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.

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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.

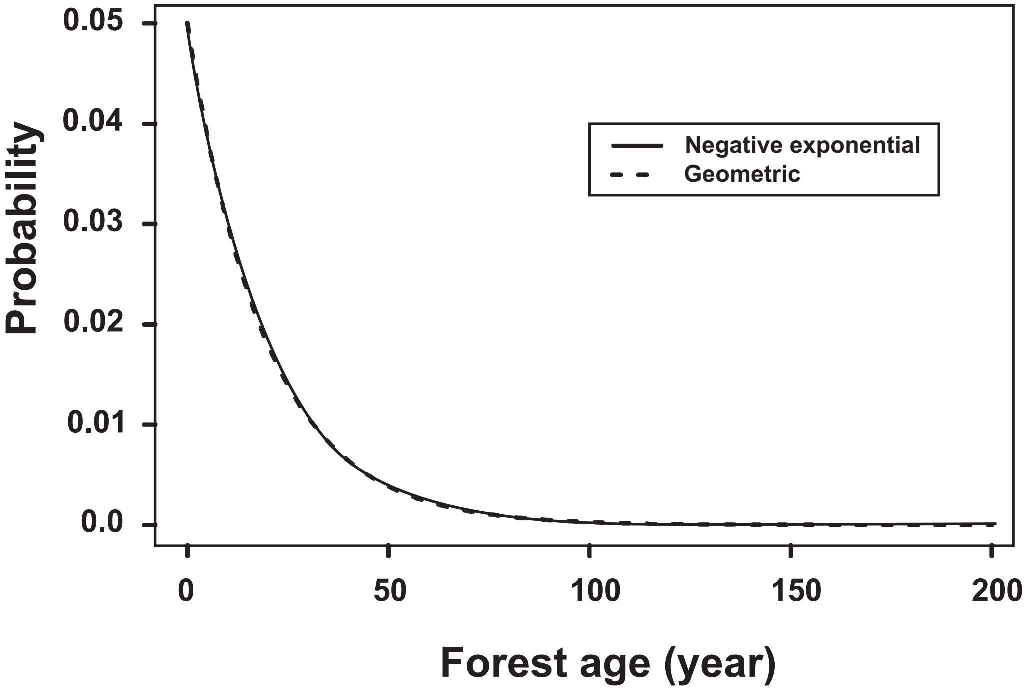

Figure 1. Negative exponential and geometric probability distributions with a same parameter value.

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).

