flying over a region in a light aircraft and recording red-topped trees on a sketch map. Polygons recorded on the map must enclose at least ten trees, but may be an area of complete mortality. The ADS data is, therefore, difficult to convert into actual number of attacked trees, but give a good idea of total impact by mountain pine beetle.

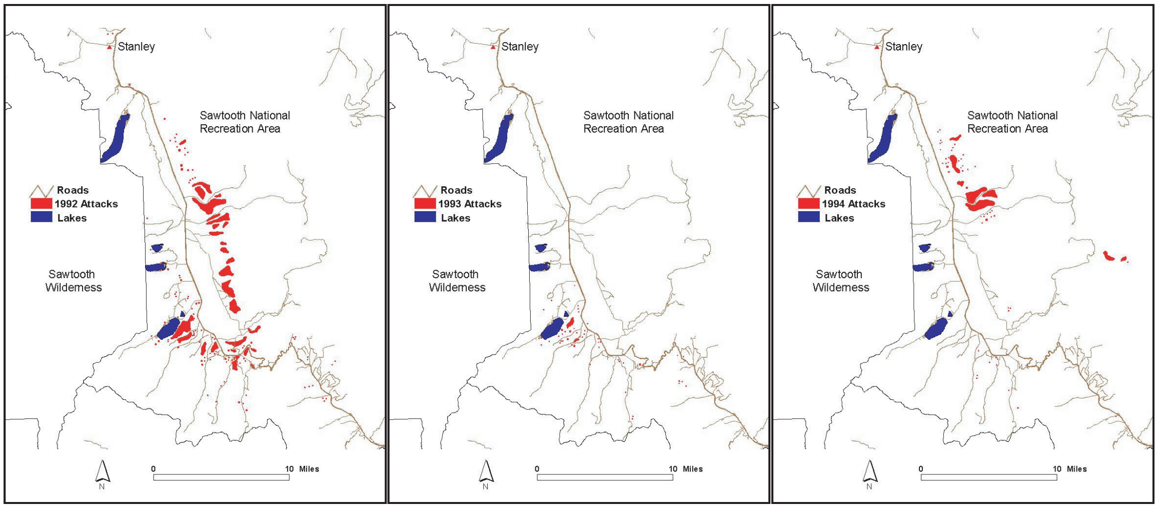

Figure 5. USDA Forest Service Aerial Detection Survey data for the Sawtooth Valley, Stanley, ID USA. See text for explanation.

From Figure 5 it is apparent that large areas of forest were impacted in 1991-92, but the pulse of beetles resulting from these attacks generated very few successful attacks the following summer (1993). During the summer of 1994, the successful attack cycle was reinitiated, although at a reduced level resulting from the population depression that occurred in 1993. If we consider the concurrent weather data, we see that the summer of 1993 (depressed population) was the coldest summer (June, July, August) on record corresponding to the worldwide impact of the Pinatubo volcanic eruption.

The impact of lowered summer temperatures is evident in the *G*-function resulting from annual phloem temperatures recorded at our Ranch site, Stanley Basin for 1993. The *G*-function (Fig. 6A) indicates a maladaptive seasonality: the curve lacks a synchronizing fixed point, oviposition periods occur too late in the year, and emergence times are inappropriate. In contrast, consider the dynamics of the *G*-function resulting from 1995 temperatures recorded at the same site (Fig. 6B). From this *G*-function, we see that an intersection with the fixed-point line occurs and that the attractor is at an appropriate time of year, indicating an adaptive annual weather cycle

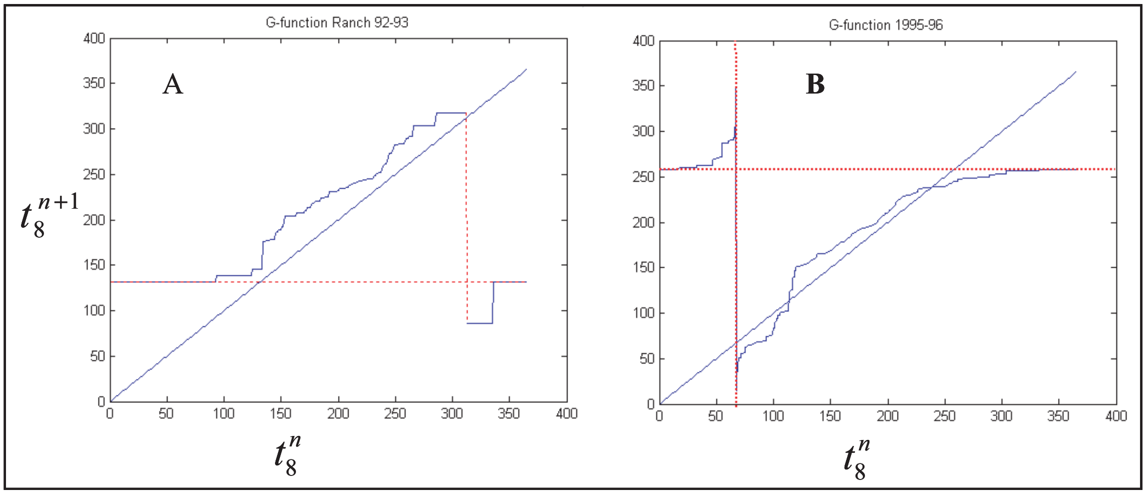

Figure 6. Effect of warming temperatures on G function intersections. A. Calculation using temperatures from the Pinatubo year of 1992-93. B. Calculation using temperatures from 1995-96.

Subsequent years have been even warmer, with results from our study sites consistently predicting adaptive seasonality accompanying an observed exponential growth for acreage impacted by the mountain pine beetle (Fig. 7)

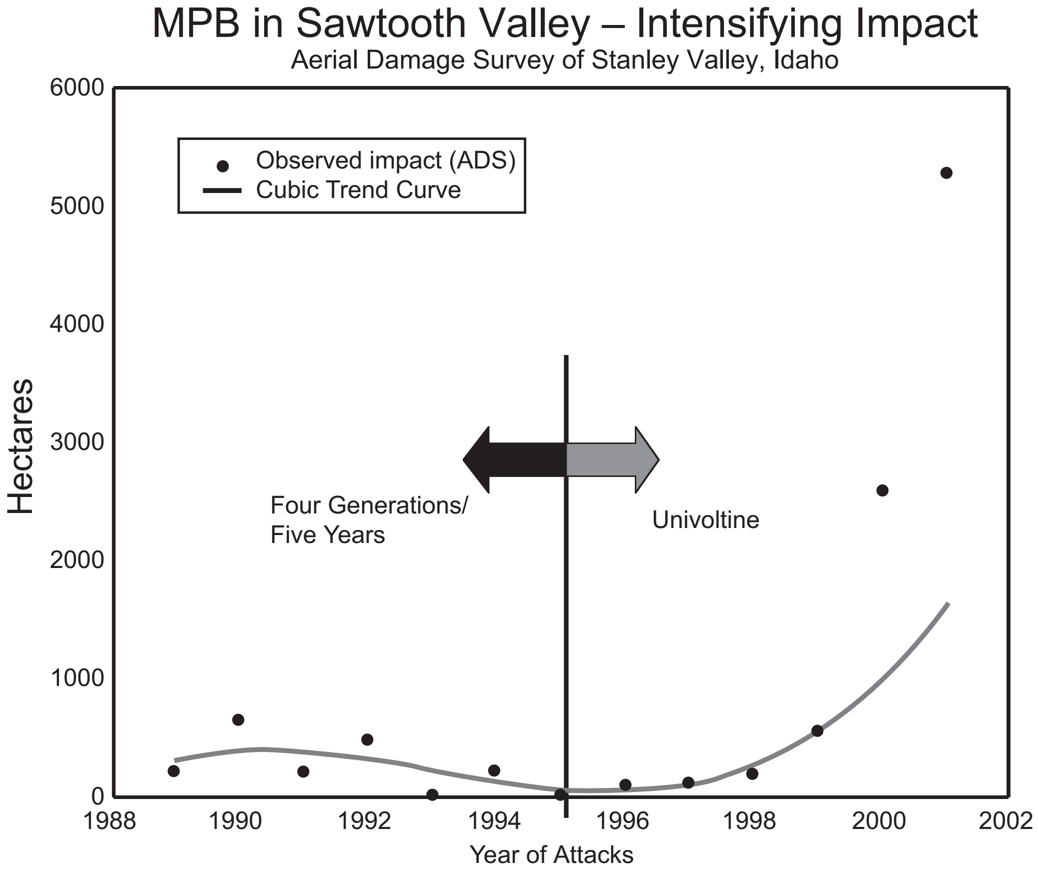

Figure 7. G-function analyses since the summer of 1995-96 have resulted in a predicted univoltine, synchronous life cycle for mountain pine beetles. These predictions have been accompanied with an explosive outbreak (the last mountain pine beetle outbreak in the Stanley area occurred in the late 1920s to early 1930, also an unusually warm period).

If this trend continues, our model predictions are for an increasing proportion of years that are favorable for mountain pine beetle populations, shifting the Stanley Basin from a low- or moderate- to a high-hazard area [see Safranyik's (1978) definition of a "high-hazard" area].

In addition to impacting the mountain pine beetle disturbance regime in the current (historical) distribution of mountain pine beetle, global warming provides the potential for mountain pine beetle to act as an invasive native species (Logan and Powell 2001). In particular, the northern expansion of mountain pine beetle into previously unoccupied jack pine habitat is discussed by Carroll et al. (2004). We note that the Canadian distribution of jack pine is contiguous not only with jack pine in the Lake States of the U.S., but also with the eastern and southeastern pines as well (Fig. 8).

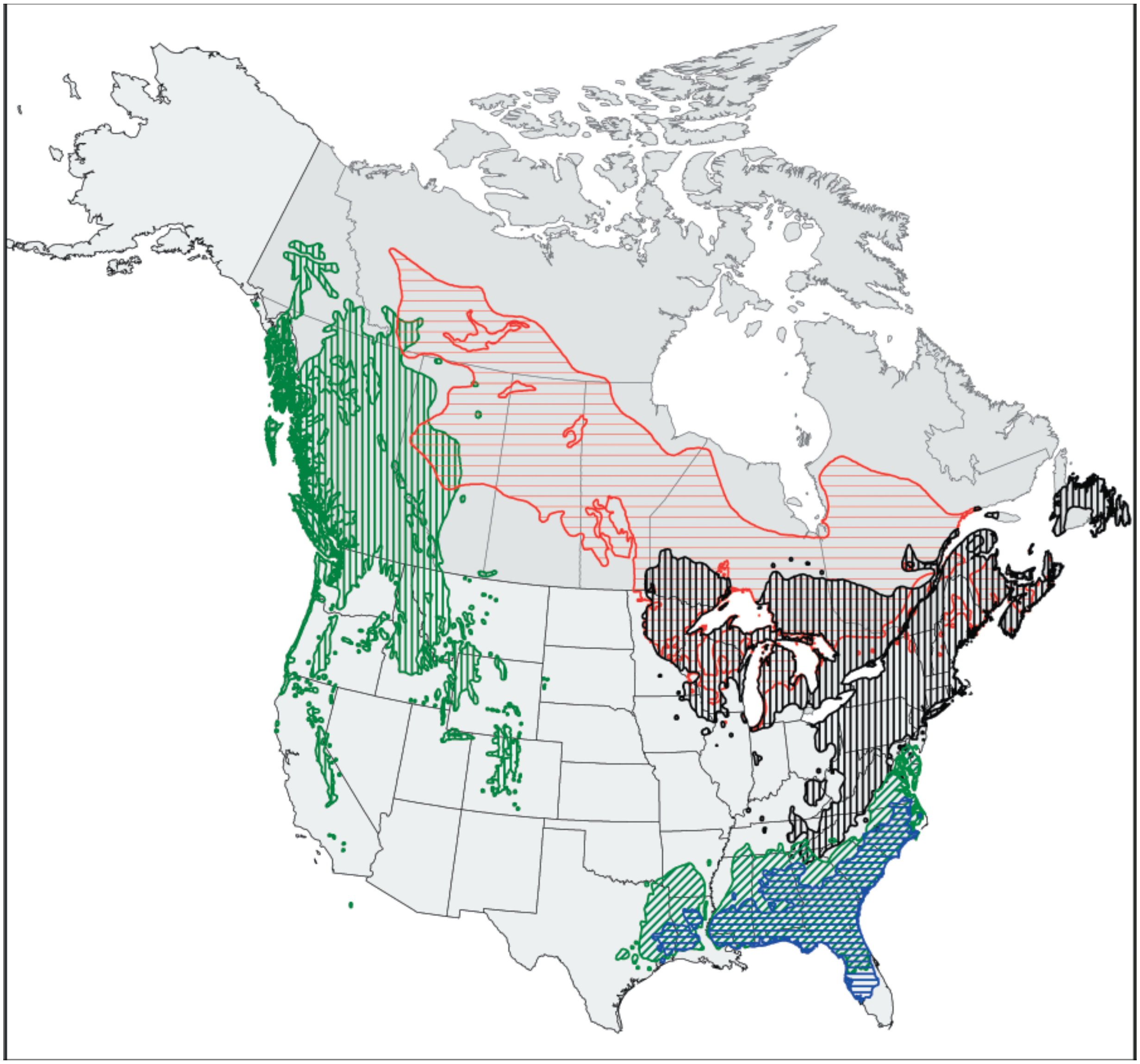

Figure 8. Major pine species connecting lodgepole pine with the eastern USA.

The potential range expansion south along the eastern coast of the U.S. raises the ecologically interesting question of eventual competition between the mountain pine beetle and the southern pine beetle, the two most economically disruptive pine beetles in the U.S. A similar global warming scenario holds for the high-elevation, five-needle pines (Logan and Powell 2001). We have ongoing research at two whitebark pine sites (one 10,000-ft site at Railroad Ridge in Central Idaho, and the other at an 8,000-ft location in western Idaho). The lower elevation site is experiencing a building outbreak, and a switch from endemic to incipient population phase occurred this past summer (2003) at the higher elevation site.

Our mountain pine beetle adaptive seasonality model has been interfaced with the BioSIM modelling system (Régnière 1996), allowing landscape level evaluation of historical events and simulation of predicted future events under various climate change scenarios. This landscape level model is currently being used to evaluate mountain pine beetle response to various climate change scenarios. The results suggest continued northwards expansion and increased vulnerability of pines at high altitude.

Conclusions

Equations (1) and (2) provide the generalized basis for modelling insect phenology; and equations (3), (4), (5) and (6) additionally provide the analytical tools for evaluating adaptive seasonality, given specifically for mountain pine beetle by the criteria:

(1) The *G*-function has an intersection with the fixed-point line;
(2) The *G*-function intersection is at an appropriate time of year;
(3) The slope of the *G*-function intersection is less than unity; and
(4) The winding number equals one.

This generalized framework is flexible, and can essentially be applied for any forest pest. In fact, it has been applied in a similar way for evaluating establishment probability for gypsy moth in both Canada (Régnière and Nealis 2002; Logan et al. 2003; Gray 2004) and Utah.

Specific applications of the above theory to mountain pine beetle have allowed historical evaluation of weather and climate with respect to geographic distribution and outbreak history. Future applications include the prediction of population responses to global warming. Predictions for mountain pine beetle include:

- Intensification of outbreaks patterns (frequency, intensity) in the historical distribution range;
- Northerly shift in population distribution, eventually connecting with the boreal jack pine distribution;
- Continental scale invasion of jack pine, the rate of which will be determined by dispersion, dispersal, and genetic adaptation;
- Subsequent invasion of pines southward in the eastern US;
- The southern limit of mountain pine beetle distribution shifting north, the degree of shift determined by genetic adaptation for maintaining phenology in a band of adaptive seasonality, and competition with other *Dendroctonus* species; and,
- Range expansion north by Mexican pine beetle, roundheaded bark beetle, and southern pine beetle into expatriated habitat.

The modelling framework we have developed for analysis of adaptive seasonality will be used to evaluate the probability of such events given reasonable climate change scenarios (Logan et al. 2003).

Current events involving bark beetle activity in North America tend to support the predictions in the preceding paragraph. Unprecedented outbreaks of spruce beetle are occurring (or have recently occurred) throughout its range from Alaska to southern Utah. Spruce mortality in some regions of the Kenai Peninsula, Alaska exceeds 95%. The magnitude of mountain pine beetle outbreaks in British Columbia, Canada are greater than at any time in recorded history, and they are occurring further north than previously recorded. Significant mountain pine beetle-caused tree mortality is also occurring in fragile high elevation whitebark pine ecosystems, habitats typically too cold for univoltine populations under pre-climate change conditions. Piñon *Ips* outbreaks are occurring throughout the entire range of the piñon, drastically altering the piñon-juniper ecozone. The occurrence of any one of these events by itself would be noteworthy; the fact that they are occurring simultaneously is remarkable. Drought and other factors undoubtedly play a role in some of these events, but the one commonality across all of these geographically and ecologically diverse phenomena is the series of unusually warm temperatures that begin somewhere in the mid 1980s. As stated in a recent Washington Post[3] article, "… Just as we underestimated the rate at which the climate would change, we have underestimated the biological responses to warming and the costs associated with the accompanying weather extremes. Climate change is weakening the hosts and emboldening the pests… ."

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[3] Climate Change is Really Bugging our Forests, by Paul R. Epstein and Gary M. Tabor, Sunday, September 7, 2003; page B05.

Acknowledgements

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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 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 mountain pine beetle 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 mountain pine beetles in British Columbia. Overlays of annual mountain pine beetle 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 mountain pine beetle populations have expanded into these new areas. Given the rapid colonization by mountain pine beetles 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

Every aspect of an insect's life cycle is dependent upon temperature because they are cold blooded. Therefore, 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, *Dendroctonus ponderosae* (Hopkins), is one of the most

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significant sources of mortality in mature pine forests in western North America (Safranyik et al. 1974). Mountain pine beetles 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 – mountain pine beetle 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 mountain pine beetle 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 mountain pine beetles 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 mountain pine beetle to significantly expand its range (Logan and Powell 2001).

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

Methods

Climatic suitability for mountain pine beetle

To quantify the climatic suitability of habitats for mountain pine beetles, we adapted a model of the impact of climatic conditions on the establishment and persistence of mountain pine beetle 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 mountain pine beetle in BC.

An index of climatic suitability for mountain pine beetle (F) was derived as follows:

$$F = P_i \sqrt{X_1 \times X_2} \tag{1}$$

where P_i is the number of years with the joint occurrence of P_1 through P_4 in runs of ≥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 mountain pine beetle infestations across its historic range (Powell 1966).

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).

Variable	Description	Rationale
P_1	> 305 degree-days above 5.5°C from Aug. 1 to end of growing season (Boughner 1964), *and* >833 degree-days from Aug. 1 to Jul. 31	A univoltine life cycle synchronized with critical seasonal events is essential for mountain pine beetle survival (Logan and Powell 2001). The minimum heat requirement is 305 degree-days 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).
P_2	Minimum winter temperatures >-40°C	Under-bark temperatures at or below -40°C causes 100% mortality within a population (Safranyik and Linton 1998).
P_3	Average maximum Aug. temperatures ≥18.3°C	The lower threshold for mountain pine beetle flight is ≈18.3°C (McCambridge 1971). It is assumed that when the frequency of maximum daily temperatures ≥18.3°C is ≤5% during August, the peak of mountain pine beetle emergence and flight will be protracted and mass attack success reduced.
P_4	Total precipitation Apr. to Jun. < long-term average	Significant increases in mountain pine beetle 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).
X_1	Variability of growing season precipitation	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).
X_2	Index of aridity[1]	Water deficit affects the resistance of lodgepole pine to mountain pine beetle, 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.

[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).

Climatic suitability	Range of index (*F*)
Very low	0
Low	0.01 – 0.05
Moderate	0.06 – 0.15
High	0.16 – 0.35
Extreme	0.36+

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 mountain pine beetles, generated by the climatic suitability model, using BioSIM© 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 BC 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 mountain pine beetle 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 BC. Universal kriging (e.g., Davis 1986) (with elevation as a drift variable) was used for interpolation between simulation points. The map outputs comprise grid coverage 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 mountain pine beetle 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 mountain pine beetles 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 mountain pine beetles. The gridded map was reclassified to produce an Arc shape file. We overlayed annual mountain pine beetle (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 mountain pine beetle 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 mountain pine beetle 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 mountain pine beetle northward, and toward higher elevations. Areas most suitable for mountain pine beetles (i.e., high and extreme CSCs) have expanded dramatically in south-central and southeastern BC (Fig. 1).

