Extension Note

BC Journal of Ecosystems and Management

Effects of fire return rates on traversability of lodgepole pine forests for mountain pine beetle: Implications for sustainable forest management

Hugh J. Barclay[1], Tina Schivatcheva[2], Chao Li[3], and Laura Benson[4]

Abstract

The spread of mountain pine beetle (MPB) depends on climate, weather, and topography, among other factors. In predicting the spread of the MPB in British Columbia, foresters should specifically consider the susceptibility and traversability of lodgepole pine forests to MPB. In order for beetle infestations to spread through the forests at endemic or incipient beetle population levels, patches of susceptible forest must exist, and these patches must be close enough together that beetles can disperse from one to another. This study determined stand susceptibility by examining simulated effects of fire return rates on the equilibrium age structure of a 1 million ha lodgepole pine forest, and then using the results to generate mosaics of susceptibilities to MPB attack. At the landscape level, "traversability" describes the condition of a forest that allows an incipient beetle population to disperse across it according to defined rules of susceptibility and maximum distance for dispersal through unsuitable habitat. We found that: (1) long fire cycles and fire suppression yielded an age structure that is highly susceptible to beetle attack; and (2) harvesting reduced the mean susceptibility to MPB attack as well as traversability. A combination of early harvesting and moderate fire suppression would theoretically yield an equilibrium forest structure that minimizes both susceptibility and traversability for MPB.

KEYWORDS: *dispersal, infestation, lodgepole pine, mountain pine beetle, susceptibility, traversability.*

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Introduction and background

The mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopk.) infestation has affected over 13 million ha of lodgepole pine (*Pinus contorta* var. *latifolia* Englm. Ex S. Wats; Pinaceae) forests in the British Columbia Interior, and has seriously impacted forest ecosystems and the forest industry—half of the harvested wood in the Interior now comes from MPB salvage. Forest fires, attack by MPB, and commercial harvesting are the three major sources of mortality for mature lodgepole pine in the Interior. Fires are usually more severe in years with hot, dry summers, and the probability of an MPB outbreak is higher (Safranyik 2004). Both are typically suppressed in years with cool, moist summers. It is thus reasonable to expect that there may be an interaction (apparent or real) between wildfires and MPB (Taylor et al. 2006), even though they may be more strongly influenced by different factors and operate on rather different scales—fires are an annual phenomenon, whereas MPB cycles can span many years. It seems likely that several factors contribute to an interaction (Safranyik and Carroll 2006), including climate, weather variations, condition of the trees, and species mix. One such factor is the age of the forest, and this will depend partly on the forest fire return rates and fire sizes (Van Wagner 1978; Armstrong 1999; Li and Barclay 2001). These will, in turn, influence the susceptibility of the forest to attack by MPB (Shore and Safranyik 1992; Shore et al. 2000).

There are two types of MPB dispersal: short-distance dispersal (in the range of 1–5 km), in which movement is predominantly by direct flight; and long-distance dispersal (in the range of 100–200 km), in which movement is mostly on air currents. Long-distance dispersal occurs in small proportions at all population sizes (Safranyik et al. 1992), but becomes important during an outbreak when population sizes are large and a small proportion of dispersing beetles might easily form the basis of new infestations (L. Safranyik, Canadian Forest Service, pers. comm., April 2007). In short-distance dispersal, the beetles usually fly within or below the canopy searching for suitable hosts to attack and for mates, often in response to pheromones released by pioneer (first-attacking) beetles (Cerezke 1989). This occurs within, as well as between, patches of suitable habitat.

It seems likely that spread rates of MPB will depend not only on the susceptibility of the surrounding trees, but also on the physical fragmentation and connectivity of the forest. Recurring random fires would tend to produce a mosaic of forest ages and corresponding patches of higher and lower susceptibility. Short-distance dispersal of MPB is in part mediated by pheromones and these are attractive over moderate distances (Safranyik et al. 1989; Barclay et al. 1998). In the absence of pheromones, dispersal and searches for suitable host trees are probably fairly random, or oriented towards vertical silhouettes or down-wind. Since MPB are slow fliers (5–6 km/h), their maximum dispersal distance is probably only a few kilometres (Safranyik et al. 1992; Safranyik and Carroll 2006), and thus habitat fragmentation will be important.