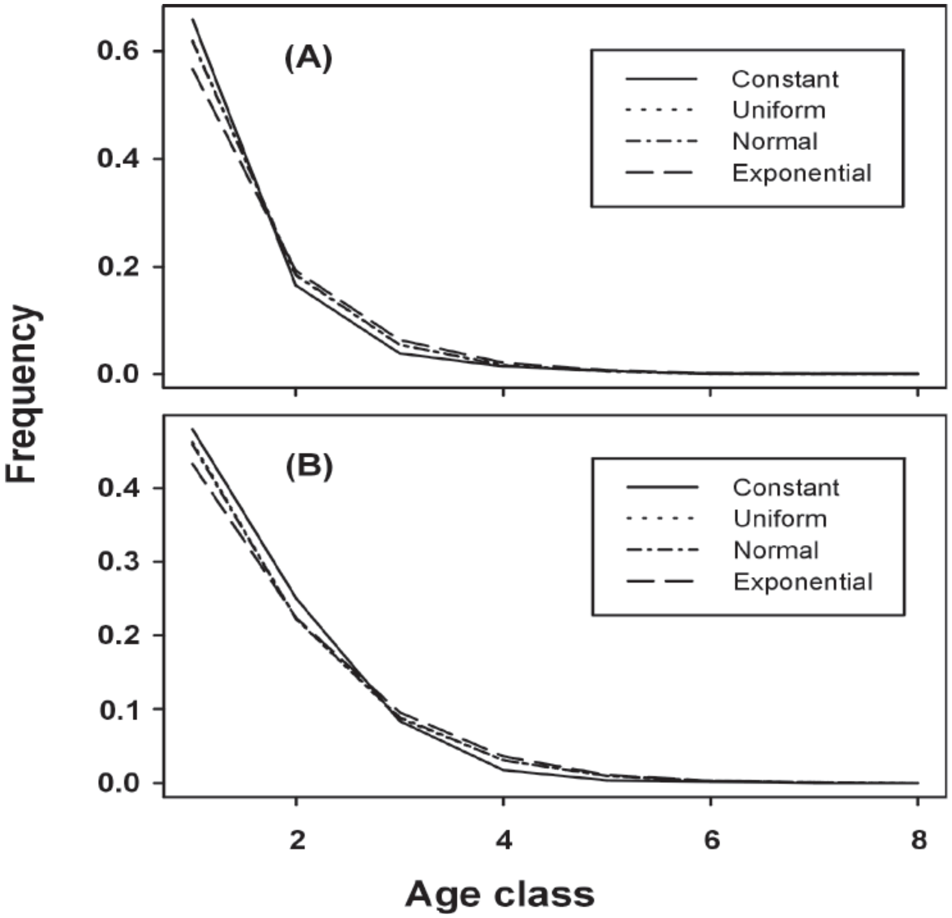

Figure 2. Relative frequencies of the first six 20-year age classes for fire ignition probability being (A) independent of age or (B) linearly increasing with age. These frequencies have been normalized and add to one over all age classes in the forest.

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*.