Interestingly, based upon a comparison of the area affected by the present mountain pine beetle 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 three 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 mountain pine beetle populations.

It is important to note that the increase in the occurrence of mountain pine beetles 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 mountain pine beetle 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 mountain pine beetles (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 mountain pine beetle outbreaks), or
(ii) adverse effects of warmer temperatures due to climate change.

Taylor and Carroll (2004) have shown that the amount of mature lodgepole pine has increased dramatically in BC during the past century in all habitat types. 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, mountain pine beetle populations may be forced into partial multi-voltinism (segments of the population having more than one generation per year) which will cause cold-susceptible stages (eggs, pupae, adults) to overwinter and thus interrupt flight synchrony and mass attack success in the following year.

Given the rapid colonization by mountain pine beetles 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 because of excessive warming in recent years also suggests that southern and low-elevation regions may become less suitable for resident mountain pine beetle populations. Unfortunately, a recent study (Bentz et al. 2001) has found a genetically based latitudinal gradient in development rates for mountain pine beetles, suggesting that, in the longer term, southern mountain pine beetle populations that are better adapted to warm temperatures may move North.

In the past, large-scale mountain pine beetle 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

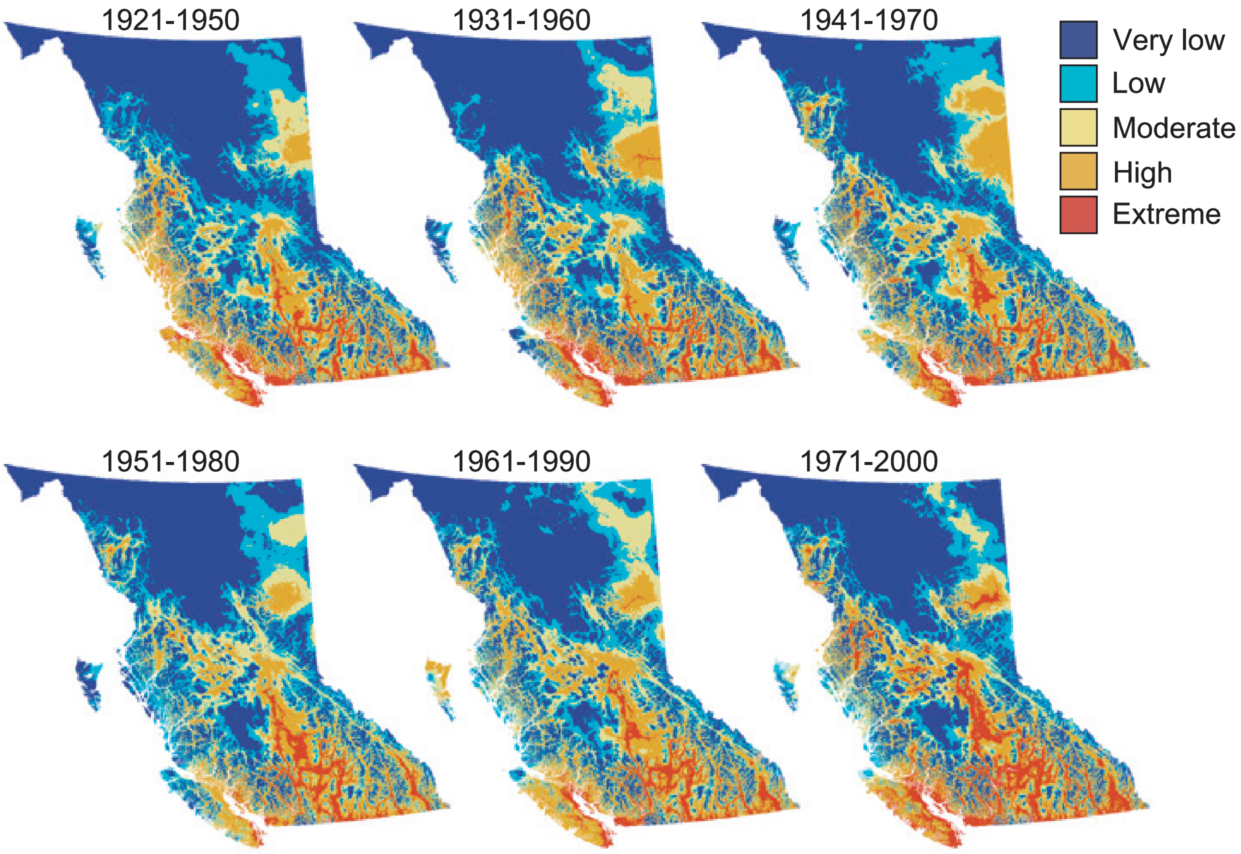

Figure 1. Historic distributions of climatic suitability classes (CSCs) derived from climate normals (30-year monthly means and extreme minima and maxima) for the mountain pine beetle in British Columbia. “Very low” CSCs are habitats with climatic conditions unsuitable for mountain pine beetle, whereas “extreme” CSCs are those considered climatically optimal.

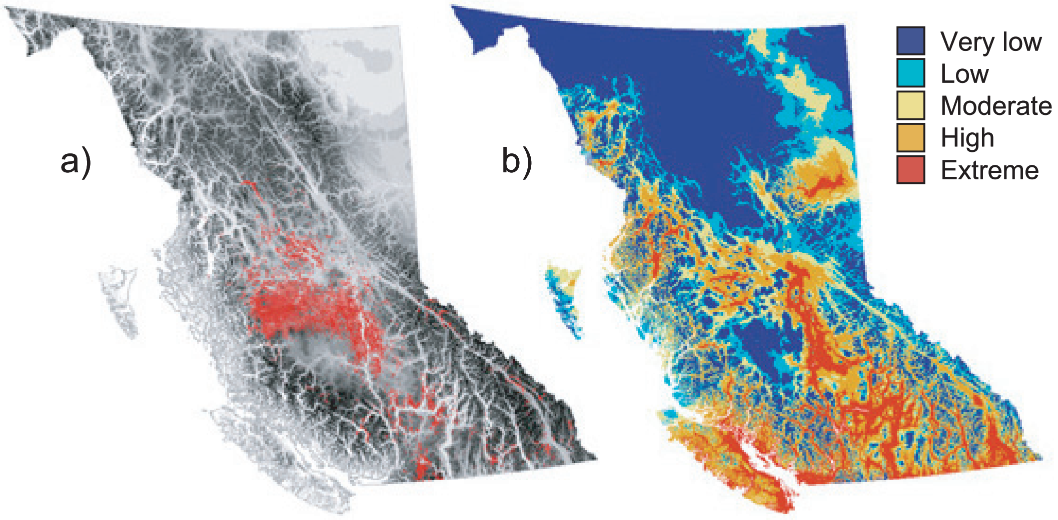

Figure 2. Mountain pine beetle infestations (all severity classes) from 1998 to 2002 (a), and the distribution of climatic suitability classes derived from 1971-2000 climate normals [30-year monthly means and extreme minima and maxima (b)] for the mountain pine beetle in BC. “Very low” CSCs are habitats with climatic conditions unsuitable for mountain pine beetle, whereas “extreme” CSCs are those considered climatically optimal.

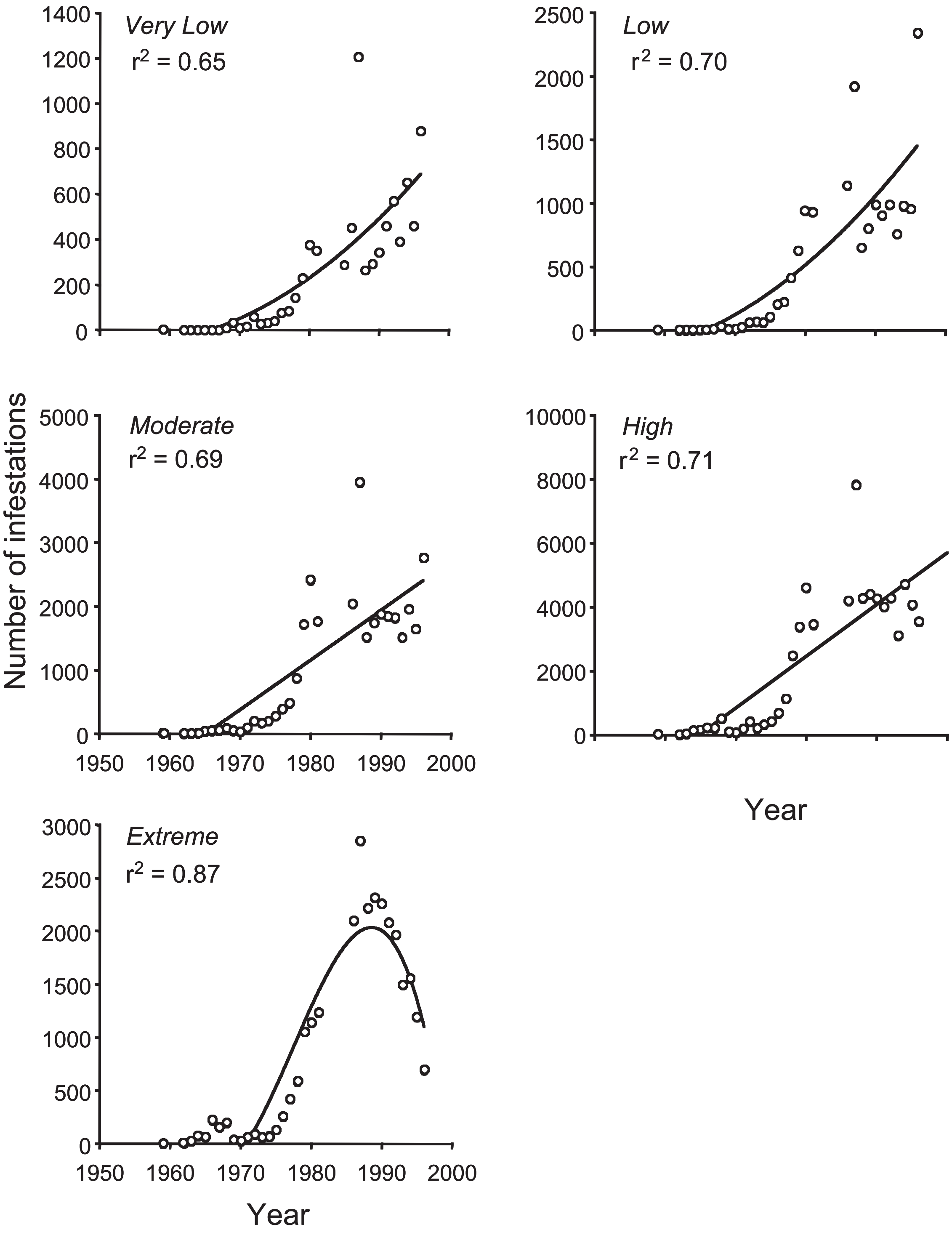

Figure 3. Number of infestations versus year and climatic suitability class derived from 1941-1970 climate normals (30-year monthly means and extreme minima and maxima) for mountain pine beetle in British Columbia. "Very low" CSCs are habitats with climatic conditions unsuitable for mountain pine beetle, whereas "extreme" CSCs are those considered climatically optimal.

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, mountain pine beetle populations have been most common in southern BC. Non-forested prairies and the high elevations of the Rocky Mountains have contributed to confining it to that distribution. With the substantial shift by mountain pine beetle 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 mountain pine beetles. Perhaps as evidence of this shift, in recent years small but persistent mountain pine beetle 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 (Furniss and Schenk 1969; Safranyik and Linton 1982; Cerezke 1995) that may soon come in contact with mountain pine beetles.

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Silviculture to Reduce Landscape and Stand Susceptibility to the Mountain Pine Beetle

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Abstract

The current landscape in western Canada includes an abundance of older pine stands that have matured without any active silviculture and are consequently very susceptible to mountain pine beetle outbreaks. The key to avoiding future damage is to focus long-term management of pine forests on relieving the conditions that facilitate landscape-level outbreaks. We present an overview of this management concept in three parts: a) landscape-level management of existing pine forests to reduce susceptibility to the development of epidemic outbreaks; b) stand-level management of future pine forests to reduce susceptibility to infestation; and, c) preliminary results of recent research examining the efficacy of spacing mature stands to prevent development of incipient outbreaks.

Introduction

The mountain pine beetle is a native insect in the pine stands of western North America. It causes little damage to forest resources at low population levels, but when populations build to an epidemic the losses are normally severe and occur at the landscape level. Where pine forest that has reached maturity without active silviculture predominates on the landscape, outbreaks last 10 years or more and kill most large-diameter pine trees on hundreds of square kilometres. When this happens, management for all forest resources is disrupted and effects on forest-dependant values and communities persist for decades. The current outbreak in central British Columbia (BC) is a good example of such a situation (Ebata 2004).

Historically, large mountain pine beetle outbreaks have been restricted by climate to a portion of the pine forests of western North America (Amman et al. 1977). However, recent analyses indicate that the suitable range for mountain pine beetle has expanded during a recent warming trend and future outbreaks are likely at higher elevations or more northerly latitudes than in the past (Carroll et al. 2004). Increasing mountain pine beetle activity is now becoming apparent in northern BC and on the eastern slopes of the Rocky Mountains in Alberta, and the potential for future expansion into hybrid and jack pine forests across Canada is questioned (Ono 2004). Lessons learned in areas historically subject to outbreaks may be applied in all these forests.

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The key to avoiding unacceptable damage by mountain pine beetle is a focus on long-term management of pine forests to alleviate those conditions that lead to outbreaks at landscape level (Safranyik et al. 1974). The objective of this paper is to present an overview of relevant management concepts, in three parts:

1) landscape-level management of present pine forests to reduce landscape susceptibility to development of epidemic outbreaks;
2) stand-level management of future pine forests to reduce stand susceptibility to development of incipient infestations; and,
3) preliminary results of a research study funded by the Government of Canada's Mountain Pine Beetle Inititative that examines the efficacy of spacing existing mature stands to reduce susceptibility to development of incipient infestations.

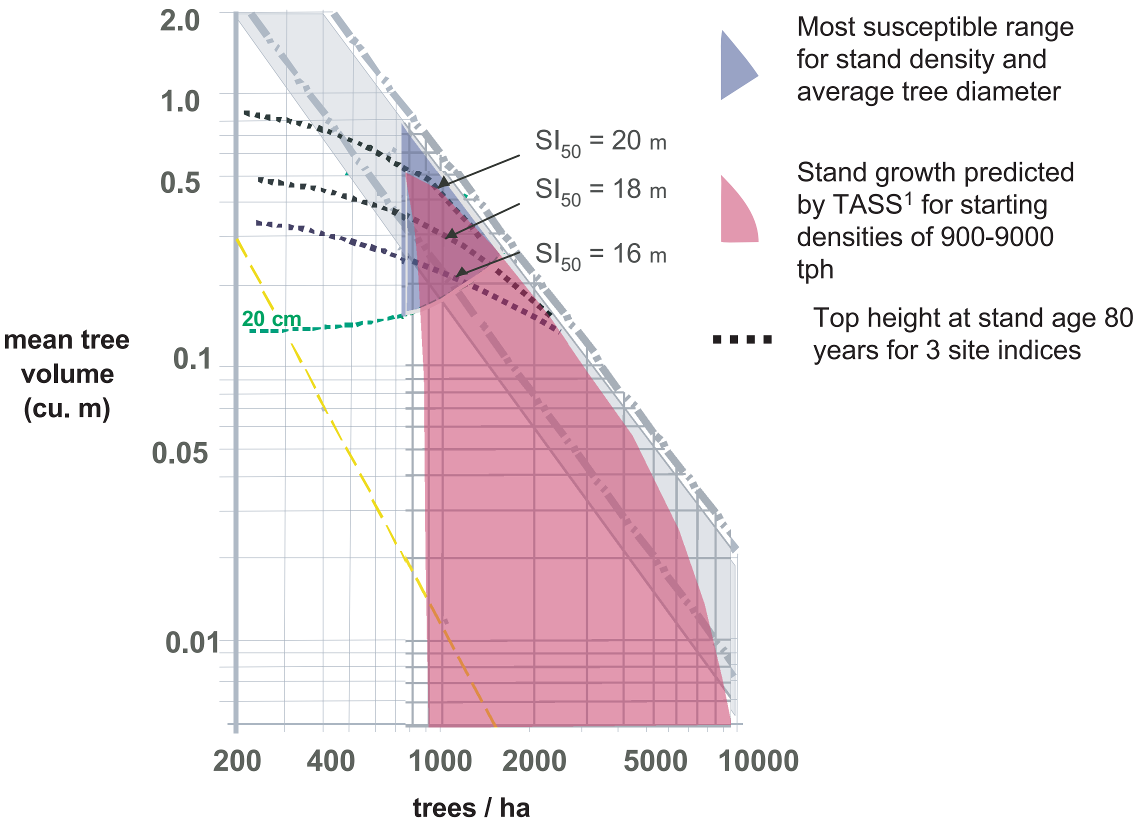
Landscape-Level Management

Management to reduce landscape susceptibility is based on knowledge of the basic biology and outbreak epidemiology of the mountain pine beetle, and their relationship with stand dynamics of lodgepole pine and its distribution on the current landscape. Carroll and Safranyik (2004) reviewed the biological basis for stand susceptibility and Safranyik (2004) reviewed the outbreak cycle. Stand characteristics usually associated with mountain pine beetle outbreaks in natural stands include stand age (more than 80 years at breast height), average tree diameter (greater than 20 cm) and stand density (750 to 1500 trees/ha) (Hopping and Beall 1948; Safranyik et al. 1974; Cole and Cahill 1976; Shore and Safranyik 1992). Age is associated with the effects of declining tree vigour on individual tree resistance to the blue-stain fungus carried by attacking beetles (Safranyik et al. 1975). Diameter is associated with the food and space requirements needed to support brood development for expanding populations (Cole and Amman 1969; Amman 1972). Stand density affects tree vigour and within-stand microclimate which influence success of bark beetle dispersal, attack or brood development (Bartos and Amman 1980). Growth modelling (Fig. 1) indicates that unmanaged natural-origin stands, which start at any density between 900 and 9,000 trees/ha at breast height age on land with typical site indices, will follow growth trajectories to a susceptible density and average diameter within 80 to 100 years (Farnden 1996). In the pine forests of western Canada, examining the age-class distribution of pine-leading stands in an area is a simple way of assessing the proportion of area carrying susceptible stands (Fig. 2).

Susceptibility of the Current Landscape

The susceptibility of any landscape unit to an epidemic outbreak depends on the amount of area in susceptible stands, how they are spatially arranged and how easy they are to access for direct control of incipient infestations. The current landscape in western Canada is very susceptible. Widespread natural and human-caused fire during early settlement followed by fire suppression and low utilization of lodgepole pine timber until fairly recently, resulted in accumulation of mature and overmature lodgepole pine forest in the BC interior and along the east slopes of the Rocky Mountains. In BC, the area of lodgepole pine greater than 80 years of age has increased from about 2.5 million ha in 1910 to more than 8 million ha in 1990 (Taylor and Carroll 2004). Most of this area is found in large swaths at mid-elevation in mountain valleys or on the large interior plateaus. It is this concentration of contiguous susceptible pine stands on large areas that make expansion of unchecked incipient infestations to landscape-level outbreaks highly likely, through a combination of local population growth and long-term dispersal, and underscores the need to bring the current landscape under active management to prevent future epidemic outbreaks.

Three main conditions must be satisfied before a landscape-level outbreak will occur. Several years of suitable weather (mild winters and warm, dry summers) are required to allow population growth to the point where large trees can be successfully attacked and small patch "incipient" infestations develop



[1] B.C. Ministry of Forests - Tree and Stand Simulator Model www.for.gov.bc.ca/hre/gymodels/TASS/model.htm

Figure 1. Stand Density Management Diagram for natural-origin lodgepole pine, illustrating how all stands starting at breast height age from densities between 900 to 9000 trees/ha become susceptible to mountain pine beetle outbreaks within 80 to 100 years.

