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Exploring Forest Management Practices Using an Agent-Based Model of Forest Insect Infestations

Liliana Pérez[a], **Suzana Dragićević**[b]
Spatial Analysis and Modeling Laboratory
Department of Geography, Simon Fraser University
8888 University Drive, Burnaby, BC, V5A 1S6, Canada
[a]lperezca@sfu.ca, [b]suzanad@sfu.ca

Abstract: The forests of British Columbia, Canada have undergone an unprecedented Mountain Pine Beetle, *Dendroctonus ponderosae* Hopkins, (MPB) infestation that has resulted in extensive mortality of lodgepole pine, *Pinus contorta*. The objective of this study is to apply the agent-based model (ABM) to simulate the MPB attack behaviour in order to evaluate how different harvesting policies influence spatial characteristics of the forest and spatial propagation of the MPB infestation over time. The first scenario is the no management action with the natural disturbance process leading the changes of the forest ecosystem. The other two scenarios implement sanitation and salvage harvesting methods. Obtained results indicate that the different management strategies significantly affect the MPB infestation rates. Statistical analysis of the simulation outcomes is performed to compare the three scenarios and prove that salvage harvesting is the most effective strategy. This study can improve our understanding of the effects of management strategies and assist policy decision making process when complex MPB agent-based model of forest insect outbreaks is used.

***Keywords**:* Agent-based modelling; complex systems; mountain pine beetle (MPB), forest infestation, forestry.

1. INTRODUCTION

Forest ecosystems have adapted to local climate, atmosphere and soils over many years [Dale et al. 2001]. However, human activity such as resource extraction, land development and management strategies have resulted in changes to the natural environment, posing real problems for forests and woodlands. British Columbia, Canada, possesses a land area of approximately ninety-five million hectares, two-thirds of which is covered by forest that are constantly being modified by natural disturbances such as fire, diseases and insect infestations [Campbell et al. 2007, Carroll et al, 2003, Dale et al. 2001]. Likewise, policies implemented by resource managers have played an important role in the modification of the landscape patterns. In a province where 15% of the economy relies on forest resources [Haley 2005], disturbances such as mountain pine beetle (MPB), *Dendroctonus ponderosae* Hopkins, infestation have putted forest values at risk impacting the economy of many British Columbian communities; these insect outbreaks have resulted in the death of trees over areas of several thousand square kilometres [Kurz et al. 2008].

The dynamics of MPB infestation taking place between stands of host trees and insects within them, form part of a complex spatio-temporal process that requires theoretical and practical approaches to provide insights for understanding and controlling the impacts of MPB outbreaks. With the purpose of comprehending and representing the internal organization of such forest ecosystems and interactions caused by insect outbreaks a bottom-up approach using an agent-based model (ABM) has been developed [Perez and Dragicevic 2010]. This ABM acknowledges the robust, flexible, adaptive, self-organized, intuitive, and scalable behaviour of insect colonies. Although the model effectively captures the emergent patterns of tree mortality due to MPB outbreaks, it has not considered how different forest harvesting management activities influence the spatial patterns of mortality tree distribution and the number of killed infested trees.

The objective of this study is to use agent-based model (ABM) to simulate the MPB attack behaviour in order to evaluate the MPB spatio-temporal dynamics under three different management scenarios. More particularly, this study evaluates how management practices, implemented trough *Management Agent*, influence the spatial distribution and patterns of insect population and their preferences for attacked and killed trees. The model simulations are implemented using three harvesting scenarios: 1) no management, 2) sanitation harvest and 3) salvage harvest. The MPB outbreaks are considered a major natural disturbance that triggers widespread mortality of lodgepole pine, one of the most abundant commercial tree species in British Columbia, Canada. The model is implemented on a study area located in the North-Central Interior of British Columbia.

2. METHODS

The methodology for this study consists of three main sections. The first section describes the behaviour and life cycle of MPB populations and the mechanism how these are represented with the model. The second section provides details regarding the interaction between the host (lodge pole pine) and the MPB, describing the role of pine trees in the model implementation; and finally the third section explains the different management practices and how these are implemented. The model consisted of three types of agents: *Beetle Agent*, *Pine Agent*, and *Forest Management Agent* that permit the representation of the MPB behaviour, the forest environment and tree health evolution, and the stakeholder respectively.