The purpose of this extension note is to help forest managers understand how fire size and fire cycle in lodgepole pine forests affect the susceptibility of these forests to attack and spread of MPB.

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Methods

In order for the beetle to spread through forests by short-distance dispersal, two main conditions have to be met:

1. patches of susceptible forest must exist, and
2. these patches must be close enough together that the beetle can disperse from one to another.

The following sections describe the concepts and tools used in various simulations exploring the effects of fire and harvesting on these forest conditions relevant to MPB spread.

Forest stand: Susceptibility

At the forest stand level, the susceptibility rating system of Shore and Safranyik (1992) provides a useful guide for assessing the susceptibility of a forest. The rating system considers several factors, such as age, density, and species mix, and indicates that dense, mature stands of pure lodgepole pine growing on optimal site locations are most susceptible to MPB.

Forest landscape: Traversability

A quality called traversability represents the ability of a beetle population to spread across the landscape. Beetles can disperse through limited areas of non-susceptible forest (or across grassland or small water bodies) to arrive at tracts of susceptible forest. A traversable landscape is one in which patches of susceptible forest are in close proximity to each other, thus allowing beetles to move along an uninterrupted path (Figure 1a) without having to cross large areas of inhospitable landscape (Figure 1b). Traversability was assessed as a combination of patch susceptibility and distance between patches (Barclay et al. 2005). The ability to get across a forested landscape, jumping from one patch to another, was assessed by defining a lower limit to the value of the susceptibility index of Shore and Safranyik (1992) as well as an upper limit of the distance that could be travelled over inhospitable habitat between patches. Then, using a combination of GIS and image processing software, we visually assessed whether a beetle could travel across the landscape while still obeying the constraint rules.

From stand to landscape: Beetle spread, fires, and harvesting

At the forest landscape scale, complex interactions of major disturbance agents, such as fires and harvesting, create a mosaic of susceptible forest patches. This mosaic of stand ages and susceptibilities reflects the proportion of the total area that burns each year, itself an indicator of fire return rates. We used computer simulations to evaluate the susceptibility of each 1-ha cell in a forest landscape of 1 000 000 ha after 2000 years of random fires. The forest at the start of each simulation had an exponential age distribution and a mean age of 100 years. Age and stand density are related for natural stands and these have been abstracted from stand tables for lodgepole pine in the Interior of British Columbia (Goudie et al. 1990).

Maximum fire size was specified, as were the probability of each cell igniting (burn probability) and the fire return rate. Once maximum fire size and burn probability were assigned, the effective burn probability was prorated downwards to keep the product of maximum fire size and burn probability (i.e., fire return rate) constant. This was to assess the effects of fire size independently of the fire return rate. The simulations determined the effects of burn probabilities and fire sizes (which combine to yield fire return intervals) on