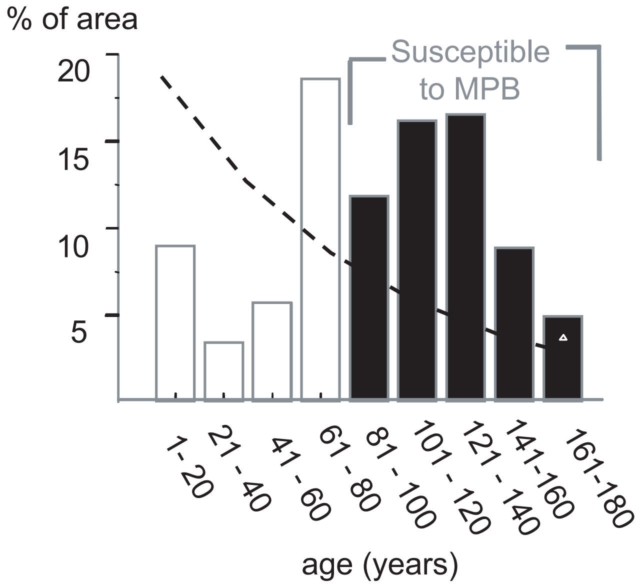


Figure 2. Age-class distribution of pine-leading stands in the SBS, SBPS, and MS biogeoclimatic zones of British Columbia. Dashed line indicates expected frequency distribution with a 100-year fire-return interval.

across the range where pine and mountain pine beetle occur together. At least some of these infestations must develop unchecked by weather or management action until they begin to export very high numbers of mountain pine beetles. Lastly, there must be an abundance of susceptible stands on the landscape to sustain these high populations. Periods of favourable weather occur from time to time throughout the range of mountain pine beetle and are not subject to management intervention. Shore and Safranyik (2004) discuss how timely and aggressive application of direct control to incipient infestations can slow or prevent transition to an outbreak at landscape level. In the current landscape, direct control will remain difficult and costly until the underlying cause (a concentrated abundance of susceptible pine on the landscape) is addressed.

Planned Stand Replacement

The primary action required to lower current landscape susceptibility is reduction of the amount and concentration of old pine stands, which can only be done through planned stand replacement. Fire and logging are the main tools available. Targets for the desired future age-class distribution will differ depending on land use emphases, but in any case a planner should aim at creating a landscape mosaic with less old pine, in smaller and more widely-separated parcels, where age-class, size and species mixes will not favour the development of large scale outbreaks. Two possible options for the pine component of a landscape unit are illustrated in Figure 3. One approximates the average age-class distribution expected in unmanaged landscapes with a natural wildfire return interval of 100 years (Taylor and Carroll 2004), which might be the desired condition for parkland or "wilderness", while the other illustrates a sustained yield for commercial timberland with most stands cycled on an 80-year rotation.

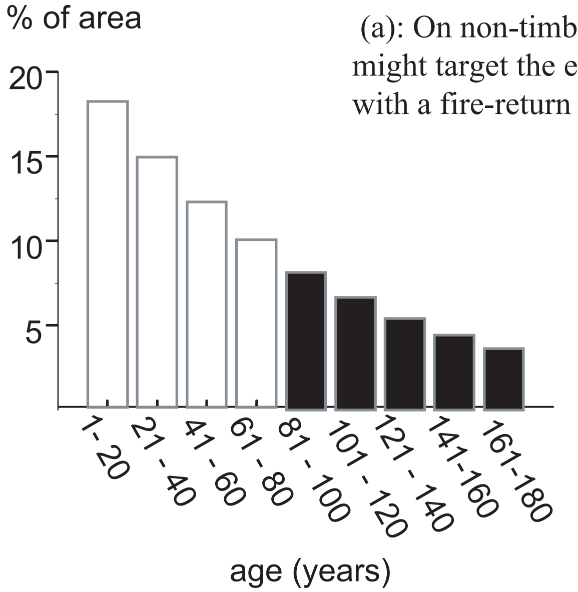
If there were no mountain pine beetle, adjusting the age-class distribution and redistributing it across the landscape in smaller patches would be relatively simple over time. Several decades of scheduled stand replacement based on a spatially-explicit inventory (through timber harvest or prescribed burning), and subsequent stand management to adjust density, growth rate or species composition would create the desired landscape condition. In the presence of mountain pine beetle the process is slightly more complex (Fig. 4). Harvest scheduling and access development must be flexible enough to incorporate direct control actions required to keep beetle populations low. A critical step is assessment of risk and susceptibility for existing stands (Shore and Safranyik 1992). High risk stands should be removed at the earliest logging chance, and access developed into areas of susceptible pine at lower risk so that they can be broken into smaller patch mosaics of diverse age, species, and tree size as opportunity allows. Consistent and thorough monitoring of the population status and location of mountain pine beetle is necessary for both risk and susceptibility rating, and for directing effective control activities during incipient infestations.

Stand-Level Management

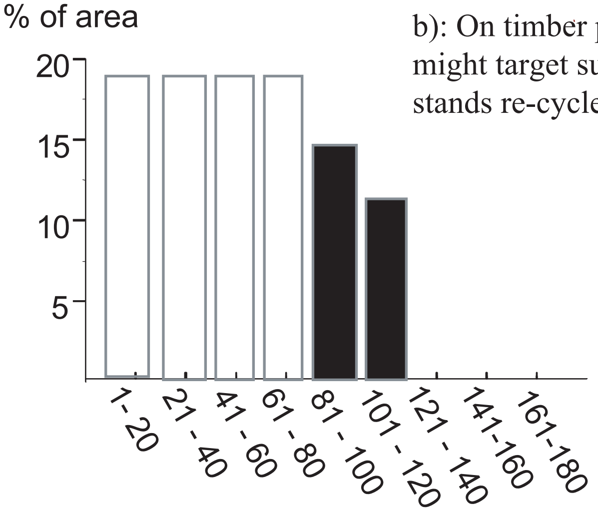
Stand-level management can also play a significant role in reducing the probability of outbreak development if it is applied within a landscape-level plan to reduce the amount and concentration of old pine. This section of the paper will briefly discuss stand-level management options to reduce the current susceptibility of existing stands, and for planning and managing new stands to avoid future susceptibility.

Species Conversion

Many existing lodgepole pine stands will succeed to more shade tolerant species in the absence of a stand-replacing disturbance such as fire. In such cases, species conversion through pine removal from maturing mixed stands will accelerate succession to non-susceptible species, reducing the amount of susceptible forest while maintaining some mature forest cover for other values. Where appropriate and needed in the landscape plan, species conversion can also be achieved through preserving advanced regeneration of non-pine species during harvest, or by establishing alternative species after harvest.



(a): On non-timber production lands a planner might target the expected “natural” distribution with a fire-return interval of 100 years.



b): On timber production lands a planner might target sustained yield with most stands re-cycled on an 80-year rotation.

Figure 3. Two possible targets for the age-class distribution of pine stands in a landscape planning unit.

Access Development and Shorter Rotations

Most stands will regenerate to lodgepole pine after harvest or burning, and the question has been asked: “If we re-establish pine on areas affected by mountain pine beetle, are we simply setting the stage for another epidemic in 80-100 years?” It is important to remember that the current scale of mountain pine beetle damage is only possible because the landscape is poorly accessed (making direct control difficult) and most stands are overmature and largely unmanaged. Bringing the land under active management relieves both these conditions. Access development facilitates control of incipient infestations, while recycling stands on a rotation less than 100 years limits the possible level of damage by reducing the amount of susceptible pine at any given time.

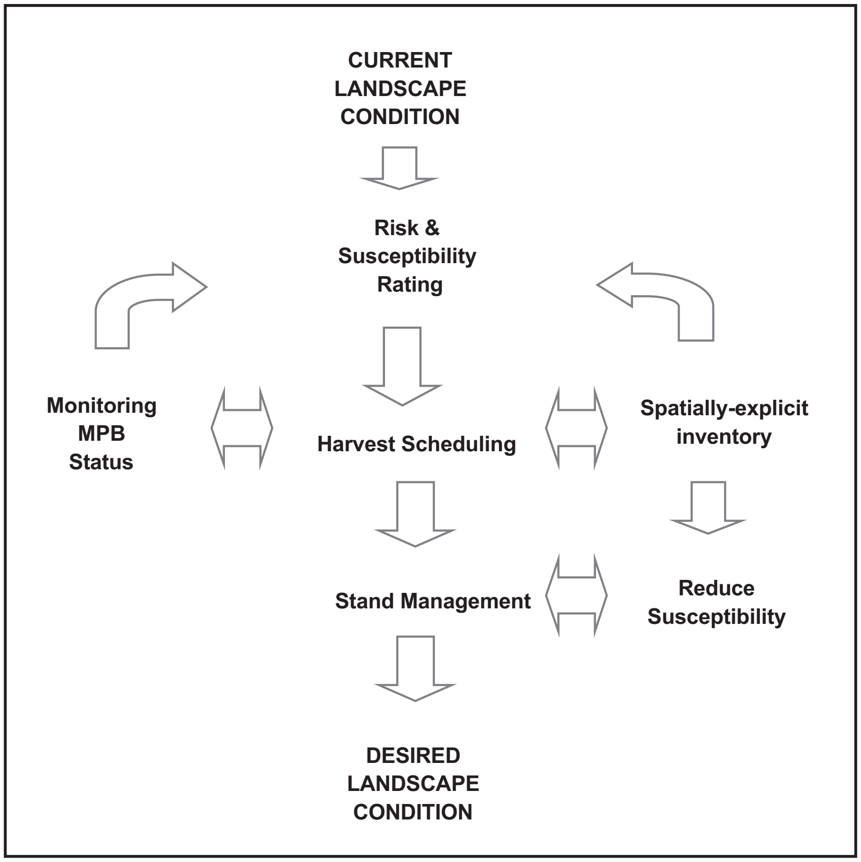


Figure 4. A simplified model for landscape management in pine-dominated operating areas.

Stand Hygiene

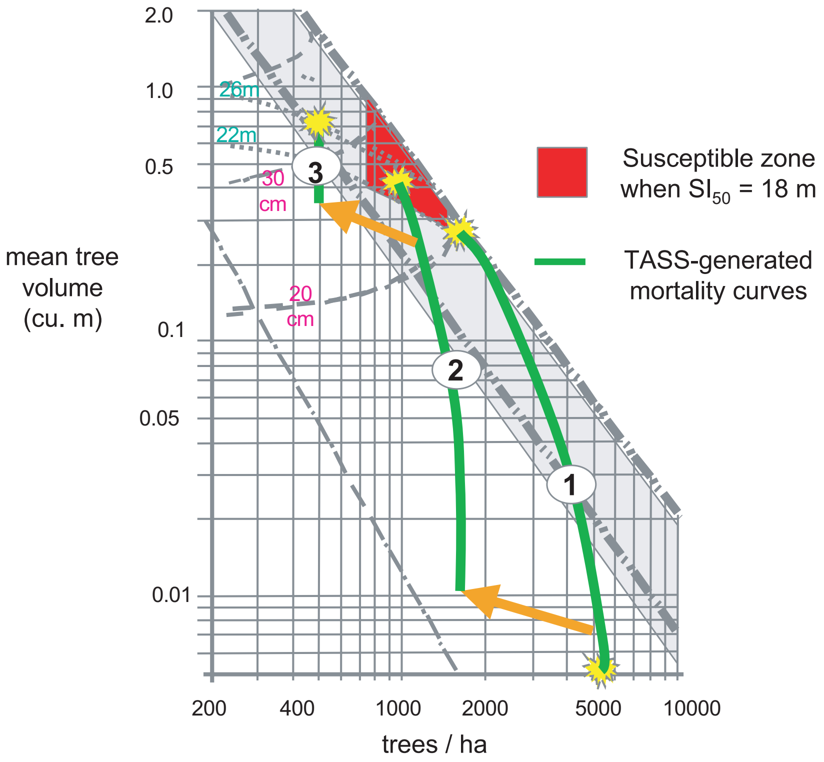
Endemic populations of mountain pine beetle generally require weakened or decadent trees for successful completion of their life cycle (Safranyik 2004). Removal of such trees during stand tending should limit potential for establishment and maintenance of endemic populations in stands managed for timber and reduce probability of incipient outbreaks when periods of weather favour population growth.

Density Management

Development of stand characteristics optimum for mountain pine beetle outbreaks coincides closely with "physiological maturity", which is defined by the point in stand development when current annual increment declines to below the mean annual increment (Safranyik et al. 1974). The onset of physiological maturity may be delayed by management actions that retain stand vigour, such as density management (Anhold and Long 1996). Density management can also be used to direct stand growth to meet specific product or timber supply objectives (Farnden 1996).

Figure 5 illustrates how two silvicultural entries to a fully-stocked, natural lodgepole stand starting at 5000 trees/ha at breast height on a site with SI_{50} = 18 m affects stand development. Without any treatment ("1" in Fig. 5), the stand would self-thin to about 1500 trees/ha by 80 years of age, just reaching average diameter where outbreaks typically develop. The stand could then be harvested, yielding 270 m^3 per ha of .25-m^3 average piece-size or, if beetle pressure is low, left to grow with regular monitoring of mountain pine beetle activity. If the same stand is pre-commercially thinned to 1600 trees/ha ("2" in Fig. 5), it develops to about 1100 trees/ha at age 80 and about 330 m^3 per ha, of larger average piece-size, which may be a more desirable logging chance if sawlogs are the product objective. If it is necessary or desirable to carry this stand to larger piece size or older age to meet some timber supply, habitat, or visual quality objective, a commercial thinning entry at about age 60 is an option. Removing approximately 100 m^3 of sawlog material would shift the growth trajectory away from conditions where outbreaks would ordinarily develop ("3" in Fig. 5), and yield about 350 m^3 per ha with large piece size at 100 years breast height age.

The above examples illustrate only three possibilities. When stands are brought under active management, there are many possible pathways for stand development that will lead to acceptable end products with reduced stand and landscape susceptibility to mountain pine beetle.



(Source of Stand Density Management Diagrams: Farnden 1996)

Figure 5. Stand Density Management Diagram for natural-origin lodgepole pine, with TASS-generated mortality curves illustrating how density management can lead to acceptable final products on 80-year rotation or maintain low susceptibility to mountain pine beetle on extended rotation.

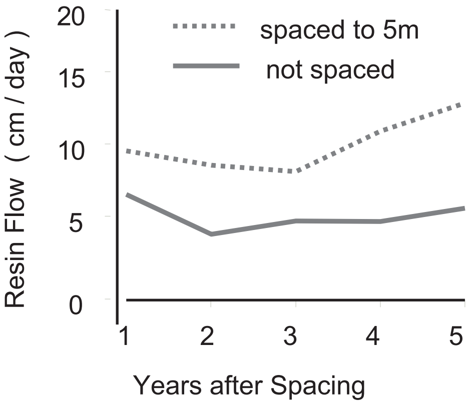
Spacing Mature Stands ("Beetle Proofing")

In most operating areas in western Canada, it is difficult to remove all stands with high susceptibility quickly without exceeding other constraints on harvest (e.g., timber supply, visual quality, habitat, etc.) and it is often important to hold some mature stands in the harvest queue while older stands are recycled. One tactic that has shown considerable promise is commercial thinning of some mature stands to a uniform inter-tree spacing at less than 600 trees/ha (also known as "beetle proofing"). The prescription requires thinning from below to enhance individual tree vigour, which increases ability to produce resins that are the primary defense against attack, and uniform spacing to create stand microclimate conditions (higher temperatures, light intensity, and within-stand winds) that negatively affect beetle dispersal, attack behaviour or survival (Bartos and Amman 1980; Amman and Logan 1988). To optimize these effects, stands must be opened to at least a 4-m inter-tree spacing (to increase wind penetration, light and temperature), with the largest, healthiest pine retained (for vigour and windfirmness) and damage to leave trees minimized to avoid stress. It is important to remember that it is increasing inter-tree spacing (not thinning to a target density or basal area) that achieves the microclimate objectives. This prescription, which takes mature stands down to between 400 and 625 trees/ha, usually removes enough volume of sufficient piece-size to ensure a commercially viable operation (Anon. 1999. *Case study in adaptive management: Beetle proofing lodgepole pine in southeastern British Columbia*. BC Min. For. Extension Note EN-039). The Canadian Forest Service has been studying "beetle proofing" for more than a decade and a few of our results are summarized in the following section.

Recent Research on Spacing Mature Stands

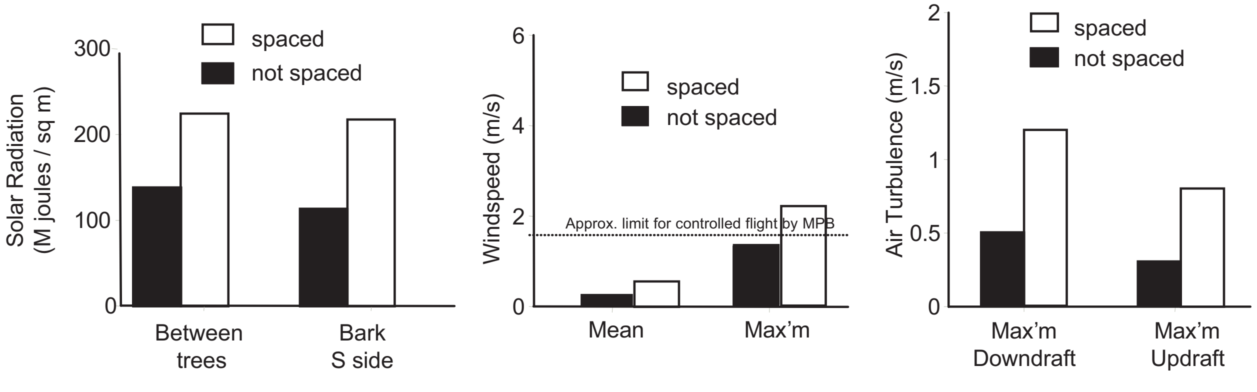
The "East Kootenay" Trial

Three levels of treatment (not treated, spaced to 4 m and spaced to 5 m) were applied to treatment units established in uniform, 90- to 110-year-old lodgepole stands at each of three sites in the East Kootenays between 1992 and 1993. Each treatment unit was instrumented to document within-stand microclimate and trees within each unit were monitored to document tree vigour. Results over the first decade since treatment suggest that the prescription achieves all the desired tree vigour (Fig. 6) and microclimate effects (Fig. 7). Until recently, these stands were not challenged by sufficient beetle pressure to directly evaluate whether these observed treatment effects impact bark beetle behaviour at a stand level.



(Source: Safranyik, Linton and Carroll, unpubl. data)

Figure 6. Comparison of resin production in response to wounding in spaced and unspaced stands from the East Kootenay Trial (mean of 10 trees/treatment on each of 3 sites).



(Source: Benton and Brown, unpublished data)

Figure 7. Comparison of 3 important within-stand microclimate parameters in spaced and unspaced stands from the East Kootenay Trial (5-year average on 3 sites for days in July and August when air temperature exceeds 18° C).

Table 1: Stand descriptions for five case studies of efficacy of "beetle proofing" to reduce incipient infestations of mountain pine beetle.

Location and Treatment Year	Prescribed Treatment	Area (ha)	Stand Density (trees/ha)	dbh (cm)	Age (years)
Cranbrook	No Treatment	3.9	1380	22.7	90
1992	Space to 4 m	5.3	443	25.3	90
	Space to 5 m	2.4	378	24.5	90
Parson	No Treatment 1	1.9	812	28.2	90
1993	No Treatment 2	1.7	1089	24.1	90
	Space to 4 m	2.9	386	22.3	110
	Space to 5 m	2.5	258	25.3	90
100 Mile House[a]	No Treatment	6.6	n/a	n/a	128
1994	Space to 4 m	7.7	549	22.1	124
Hall Lake	No Treatment	3.8	1169	22.3	109
1994	Thin to 500 tph	4.7	573	22.7	109
Quesnel	No Treatment	1.0	1300	21.5	83
1991	Space to 4 m	1.0	484	25.1	83

[a] Some data are not available (n/a) for 100 Mile House because the untreated control area was partially harvested to remove infested trees prior to the survey.