2.1 Attack Behaviour of MPB and Life Cycle: The Beetle Agent

The behaviour and life cycle of the MPB are captured by the *Beetle Agent* which follows a series of rules or steps to decide where to fly within the forest and to select a healthy tree to attack, feed and breed. In its natural environment, MPB typically kills host trees in order to successfully reproduce [Logan et al. 1998]. Their beetle larvae feed on the inner bark of mature pine trees, girdling and killing them [Cole 1973]. The host tree must be sufficiently large and have thick inner bark for the beetles to successfully reproduce and reach epidemic populations [Berryman et al. 1989]. MPB outbreaks end when the food supply depletes and is no longer enough to support the population or when climatic conditions become unfavourable for the beetle [Safranyik et al. 1999].

In real life, female MPB emerge from the tree before the males do and fly varying distances in search of a new host tree [Safranyik and Carroll 2006]. To simulate the emergence behaviour within the model, each B*eetle Agent* had to query the Diameter at Breast Height (DBH) of the tree where it inhabits before start flying. Therefore, the first female *Beetle Agents* to emerge are the ones living or located in big trees, afterwards the ones that find themselves in medium trees, and finally the female beetles placed in small trees. The emergence of the male *Beetle Agents* is initiated only when at least one of the females *Beetle Agents* has located and selected a new host tree. To simulate the flying distances of each *Beetle Agent*, fuzzy sets were used to allow them to come to a final decision. The *Beetle Agent* captures wind influences within the natural range of MPB flying distances. The decision rules for determining the flying distance for each *Beetle Agent* are based on the fuzzification of three variables: flying distance, DBH, and tree proportion within the stand [Perez and Dragicevic 2010]. Once potential host trees are located, *Beetle Agents* initiate the process of evaluation to determine if the trees fulfill their requirements of food and allow them to start the reproduction stage. The host selection process involves the evaluation of four parameters of health state of the trees within the stand, type of trees, average age and DBH. After the assessment of the hosts, the *Beetle Agents* reach a decision whether to stay or fly to a different stand.

In the real-world, at some point of the MPB attack, the number of beetles per tree reaches the host tree capacity and an anti-aggregation chemical compound is released by the beetles in order to redirect the attacks towards nearby trees [Huber and Borden 2001]. This specific behaviour is modeled using the *Pine Agent* which is in charge of calculating the beetle population density per stand and pass the information in to the *Beetle Agents*.

When the attack is successfully initiated, eggs are laid inside the galleries of newly attacked trees and normally hatch within a week or so following deposition and the young larvae commence feeding immediately. In the simulation, *Beetle Agents* have to query the age of the tree in order to establish the number of eggs to be laid; this number is randomly generated based on the average age of trees. The MPB experience high levels of mortality each winter when cold temperatures have detrimental effects on the developing stages of the beetles. During outbreaks, it is common to have a mortality level of 80% due to cold temperatures [Carroll et al. 2003, Safranyik and Carroll 2006]. Winter mortality of *Beetle Agents* is simulated by having removed 80% of the newly created beetle population. This final stage represents the completion of one life cycle of the MPB which is equivalent to one year.

2.2 Lodgepole Pine Forest in a MPB outbreak: The Pine Agent

The MPB employ a specific strategy to overcome the defences of lodgepole pine. It relies upon cooperative behaviour in the form of mass attack by rapidly concentrating on selected host trees in response to aggregation pheromones; therefore the beetles exhaust the host's defensive response [Safranyik et al. 1999, Raffa and Berryman 1983, Berryman et al. 1989]. If sufficient beetles arrive at a rate that exceeds the resistance capacity of a particular tree, then colonization is successful. The *Pine Agent* is implemented to simulate the resistance of lodgepole pine with its own thread of control that identifies the state and attributes of each stand. This autonomous entity watches out for its own set of internal responsibilities and is capable of sending messages about tree resistance capacity to the *Beetle Agents*. The attributes of the tree stands (type, age, height, health state, and DBH) are also used as important input information to the agent-based model.