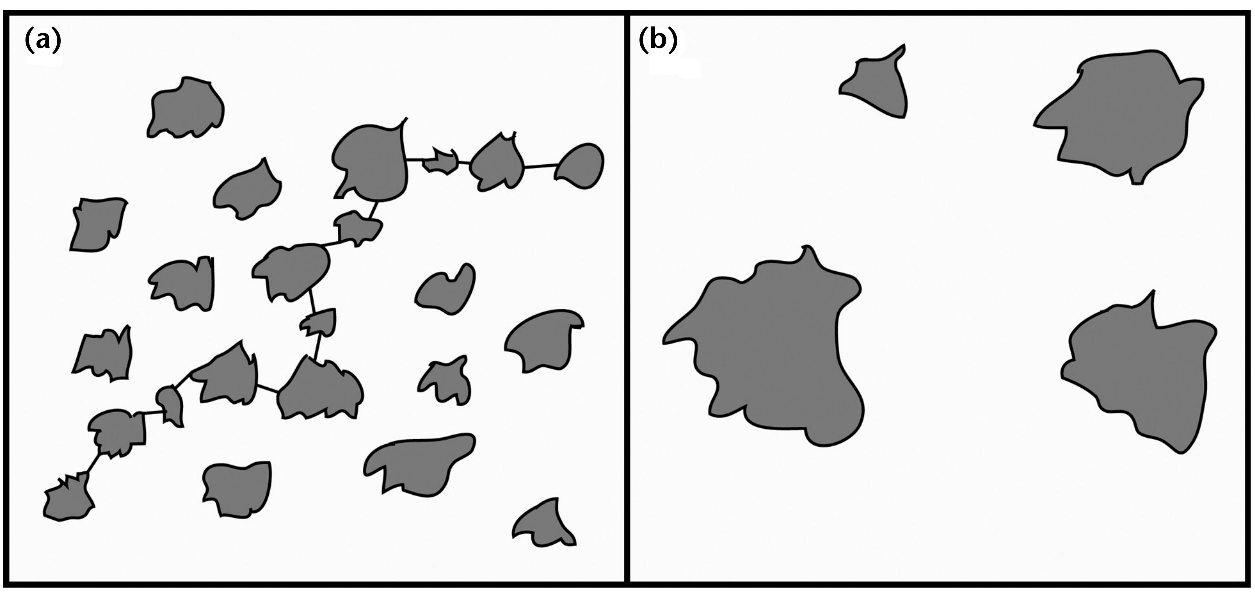

FIGURE 1. Random fires result in areas of higher susceptibility surrounded by areas of lower susceptibility: (a) the black lines between areas of high susceptibility indicate that these areas are less than a given dispersal distance from each other; (b) the patches are too far apart for beetles to disperse from one patch to another.

the equilibrium age structure of a lodgepole pine forest. Burn probability was independent of age and three burn probabilities were used: 0.05, 0.01, and 0.004 (representing fire cycles of 20, 100, and 250 years). These three fire cycles or burn probabilities encompass most of those observed in the province's pine forests, though fire cycles can certainly exceed 250 years (for example, in the Sub-boreal Spruce zone). Maximum fire sizes simulated were 1 ha, 10 ha, 100 ha, 1000 ha, 10 000 ha, 100 000 ha, and 1 000 000 ha; fire size was determined by a random draw from an exponential distribution, and a given fire burned adjacent cells in concentric squares until the chosen size had been achieved—no unburned islands were left behind in the simulations. Since the probability of fire size was exponentially distributed, the mean fire size was adjusted to 0.125 of the maximum size in all cases. Thus, the proportion of forest burned was the burn probability times the mean fire size, except that there was overlap when mean fire size was large. Forest patterns had no influence on patterns of individual fires. The seven maximum fire sizes and three burn probabilities resulted in 21 fire conditions.

To simulate harvesting, one entire age class of trees was harvested, being 80, 100, or 120 years old. This would vary somewhat from year to year, but at equilibrium, the variation would be small. In addition, after a few hundred years, no older trees would exist, so that the year class harvested would constitute the oldest age class. This scenario is for comparative purposes in the investigation—in reality, age classes would not usually be at equilibrium and more than one age class would be partially harvested; therefore, harvesting would be buffered against changes in the size of single age classes. Trees killed by fire were not harvested, but such stands were regenerated immediately.

Fire control was modelled by disallowing a certain percentage of fires from burning. Four percentages of fire control were used—0, 50, 80, and 95%—and these were applied in combination with harvesting. The resulting landscape was further assessed with regards to its traversability to see if a beetle could cross without having to disperse too far between suitable habitats.

The mean susceptibility of the forest to beetle attack increased with age at harvest.

Results and discussion

Effects of harvesting and fire control on susceptibility

The mean susceptibility of the forest to beetle attack increased with age at harvest; thus, mean susceptibility was lower when harvests were done at 80 years than at 120 years. On the other hand, volume harvested decreased with age at harvest (Barclay et al. 2006), a result of the balance between the current and mean annual increments. Thus, harvesting earlier age classes minimized susceptibility to beetle attack and also maximized harvest—this is mainly a consequence of the culmination of the mean annual increment being before 80 years of age.

Mean susceptibility increased with the extent of fire control, as did volume harvested. There was a positive interaction between age of harvest and fire suppression, so that the greatest difference in susceptibility between harvests at 80 and 120 years was seen for 95% fire control. Thus, both late harvesting and extensive fire control allowed a greater proportion of the forest to be in age classes susceptible to beetle attack (Figure 2). The optimal combination for reducing susceptibility appeared to be early harvesting with moderately intensive fire control; although susceptibility increased with fire control, it was drastically decreased by early harvesting (Figure 2).