Five Case Studies of "Beetle Proofing"

This field season, we examined five existing side-by-side comparisons of "beetle proofed" and untreated stands[2] (including two of the East Kootenay Trial sites) established since 1991 to determine if changes in microclimate or tree vigour actually translate to a lowered frequency of mountain pine beetle activity at stand level (Fig. 8). Brief stand and treatment descriptions are listed in Table 1.

At each site, we laid out regular areas of known size in each treatment unit and systematically examined every living or dead tree over 10 cm in diameter at breast height for evidence of mountain pine beetle activity. The proportion and number of trees successfully attacked in each stand, attack density and ratio[3] of "green attack" to "red attack" are shown in Table 2. Density of attack and green:red attack ratio is lower in beetle-proofed treatment units than in untreated stands in every case; however, the magnitude of that difference reflects site-specific factors. The Quesnel site, which is located on the leading edge of the expanding epidemic outbreak described by Ebata (2004) has experienced extreme beetle pressure for the last 2 years. Beetle proofing is intended to prevent transition between endemic and incipient phases of the outbreak cycle, not to save stands during an epidemic. About 35% of all trees in each treatment unit have been attacked. In the untreated unit, this fraction includes more than 80% of all trees over 20 cm diameter at breast height (dbh) and attacks are now occurring in smaller diameter trees while about half of trees over 20 cm dbh have been attacked so far in the "beetle-proofed" unit. Although the green: red attack ratio is much lower than in the untreated stand, we expect this already unacceptable level of damage to worsen as large diameter pine in the surrounding area are killed and pressure on the "beetle-proofed" stand increases.

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[2] Funding for this work was provided by the Risk Reduction Research Component of the Canadian Forest Service's Mountain Pine Beetle Initiative as part of a project titled "Expansion of "Beetle-Proofing" Research, and Operational Evaluation for Feedback and Adaptive Management."

Figure 8. Location of five case studies assessed for efficacy of "beetle proofing" in 2003.

The other four sites are more representative of the situation for which "beetle proofing" is intended. At Cranbrook, Parson, and 100 Mile House, the prescribed spacing treatment produced the intended result. Untreated stands in all three areas have developed incipient infestations that require direct control intervention, while the "beetle proofed" stands have not. The Hall Lake demonstration area is different in that the prescription called for thinning to 500 trees/ha, rather than spacing to a minimum inter-tree distance. The proportion and density of trees attacked in the untreated stand is three to four times higher than in the thinned area, but the green:red attack ratios are similar (1.8 and 1.4 respectively). Our methods of data collection did not allow testing the influence of density on attack frequency; however, our surveys indicated considerable variation in stand density (142 – 2059 trees/ha) within the thinned stand, and a somewhat higher mean than prescribed. When thinning to target densities, patches of higher density are often left to compensate for natural stand openings and removal of damaged trees along skid trails. These patches may still provide good microclimate for host selection and initiation of attack. It is important to remember that "beetle proofing" requires thinning to minimum inter-tree spacing to maximize the desired results.

Summary

The current landscape in western Canada, which includes an abundance of largely undeveloped older pine stands that have developed without active silviculture, is very susceptible to development of landscape-level outbreaks of mountain pine beetle. Planned stand replacement is required to create a landscape mosaic with less old pine in smaller and more widely separated parcels, where age-class, size and species mixes will not favour the development of large scale outbreaks. Opportunities for reducing future susceptibility of replacement stands include conversion to non-pine species, management on shorter rotations, density management to control stand growth and attention to stand hygiene. There are also limited opportunities for stand-level management of current stands, including pine removal from mixed stands and "beetle proofing" some mature stands to provide flexibility for integration of non-timber objectives on the timber harvest landbase.

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[3] As used here, the "Green:Red Attack Ratio" is a ratio of the total number of trees attacked (whether successful or unsuccessful) in the most recent year to the total number of trees attacked in the preceding year. Some trees may have been attacked in both years.

Table 2: Mountain pine beetle activity since treatment at five case studies of "beetle proofing" to reduce incipient infestations of mountain pine beetle.

Location and Treatment Year	Prescribed Treatment	Proportion of Stand Attacked (%)	No. of Trees Attacked		Green:Red Attack Ratio
			Total	per ha	
Cranbrook	No Treatment	1.6	88	22	1.8
1992	Spaced to 4 m	0.5	12	2	0.3
	Spaced to 5 m	1.9	16	7	0.5
Parson	No Treatment 1	6.9	98	56	2.9
1993	No Treatment 2	1.4	24	15	0.3
	Spaced to 4 m	0.0	0	0	-
	Spaced to 5 m	0.4	1	0	-
100 Mile House[a]	No Treatment	n/a	433	67	n/a
1994	Spaced to 4 m	0	0	0	-
Hall Lake	No Treatment	13.5	579	158	1.8
1994	Thin to 500 tph	56.5	161	37	1.4
Quesnel	No Treatment	34.8	453	453	3.3
1991	Spaced to 4 m	34.5	167	167	1.2

[a] Data for the untreated control area at 100 Mile House are adapted from the pre-harvest survey undertaken by the Ministry of Forests.

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Dendroecological Reconstruction of Mountain Pine Beetle Outbreaks in the Chilcotin Plateau of British Columbia

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Abstract

The mountain pine beetle (*Dendroctonus ponderosae* Hopk.) (Coleoptera: Scolytidae) is an aggressive bark beetle that periodically increases to outbreak levels killing thousands of trees. It is considered one of the major natural disturbance agents in North America. In British Columbia, the main host species is lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), but western white pine (*Pinus monticola* Dougl.), ponderosa pine (*Pinus ponderosa* Laws.), whitebark pine (*Pinus albicaulis* Engelm.), and limber pine (*Pinus flexilis* James) are also attacked. We used dendrochronology to establish the history of canopy disturbances indicative of potential past beetle outbreaks. For this we relied on the fact that beetle outbreaks do not normally kill all the trees in a stand and that trees that survive outbreaks, experience extended periods of increased growth, visible in tree ring series as prolonged periods of release. Increased growth is thus used as a proxy for canopy disturbance. Fifteen chronologies studied in the south central area of British Columbia showed three fairly synchronous large-scale release periods which are proposed as three large outbreaks: 1890s, 1940s and the 1980s. The three releases averaged 13.8 years (Min=5, Max=23 years) in duration and recurred every 42 years (Min=28, Max=53 years), counted from the start of the release.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopk.) (Coleoptera: Scolytidae) is an aggressive bark beetle whose populations periodically increase to outbreak levels in infestations that kill thousands of trees. It is considered one of the major natural disturbance agents in North America (Furniss and Carolin 1977). In British Columbia (BC), the main host species is lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), but western white pine (*Pinus monticola* Dougl.), ponderosa pine (*Pinus ponderosa* Laws), whitebark pine (*Pinus albicaulis* Engelm.), and limber pine (*Pinus flexilis* James) are also attacked (Furniss and Carolin 1977). Occasionally, non-host trees such as Engelmann spruce (*Picea engelmannii* Parry) are attacked, but beetle populations do not persist in these occasional hosts (Unger 1993). Mountain pine beetles generally attack stands that are more than 80 years old, containing many trees of large diameter (Safranyik et al. 1974).

Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Although mountain pine beetles can attack younger trees, outbreaks have not been reported in stands younger than 60 years (Safranyik et al. 1974).

The mountain pine beetle occurs from northern Mexico (latitude 30°N), north to central BC (latitude 56°N) and from the Pacific Ocean in the west, to North Dakota (Safranyik 2001). Mountain pine beetle is distributed throughout most lodgepole pine stands in BC, with infestations being the greatest in the south-central and southeastern part of the province (Safranyik et al. 1974).

The life cycle of the mountain pine beetle varies considerably (Furniss and Carolin 1977). The normal cycle takes one year to complete; however, during warmer than average summers, adult parents may re-emerge and establish a second brood in the same year. In cooler summers or at higher elevations, broods may require two years to mature. Beetle flights normally occur throughout July and into August. After locating a suitable host, females bore through the bark to the phloem and cambium region where the egg gallery is constructed. The first beetles attacking a tree use aggregating pheromones to attract additional beetles to mass attack and overcome the tree's resistance. Fungi, which are introduced by the beetle, cause blue stain in the sapwood. As the fungi become established in the phloem and xylem, they interrupt the flow of water to the tree crown and reduce the tree's ability to produce resin, which is its main defence mechanism against beetle attack. The combined action of the beetle and fungi kills the tree.

Peterman (1978) described the post-outbreak dynamics in climax lodgepole pine stands and indicated that beetle attack thins the stand and promotes increased growth among the remaining pines and other vegetation in the stand, allowing regeneration in the understory. During an outbreak, the beetles preferentially kill trees of the largest diameter (McGregor and Cole 1985). Cole and Amman (1980) investigated the characteristics of residual stands (>100 years old) in Wyoming and Idaho to determine the effect of past beetle outbreaks on stand structure. Increment cores from understory fir and spruce indicated a growth release following the death of overstorey pine trees killed by mountain pine beetle.

Roe and Amman (1970) compared the stand structure of lodgepole pine forests that had gone through beetle epidemics with those that had not. They found that by removing the largest trees in the stand, the beetle promoted succession to spruce and fir. In the absence of fire, consecutive mountain pine beetle attacks in the stand contributed to the conversion of an even-aged stand to an uneven aged stand. Similarly, Heath and Alfaro (1990) found that mountain pine beetle-attacked forests in the Cariboo Region of BC shifted in species composition from lodgepole pine-Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), to predominantly Douglas-fir.

Tree rings maintain a record of the canopy disturbance history for a locality, and are therefore useful as indicators of ecosystem function (Becker et al. 1988; Alfaro 2001), and have been used to determine past outbreaks of bark beetles (Stuart et al. 1989; Heath and Alfaro 1990; Veblen et al. 1991a, b; Zhang et al. 1999; Eisenhart and Veblen 2000) and defoliating insects (Zhang and Alfaro 2002, 2003). The identification of growth release periods in surviving host and non-host trees, synchronous with the mortality of host trees, is the most common method of historical beetle outbreak detection in tree ring series. The release is not precisely simultaneous because not all hosts are attacked nor die in the same year (Eisenhart and Veblen 2000).

In spite of its prevalence as a disturbance agent of BC forests, studies to understand the impacts of mountain pine beetle on stand dynamics are few. Heath and Alfaro (1990) measured stand structure and growth of surviving trees after an infestation, which occurred from 1971 to 1975 at Bull Mountain, near Williams Lake, BC. In addition, in 1987, the Pacific Forestry Centre established 30 research plots to measure ecological changes induced by beetle in lodgepole pine forests in south-central BC (Shore and Safranyik 1996). In 2001, a comprehensive study of beetle impacts on stand dynamics was launched in response to increased outbreaks in BC. As part of that study, in the summer of 2001, we re-measured 15 of the plots established by Shore and Safranyik (1996) (Fig. 1) in order to determine their condition in 2001, i.e., 14 years after plot establishment. The plots are located in the Chilcotin Plateau of the Cariboo Region of BC and are henceforth referred to as the Cariboo plots.

The objective of the work presented here was to determine the long-term history of mountain pine beetle outbreaks in these 15 plots. These plots cover a substantial portion of the range of mountain pine beetle in BC. For this, we used dendrochronological methods to identify release periods attributable to beetle outbreaks in increment cores collected in 2001.

Brief history of mountain pine beetle in the Chilcotin Plateau area of British Columbia

The following information on the history of mountain pine beetle outbreaks in central BC was summarized from Wood and Unger (1996) and is based on available reports, and on ground and aerial observations by the Forest Insect and Disease Survey (FIDS) of the Canadian Forest Service, conducted annually from the 1960s until 1995. Since then, with the discontinuation of FIDS, records have been less consistent.

An outbreak of mountain pine beetle was reported in the Cariboo Region of BC from 1930 to 1936 in the Tatla Lake area, when 60% to 90% of infested lodgepole pine was killed over 650,000 ha. In the 1940s beetle-killed trees were reported in the Alexis Creek area (Personal communication, Dr. Les Safranyik, Canadian Forest Service, Victoria). A series of mountain pine beetle outbreaks occurred throughout the 1970s in the Cariboo Region. In 1974, the Klinaklini River drainage had infestations, which by 1975 had spread over most of the West Chilcotin. In 1981, mountain pine beetle killed over 9 million trees on 72,800 ha of the Chilcotin Plateau.

Dendroecological Methods

In the summer of 2001, increment cores were collected and analyzed from each of 15 locations in the Cariboo Region of BC (Fig. 1).

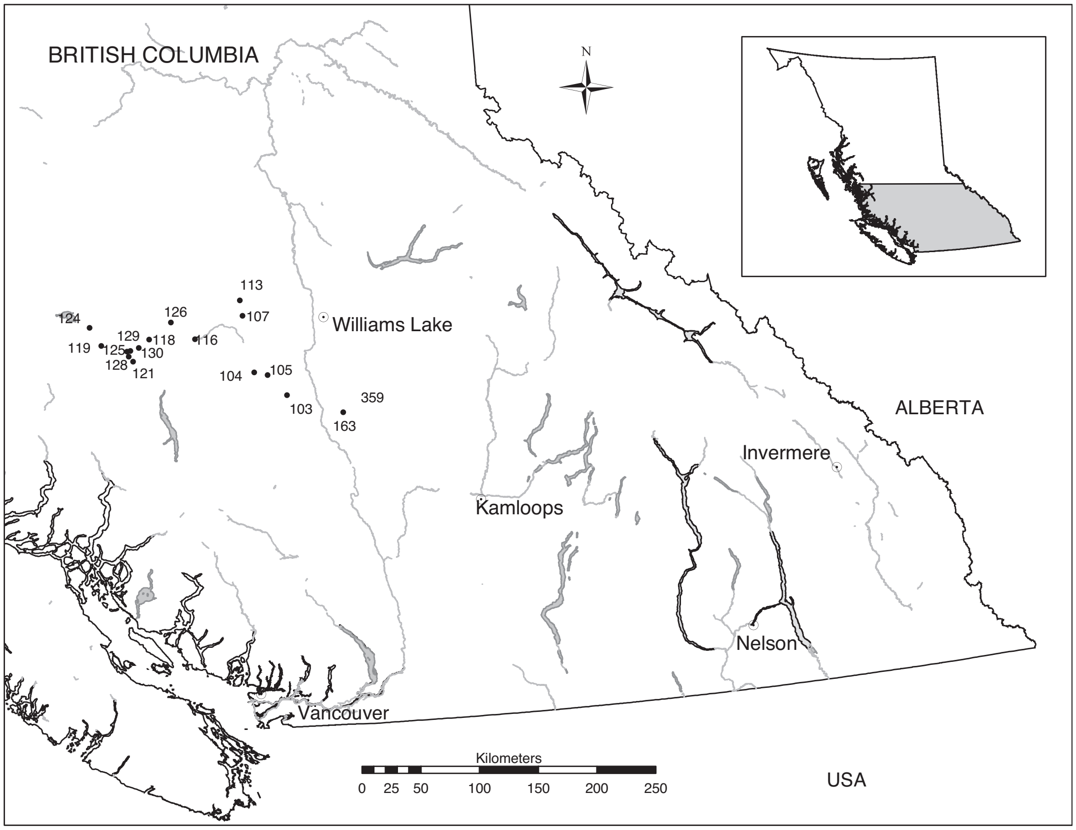

Figure 1. Map of the location of plots used to study the recurrence of mountain pine beetle infestations in lodgepole pine, in Central BC. Shaded area represents the enlarged map.

Stands were located in the Sub-boreal Pine Spruce (SBPS) and Interior Douglas-fir (IDF) biogeoclimatic zones (Meidinger and Pojar 1991) (Table 1). The SBPS zone is characterized by cold, dry winters and cool, dry summers. Mean annual precipitation ranges from 335 to 580 mm (Steen and Coupe 1997). Lodgepole pine is the climax tree species in this zone and is the most common species regenerating in the understory (Steen and Coupe 1997). The IDF zone is characterized by warm, dry summers and cool, dry winters (Meidinger and Pojar 1991). Climax vegetation on sites in the IDF zone is a Douglas-fir forest, often with intermixed lodgepole pine in the forest canopy (Steen and Coupe 1997).

Table 1. Summary data for lodgepole pine (host) stand chronologies used to study recurrence of mountain pine beetle disturbance in the Chilcotin Plateau area of BC.

Location	Stand No.	No. of cores cross-dated	BGC[1] zone	BGC sub-zone	Chronology period	Year with >5 cores[2]	Mean Serial Correlation[3]
Cariboo	103	21	IDF	dk4	1890-2001	1897	0.618
Cariboo	104	21	IDF	dk4	1849-2000	1890	0.590
Cariboo	105	16	IDF	dk4	1865-2000	1869	0.569
Cariboo	107	9	SBPS	xc	1886-2000	1915	0.493
Cariboo	113	14	SBPS	xc	1758-2000	1809	0.448
Cariboo	116	19	IDF	dk4	1849-2001	1889	0.558
Cariboo	118	14	SBPS	xc	1853-2000	1867	0.456
Cariboo	119	14	SBPS	xc	1912-2000	1951	0.544
Cariboo	121	13	IDF	dk4	1901-2000	1931	0.403
Cariboo	124	16	SBPS	xc	1887-2000	1915	0.430
Cariboo	125	17	SBPS	xc	1886-2000	1905	0.454
Cariboo	126	14	IDF	dk4	1864-2000	1915	0.496
Cariboo	128	16	SBPS	xc	1865-2000	1941	0.457
Cariboo	129	18	SBPS	xc	1860-2000	1891	0.495
Cariboo	130	18	SBPS	xc	1895-2000	1906	0.493

[1] Biogeoclimatic zone

[2] Starting year when the chronology is based on 5 or more trees

[3] Describes the amount of common signal within the chronology (Fritts 1976)

Increment core sample collection and preparation

Increment cores were collected from lodgepole pine as well as from non-host (these are trees not normally attacked by mountain pine beetle) Douglas-fir and interior spruce trees. In total, we collected 259 increment cores: 240 from lodgepole pine and 19 from non-host Douglas-fir and spruce. The cores (one per tree) were extracted at breast height with an increment borer parallel to the slope contour. In the field, each core was labelled with stand and plot number, tree number and species. Collected cores were transported to the Pacific Forestry Centre, Canadian Forest Service, Victoria, BC, for storage and analysis. Cores were glued and mounted in slotted mounting boards, which were labelled with tree identifiers. The surface of the cores was sanded with progressively finer sand paper (grits 220 to 600) to enhance the boundaries between annual rings.

Sample measurement and chronology development

Ring-width measurement was conducted in the Tree-Ring Laboratory of the Pacific Forestry Centre using a Windendro™ tree-ring measuring system and a Measu-Chron incremental measuring system. The precision of the measurement was 0.01 mm. The measured ring-width sequences were plotted and the patterns of wide and narrow rings were cross-dated among trees. The cross-dating was aided by the presence of distinctive narrow rings, and the quality of cross-dating was examined by the program COFECHA (Holmes 1983). COFECHA (Holmes 1983) detects measurement and cross-dating errors by computing correlation coefficients between overlapping 50-year segments from individual series (Eisenhart and Veblen 2000).

We standardized all cross-dated series by dividing each ring width by the mean series ring width (Eisenhart and Veblen 2000). Standardizing series by their mean preserved the long-term growth trend necessary to identify canopy disturbances (Veblen et al. 1991a). Each chronology was visually inspected for growth releases that might indicate a mountain pine beetle outbreak. After trying different methods to remove subjectivity from the process of identifying the release periods, we settled for a purely visual method, in which a release was called a mountain pine beetle release if it was abrupt and sustained over several years (Fig. 2).