In order to estimate the beetle population density per tree, *Pine Agents* are in charge to calculate the total bole surface area (S_t) as follows:

$$S_t = 0.3455 + 1.9708 \times D \times H \qquad (1)$$

where the constants are regression coefficients calculated by Safranyik [1988]; H is total tree height (m) and D is the tree diameter (m) at 1.37 m [Safranyik et al. 1999]. Once (S_t) is calculated for each stand, *Pine Agent* determines the number of *Beetle Agents* located within the trees per stand and proceed to evaluate their population density per 1 m^2 [Perez and Dragicevic 2010].

2.3 Management Practices: The Forest Management Agent

To date, there is no consensus about a unique method for suppressing the MPB infestations. Long-term mitigation of MPB outbreaks can only be accomplished through the implementation of management strategies in order to lower the susceptibility of lodgepole pine landscape [Bone et al. 2007]. Management practices available for controlling MPB outbreaks depend on the size of the outbreak, the age of the stand, the size of the trees, and the conditions of the site amongst others. Generally, managing involves a reduction of susceptible and/or infested stands in an effort to prevent new attacks [Fettig et al. 2007]. The most common management strategies used to minimize future resource losses from the beetle-induced tree mortality are the silvicultural treatments of sanitation and salvage harvesting. To explore the effects of management strategies in the spatial propagation of MPB outbreaks, this model simulate at stand level the two common silvicultural practices and the one with no management trough the *Forest Management Agent*.

In the *sanitation* and *salvage harvest* silviculture strategies the *Forest Management Agent* evaluates each forest stand within its Moore neighbourhood. To cut down an evaluated stand, using the *sanitation harvest* strategy, the number of infested trees has to be greater than a set threshold. Likewise, any healthy neighbour stand is cut down whenever its average DBH value is greater than 30cm. In the *salvage harvest* strategy, if a stand does not register MPB attack and a predetermined number of neighbours are under a MPB attack, the *Forest Management Agent* proceeds to cut down the stand.

3. MODEL IMPLEMENTATION AND RESULTS

The model proposed in this study simulates the dynamic process of MPB outbreaks under different scenarios of forest harvesting. A forested area of approximately 560 ha, located in North-Central Interior of British Columbia, Canada (Figure 1) is used to implement and test the ABM previously described. The forest landscape consists of stands of small, medium and large diameter trees that are dominated by lodgepole pine, with relatively smaller proportions of Douglas fir, *Pseudotsuga menziesii*, and white spruce, *Picea glauca,* scattered throughout. The spatial resolution of the study area is 1ha, where each raster cell represents a stand.

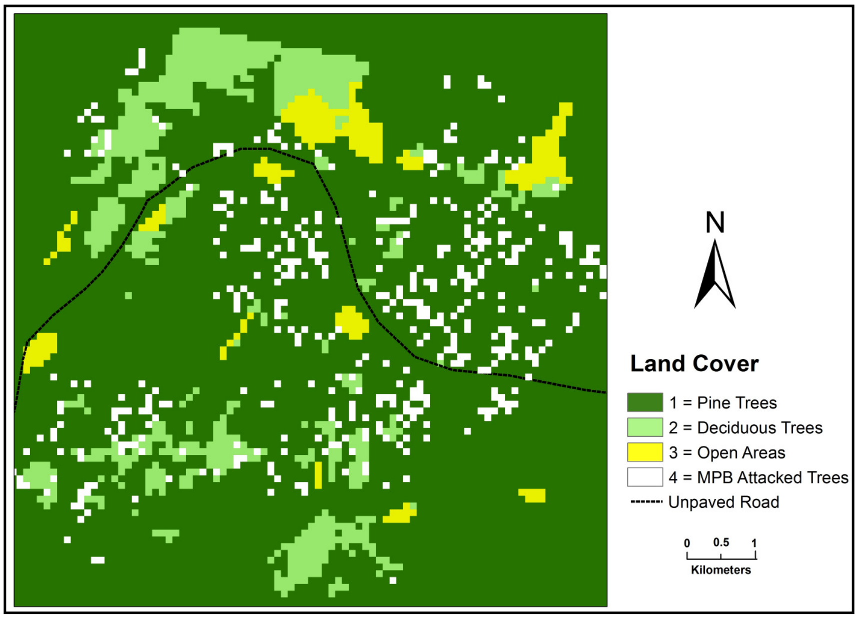

Figure 1. Study area located in the north-central interior of British Columbia, Canada, with its land cover categories

Beetle Agents are randomly dispersed in the forest landscape as discrete data points within a raster GIS layer. Agents representing MPB have the unique attribute that allows discriminating the beetle population by gender and helps to simulate and maintain the male:female sex ratio of 1:2 as observed in reality [Safranyik and Carroll 2006].