Traversability and dispersal potential

Since it is possible for beetles to attack pine trees in a stand for any positive value of the susceptibility index, an arbitrary "bounding value" was assumed to separate "susceptible" stands from "non-susceptible" stands—this was allowed to vary from 10% to 90% to assess the importance of identifying such a value. Similarly, it was necessary to assume a "maximum dispersal distance," as in reality not all beetles disperse the same distance—this was allowed to vary from 1 km to 5 km to assess its importance. Maximum fire sizes of 1, 10, and 100 ha produced patterns of susceptible forest that were traversable for all three burn probabilities. For fire sizes of 1000, 10 000, and 100 000 ha, in many cases traversability changed to non-traversability as the bounding value of susceptibility was increased and/or the maximum dispersal distance decreased. Large, infrequent fires tended to yield a landscape that MPB cannot easily traverse; fires of maximum size (1 000 000 ha) formed a continually changing distribution of forest ages, so that equilibrium was never even approached for fires of that

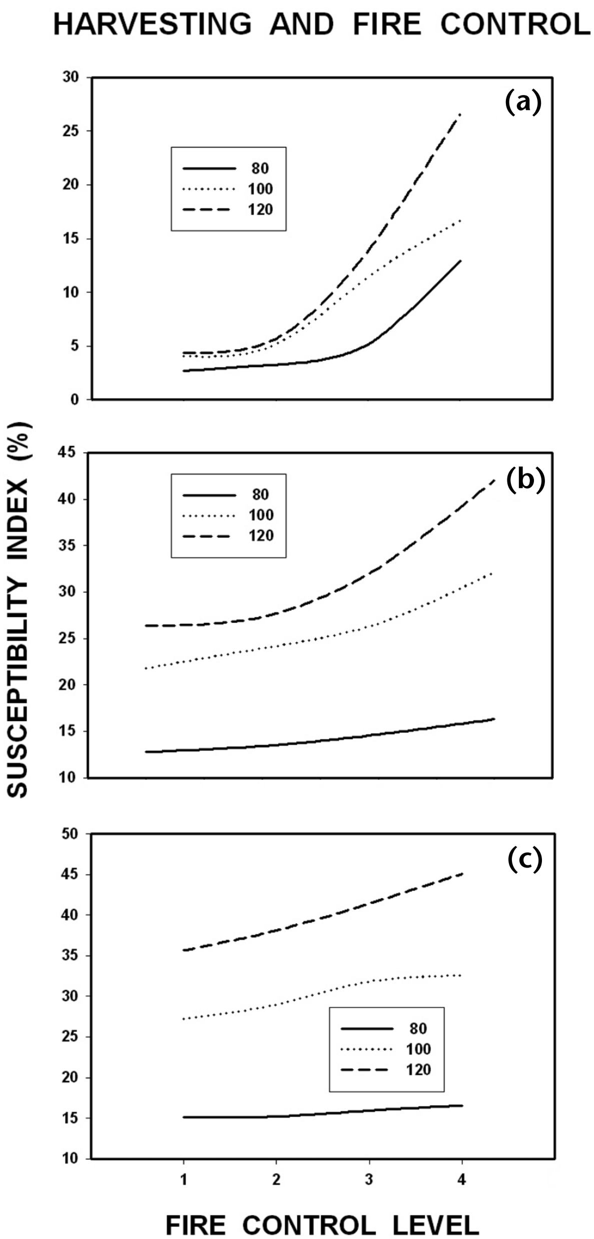

FIGURE 2. Effects on susceptibility of fire control for three levels of burn probabilities: (a) 0.05, (b) 0.01, and (c) 0.004, and three ages at harvest (80, 100, and 120 years). Horizontally, 1 = no fire control, 2 = 50% fire control, 3 = 80% fire control, and 4 = 95% fire control.

size and the landscape was non-traversable. Thus, in theory, mimicking the effects of large fires by harvesting and replanting in large blocks would create a landscape that minimizes traversability, and thus dispersal, of an incipient beetle population.

Harvesting and fire control interacted to yield a minimum value of traversability when fire control was about 80%. Therefore, analysis of the simulation results showed that the best combination to reduce traversability was early harvest with intermediate fire suppression.

The concept of traversability is applicable mainly to endemic and incipient beetle populations—during an outbreak, understanding of short-distance dispersal fails to adequately describe patterns of spread. In long-distance dispersal, the beetles often travel dozens or even hundreds of kilometres before dropping to earth again. Once an outbreak is in progress, beetles may drift on the wind above the forest canopy to start spot infestations at considerable distances from the source (L. Safranyik, Canadian Forest Service, pers. comm., May 2007).