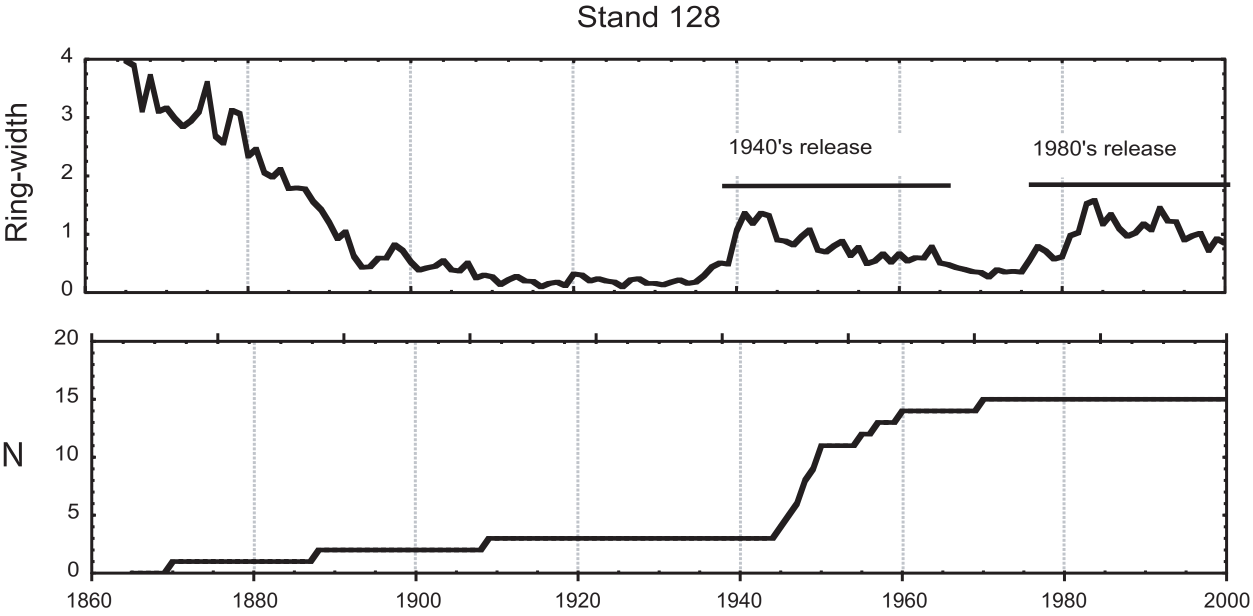

Figure 2. Example of tree ring chronology (top) and sample size for the chronology (bottom). Ring width indices for this stand (#128, Cariboo Region) clearly show two release periods attributable to canopy disturbances caused by outbreak of the mountain pine beetle (1940s and 1980s).

We defined the start of a growth release as a year that exhibited a 50% increase with respect to the mean ring width of the previous 5 years. The end of a release was defined by the year when rings returned to pre-release levels. Thus, the start and end of the release was compared only with the tree-ring indices that directly preceded the release and not to the whole chronology. Releases that lasted less than 5 years were ignored as we expected that canopy openings caused by beetle thinning would cause release periods that would last until full canopy closure was re-established. Although no data exists on the length of this process, we expected that, for severe outbreaks, it would last more than 5 years. Veblen et al. (1991a, b) used a similar method for detecting release in Engelmann spruce trees following spruce bark beetle outbreaks in Colorado.

Lodgepole pine (host) chronologies were developed for each of the 15 stands. In the initial decades of long tree-ring chronologies, when sample size is inevitably small, identification of releases is unreliable (Eisenhart and Veblen 2000). Therefore, interpretation of chronologies was limited to where the sample size was at least five trees per stand.

It was difficult to find sufficient non-host trees in the study area to build reliable chronologies for species other than pine. However, we succeeded in building two non-host chronologies: one spruce chronology for stand 113 and a Douglas-fir chronology for stand 116 in the Cariboo region. Non-host chronologies were examined for periods of release and compared to host chronologies to determine if periods of release in non-host species were synchronous with periods of release in lodgepole pine.

Searching for spatial outbreak patterns

To study the spatial synchrony of mountain pine beetle outbreaks, the entire chronologies were visually compared and the release periods attributable to beetle-induced thinning were tabulated and plotted for each sampled stand. The average start and end year of the release and the interval between initial dates of release were calculated.

Results

Outbreak history based on tree rings

Over 90% of lodgepole pine cores were successfully cross-dated and included in the tree-ring analysis. The number of cores included in the stand chronologies ranged from 9 to 21 (Table 1). Although one chronology (stand 113) contained one tree dating to 1758 (243 years old at breast height, Table 1), for most chronologies the oldest date when the sample size was at least five trees was in the1880s. Therefore our results can be applied with confidence only to the period after this date, i.e., we provide a beetle history for the last 120 years.

On average, the 15 chronologies studied showed three fairly synchronous release periods: 1890s, 1940s and the 1980s (Tables 2 and 3, Figs. 3 and 4). The three releases averaged 13.8 years (Min=5, Max=23 years) in duration and recurred every 42 years (Min=28, Max=53 years), counted from the start of one release to the start of the next release (Table 2).

The *first release* (1890s) appears in only 5 of the 12 stands that were old enough to register this release (Figs. 3,4). The median of the initial release date for these five stands was 1893, but ranged from 1887 to 1898. The average duration of this release was 13.2 years. Examination of fire and beetle scars in discs from these areas indicates possible activity of these two disturbances simultaneously (Fig. 3). Without additional sampling and lacking written records, the causes of this release are uncertain.

The *second release* (Figs. 3, 4) appeared with relative synchrony in 13 of the 15 stands sampled and had an initial median date of 1935 (Min=1926, Max= 1959). The average duration of this release was 13.6 years (Min= 5, Max= 23 years). The start of the second release occurred, on average, 40.8 years after the start of the first release. Cross-section samples collected by Hawkes et al. (2004) showed many beetle scans in this period (Fig. 3).

The *third release* was evident in 12 of the 15 stands sampled and also appeared with relative synchrony (Figs. 3, 4). This release had a median initial date of 1982 (Min=1975, Max= 1989) and lasted, on average 14.3 years, and in some stands it still continued in 2000. This release occurred, on average, 42.9 years after the start of the second release. Cross-section samples also show many beetle scans dating in this period (Fig. 3).

Non-host. In the two stands that had both host and non-host chronologies constructed (Tables 4 and 5, Fig. 5), both species responded to canopy disturbance approximately at the same time as lodgepole pine. Similarly to lodgepole pine, release periods were evident starting in the 1890s, 1930s and 1980s. Release durations were 8, 25 and 15 years for the first, second and third releases.

Table 2. Dates of growth releases attributable to mountain pine beetle thinning of lodgepole pine stands, duration of release, and interval between releases, in the Chilcotin Plateau area of BC. Dashed line indicates that there was no interval.

Stand No.	Release Dates	Duration of release (Years)	Interval between adjacent[1] releases (Years)
103	1939-1950	11	---
	1989-2000	11	50
104	1895-1903	8	---
	1938-1950	12	43
	1975-1985	10	37
105	1939-1950	11	---
107	1932-1944	12	---
113	1898-1904	6	---
	1926-1947	21	28
116	1887-1902	15	---
	1933-1944	11	46
	1986-1998	12	53
118	1895-1910	15	---
	1980-2000	20	---
119	1941-1946	5	---
	1975-1993	18	34
121	1932-1955	23	---
	1980-1987	7	48
124	1959-1968	9	---
	1988-1993	5	29
125	1935-1944	9	---
	1980-1997	17	45
126	1934-1951	17	---
	1975-1996	21	41
128	1939-1956	17	---
	1982-1998	16	43
129	1890-1912	22	---
	1936-1951	15	46
	1981-1998	17	45
130	1935-1953	18	---
	1982-2000	18	47
Overall Mean		13.8	42.3

[1] Three release periods were found: 1890s, 1940s and 1980s. Intervals are between consecutive release periods.

Table 3. Characteristics of lodgepole pine growth releases attributable to stand thinning by mountain pine beetle outbreaks in the Chilcotin Plateau area of the Cariboo Region.

	First release		Second release		Third release	
	Initial year	End year	Initial year	End year	Initial year	End year
No. stands	5	5	14	14	12	12
Mean	1893	1906	1937	1951	1981	1995
Median	1895	1904	1935	1950	1982	1997
Range	1887-1898	1902-1912	1926-1959	1944-1968	1975-1989	1985-2000

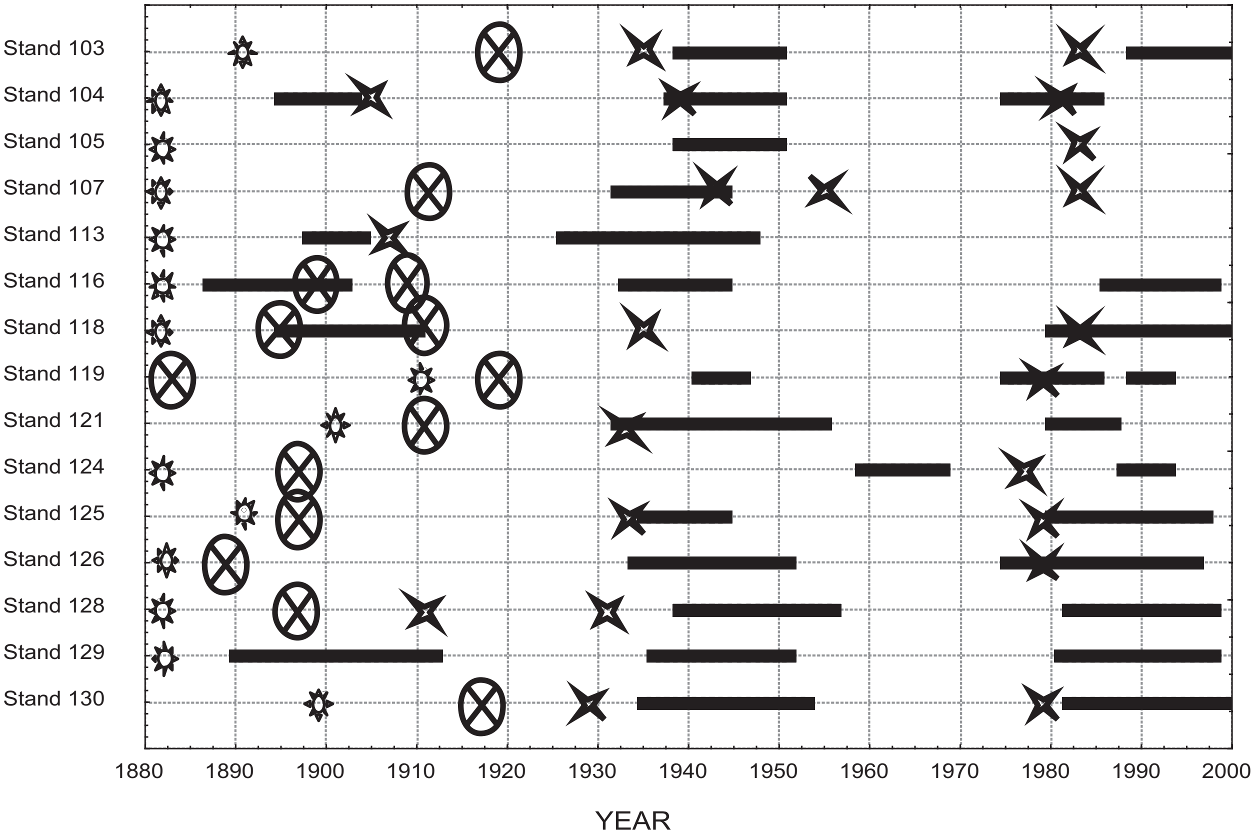

Figure 3. Release periods attributable to mountain pine beetle outbreaks in Chilcotin Plateau, BC, inferred from growth-release periods using tree-ring chronologies. Fire (circle with cross in middle) and mountain pine beetle (star shaped symbol) scar dates are given for each stand. For details of fire and beetle scars, please see Hawkes et al. (2004). Asterisk indicates start year for the tree-ring chronology.

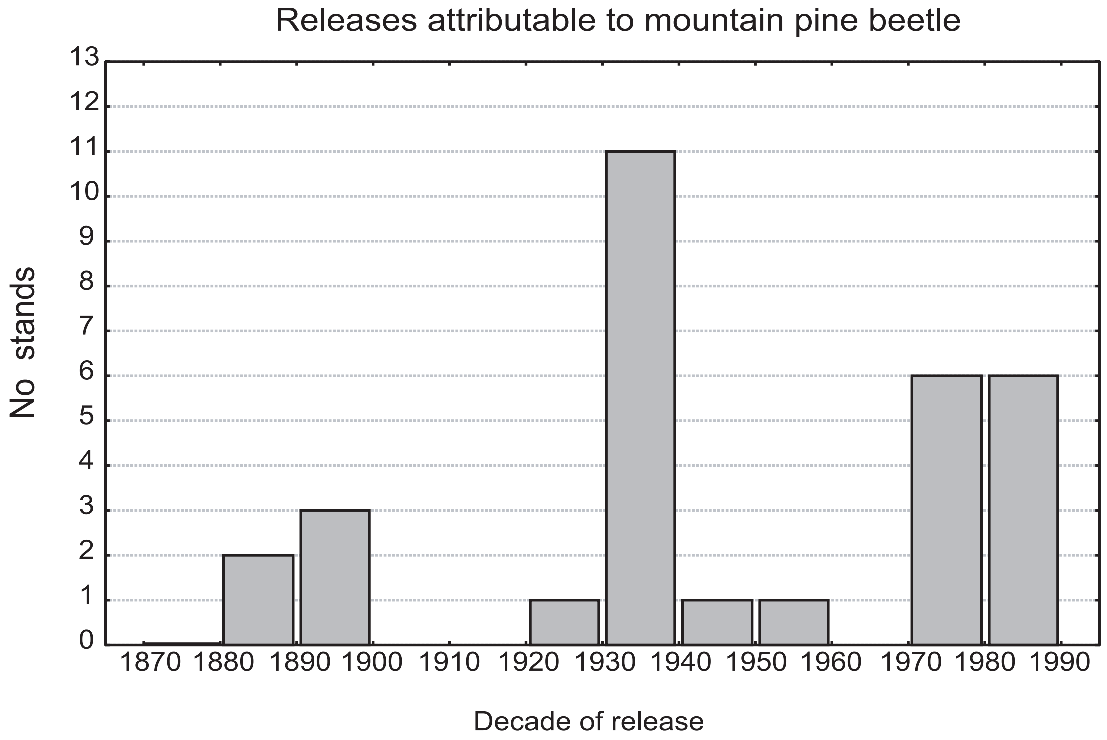

Figure 4. Histogram of the initial growth release year for 15 lodgepole pine stands in the Chilcotin Plateau area of BC. Releases are attributable to stand thinning caused by beetle outbreaks occurring in the late 1890s, 1930s and 1970s. Years indicate interval during which release occurred.

Table 4. Summary data for non-host stand chronologies used to study recurrence of mountain pine beetle disturbances in the Chilcotin Plateau area of BC.

Location	Stand No.	Species	No. of cores cross-dated	Chronology period	Mean Serial Correlation
Cariboo	113	Spruce	10	1894-2000	0.379
Cariboo	116	Douglas-fir	9	1901-2001	0.764

Table 5. Characteristics of growth releases in non-host trees attributable to mountain pine beetle thinning in the Chilcotin Plateau area of BC.

Location	Stand No.	Species	First release		Second release		Third release	
			Initial year	End year	Initial year	End year	Initial year	End year
Cariboo	113	Spruce	1896	1903	1925	1946	1975	1993
Cariboo	116	Douglas-fir	1911	1920	1932	1955	1984	1997
		Mean	1904	1912	1928	1951	1980	1995

Discussion

We identified dates of releases caused by potential mountain pine beetle outbreaks using tree ring release as a proxy for canopy disturbance (Table 2, Fig. 3). Because lodgepole stands do not grow to be very old, we were able only to examine the disturbance history from the late 19th century forward. Because of a delayed response in tree growth response to thinning, the initial date of release is not necessarily the year when mountain pine beetles began to thin the stands. Heath and Alfaro (1990) indicated that the thinning response of lodgepole pine, expressed as significant increases in ring growth, began 2 to 6 years after the start of a severe beetle outbreak and peaked 5 to 9 years after. Therefore, the potential mountain pine beetle outbreaks dates would have started 2 to 6 years prior to the initial release dates indicated in this paper.

There is some uncertainty in the dendrochronological approach when establishing mountain pine beetle disturbance history, because dendrochronology is unable to distinguish between growth releases induced by beetle thinning from above-normal periods of growth caused by better than normal climatic conditions, e.g., above-normal precipitation. In the case of dating defoliating insect outbreaks, the dendrochronology method makes it possible to separate the climatic signal from defoliator-induced growth reduction by adjusting the signal of the host tree by that of the non-host tree, as both types of trees have opposite reactions to defoliation (Swetnam and Lynch 1993; Zhang and Alfaro 2002). Separation of climatic release from beetle-induced thinning is not possible as both beetle host and non-host trees respond equally to the thinning action of the beetle (Heath and Alfaro 1990). However, we can be increasingly re-assured that the 1940s and 1980s releases are beetle-induced because the records indicate widespread infestations in the 1940s in the Chilcotin area and the 1980s plots were established in areas with ongoing beetle infestations. Also many cros-section samples from these areas contain beetle attack scars dating to the 1940's and 1980's (Hawkes et al. 2004). For complete certainty, we need samples from control areas, i.e., from areas where we know beetle outbreaks did not occur. This is impossible for the early outbreaks (1890s and 1940s), which are not well documented. In the 1980s the outbreak was very large; therefore, potential control sites occurred only in very different ecosystems, which would make comparisons inaccurate.

There is some uncertainty as to the cause of the 1890s release, as records are non-existent for this period. In addition, fire scars in four stands in the Chilcotin date to this period, suggesting that ground fires also played a role. Apart from beetle, ground fire is the only large-scale canopy disturbance capable of thinning a lodgepole pine stand. However, comparing the tree ring patterns for trees that originate from fully documented outbreaks (Heath and Alfaro 1990; Veblen et al. 1991a, b) and with the tree ring signals in this study, strongly suggests that the 1890s release also represent responses to beetle thinning.

Several of the stands did not record a release in response to the last outbreak. This could be attributed to the fact that many of the cores were sampled from trees that are old, fire scarred, infested with mistletoe, and stem and root diseases, and have been previously unsuccessfully attacked by mountain pine beetle. These trees may not have the resources (i.e., foliar biomass, live cambium, and fine root biomass) to respond to canopy disturbance in a manner that, using the criteria of this study, would be detected as a growth release.

The average interval between the first (1890s) disturbance and the second (1940s) was 41 years, and between the second and third (1980s) disturbance was 43 years. This points to a strong cyclical nature of beetle outbreaks. The cycle, recorded in the tree rings, consists of thinning of the stand by beetles which creates a strong and sustained increase in ring-width growth, followed by a gradual decline in ring width as the stand returns to full site occupancy by lodgepole pine and other species. The average length of the growth release was 13.2 (1890s), 13.6 (1940s) and 14.3 years (1980s, still ongoing in some stands).

What causes the cycle?

We hypothesize that lodgepole pine stands alternate between a susceptible state and a resistant state, on average every 42 years, with some variability between locations. Stands in the susceptible state are overstocked, mature stands, usually older than 80 years and with many trees of large diameter. Under these conditions, trees are stressed and unable to fend off beetle attack (Safranyik et al. 1974). When conditions such as climate and proximity to active infestations (Shore and Safranyik 1992) are suitable for population increase, outbreaks develop, which gradually, over the course of an infestation, thin the stand. Surviving trees benefit from the additional space and resources made available through tree mortality, and gradually become resistant to beetle invasion. This causes the outbreak to decrease and eventually cease. Without beetle thinning, stocking increases, as trees accelerate growth and regeneration is recruited into the overstorey. Thus, gradually, over a process that may last on average 42 years, the stand again becomes susceptible to outbreaks.

We hope that the recurrence rates established here will assist in forecasting potential outbreaks and in planning the timber supply of BC.

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Simulation of Interactions among Fire, Mountain Pine Beetle and Lodgepole Pine Forest

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Abstract

This paper describes a modelling research approach for the proposed new study of the interaction of fire and mountain pine beetle via forest age structure. This approach is theoretical and provides an analysis of how the stability of forest age-distributions is related to fire regimes. Starting with the derivation of the theoretical negative exponential forest age-distribution, we have used three models to explore the conditions under which a stable age-distribution could be expected. The results suggested that a stable age-distribution could always be achieved as long as the forest age-specific mortality is constant over time, and the shape of a stable age-distribution is mainly determined by the forest age-specific mortality. However, the stability of the forest age-distribution will be reduced when a small variation in the age-specific mortality is introduced. The simulation results of the possible patterns of the age-distribution under various fire regimes indicated that a variety of age-distribution curves could appear, including negative exponential and also other curves with one or multiple peaks. The results suggested that a stable forest age-distribution might never be achieved if the forest landscape is subjected to large and irregular fire disturbances. The age distributions are then related to susceptibility to mountain pine beetle attack, via a susceptibility algorithm.