Five different GIS raster data sets were used as input for the model simulations containing the information regarding tree species, health state, diameter at breast height (DBH), tree age, and tree height of each stand in the study area. The data is obtained from the aerial photographs collected during the summers of 2001-2003 [Roberts et al. 2003]. Auxiliary cartography is used to verify classification of average tree species and tree sizes within a stand, and whether or not a stand had been attacked by MPB [B.C. Ministry of Forests and Range 2004]. The thematically classified images are analyzed in a GIS, georefenced and resampled so the spatial resolution corresponded to stand level scale. The DBH values are randomly assigned based on the tree age. The management and processing of the GIS data sets are carried out using ArcGIS 9.3. To understand the influence of management practices in the number of lodgepole pine stands killed by the MPB infestation, in the course of time, model simulations are performed for five time steps. Each time step represents a year – from the end of the first year (T_{i+1}) to the end of the fifth year (T_{i+5}). A series of thirty experiments are conducted in order to evaluate the results due to the stochasticity of some parts of the model. During the thirty simulation runs for each management scenario, none of the parameters were changed. Figure 2 presents the simulation results corresponding to three different scenarios: 1) *Scenario 1* – MPB dispersion under no management strategy implemented, 2) *Scenario 2* – MPB dispersion under a sanitation harvest strategy, and 3) *Scenario 3* – MPB dispersion under a salvage harvest strategy. These scenarios depict three different dispersal patterns, and spatial distributions of stands attacked by MPB. Furthermore, they permit to identify the effects of using forest management techniques in the presence of an insect disturbance for the study area.

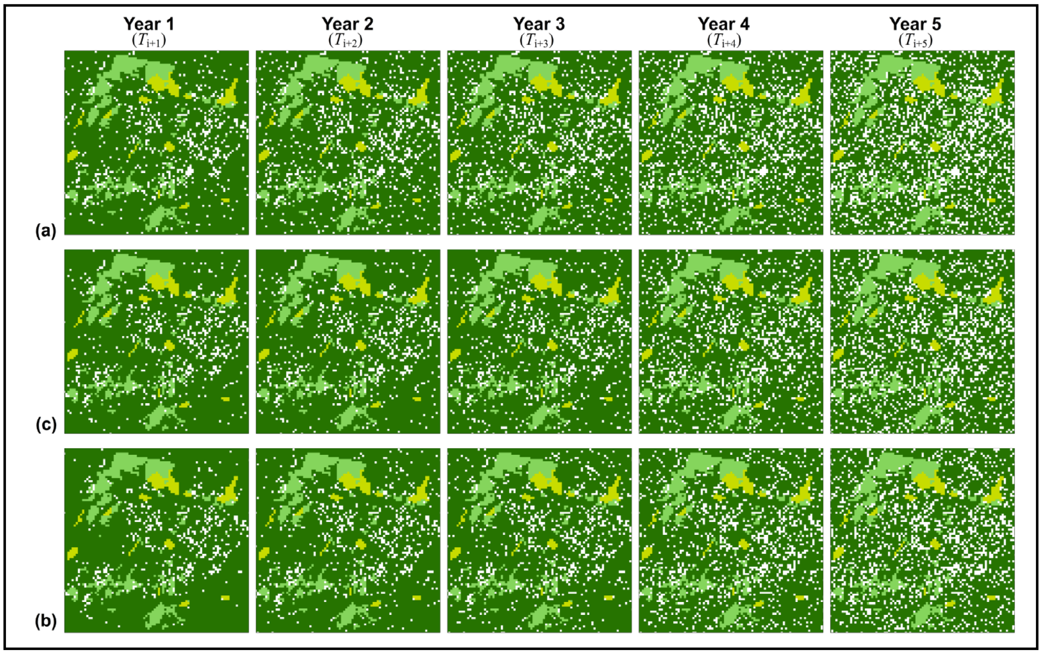

Figure 2. Five year simulation of lodgepole pine stands' mortality patterns using three different management strategies (a) MPB dispersion under no management, (b) MPB dispersion under a *sanitation harvest* strategy, and (c) MPB dispersion under a *salvage harvest* strategy. Legend for land uses are the same as on Fig. 1.

