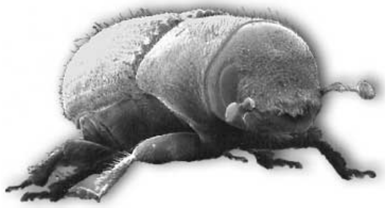

INCORPORATING CLIMATE INFORMATION INTO MANAGEMENT STRATEGIES FOR THE MOUNTAIN PINE BEETLE IN CENTRAL BRITISH COLUMBIA, CANADA

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EXECUTIVE SUMMARY

The mountain pine beetle (*Dendroctonus ponderosae*) epidemic that BC's central forests are currently experiencing has the potential to disrupt the economies of the many resource-based towns throughout the region. Current management practices do not incorporate climate information into planning, in spite of the significant impacts that climate variability has on operational constraints and the beetle population dynamics. Aggressive harvesting of infested timber is intended to mitigate economic losses and reduce the rate of beetle spread, but is proving to be of limited utility in both of these regards: salvage timber is producing a surplus, and therefore reducing the market price; the bluestain fungus associated with the beetle reduces the quality of the wood depreciating the revenue further. In this report I review the ecology of the mountain pine beetle in the context of both its natural environment (i.e. lodgepole pine forests) and its socioeconomic environment (i.e. within the logging sector of British Columbia). I identify two key regions where good quality climate forecasts could improve management effectiveness:

1. Accurate seasonal forecasts of summer conditions would allow managers to allocate resources into sanitation or salvage logging, depending on the expected seasonal synchrony of beetle popluations. In the event that cool summers are expected many of the operational requirements of timber transport, outbreak mapping and planning are not possible due to the extended beetle flight season. Hot dry summers are favorable for beetle dispersal and successful attack, but synchronize the beetle's life cycle with the seasonal cycle, leaving ample opportunity for sanitation logging.
2. Because beetle outbreaks are ended by severe cold weather outbreaks even moderately skillful predictions would improve management decision-making. In the event that high beetle mortality rates are expected forest managers will not need to invest energy in beetle control. Because beetle control operations are much more expensive than conventional

logging operations, and because they often contribute to a market surplus of low quality timber, the opportunity to return to conventional logging would have substantial economic benefits for forestry communities.

Strategy (1) is operationally difficult, due to poor understanding of summertime climate processes. Strategy (2) could likely be applied in the very near future, due to improved seasonal forecasting models and robust links that are believed to exist between severe cold weather and modes of climate variability – in particular El Niño (ENSO), the Pacific Interdecadal Oscillation (PDO) and the Northern Hemisphere Annular Mode (NAM).

Global climate change will likely contribute to more persistent beetle outbreaks, and could potentially cause the beetle's range to expand into eastern and high elevation pine forests. Because the severe cold events that end beetle outbreaks are expected to occur less frequently in the future, management agencies need to focus efforts on "beetle proofing" lodgepole pine stands. Given the long rotation length of lodgepole pine (ca. 60 years), appropriate management needs to be initiated soon. Stand resilience can be increased by managing for younger, less dense stands composed of mixed species, and by incorporating a more natural fire regime in these forests.

OVERVIEW

The mountain pine beetle (*Dendroctonus ponderosae*) is a forest pest species that attacks all commercially grown species of pine (*Pinus* spp.) in British Columbia. As a damaging agent it is second only to fire in the number of trees affected annually. It occurs throughout British Columbia (south of 56°N), from sea level to the maximum elevation at which pine can survive. Mountain pine beetle outbreaks occur when food and habitat opportunities are abundant, and climatic conditions are favorable for reproduction. Outbreaks generally last 8 to 10 years, but British Columbia is currently experiencing an infestation of a magnitude not previously seen. As of 2001 an estimated 8 million hectares of lodgepole pine forest were under attack by the mountain pine beetle, affecting a total of 900 million cubic meters of lodgepole pine timber. This extent represents approximately 17 percent of the provincial working forest. One theory suggests that this outbreak has been preconditioned by several decades of effective fire suppression. The consequent stand density and size distribution provide ample food and habitat for the beetles. Furthermore, either global warming or natural variability may be contributing to a favorable climate. The mountain pine beetle exists in a symbiotic relationship with a bluestain fungus (*Ceratocystis* spp.) that suppresses the defense mechanisms of attacked trees, and reduces the value of the attacked tree as timber. Efforts to control the current outbreak by aggressively logging infested stands have been largely unsuccessful, but have resulted in unsustainable harvest levels, lower quality wood products, and reduced revenue from timber sales. Accurate seasonal forecasting of severe cold outbreaks would assist management efforts by providing improved forecasts of beetle mortality rates. If forecasts predict high beetle mortality due to climate variability then logging operations do not need to concentrate on beetle suppression activities and can target more valuable timber. Harvest levels can also be reduced to match the long-term sustainable harvest level.