Introduction

Safranyik et al. (1973) showed that lodgepole pine resistance to mountain pine beetle attack increases with tree age up to about 60 years and then declines. This suggests that forest age is one of the major predictors of stand susceptibility to mountain pine beetle, and an understanding of forest age structure over space and time is thus one of the main factors in predicting mountain pine beetle susceptibility for a given region.

Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Theory has generally predicted an exponential age distribution, whereas real forests are often quite different. Changes in forest age distribution have thus been puzzling in the understanding of forest dynamics, due to this discrepancy between theory and observations. This discrepancy has produced much confusion in forest management practice, such as setting up a management goal of maintaining a fixed age distribution shape. This discrepancy has also produced difficulties in predicting mountain pine beetle dynamics in space and time. Therefore, the capability of predicting mountain pine beetle dynamics will partly rely on understanding this discrepancy.

Forest age structure has been demonstrated to correlate with forest fire disturbance pattern (Li and Barclay 2001), thus the understanding of forest fire dynamics is a necessary component in predicting mountain pine beetle dynamics in space and time.

Taylor (2004) has demonstrated for stand replacement fire regimes the feasibility of calculating the effects of different fire cycles on the age distribution of the resulting forest, and from this has inferred the proportion of a lodgepole pine stand that is susceptible to mountain pine beetle.

In this paper, we describe briefly the research that relates forest age distribution dynamics to fire disturbance regimes (Li and Barclay 2001), and provide not only a theoretical explanation for the discrepancy between theory and observations, but also the linkage between fire and mountain pine beetle regimes via the age distribution of a lodgepole pine forest by extending and generalizing Taylor and Carroll's (2004) methodology and results.

Theoretical forest age distribution

Van Wagner (1978) developed a theory of forest age class distribution based on the following assumptions:

- A forest is composed of many equal-sized stands characterized by age.
- Forest climate is constant over time and the same number of stands burn every year.
- Forest fires are ignited at random locations, the same fire probability, p, applies to each stand, and each fire only burns a single stand.
- Forest regeneration occurs immediately after stands are burned.

Two well known probability distributions were then obtained: the negative exponential distribution and the geometric distribution:

$$f(x) = pe^{-px}$$

$$f(x) = p(1-p)^x$$

where x is stand age in years, and $f(x)$ is the relative frequency of forest stands with age x. Figure 1 shows the two probability distributions with the same p value. The negative exponential distribution has been used in the presentation of the age class distribution theory and has received wide attention, because of its simple mechanism of generation as well as the convenience in computation and plotting as a descending straight line on semi-logarithmic paper.

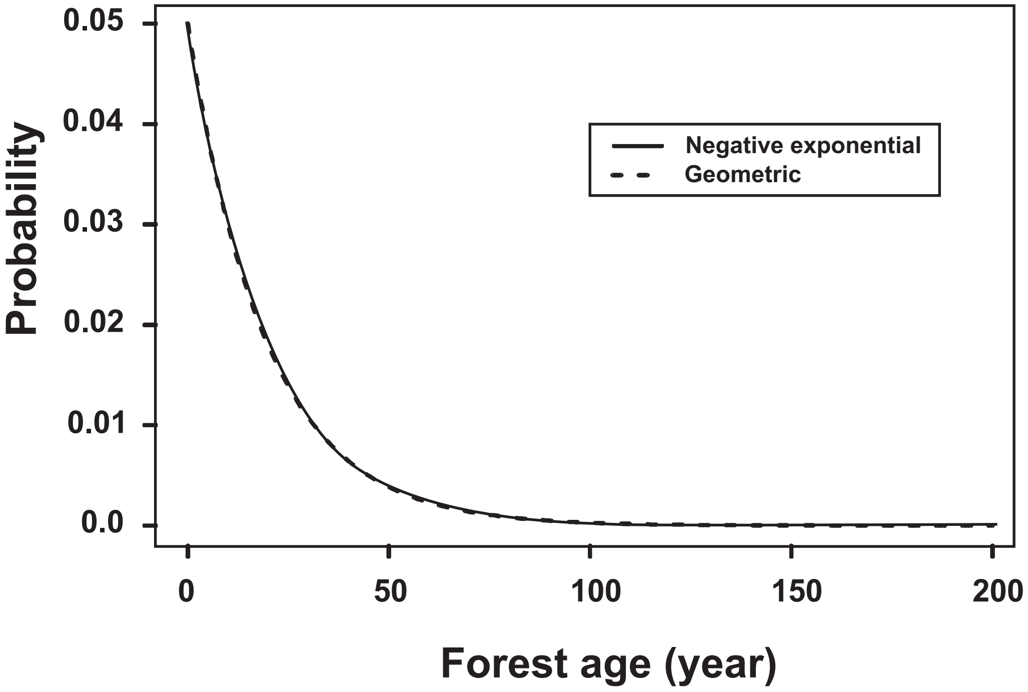

Figure 1. Negative exponential and geometric probability distributions with a same parameter value.

Discrepancy between theory and observation

Empirical observations on forest age distribution, however, are often not consistent with the theory. For example, many provincial forest age distributions in Canada display quite different patterns (Table 1).

Predictions from theoretical population ecology

If we superimpose a grid of cells onto a forest landscape with each cell being treated as an individual and represented by its age and type, the dynamics of the age distribution of the forest landscape could be studied from the perspective of population dynamics theory using the well-known Leslie transition matrix theory of population dynamics (Leslie 1945, 1948). In population dynamics studies, the stable age class distribution means that the age class vector at time $t + 1$, N_{t+1}, is a simple multiple of N_t, and the total size of the population at time $t + 1$ will be λ times the total size at time t.

$$N_{t+1} = MN_t = \lambda N_t$$

where M is the matrix of age-specific fecundities and survivorships. Mathematical analyses have shown that when $\lambda = 1$, a stable age class distribution can always be obtained regardless of its initial condition on age-distribution (Leslie 1945, 1948; Pielou 1969). Since the total area of a forest landscape does not change over time (i.e., $\lambda = 1$), a stable forest age-distribution can be achieved as long as the age-specific mortality is fixed and recruitment continues. This is consistent with Van Wagner's (1978) results that the age class distribution eventually converged to the same final shape regardless of the starting arrangement of forest stand ages across the forest landscape.

According to Leslie transition matrix theory, the conditions for achieving a stable forest age-distribution can be relaxed from a constant mortality rate across all forest ages (Van Wagner 1978) to fixed age-specific mortality rates. Therefore, Van Wagner's results can be seen as a special case of the Leslie transition matrix theory.

Table 1. Observed forest age distributions of different eco-climate zones in BC and Alberta.

British Columbia	Age Class								
Eco-climate zone	1	2	3	4	5	6	7	8	9
Alpine North Pacific Cordilleran+	0.0	0.9	2.7	2.8	10.4	4.6	3.6	42.3	32.6
Boreal Northern Cordilleran	0.0	0.4	3.1	5.3	10.9	11.2	10.8	58.1	0.1
Alpine Mid-Cordilleran+	0.2	4.5	5.1	7.6	8.4	9.4	9.6	53.5	1.6
Alpine Northern Cordilleran+	0.0	0.0	0.7	17.7	1.6	11.2	25.5	43.2	0.2
Boreal Mid-Cordilleran	0.8	12.5	9.9	10.8	13.1	22.7	12.9	17.1	0.0
Subhumid Mid-Boreal	0.2	6.0	20.5	13.3	13.5	21.3	12.5	12.7	0.1
Maritime South Pacific Cordilleran+	8.4	7.2	5.7	4.5	2.0	2.0	1.3	35.5	33.4
Subhumid High Boreal	0.0	5.0	37.1	20.8	19.1	11.6	3.7	2.7	0.0
Boreal Southern Cordilleran+	4.3	3.3	4.7	9.6	8.3	12.8	9.1	41.1	6.9
Subalpine Southern Cordilleran+	5.2	4.9	6.8	9.4	10.7	7.7	3.5	38.9	12.8
Oceanic South Pacific Cordilleran	3.2	1.0	0.4	0.2	0.2	0.3	0.4	38.5	55.9
Maritime South Pacific Cordilleran	5.4	3.5	1.9	1.5	1.0	4.9	0.7	44.3	36.8
Boreal Southern Cordilleran	2.4	12.0	11.5	11.2	24.8	14.3	9.9	13.3	0.6
Oceanic South Pacific Cordilleran+	1.4	0.6	0.3	0.2	0.2	0.2	0.2	21.5	75.3
Boreal Interior Cordilleran	3.1	4.8	9.4	14.2	11.4	13.0	13.8	26.8	3.5
Subhumid Low Boreal	3.0	8.4	18.5	15.8	31.1	15.7	4.5	2.9	0.0
Subalpine Southern Cordilleran	2.8	6.4	16.2	13.9	11.4	7.1	5.6	25.9	10.8
Alpine Southern Cordilleran+	3.0	2.3	7.4	7.5	12.0	7.5	6.7	34.6	18.9
Ecoclimatic Regions of the Vertically Stratified Interior Map Unit	3.2	3.5	8.9	11.3	13.3	15.8	9.1	30.2	4.6
Coastal South Pacific Cordilleran	12.8	14.6	24.0	17.4	8.7	5.0	1.6	10.3	5.7
BC average	3.0	5.1	9.7	9.7	10.6	9.9	7.2	29.7	15.0
Alberta									
Subhumid High Boreal	2.5	3.9	39.7	33.7	11.9	4.8	2.6	0.7	0.3
Subhumid Mid-Boreal	1.4	5.2	34.3	21.6	13.5	10.8	9.6	2.6	1.1
Boreal Southern Cordilleran	0.4	5.0	13.1	14.4	33.3	17.2	10.1	3.7	2.8
Subhumid Low Boreal	0.7	7.8	33.7	20.7	14.5	12.9	8.1	1.4	0.2
Water	6.3	1.6	25.5	15.6	3.8	29.4	17.5	0.2	0.1
Subalpine Southern Cordilleran	0.0	1.5	12.5	16.8	21.0	13.7	9.8	5.2	19.5
Alpine Southern Cordilleran+	0.0	0.5	21.3	5.6	7.2	41.8	6.2	8.7	8.7
Transitional Grassland	0.2	10.7	24.5	33.1	27.2	1.6	2.1	0.1	0.4
Arid Grassland	0.2	0.2	4.0	27.1	28.5	39.1	0.9	0.0	0.1
Subhumid Grassland	0.5	7.4	18.8	43.6	13.1	13.8	1.0	0.7	1.0
Montane Southern Cordilleran	0.1	2.2	19.5	37.3	26.3	9.8	1.7	0.9	2.2
Alberta average	0.9	5.4	27.0	19.7	19.8	13.2	9.0	2.8	2.2

Effect of small variation in age-specific tree mortality

A Leslie transition matrix model was used to investigate the dynamics of the forest age distribution when small variations are introduced into age-specific tree mortalities. The results indicated that such small variations could have a profound impact on the stability of the forest age distribution. Table 2 shows that the time required to reach a stable age distribution will be significantly increased when the standard deviation is enlarged from 0.001 to 0.004 (Li and Barclay 2001). For a standard deviation of 0.005, some simulation runs did not reach a stable age distribution, even after 10,000 time steps.

Table 2. Time steps to reach a stable age-distribution under various treatments.

Random numbers from the Normal probability distribution			Time steps to reach a stable age-distribution			
SD	Maximum	Minimum	Mean	Minimum	Maximum	SE
0.001	0.304	0.296	15.900	7.000	33.000	2.738
0.002	0.309	0.292	54.700	14.000	132.000	10.627
0.003	0.314	0.287	199.800	11.000	664.000	61.455
0.004	0.318	0.284	982.300	70.000	2418.000	190.328

Simulation of forest age distributions under different fire regimes

We have used two models to investigate the consequences of different fire regimes for the forest age distribution. The first model was a Monte-Carlo fire scenario model (see Li and Barclay 2001) that simulated a fire regime consisting of a large number of small fires with the largest fire size limited to 25 ha. The second model was the SEM-LAND (Spatially Explicit Model for LANDscape dynamics) model (Li 2000) that simulates a fire regime consisting of a large number of small and intermediate fires, and a few large fires.

The Monte-Carlo Simulation

In the Monte-Carlo fire scenario model simulation, a grid of 1,000,000 cells represented a forest landscape and each cell (1 ha) assigned an age from the negative exponential distribution with a mean of 100 years. Fires were randomly initiated with a size following uniform, normal or exponential distributions (mean size of 12.5 cells and maximum size of 25 cells). The ages of burned cells were reset to zero, and other cells advanced in age by one year. Simulated age distributions were grouped into 20-year intervals. The resulting forest age distributions were all very close to the negative exponential theoretical prediction, regardless of whether fire ignition probability was independent of age or linearly dependent on age, and also whether fire sizes varied according to the uniform, normal, or negative exponential. Figure 2 (adapted from Li and Barclay 2001) shows the simulated forest age distributions under various conditions.

The SEM-LAND model

SEM-LAND model (Li 2000) is raster-based, and relationships from the Canadian Forest Fire Weather Index system (FWI) and the Canadian Forest Fire Behavior Prediction system (FBP) drive the simulation model with a spatial resolution of 1 ha and a yearly time step. It simulates a fire process in two stages: initiation and spread. Both the probabilities of fire initiation and of spread were assumed to be a function of weather and fuel conditions. The probability of fire spread was also assumed to be a function of topography (slope).

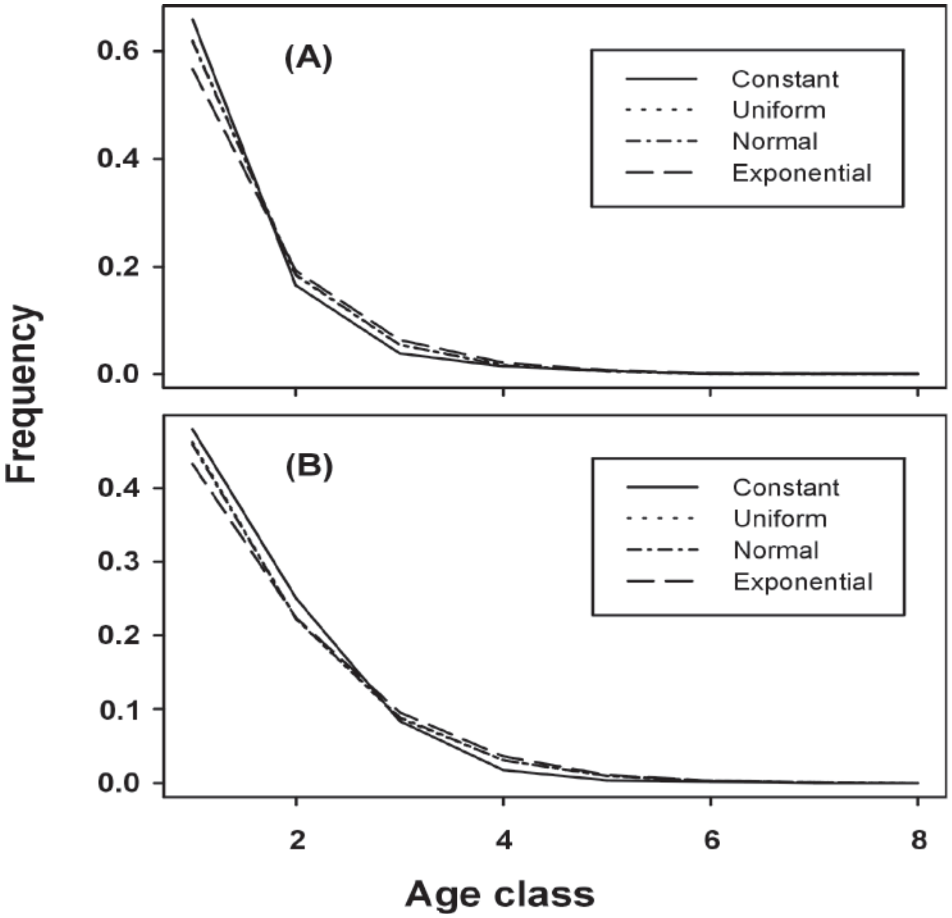

Figure 2. Relative frequencies of the first six 20-year age classes for fire ignition probability being (A) independent of age or (B) linearly increasing with age. These frequencies have been normalized and add to one over all age classes in the forest.

The SEM-LAND model experiment consisted of four scenarios with fire-cycle lengths: 125, 213, 864, and 3800 years. For each scenario, the model was run for 1200 years and the age distribution at the end of each time step was calculated using 10-year age classes. Figure 3 summarizes the simulation results.

In all four graphs, the dark color indicated a high percentage of an age class within the stand. The dark color becomes lighter with time, i.e., the percentage of the age class is reduced and the age-distribution curve declines. The small graphs associated with the four scenarios are the age class distributions at given years. A common initial forest age-distribution, in which the very dark color appeared at age class 12, was used in all of the simulation replications to ensure the comparability of the experimental results.

At the time indicated by A in Figure 3(I), the only dark color was at age class 1, indicating that the age-distribution had one peak at the youngest age class and quickly declined with older age classes, thus characterized by a negative exponential shape. There were two peaks in the age-distribution at time *B* - a small peak also appeared at age class 5. There were two peaks at different age classes at time *C*, but with a different pattern from time *B*. There were three peaks in the age-distribution at time *D*, but the peaks appeared more widespread across the age classes. There was only one peak again in the age-distribution at time *E*; however, it was at age class 3, not in age class 1 as at time *A*. There were three peaks again at time *F*, but they were in age classes 4, 6, and 8, i.e., different peak locations than those at time *C*.

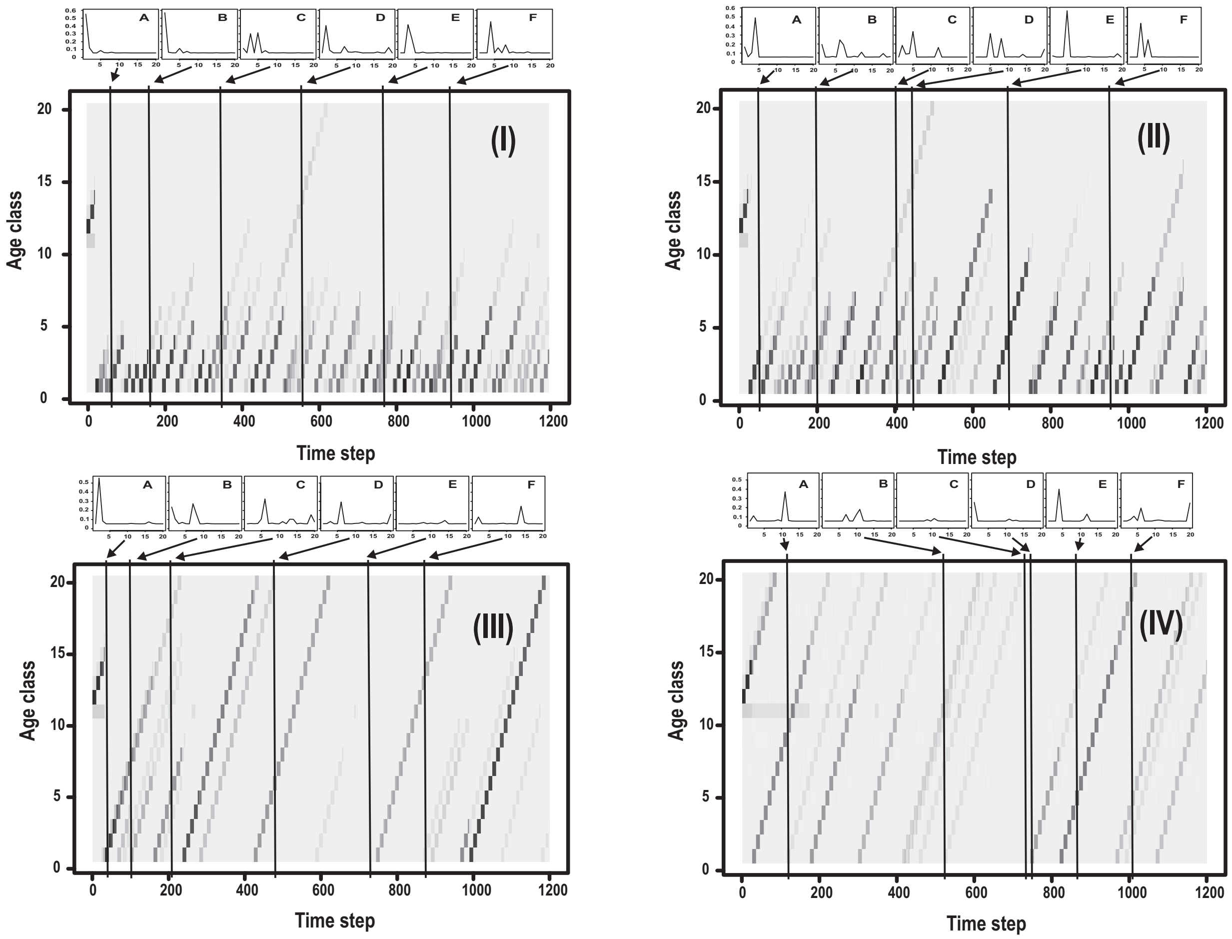

Figure 3. Simulated dynamics of forest age-distribution under fire cycles of 125 (I), 213 (II), 864 (III), and 3,800 years (IV). Each age class represents a 10-year interval, and the dark color indicates high relative frequency. The small graphs associated with the four scenarios are the age class distributions at given years.