The statistical analysis of the number of stands killed is provided for one and thirty different simulations performed and for each management scenarios are presented in Figures 3 and 4 respectively. In average a 4% of variation amongst the thirty simulation outcomes was identified for the *no management* and *sanitation harvest* scenarios and a 2% variation for the *salvage harvest* scenario. The model outcomes indicate that the insect outbreak simulated without applying a management strategy results in highest overall stands infestation during the five years. Comparing the total number of stands killed by MPB in five years, the *Scenario 1*, *Scenario 2* and *Scenario 3* yielded values of 2299, 1884 and 1775 lodgepole pine forest stands respectively, which indicates that greater timber losses, in areas undergoing insect outbreaks, can be reduced through silvicultural practices. The reason for getting a higher number of attacked stands for the *Scenario 1* is that more forest stands were available for a higher MPB population's production, therefore every year the insect population increased.

The evaluation of the *sanitation* and *salvage harvest* strategies indicates that the salvage practice is more efficient in the task of diminishing the total loss of timber in a period of five years. The use of this management technique generates a reduction of 25% in the number of forest stands killed by MPB, while the sanitation harvest reduced the mortality by a 19%. In the absence of a management strategy the MPB outbreak killed a greater number of stands. The outcomes from the *salvage harvesting* scenario reveal that the implementation of this technique reduces the mortality rates of pine trees by successfully controlling MPB. The reason for this is that the outbreak is contained by cutting down all the healthy and mature trees with the purpose to reduce the wood loss.

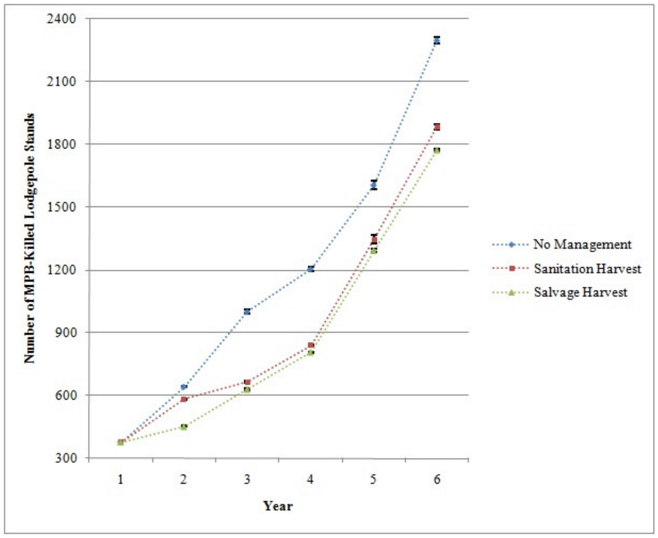

Figure 3. Number of stands killed at each year of the model simulation for each management scenario and its standard error bars.

Table 1 show the results of the ANOVA test that was used to establish the difference between the three management scenarios. The null hypothesis stated that there was no difference between the results out of the three different scenarios simulated; H_0: $\mu_1 = \mu_2 = \mu_3$; H_1: $\mu_1 \neq \mu_2 \neq \mu_3$; $\alpha = 0.05$. Given that the obtained value for F is smaller then the critical (F< Fcrit), therefore the null hypothesis is rejected. This statistical test confirms that different management strategies significantly affect the MPB infestation rates.

SUMMARY

Groups	Count	Sum	Average	Variance
No Management	30	70742.01	2358.07	6137.29
SanitationHarvest	30	57120.00	1904.00	4130.07
SalvageHarvest	30	52788.11	1759.60	857.41

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5851854	2	2925926.82	789.030	1.73E-56	3.101
Within Groups	322618	87	3708.2569			
Total	6174472	89				

Table 1. ANOVA Table

4. CONCLUSION

The objective of this study is to test different management strategies based on an existing AB model for simulating MPB-induced tree mortality patterns in order to evaluate the influence of different forest management practices to control insect outbreak. The model was implemented using three different scenarios on data sets from the BC Ministry of Forest, for a study site in the North-Central Interior of British Columbia, Canada. The results of the model simulations indicate that the use of different management strategies affects significantly the number of stands attacked and killed by the MPB. The importance of the model used and the scenarios developed can help with managing harvesting techniques and forest areas undergoing MPB outbreaks. The model can be used as exploratory tool that can help building meaningful forest management polices. In addition this study can be extended to incorporate other management strategies that can include the economic elements. Valuing the cost of using different harvesting strategies could permit to establish more effective policies to control MPB infestations with the less impact to local economies.