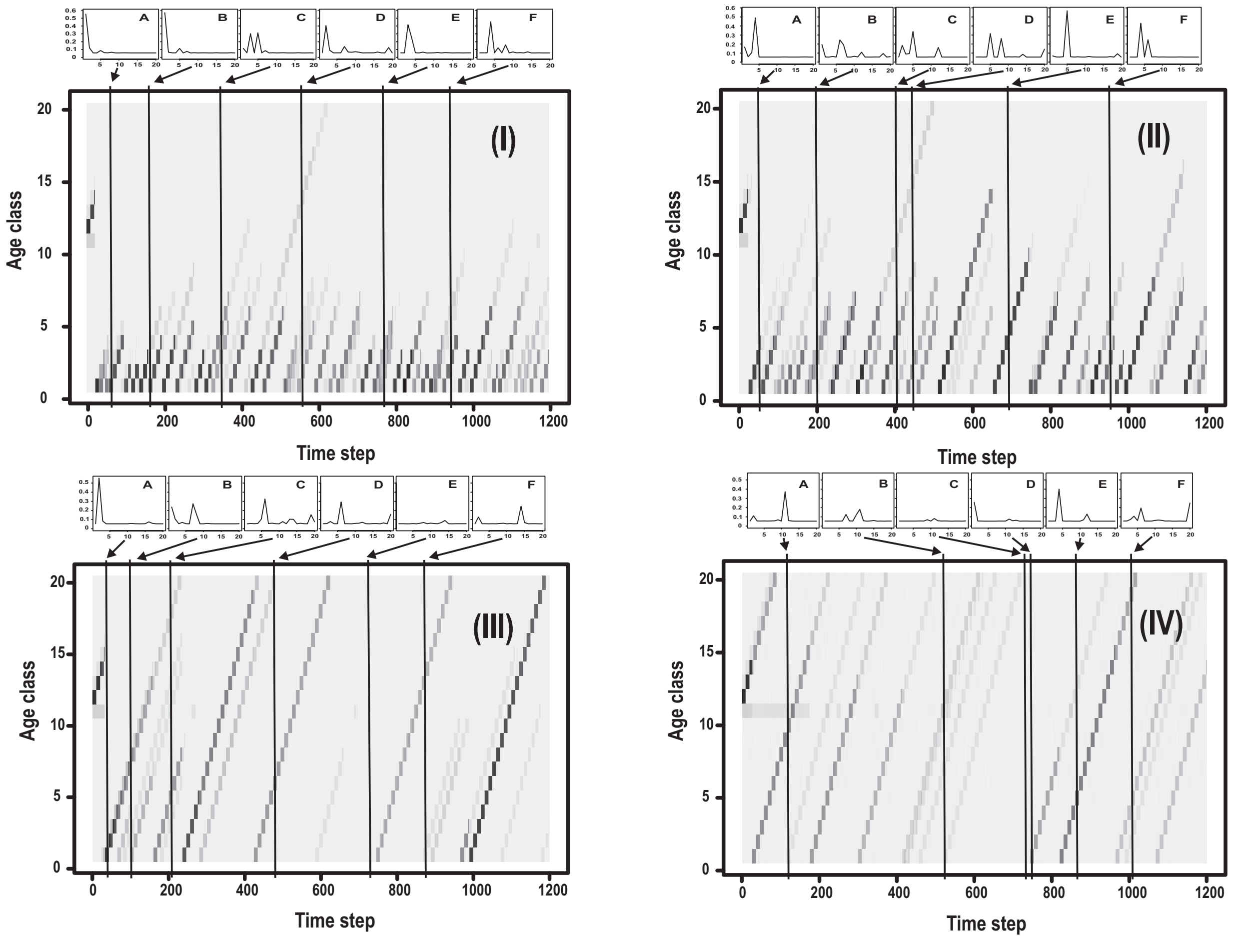

Figure 3. Simulated dynamics of forest age-distribution under fire cycles of 125 (I), 213 (II), 864 (III), and 3,800 years (IV). Each age class represents a 10-year interval, and the dark color indicates high relative frequency. The small graphs associated with the four scenarios are the age class distributions 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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Literature Cited

Leslie, P.H. 1945. On the use of matrices in certain population mathematics. Biometrika 33: 183-212.

Leslie, P.H. 1948. Some further notes on the use of matrices in population mathematics. Biometrika 35: 213-235.

Li, C. 2000. Reconstruction of natural fire regimes through ecological modelling. Ecological Modelling 134: 129-144.

Li, C.; Barclay, H.J. 2001. Fire disturbance patterns and forest age structure. Natural Resource Modeling 14: 495-521.

McGarigal, K.; Marks, B. 1994. FRAGSTATS: a spatial pattern analysis program for quantifying landscape structure v 2.0. (unpublished computer programmer user manual and guide). Oregon State University, Corvallis.

Pielou, E.C. 1969. An Introduction to Mathematical Ecology. Wiley-Interscience, New York and London.

Safranyik, L.; Shrimpton, D.M.; Whitney, H.S. 1973. An interpretation of the interaction between lodgepole pine, the mountain pine beetle, and its associated blue stain fungi in western Canada. Pages 406-428 *in* Symposium Proceedings: Management of Lodgepole Pine Ecosystems. Washington State University, Pullman, Washington.

Safranyik, L.; Shrimpton, D.M.; Whitney, H.S. 1974. Management of lodgepole pine to reduce losses from the mountain pine beetle. Can. For. Serv., Pac. For. Cent. For. Tech. Rep. No. 1. 24 p.

Safranyik, L.; Barclay, H.J.; Thomson, A.J.; Riel, W.G. 1999. A population dynamics model for the mountain pine beetle, *Dendroctonus ponderosae* Hopk. (Coleoptera: Scolytidae). Can. For. Serv., Pac. For. Cent. Inf. Rep. BC-X-386. 35 p.

Shore, T.L.; Safranyik, L. 1992. Susceptibility and risk rating systems for the mountain pine beetle in lodgepole pine stands. Can. For. Serv., Pac. For. Cent. Inf. Rep. BC-X-336. 12 p.

Taylor, S.; Carroll, A. 2004. Disturbance, forest age, and mountain pine beetle outbreak dynamics in BC: A historical perspective. Pages 41-51 *in* T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

Van Wagner, C. E. 1978. Age-Class Distribution and the Forest Fire Cycle. Canadian Journal of Forest Research 8: 220-227.