We also applied the concept of traversability to the whole province by assessing the letter blocks of the British Columbia Geographic System of Mapping (BCGS). The letter blocks are on average slightly over 1 000 000 ha, and thus similar in size to the simulated mosaics. We calculated susceptibility for the whole province using inventory data obtained from the BC Ministry of Forests and Range at a resolution of 400 × 400 m, and a digital elevation map. Figure 3 shows susceptibility and traversability calculated for British Columbia. The inventory maps we used were for the year 2000, and both susceptibility and the measured traversability correlate well with the observed beetle outbreak. The information in the 2000 map is already out of date as a result of increased numbers of beetle-killed stands, but our methods used with subsequent inventories following the collapse of the present infestation could lay the foundation for predicting the likelihood of future outbreaks.

The fires in the simulation were all approximately square. This is most apparent in the largest fires and may affect their traversability values, although probably not greatly. For small fires, the resulting age classes were agglomerations of ages and tended to be very irregular, resembling fires in the wild. In addition, the simulation assumed randomness of fire starts and spread; in reality, fires are affected by weather, topography, and even species mix, so that exact predictions are not to be expected. In addition, fire suppression works better in low fire years than in extreme fire years, so again exact prediction is not expected; trends, however, are mostly expected to be realistic.

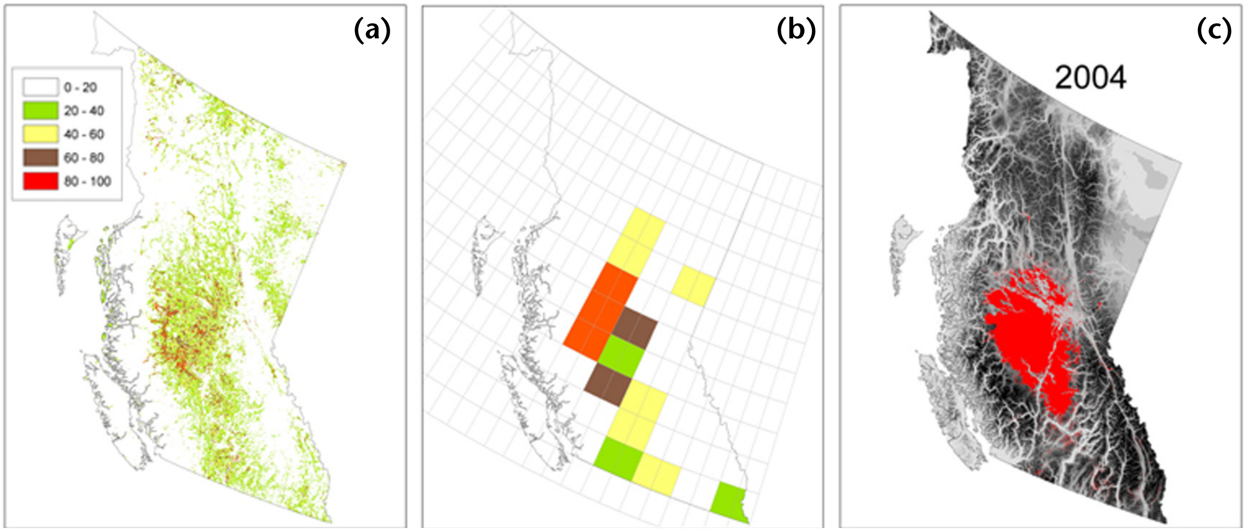

FIGURE 3. Mean susceptibility (a) and traversability (b) for the province of British Columbia, calculated over four susceptibility boundaries (20, 40, 60, and 80%) and the five maximum dispersal distances (1, 2, 3, 4, and 5 km). Each polygon in the grid is one letter block in the British Columbia Geographic System of Mapping. Also shown (c) is the state of the current infestation in 2004. Source: Barclay et al. 2005, reprinted with permission.

Due to harvesting only one age class, a certain amount of variability of harvest volume is expected in the simulation. In reality, mills and governments will attempt to keep harvest more stable over time. This would likely have little effect on the results of the simulation, however, as the variations would simply either leave some of the target age class standing, or cut some of the preceding age class, and the variations would tend to even out the simulation results in the long run.