BIOLOGICAL CONTEXT

The mountain pine beetle range is closely linked to the distribution of its host species – primarily lodgepole pine (*Pinus contorta*) and ponderosa pine (*P. ponderosae*), although lodgepole pine exists at higher latitudes than mountain pine beetle and ponderosa pine at lower latitudes (Figure 1). The mountain pine beetle lifecycle is composed of four distinct developmental stages that are normally completed within a single year: adult, egg, larva and pupa. Adult beetles emerge in mid summer, and attack potential host trees – usually in close proximity to their birth site, but a small number of "pioneer" beetles will travel much greater distances to find suitable habitat. Beetles tend to disperse downwind, and most flight occurs on warm, rain-free days. Attacked trees defend against beetle infestation by excreting large amounts of resin to "pitch out" attacking beetles, however beetle attack occurs at a time when the trees are experiencing maximum moisture stress, limiting their ability to respond effectively. Additionally, attacking beetles emit an aggregating pheromone that attracts other beetles to the tree in an effort to overwhelm the tree's defenses. Lastly, the beetles also carry a bluestain fungus that suppresses resin production by host trees, making them more vulnerable to beetle attack. Following a successful attack beetles establish galleries underneath the bark and lay eggs. The eggs hatch in 10-14 days, and the larva feed on the phloem of the tree – ultimately girdling the tree and killing it. As winter sets in the larvae fill their bloodstream with glycerol, allowing them to tolerate body temperatures as low as -37°C. Larval development is completed in early summer the following year. Following a short pupation period adult beetles emerge to attack new trees, restarting the cycle. The beetles have a number of natural predators, of which woodpeckers are the most important. However there are no organisms that feed exclusively on the mountain pine beetle, and none of the predators is sufficiently abundant to significantly affect beetle population size.

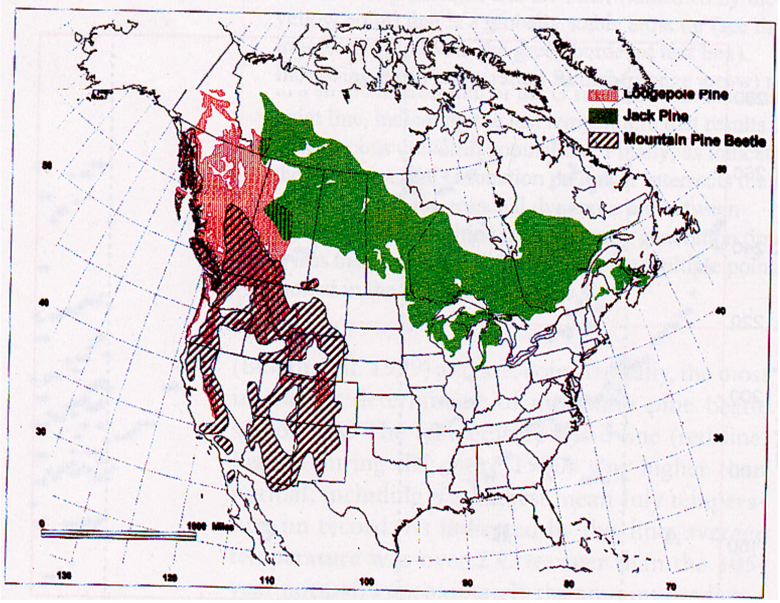

Figure 1. The natural distributions of mountain pine beetle (hashed region), lodgepole pine (red) and jack pine (green). In the southern portion of its range ponderosa pine (distribution not shown) is a more important host than in British Columbia. (From Logan and Powell 2001)

Although beetle infestations are generally lethal to the host trees, the mountain pine beetle may represent a necessary component of lodgepole pine ecology. Lodgepole pine stands are maintained by episodic stand replacing disturbances – primarily high-intensity fire – that kill shade tolerant species that would otherwise gain a competitive advantage. Indeed, many lodgepole pine individuals produce serotinous cones – which require fire to release the seeds inside. Beetles contribute to this cycle by killing large numbers of individuals, thereby increasing the fuel load and flammability of the landscape. Downed branches and stems are highly flammable and will carry fire readily. Standing dead trees act as ladder fuels, conducting fire into the canopy and generally increasing the severity of wildfire.