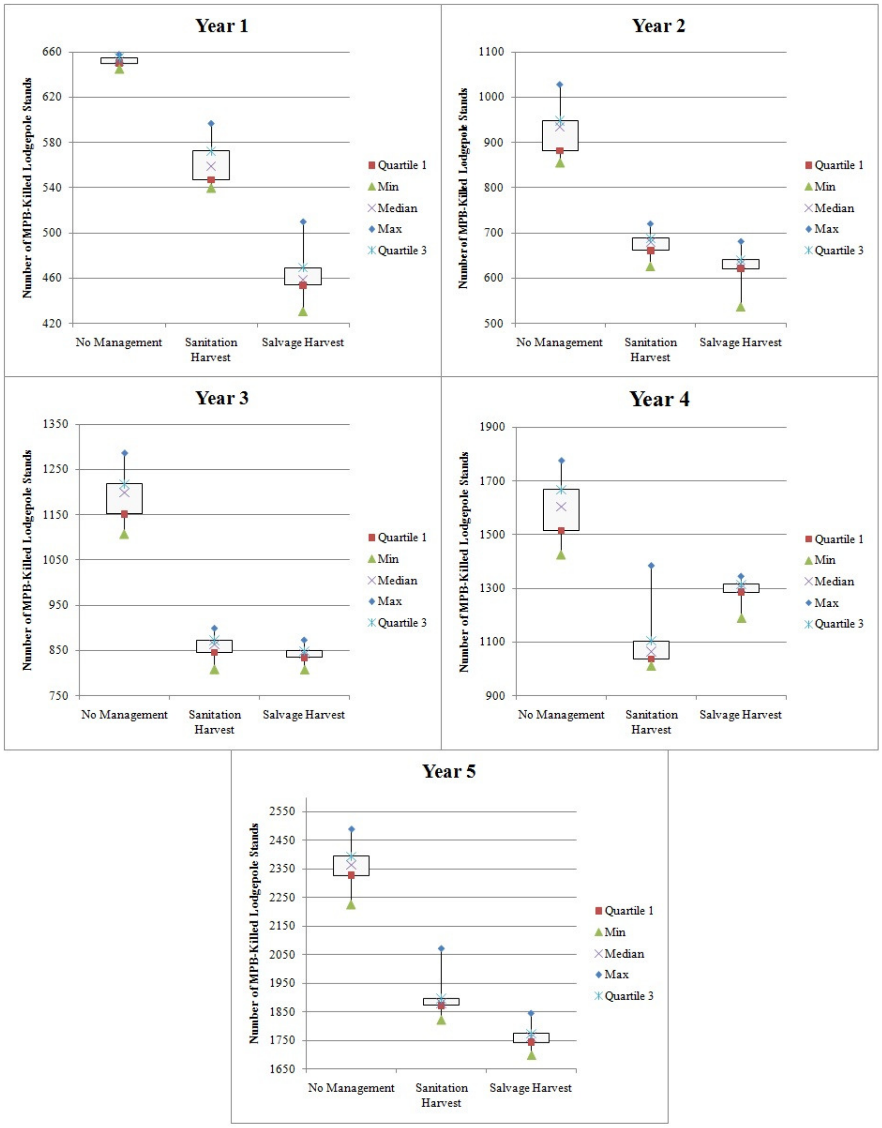

Figure 4. Box plots comparing the outcomes of thirty different simulation runs performed for each of the three management scenarios.

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REFERENCES

B.C. Ministry of Forests and Range. Aerial Detection for Bark Beetle Management Activity. Forest Practices Branch and Canadian Forest Service, Victoria, BC, Canada. http://www.for.gov.bc.ca/hcp/fia/landbase/aerial_detection.htm, 2004. Last accessed December 2009.