Historical perspective: British Columbia

Over the past century, the number of fires in British Columbia has decreased and the area attacked by MPB has increased. Mean areas burned by fire declined for each decade of the 20th century except the first, and mean areas attacked by MPB increased with successive outbreaks (Barclay et al. 2005). It is worth noting that the area attacked by MPB since 2000 has been much higher than in the 1980s, and the present infestation is the largest on record.

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Fire control was begun about a century ago, intensifying and becoming more efficient with the advent of airborne water tankers about 50 years ago (Taylor et al. 2006). However, pine was not extensively harvested until about the early 1960s (Taylor and Carroll 2004). These factors have allowed aging of the forest and have contributed to a consequent increase in mean susceptibility to MPB attack (Taylor and Carroll 2004). In the long term, strategies to save more timber for harvesting might involve either planting species other than pine, where possible, or harvesting at an earlier age. Neither of these would be totally satisfactory. An alternative strategy would be to plant other species as well as lodgepole pine in mosaics such that the spatial arrangement would minimize the probability of both fire and attack by MPB.

Conclusions and management implications

To gain an understanding of the interactions amongst natural disturbance regimes, harvesting patterns, and forest management practices to inform MPB management in British Columbia, this study has characterized the province's forests in terms of two properties: (1) stand-level susceptibility, and (2) landscape-level traversability. Fire control and longer harvest rotations or preferential harvesting of non-pine stands (effectively lengthening harvest rotation) are important factors in creating older forest stands, which are more susceptible to MPB. Yet, essential for long-range beetle dispersal is the forest landscape property of traversability. Traversability describes the potential for beetles to disperse across a landscape, and is maximized by small-scale, frequent, stand-replacing disturbances, such as small and frequent fires.

The major conclusions and management implications based on this study's simulation results are that:

- Both long fire cycles and fire suppression yield an older age-class structure that is highly susceptible to beetle attack.
- In the long term, harvesting considerably reduces the mean susceptibility of the forest to beetle attack, and also reduces traversability—this is especially true of harvesting younger age classes (i.e., 80 years) to yield shorter rotations, although early harvest may result in timber supply shortfalls.
- The occurrence of many small fires yields a landscape susceptible to widespread and sustained beetle dispersal, as the distances that must be travelled over inhospitable habitat are all within the beetles' short-distance dispersal capabilities.
- The combination of early harvesting and moderate fire suppression yields a long-term forest structure that minimizes both susceptibility and traversability for MPB.
- Large fires reduce traversability by widely separating susceptible forest patches. To emulate this, replanting should be done so that adjacent blocks are of widely differing ages and, if possible, different species.

The current MPB outbreak poses a significant challenge to our understanding of British Columbia's forest landscapes. It is clear, though, that in order to address the current outbreak and the potential for future outbreaks, scientific analyses and forest management approaches that synthesize our understanding of beetle biology, and of stand- and landscape-level forest characteristics, are needed. A synergistic understanding of the causes of the MPB spread is essential for the development of strategies that will ensure the sustainable management of the forest landscapes of British Columbia.

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The combination of early harvesting and moderate fire suppression yields a long-term forest structure that minimizes both susceptibility and traversability for MPB.

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Test Your Knowledge . . .

Effects of fire return rates on traversability of lodgepole pine forests for mountain pine beetle: Implications for sustainable forest management

How well can you recall some of the main messages in the preceding Extension Note?
Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. What are the effects of random fires on the distribution of age classes in a forest in which the main source of mortality is due to many small fires?
   A) The distribution becomes noticeably truncated
   B) The frequencies of all the age classes become about equal
   C) The age distribution approaches the exponential distribution
   D) The age distribution becomes unpredictable

2. Which combination of harvesting and fire control will result in a forest that is highly susceptible to attack by the mountain pine beetle?
   A) Early harvest and intensive fire control
   B) Late harvest and intensive fire control
   C) Late harvest and no fire control
   D) No harvest and no fire control

3. How should a forest be regenerated following destruction by fire or mountain pine beetle in order to minimize the susceptibility and traversability for mountain pine beetles?
   A) It should be naturally regenerated
   B) It should immediately be planted with one species of pine throughout
   C) It should be planted with only spruce
   D) It should be regenerated in blocks of different ages and, where possible, different species

ANSWERS

1. C 2. B 3. D