Different shapes of the forest age-distributions can be found in other simulation results, such as shown in Figures 3(II), 3(III), and 3(IV). There are also situations where no peaks in the age-distribution could be identified, such as at time *E* in Figure 3(III) and at time *C* in Figure 3(IV).

The simulation experiment results suggest the expected stable age-distribution, and thus stable landscape dynamics, could never be achieved if a forest landscape is subject to large and irregular fire disturbances. The forest age-distribution could result in different patterns from various fire cycles. In practice, the forest age-distribution was evaluated at a particular time through sampling and mapping, and consequently the chance of finding an age-distribution with a negative exponential shape might be slim. The results, therefore, can serve as a theoretical explanation of why the negative exponential forest age-distribution is not always observed.

Link between forest age structure and susceptibility to mountain pine beetle

Safranyik et al. (1974) have shown that tree resistance increases with age up until 60 years and declines thereafter. Young and old trees are thus not very resistant, but young trees and trees older than about 200 years have thin bark and are less suitable for mountain pine beetle brood establishment and survival. Thus, trees between about 80 and 200 years will be most susceptible to attack and also most suitable for breeding mountain pine beetles. Pine forests in which these age classes predominate will be highly susceptible to attack, while forests in which these age classes are not well represented will be relatively immune from attack except in a full-scale epidemic. Shore and Safranyik (1992) have developed a susceptibility function based on age, stand density, percent pine and location, and we intend to use this as the link between age structure and susceptibility.

Summary of results to date

- An interaction between fire and mountain pine beetle regimes is likely through the age structure of lodgepole pine forest landscapes; thus, a simulation of the interaction will yield a better understanding of the dynamics of forest age distribution.
- The dynamics of forest age distribution are related to fire disturbance patterns.
- The theoretical prediction of the negative exponential age distribution is not always supported by empirical observations.
- The theoretical prediction of the negative exponential age distribution implies a stable forest landscape and requires constant stand mortality across ages.
- Stability of the age distribution is reduced when variations are introduced into the age-specific tree mortality.
- The expected stable age distribution, and thus stable landscape dynamics, could never be achieved if a forest landscape is subject to large and irregular fire disturbances.
- The results can serve as a theoretical explanation of why the negative exponential distribution forest age-distribution is not always observed in real forests.

Work in Progress

Monte-Carlo Simulation

The following characteristics will be incorporated into the simulation:

1) Ignition probability, being either age-independent or age-dependent;
2) Fire sizes being in the range of 1, 100, 10,000 or 1,000,000 ha;
3) Constant fire sizes, the sizes are as above in (2);
4) Variable fire sizes, the fires range from 1 to the sizes in (2) above;
5) Variable fire sizes, the size distributions are (i) uniform, (ii) normal, or (iii) exponential;
6) Three ignition probabilities: 0.05, 0.01, 0.004, which correspond to fire return times of 20, 100 and 250 years; and
7) As a special case, the lower 20%, 40% and 80% of fires will be immediately put out, by simply never starting them. This will simulate fire control.

Analysis will be done to determine the following characteristics:

- Computation of age distributions, as before;
- Derivation of a susceptibility function to mountain pine beetle;
- Application of the susceptibility function to the age distributions to assess stand susceptibility;
- Computation of sizes and numbers of patches of trees of susceptible ages; and,

- Assessment of connectivity of these patches to assess potential spread of an incipient beetle population.

SEM-LAND

GIS data set compilation (sources):

Alberta: Weldwood Canada and Weyerhaeuser Ltd.
BC: Steve Taylor, Natural Resources Canada, Pacific Forestry Centre.

Modelling activities:

- To adapt the SEM-LAND model to BC conditions.
- To incorporate the Canadian Forest Service stand level mountain pine beetle model (Safranyik et al. 1999) into the landscape model.
- To incorporate a spatial harvest module into the landscape model.

Model experiments:

- Scale effect on forest age distribution dynamics subject to fire disturbances;
- Effects of different fire cycles (e.g., 100, 200, 500, and 1,000 years) on lodgepole pine forest age distribution dynamics;
- Effects of fire suppression on lodgepole pine forest age distribution dynamics;
- Effects of different levels of fire ignition source (lightning only, and lightning plus human) on lodgepole pine forest age distribution dynamics;
- Landscape scale mountain pine beetle dynamics using a derived resistance function, under various fire cycles;
- Effects of different initial mountain pine beetle population densities on landscape scale mountain pine beetle dynamics; and,
- Effect of changes in the annual allowable cut (AAC) on lodgepole pine forest age distribution dynamics.

Output and data analysis:

We shall have both non-spatial and spatial simulation output. Non-spatial output includes forest age distribution at a yearly time step with 10-year interval age classes. The total area of lodgepole pine forest susceptible to mountain pine beetle over time can then be calculated. Spatial output includes a forest stand age map at 10-year intervals, and landscape matrices can then be calculated by using FRAGSTATS (McGarigal and Marks 1994) in terms of landscape fragmentation, patch size distribution, and connectivity of susceptible lodgepole pine stands. A correlation analysis between these results and mountain pine beetle dynamics is planned.

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Potential Approaches to Integrating Silvicultural Control of Mountain Pine Beetle with Wildlife and Sustainable Management Objectives

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Abstract

There are 195 vertebrate species occurring in mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infested areas in interior British Columbia that will likely be impacted by beetle control measures. The effects of these measures on wildlife will depend on whether they increase or decrease the availability of critical habitat attributes such as large trees, dead and dying trees, down wood, shrubby undergrowth, continuous canopy cover, and deciduous trees. Shifting the forest age class distribution to early seral stages to reduce landscape susceptibility to mountain pine beetle attack will harm many wildlife species that are dependent on mature forest conditions, but will benefit the few species that thrive in more open habitats. In contrast, the conversion of lodgepole pine forests to non-pine tree species, and fall and burn treatments, should have relatively minor impacts. The effects of many beetle control measures on wildlife will devolve to the effects of tree retention level on wildlife. Manipulating the tree retention level, and the size, location and dispersion pattern of residual trees and tree patches can significantly advance wildlife management goals. We conclude this paper by suggesting potential approaches to integrating mountain pine beetle control with wildlife and sustainable management objectives.

Introduction

Many management options that are being implemented to control the mountain pine beetle may not be favourable to forest wildlife species, many of which depend on mature seral stages for at least some if not all of their habitat requirements (Bunnell and Chan-McLeod 1997). The selective removal of large-diameter trees, and the creation of young age-class distributions that largely exclude trees older than 80 years, reduce susceptibility to mountain pine beetle attack, but negatively impact vertebrate species that depend on older forests or large-diameter trees. Similarly, spacing to improve tree vigour and resistance to mountain pine beetles has raised concerns of compromised thermal cover and snow interception for ungulates in winter (Whitehead 2002). An even graver threat to habitat values are large-scale clearcut harvesting, which is the only effective control for severe mountain pine beetle infestations in the middle

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of epidemic areas. The catastrophic nature of the mountain pine beetle epidemic, and the silvicultural controls that must be implemented to contain its damage, have immense implications for wildlife and non-timber resources.

The successful integration of beetle control with wildlife and sustainable management objectives requires an understanding of fundamental wildlife needs. The objective of this paper is to provide the foundation from which researchers and managers can develop and evaluate potential strategies for integrating beetle control with wildlife and sustainable management objectives. We will achieve this by: 1) providing an overview of wildlife species that will potentially be impacted by mountain pine beetle controls, and their habitat requirements; 2) considering some likely consequences of beetle control measures on wildlife species occurring within beetle infested regions; and 3) suggesting potential approaches to integrating mountain pine beetle with wildlife and sustainable management objectives.

Wildlife Species Occurring in Beetle-Infested Regions

We tallied 195 vertebrate species occurring in beetle-infested regions in interior British Columbia (BC). These comprise of 140 birds, 49 mammals, and 6 herptiles (Appendices 1 and 2). This tally was based on the 2002 mountain pine beetle distributions and therefore may be conservative, as the infestation has spread to a much greater area.

There are at least nine wildlife species occurring in beetle-infested areas that are considered to be at risk (Appendices 1 and 2). These comprise of five mammals (4 blue-listed; 1 red-listed) and four birds (2 blue-listed; 2 red-listed). Twelve additional species that occur within the range of the mountain pine beetle, though not at risk within beetle-infested regions, are at risk elsewhere in the province.

The woodland caribou (*Rangifer tarandus caribou* Linnaeus) is an at-risk species that epitomizes the conflict between timber harvesting and habitat requirements. It is a mature-forest-dependent species requiring extensive areas of continuous old-growth forests (Smith et al. 2000; Apps et al. 2001) to avoid predation. In winter, woodland caribou crater through the snow to feed on terrestrial lichens, so snow interception by a closed canopy is very important in dictating food availability. Where terrestrial lichens are not accessible because the snow is too deep or crusty, caribou forage instead on arboreal lichens (Johnson et al. 2001) that accumulate slowly in old-growth trees.

Wildlife Habitat Requirements

In general, six forest stand structures are particularly important as wildlife habitat:

- large trees;
- dead and dying trees;
- down wood;
- shrubby undergrowth;
- canopy cover;
- deciduous trees

These components must be maintained in the form and quantities needed to support viable populations of native fauna.

Large trees are important for many reasons. First, they have very deep and complex crowns, which provide a diversity of niches for birds and small mammals, including a microclimatic gradient from high exposed radiation environments at the top to buffered environments toward the forest floor (Spies and Franklin 1996). In addition to vertical niche stratification, horizontal stratification is sometimes also evident, with different species occupying areas at the edge and at the core of the crown. Second, large trees have rough bark, which harbors more arthropods for bark gleaners (Adams and Morrison 1993) and provides more opportunities for bats and birds (e.g., brown creepers, *Certhia americana* Bonaparte) to nest under the bark. Large trees are also big enough to be used by large species such as black bears (*Ursus* *americanus* Pallas) (Oli et al. 1997). Furthermore, they are older and tend to have the heart rot conditions that are favourable to many wildlife species.

In fact, it is the dead and dying trees that will support the greatest diversity of species, since sound trees are rejected by even strong cavity-nesters in nest tree selection. Heartwood decay has been shown to be the most important factor in tree selection by primary cavity-nesting birds in interior Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) forests (Harestad and Keisker 1989), and zones of rotten wood, such as those occurring under fungal entry points in broken tops or branches, are selected to reduce the energy demands of excavating nest sites (Harmon et al. 1986). Trees or snags that have a soft interior core but a hard exterior shell are ideal, as this allows easy excavation without compromising the protective shell. When a snag has decayed to the point where it is completely soft, then its value is primarily as a foraging site for insectivores and as a source of down wood.

Downed wood is used by more than 179 forest vertebrates in the Pacific Northwest (Thomas 1979). Initial use of newly created downed wood is primarily as perches and cover, but use becomes internal as the decay progresses. Loose bark provides places for hiding and thermal cover, while highly decayed logs are burrowed by small mammals, which in turn facilitates access by amphibians and reptiles (Harmon et al. 1986). The use of downed wood as a foraging medium by insectivores probably peaks toward the middle to late stages of decay (Harmon et al. 1986). Downed wood also modifies the microclimate by evening out extreme fluctuations in environmental conditions, and by holding in the moisture that is vitally important for amphibians (Aubry et al. 1988; Grover 1998).

The role of downed wood is complemented by that of understory vegetation, which provides nesting sites, cover (Althoff et al. 1997), and food in the form of berries, foliage, seeds, and associated ectomycorrhizal fungi and insects (Carey and Johnson 1995).

Canopy cover is another structural attribute that is directly affected by forest practices. Many species such as the marten require continuous mature forest cover to move around and satisfy its requirements. Dense canopies provide better thermal cover and intercept more snow; while open stands allow more light to reach the forest floor and encourage forage production. In general, deep crowns are preferred to shallow crowns because this allows for vertical stratification. Canopy complexity is hypothesized to promote niche differentiation for forest organisms, nutrient cycling, improved invertebrate communities, and dispersal opportunities for species that are forest obligates (Swanson and Franklin 1992).

Deciduous trees are favored by many cavity nesting birds as well as mammals (e.g., fisher, *Martes pennanti* Erxleben) that den in trees (Paragi et al. 1996). In part, this is because they are shorter-lived and produce the right kind of decay conditions earlier in the rotation. The rich litter layer encourages the proliferation of invertebrates (Valovirta 1968; Suominen et al. 2003) by providing favorably moist conditions, food resources, and high calcium concentrations for gastropod shell formation (Karlin 1961; Valovirta 1968). The high invertebrate populations in turn encourage populations of small mammals and amphibians. Small mammals are also attracted to the unique fungal and lichen associations, while amphibians also benefit from the moist physical conditions.

Potential Impacts of Mountain Pine Beetle Controls

One prescription for reducing landscape susceptibility to mountain pine beetle attack is to shift the age class distribution to early seral stages. This will benefit species that thrive in open conditions, such as the dark-eyed junco (*Junco hyemalis* Linnaeus), white-crowned sparrow (*Zonotrichia leucophrys* Forster), porcupine (*Erethizon dorsatum* Linnaeus), and snowshoe hare (*Lepus americanus* Erxleben)(Koehler 1990). Increases in open-habitat species may in turn lead to other changes in vertebrate assemblages. For example, as snowshoe hare populations go up, so will predators such as bobcats (*Lynx rufus* Schreber) because their abundance is highly dependent on the prey base. Conversely, the abundance of species dependent on mature forests will decline. These include the fisher (Carroll et al. 1999), pine grosbeak (*Pinicola enucleator* Linnaeus), Hammond's flycatcher (*Empidonax hammondii* Xantus de Vesey), boreal red-backed vole

(*Clethrionomys gapperi* Vigors), and woodland caribou (Smith et al. 2000). For these species, total numbers will decline and sub-populations may be in may be in danger of extirpation.

Conversion of lodgepole pine (*Pinus contorta* Pinaceae) forests to non-pine tree stands should have relatively minor impact on wildlife habitat. Although lodgepole pine provides hiding and thermal cover for many species, its needles are eaten by blue (*Dendragapus obscurus* Say) and spruce (*Dendragapus canadensis* Linnaeus) grouse in the winter (Zwickel and Bendell 1970; Pendergast and Boag 1971), and its seeds are consumed by many songbirds and small mammals (Lotan and Perry 1983), forest vertebrates should be able to derive similar benefits from fir or spruce. In fact, the conversion of pine to non-pine species may benefit some wildlife. For example, spruce seeds are preferred by red squirrels (*Tamiasciurus hudsonicus* Erxleben) even though lodgepole pine seeds are an important part of the diet.

Silvicultural control of mountain pine beetle generally requires some form of tree removal, whether the objective is salvage logging, sanitation harvesting, pine removal, spacing to improve tree vigour, or beetle proofing. The effects of many beetle control measures may therefore devolve largely to the effects of tree retention level on forest wildlife. Our preliminary results for coastal ecosystems suggest that vertebrate species diversity remains relatively constant at residual tree retention levels between 20% and 100%. Species diversity declines precipitously only when less than 20% of the trees are retained within the cut block. These results are consistent with our understanding of wildlife habitat requirements; in moderately open stands, early-seral wildlife species replace the late-seral wildlife species that are lost.

In contrast to species diversity, relative abundance of individual wildlife species does not stay constant over a wide range of retention levels. For mature forest species such as the Hammond's flycatcher, a positive correlation is observed between tree retention level and abundance. Similar to species diversity however, the steepest part of the curve is at retention levels below 20%. This implies that slight changes in retention level at the low end will result in dramatic differences in flycatcher abundance. For early-seral forest species such as the dark-eyed junco, a negative correlation is apparent between tree retention level and abundance. As before, the sensitivity of junco populations to changes in retention level is most marked at retention levels below 20%. This again supports the conjecture that minor manipulation of retention levels at the low end can strongly alter the vertebrate community.

In addition to retention level, the spatial dispersion of residual trees within the cut block will govern the effects of tree removal on wildlife species. Our data on the coast indicates that some songbirds respond more strongly to dispersion pattern than they do to retention level. For a given retention level, residual trees left in aggregated patches will retain wildlife communities most closely resembling those in old-growth control forests. In contrast, residual trees left either as individual scattered stems or in small clusters will not maintain mature-forest dependent species, and in fact, may only support avian communities normally associated with clearcuts. Our preliminary results for songbirds are consistent with earlier research on small mammals indicating the superior benefits of tree patches as compared to individual residual trees (Sullivan and Sullivan 2001).

Beetle control measures that retain residual trees as aggregated patches should consider the effects of tree patch size on wildlife species. Larger tree patches are more likely to attract amphibians moving through the cutblock, and are significantly more likely to be used as habitat, at least in the short term. Chan-McLeod's research in coastal BC indicated that virtually all radio-harnessed frogs released at the base of individual trees or inside small tree clusters left the site within 72 hours, but the proportion that left decreased curvilinearly with increasing patch size. In contrast, no frogs left streamed tree patches that were at least 0.8 ha. This threshold patch size corresponded to Merrill's (1994) recommended minimum patch size of 0.8 ha for birds. Schieck et al. (1995) concurred that there were no incremental benefits to patches bigger than 4 ha.

Beetle control measures that involve some form of burning will have varying effects on wildlife. Burning *per se* is not detrimental to wildlife – wildfires often lead to higher faunal species richness and abundance (Bock and Lynch 1970; Apfelbaum and Haney 1981; Simon et al. 2002) because they leave behind pockets of live as well as standing dead trees. In fact, some wildlife species that are absent from harvested cutblocks are found almost exclusively in old-growth forests or recent burns (Gagnon et al. 1999). For example, the black-backed woodpecker (*Picoides arcticus* Swainson) selectively feed on charred trees and exploit only newly burnt forests (Murphy and Lenhausen 1998). However, prescribed burns do not mimic wildfires because they burn much more homogeneously and may eliminate key habitat attributes such as snags and downed wood. Sizeable prescribed burns may, therefore, have some detrimental effects on wildlife habitat. Conversely, prescribed burns may benefit wildlife by encouraging early green up and shrub growth, and by removing slash piles that may hinder movement by deer. Fall-and-burn areas, which are generally very small, will have relatively minor impacts and may enhance species richness by providing small openings within a largely intact forest. In general, habitat generalists, omnivores, and species that nest on the ground or in shrubs would be least sensitive to burn treatments (Morisette et al. 2002).

Integrating Mountain Pine Beetle Control with Wildlife and Sustainable Management Objectives

In many cases, broadly defined control measures have flexible elements that can be tailored to benefit wildlife and sustainable management indicator values. For example, the spacing and harvesting prescriptions for mountain pine beetle management are highly analogous to the variable-retention harvesting that is increasingly being applied in working forests in the Pacific Northwest. As discussed above, the location and dispersion pattern of residual trees and tree patches, and even slight differences in retention level, can yield significantly different impacts on wildlife populations.