Berryman, A.A.; Raffa, K.F.; Millstein, J.A.; Stenseth, N.C. Interaction dynamics of bark beetle aggregation and conifer defense rates. *Oikos*, 56(2), 256-263, 1989.

Bone, C., Dragicevic, S., Roberts, A. Evaluating forest management practices using a GIS-based cellular automata modeling approach with multispectral imagery. *Environmental Modeling and Assessment*, 12(2), 105–118, 2007.

Campbell, E.M., Alfaro, R.I., Hawkes, B. Spatial Distribution of Mountain Pine Beetle Outbreaks in Relation to Climate and Stand Characteristics: A Dendroecological Analysis. *Journal of Integrative Plant Biology*, 49(2), 168-178, 2007.

Carroll, A. L., Taylor, S. W., Régnière, J. and Safranyik, L. Effects of Climate Change on Range Expansion by the Mountain Pine Beetle in British Columbia. Mountain Pine Beetle Symposium: Challenges and Solutions, Kelowna, British Columbia, Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 2003.

Cole, W. Crowding effects among single-age larvae of the mountain pine beetle, *Dendroctonus ponderosae* (Coleoptera: Scolytidae). *Environmental Entomology*, 2(2), 285-293, 1973.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J. and Wotton, B.M. Climate change and forest disturbances. *BioScience*, 51(9), 723-734, 2001.

Fettig CJ, Klepzig KD, Billings RF, Munson AS, Nebeker TE, Negro´ n JF, Nowak JT. The effectiveness of vegetation management practices for prevention and control of bark beetle outbreaks in coniferous forests of the western and southern United States. *Forest Ecology and Management*, 238(1-3), 24–53, 2007.

Haley, D. *Forestry Handbook for British Columbia, Fifth Edition*. Faculty of Forestry, University of British Columbia, 773 pp., Vancouver, 2005.

Huber, D. P. W., and Borden, J. H. Protection of lodgepole pines from mass attack by mountain pine beetle, Dendroctonus ponderosae, with nonhost angiosperm volatiles and verbenone. *Entomologia Experimentalis Et Applicata*, 99(2), 131-141, 2001.

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T. and Safranyik, L. Mountain pine beetle and forest carbon feedback to climate change. *Nature*, 452, 987-990, 2008.

Logan, J. A., White, P., Bentz, B. J. and Powell, J. A. Model analysis of spatial patterns in mountain pine beetle outbreaks. *Theoretical Population Biology*, 53(3), 236-255, 1998.

Malanson, G. P. and Armstrong, M. P.. Dispersal probability and forest diversity in a fragmented landscape. *Ecological modelling*, 87(1-3), 91-102, 1996.

Perez, L. and Dragicevic, S. Modeling mountain pine beetle infestation with an agent-based approach at two spatial scales. *Environmental Modelling & Software*, 25(2), 223-236, 2010.

Raffa, K.F.; Berryman, A.A. Physiological aspects of lodgepole pine wound responses to a fungal symbiont of the mountain pine beetle, Dendroctonus ponderosae (Coleoptera: Scolytidae). *The Canadian Entomologist*, 115(7), 723-734, 1983.

Roberts, A., Dragicevic, S., Northrup, J., Wolf, S., Li, Y. and Coburn, C. Mountain pine beetle detection and monitoring: remote sensing evaluations. Vancouver, Simon Fraser University, 2003.

Safranyik, L. and Carroll, A. L. The biology and epidemiology of the mountain pine beetle in lodgepole pine forests, 3-66p. In: L. Safranyik and B. Wilson (Eds), The mountain pine beetle: a synthesis of biology, management, and impacts on lodgepole pine. Pacific Forestry Centre: Victoria, BC, 2006.

Safranyik, L. Estimating attack and brood totals and densities of the mountain pine beetle in individual lodgepole pine trees. *The Canadian Entomologist*, 120(4), 323-331, 1988.

Safranyik, L., H. Barclay, Thomson, A. and Riel, W. G. A population dynamics model for the mountain pine beetle, Dendroctonus ponderosae Hopk. (Coleoptera : Scolytidae). Pacific Forestry Centre, 41pp., Victoria, British Columbia, 1999.