The first potential strategy for integrating mountain pine beetle control with wildlife and sustainable management objectives is therefore to incorporate wildlife considerations in partial-cut control measures. Our preliminary results from the coast suggest the following targets may be appropriate:

- Retention levels > 20% to maintain wildlife species occurrence; retention levels > 90% to maintain abundance of mature-forest-dependent species;
- Aggregated pattern for residual trees is superior to dispersed pattern;
- Tree patch size > 0.8 ha;
- Residual trees placed in deeper soils, by riparian, in patches with high snag composition.

These speculated targets would of course have to be evaluated in beetle-infested ecosystems, the wildlife of which may respond differently from those in the coast to partial harvests.

A second potential strategy is to maintain key habitat structures, including live trees, snags, and downed wood whenever possible. Critical habitat attributes should be created through girdling, topping, or stubbing where safety regulations or other factors preclude the maintenance of existing habitat structures. Retained or created habitat structures must however be consistent with wildlife requirements. For example, snags that are less than 25 cm DBH (Bull 1983) will not be used by cavity nesters and, furthermore, will probably not stand for very long because of windthrow. Woodpeckers can be extremely efficient predators of the beetle, especially in epidemic areas (Tunnock 1960; Amman 1984; Bergvinson and Borden 1992) – harvesting efficiencies of mountain pine beetle by woodpeckers often exceeded 90%, while debarking only 5% of the bole surface could reduce the beetle brood by up to 50% (Tunnock 1960; Bergvinson and Borden 1992). However, woodpeckers are often insignificant factors in controlling epidemic outbreaks because they are too limited by the number of nesting sites (Otvos 1965). Enhancement of nest sites for woodpeckers where these are limiting can be rewarding for both wildlife and beetle control. Where nest sites are not limiting, woodpecker densities have increased with beetle density (Koplin 1969).

A third potential strategy is to leave beetle-killed stands in strategic locations that will maximize the benefit to wildlife. This strategy has excellent potential since forest companies will not be able to salvage log all infested stands within the commercial shelf life of the dead trees. On the other hand, such stands can be highly valuable to wildlife. Bull (1983) documented that lodgepole pines were important feeding and nesting sites for at least 8 years after the trees were beetle-killed. We suspect that these stands will have important habitat value for much longer; the 8-year timeframe simply marked the end of Bull's study. For many stands, even those that are heavily infested, live trees will be interspersed amongst the dead trees. Selection of beetle-killed stands where there is a live tree component will further enhance the value of the stand as wildlife habitat.

A fourth potential strategy is to balance silvicultural mosaics at the landscape level as much as possible to satisfy both beetle control and wildlife objectives. Strategies for both beetle control and wildlife objectives agree that it is important not to apply the same silvicultural treatments across the landscape. Extensive homogenous landscapes may increase susceptibility to mountain pine beetle epidemics over time, while failing to meet the requirements of different wildlife species for different habitat types. Any given silvicultural control for mountain pine beetle can benefit some wildlife species but be detrimental to other wildlife species, because there will be widely varying and often opposing habitat requirements. For every management option exercised, there will be winners and losers among wildlife populations, and these tradeoffs must be balanced across the landscape so that species requirements are met at both the stand and landscape levels.

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Appendix 1. Birds occurring in mountain-pine beetle-infested regions in BC.

Species	Latin Name
Blackbird, Brewer's	*Euphagus cyanocephalus*
Blackbird, Red-winged	*Agelaius phoeniceus*
Blackbird, Rusty	*Euphagus carolinus*
Blackbird, Yellow-headed	*Xanthocephalus xanthocephalus*
Bluebird, Mountain	*Sialia currucoides*
Bobolink[2]	*Dolichonyx oryzivorus*
Bunting, Lazuli	*Passerina amoena*
Bunting, Snow	*Plectrophenax nivalis*
Chickadee, Black-capped	*Poecile atricapilla*
Chickadee, Boreal	*Poecile hudsonica*
Chickadee, Mountain	*Poecile gambeli*
Cowbird, Brown-headed	*Molothrus ater*
Creeper, Brown	*Certhia americana*
Crossbill, Red	*Loxia curvirostra*
Crossbill, White-winged	*Loxia leucoptera*
Crow, American	*Corvus brachyrhynchos*
Eagle, Bald	*Haliaeetus leucocephalus*
Eagle, golden	*Aquila chrysaetos*
Falcon, Peregrine[1]	*Falco peregrinus*
Finch, Cassin's	*Carpodacus cassinii*
Finch, Purple	*Carpodacus purpureus*
Flicker, Northern	*Colaptes auratus*
Flycatcher, Alder	*Empidonax alnorum*
Flycatcher, Dusky	*Empidonax oberholseri*
Flycatcher, Hammond's	*Empidonax hammondii*
Flycatcher, Least	*Empidonax minimus*
Flycatcher, Olive-sided	*Contopus cooperi*
Flycatcher, Pacific-sloped	*Empidonax difficilis*
Flycatcher, Yellow-bellied	*Empidonax flaviventris*
Goldfinch, American	*Carduelis tristis*
Goshawk, Northern[3]	*Accipiter gentilis*
Grosbeak, Black-headed	*Pheucticus melanocephalus*
Grosbeak, Evening	*Coccothraustes vespertinus*
Grosbeak, Pine[2]	*Pinicola enucleator*
Grosbeak, Rose-breasted	*Pheucticus ludovicianus*
Grouse, Blue	*Dendragapus obscurus*
Grouse, Ruffed	*Bonasa umbellus*
Grouse, Spruce	*Falcipennis canadensis*
Harrier, Northern	*Circus cyaneus*
Hawk, Cooper's	*Accipiter cooperii*
Hawk, Red-tailed	*Buteo jamaicensis*
Hawk, Rough-legged	*Buteo lagopus*
Hawk, Sharp-shinned	*Accipiter striatus*
Hummingbird, Anna's	*Calypte anna*
Hummingbird, Calliope	*Stellula calliope*
Hummingbird, Rufous	*Selasphorus rufus*
Jay, Gray	*Perisoreus canadensis*
Jay, Steller's[3]	*Cyanocitta stelleri*
Junco, Dark-eyed	*Junco hyemalis*
Kestrel, American	*Falco sparverius*
Kingbird, Eastern	*Tyrannus tyrannus*
Kingbird, Western	*Tyrannus verticalis*
Kingfisher, Belted	*Ceryle alcyon*
Kinglet, Golden-crowned	*Regulus satrapa*
Kinglet, Ruby-crowned	*Regulus calendula*
Lark, Horned[3]	*Eremophila alpestris*
Longspur, Lapland	*Calcarius lapponicus*
Meadowlark, Western[3]	*Sturnella neglecta*
Merlin	*Falco columbarius*
Mockingbird, Northern	*Mimus polyglottos*
Nighthawk, Common	*Chordeiles minor*
Nuthatch, Red-breasted	*Sitta canadensis*
Nuthatch, White-breasted	*Sitta carolinensis*
Osprey	*Pandion haliaetus*
Ovenbird	*Seiurus aurocapillus*
Owl, Barred	*Strix varia*
Owl, Great Gray	*Strix nebulosa*
Owl, Great-horned	*Bubo virginianus*
Owl, Long-eared	*Asio otus*
Owl, Northern Hawk	*Surnia ulula*
Owl, Northern Pygmy[2]	*Glaucidium gnoma*
Owl, Northern Saw-whet[2]	*Aegolius acadicus*
Phoebe, Say's	*Sayornis saya*
Pigeon, Band-tailed[2]	*Columba fasciata*
Raven, Common	*Corvus corax*
Redpoll, Common	*Carduelis flammea*
Redpoll, Hoary	*Carduelis hornemanni*
Redstart, American	*Setophaga ruticilla*
Robin, American	*Turdus migratorius*
Sapsucker, Red-breasted	*Sphyrapicus ruber*
Sapsucker, Yellow-bellied	*Sphyrapicus varius*
Shrike, Northern	*Lanius excubitor*
Siskin, Pine	*Carduelis pinus*
Solitaire, Townsend's	*Myadestes townsendi*
Sparrow, American Tree	*Spizella arborea*
Sparrow, Brewer's	*Spizella breweri*
Sparrow, Chipping	*Spizella passerina*
Sparrow, Clay-colored	*Spizella pallida*
Sparrow, Fox	*Passerella iliaca*
Sparrow, Golden-crowned	*Zonotrichia atricapilla*
Sparrow, Harris's	*Zonotrichia querula*
Sparrow, Lark	*Chondestes grammacus*
Sparrow, Lincoln's	*Melospiza lincolnii*
Sparrow, Savannah	*Passerculus sandwichensis*
Sparrow, Song	*Melospiza melodia*
Sparrow, Swamp	*Melospiza georgiana*
Sparrow, Vesper	*Pooecetes gramineus*
Sparrow, White-crowned	*Zonotrichia leucophrys*
Sparrow, White-throated	*Zonotrichia albicollis*
Starling, European	*Sturnus vulgaris*
Swallow, Bank	*Riparia riparia*
Swallow, Barn	*Hirundo rustica*
Swallow, Northern Rough-winged	*Stelgidopteryx serripennis*
Swallow, Tree	*Tachycineta bicolor*
Swallow, Violet-green	*Tachycineta thalassina*

Appendix 1 (continued). Birds occurring in mountain-pine beetle-infested regions in BC.

Species	Latin Name
Swift, Vaux's	*Chaetura vauxi*
Tanager, Western	*Piranga ludoviciana*
Thrush, Hermit's	*Catharus guttatus*
Thrush, Swainson's	*Catharus ustulatus*
Thrush, Varied	*Ixoreus naevius*
Veery	*Catharus fuscescens*
Vireo, Cassin's	*Vireo cassinii*
Vireo, Red-eyed	*Vireo olivaceus*
Vireo, Warbling	*Vireo gilvus*
Warbler, Black-and-white	*Mniotilta varia*
Warbler, Blackpoll	*Dendroica striata*
Warbler, Cape May[1]	*Dendroica tigrina*
Warbler, Chestnut-sided	*Dendroica pensylvanica*
Warbler, MacGillivray's	*Oporornis tolmiei*
Warbler, Magnolia	*Dendroica magnolia*
Warbler, Nashville	*Vermivora ruficapilla*
Warbler, Orange-crowned	*Vermivora celata*
Warbler, Palm	*Dendroica palmarum*
Warbler, Tennessee	*Vermivora peregrina*
Warbler, Townsend's	*Dendroica townsendi*
Warbler, Wilson's	*Wilsonia pusilla*
Warbler, Yellow	*Dendroica petechia*
Warbler, Yellow-rumped	*Dendroica coronata*
Waterthrush, Northern	*Seiurus noveboracensis*
Waxwing, Bohemian	*Bombycilla garrulus*
Waxwing, Cedar	*Bombycilla cedrorum*
Woodpecker, Black-backed	*Picoides arcticus*
Woodpecker, Downy	*Picoides pubescens*
Woodpecker, Hairy	*Picoides villosus*
Woodpecker, Pileated	*Dryocopus pileatus*
Woodpecker, Three-toed	*Picoides tridactylus*
Wood-pewee, Western	*Contopus sordidulus*
Wren, House	*Troglodytes aedon*
Wren, Marsh	*Cistothorus palustris*
Wren, Winter	*Troglodytes troglodytes*
Yellowthroat, Common	*Geothlypis trichas*

[1] Red-listed

[2] Blue-listed

[3] At-risk elsewhere in BC (outside beetle-infested regions)

Appendix 2. Mammals and herptiles occurring in mountain-pine beetle-infested regions in BC.

Common Name	**Latin Name**
Mammals	
Common Shrew	*Sorex cinereus*
Dusky Shrew	*Sorex monticolus*
Pygmy Shrew	*Sorex hoyi*
Little Brown Myotis	*Myotis lucifugus*
Western Long-eared Myotis	*Myotis evotis*
Yuma Myotis	*Myotis yumanensis*
Long-legged Myotis	*Myotis volans*
Silver-haired Bat	*Lasionycteris noctivagans*
Big Brown Bat	*Eptesicus fuscus*
Hoary Bat	*Lasiurus cinereus*
Townsend's Big-eared Bat[2]	*Corynorhinus townsendii*
Grizzly Bear[2]	*Ursus arctos*
Black Bear[3]	*Ursus americanus*
Fisher[1]	*Martes pennanti*
Marten	*Martes americana*
Least Weasel	*Mustela nivalis*
Short-tailed Weasel	*Mustela erminea*
Long-tailed Weasel[3]	*Mustela frenata*
Mink	*Mustela vison*
River Otter	*Lontra canadensis*
Wolverine[2]	*Gulo gulo luscus*
Striped Skunk	*Mephitis mephitis*
Coyote	*Canis latrans*
Gray Wolf	*Canis lupus*
Red Fox	*Vulpes vulpes*
Mountain Lion	*Puma concolor*
Bobcat	*Lynx rufus*
Lynx	*Lynx canadensis*
Yellow-Pine Chipmunk	*Tamias amoenus*
Red Squirrel	*Tamiasciurus hudsonicus*
Northern Flying Squirrel	*Glaucomys sabrinus*
Beaver	*Castor canadensis*
Deer Mouse	*Peromyscus maniculatus*
Bushy-tailed Woodrat	*Neotoma cinerea*
Northern Bog Lemming[3]	*Synaptomys borealis*
Brown Lemming	*Lemmus trimucronatus*
Southern Red-backed Vole[3]	*Clethrionomys gapperi*
Heather Vole	*Phenacomys intermedius*
Meadow Vole	*Microtus pennsylvanicus*
Long-tailed Vole	*Microtus longicaudus*
Western Jumping Mouse	*Zapus princeps*
Meadow Jumping Mouse[3]	*Zapus hudsonius*
Porcupine	*Erethizon dorsatum*
Snowshoe Hare[3]	*Lepus americanus*
Elk[3]	*Cervus canadensis*
White-tailed Deer	*Odocoileus virginianus*
Mule Deer	*Odocoileus hemionus*
Moose	*Alces alces*
Woodland Caribou (Mountain)[2]	*Rangifer tarandus caribou*

Common Name	**Latin Name**
Herptiles	
Long-toed Salamander	*Ambystoma macrodactylum*
Western Toad	*Bufo boreas*
Pacific Treefrog	*Pseudacris regilla*
Spotted Frog	*Rana pretiosa*
Wood Frog	*Rana sylvatica*
Common Garter Snake	*Thamnophis sirtalis*

[1] Red-listed
[2] Blue-listed
[3] At-risk elsewhere in BC (outside beetle-infested regions)

Assessing the Economic Impacts of Mountain Pine Beetle Infestations in the Northern Interior of British Columbia

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Abstract

The current mountain pine beetle infestation in British Columbia has the potential to significantly impact the economy and forest-dependent communities of the northern interior. This study uses a hybrid approach in the construction of region-specific economic impact models for the Morice Lakes Innovative Forest Practices Agreement Area, the McGregor Model Forest Region, and the larger combination of the two regions. The results will also identify the impacts on the rest of the province. The hybrid approach involves the collection of secondary data to mechanically regionalize provincial data, and the collection of primary data in the form of a business survey examining economic activity to improve the regional nature of the models through a process of superior data insertion. The surveys and model construction are currently underway and the comprehensive project results will be available in the summer of 2004.

Introduction

The current mountain pine beetle infestation in the British Columbia (BC) Northern Interior Forest Region will have serious implications for the state of the economy and the affected human communities. While BC as a whole may be able to assimilate the economic impacts related to natural disturbance, concentrated regional impacts may transform small economies and thus have serious consequences for forest-dependent communities. This study seeks to identify and quantify the socio-economic impacts associated with the current mountain pine infestation in two regions of BC (the Morice-Lakes Innovative Forest Practice Agreement Area and the McGregor Model Forest Region). This study will examine the economic impacts using a general equilibrium analysis on a provincial and a regional scale.

Study Sites

The study region for this project consists of the combined area of the Morice-Lakes Innovative Forest Practices Agreement (ML IFPA) Area and the McGregor Model Forest Region (MMF) (Fig. 1). Sub-projects are also underway examining specific models for each of the two component regions. The ML

Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

IFPA Area is also known as the Nadina Forest District (formerly the Lakes Forest District and the Morice Forest District). The main communities in the ML IFPA Area are Burns Lake, Houston, and Granisle. The MMF Region is comprised of the Fort St. James Forest District, the Prince George Forest District, and the Vanderhoof Forest District. The main communities in the MMF Region are Fort St. James, Fraser Lake, Prince George, and Vanderhoof.

Figure 1. Map of the project study region (dark area) within British Columbia.

Regional Economic Impact Assessment

In 2002, a project was initiated to examine the socio-economic impacts of varying natural resource management scenarios under the ML IFPA. This initial project was then expanded under the Government of Canada's Mountain Pine Beetle Initiative (MPBI) to include an assessment of the impacts of mountain pine beetle on community sustainability in the MMF. The ML IFPA project will also be expanded under the MPBI to specifically address mountain pine beetle scenarios.

General equilibrium methods are commonly applied by economists to assess the economic impacts of changes in natural resource management (Richardson 1985; Loomis 1993; Alavalapati et al. 1996, 1999; Patriquin et al. 2002, 2003a, b). The regional economic impact assessments for the study areas identified under the MPBI will each consist of a regional economic overview and a computable general equilibrium economic impact model.

Regional Economic Overview

The purpose of the regional economic overview is two-fold. First, it provides a means for compiling and reporting indicators of the state of the economy. This involves data collection from a variety of primary and secondary sources. A baseline year is selected (usually the most recent census year) and where possible, trend data is also reported. Second, the baseline data will be used to calibrate the region-specific economic impact models. Secondary data sources include the Statistics Canada 2001 Census of Population, the Statistics Canada 2001 Census of Agriculture, the 1999 British Columbia Input-output Tables, and previous research reports. Primary data is being collected through two separate surveys of local businesses, one in the ML IFPA Area and the other in the MMF Region.

In addition to asking business respondents to identify quantitative levels of business activity in the region, they were also asked a number of questions about their perceptions of the local economy and the impacts of mountain pine beetles and other natural disturbance on their business and the overall economy.

Economic Impact Modelling

The second major component of the regional economic impact assessment is the construction of region-specific impact models. General equilibrium impact models will be constructed for three regions; the ML IFPA Area, the MMF Region, and the combined area of the previous two regions. In addition, the impacts on the economy of the “rest of British Columbia” will also be examined at the provincial accounting stance. A hybrid methodology is being used to gather region-specific information to populate the computable general equilibrium (CGE) models following the methods identified in Richardson (1985) and Patriquin et al. (2002). The hybrid methodology involves a mechanical regionalization of provincial data followed by a process of superior data insertion where primary data exists. Following the literature review, the Johansen CGE structure and solution techniques have been adopted for this project (Johansen, 1974; Patriquin et al., 2003a).

Project Status

The ML IFPA sub-component of this project began in the fall of 2002. The larger assessment project was approved under the Government of Canada Mountain Pine Beetle Initiative in the spring of 2003. Previous literature for the ML IFPA was reviewed over the winter of 2002 and the British Columbia Input-output Tables were obtained and transformed into a social accounting matrix.

Sub-project 1 – the Morice Lakes Innovative Forest Practices Agreement

The ML IFPA business survey was delivered or conducted in person over the period of June 9th to June 15th, 2003. Non-respondents were contacted by telephone from July 7th to August 29th, 2003. In total, 191 (24.4%) businesses were sampled from the ML IFPA population of 782 active businesses across all major industrial sectors. There were 67 respondents and 124 refusals for an overall survey response rate of 35.1%. The population, sample, and respondents were approximately split evenly between the Lakes District and the Morice District that comprise the ML IFPA Area. Survey data entry is complete and the analysis is underway. Survey results to date have been used to construct a region-specific social accounting matrix that will be used to construct the ML IFPA computable general equilibrium model for scenario analysis.

The preliminary ML IFPA sub-project is scheduled for completion in December of 2003. A specific mountain pine beetle analysis for the ML IFPA under the Mountain Pine Beetle Initiative (including a comprehensive survey analysis) is scheduled for completion in the summer of 2004.

Sub-project 2 – the McGregor Model Forest

The MMF sub-project commenced under the Government of Canada Mountain Pine Beetle Initiative upon approval in the spring of 2003. The MMF business survey was mailed out to more than one thousand businesses on September 29th and 30th, 2003. Depending on response rate, a second survey mail out is scheduled for the end of October 2003. This sub-project and the overall study area assessment are scheduled for completion in the summer of 2004.

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