The susceptibility of lodgepole pine stands to beetle infestation is dependent in part on the stand conditions at the time of attack. Lodgepole pine individuals are most resilient to attack at ca. 60 years old. They become increasingly prone as they get older, and by 80 to 100 years old very few trees are resistant to the beetle attack. Stand density also affects their ability to defend against beetle attack. More dense stands generally experience greater competitive stress, leading to reduced defensive capacity. Also, the lower light levels and more buffered microclimate typical of dense stands improve beetle survival rates during extreme cold events.

SOCIAL CONTEXT & CURRENT MANAGEMENT PRACTICES

Lodgepole pine is the most important commercial timber species in central British Columbia, accounting for 24 percent of the province's total growing stock and half of the growing stock in the central and interior regions of the province. An estimated 45 000 jobs are maintained through the harvest of pine in central British Columbia. Because the mountain pine beetle kills its host trees and reduces the value of salvaged timber there is considerable political pressure to control outbreaks. The BC government has responded to the current epidemic by issuing a *Mountain Pine Beetle Action Plan*, declaring war on the insect and proposing a coordinated program of action. There are several important limitations to management actions, including operational and geographic constraints as well as legal requirements.

Efforts to control beetle outbreaks typically employ one of four methods of suppression, depending on the location and size of the infested patch: (1) when the outbreak is small (one or several trees) individual brood trees may be falled and burned. (2) Similarly, monosodium methanearsonate (MSMA; a herbicide with insecticidal properties) may be injected into individual affected trees. This strategy can only be applied during a two to three week window during the larval life stage of the beetle. Strategies (1) and (2) are effective only in very small patches, and are most commonly used when it is impractical to transport the timber offsite for milling. (3) Small patches may be baited with pheromone traps and harvested as a block. Special care needs to be taken when transporting and milling this timber, since beetles may be inadvertently dispersed along transportation lines and near mills. (4) Clear-cut harvesting is used when large areas are affected. The management objective in these cases may be sanitation (where the goal is to remove the beetles from the site) or salvage (where the goal is to mitigate economic losses). Of these methods, (4) is the most important since it affects the greatest volume of timber and involves the greatest economic investment. In all cases, harvest efforts are diverted from non-infested stands so that where possible the annual allowable cut is not increased due to the control and salvage operations. Over the last several years, however, the chief forester of BC has approved increases to the annual allowable cut to meet the demands of beetle management – to the extent that beetle management operations now account for 98 percent of the long-term harvest levels.

There are several important consequences of the current management practices: (1) increases to the annual allowable cut create a false economy that attracts forest workers to regions with large beetle outbreaks. Mill operations expand to process the increased volume of wood. When the epidemic ends these mills are forced to close and jobs are lost. Furthermore, present-day increases to the annual allowable cut will need to be offset by future reductions; otherwise the growing stock will gradually decline. (2) The excess volume of timber on the market drives the price of pine down, leading to reduced revenue from timber sales. (3) The bluestain fungus reduces the market value of the wood. The Japanese market in particular accounts for 10 percent of all pine exports from BC and will not buy wood that is stained.

Beetle management efforts are limited by several considerations: (1) operational difficulties in identifying attacked trees. While it is easy to spot trees that were attacked the previous year (these are the distinct red trees that are evident throughout the province) newly attacked trees appear healthy from a distance. It is usually necessary to do a ground survey to identify attacks.

(2) The *Forest Practices Code* allows only moderate increases to the annual allowable cut and to individual cutblock size for beetle control purposes. It does not allow even sanitation logging within riparian areas, old growth areas, wildlife tree patches and wildlife habitat areas. (3) Tree removal is strictly forbidden for any reason within National and Provincial Parks, although prescribed burning may be used where fire is a naturally occurring ecological process. (4) Many areas of the province are simply too remote to manage beetles effectively. The road infrastructure that would be required to access infested stands would be too costly and would take too long to construct to use harvesting as an effective beetle control measure at many locations.

INCORPORATING CLIMATE INFORMATION: NEAR-TERM SOLUTIONS

Current control efforts are predicated on the assumptions that climate is unpredictable and that natural processes will not end a given outbreak. There are two primary management activities that could benefit from climate information: (1) beetle dispersal models assume that the timing and distance beetles will fly to find new hosts fits a non-varying distribution; and (2) winter mortality is assumed to be negligible. Both of the sets of processes involved in these activities (both biological and climatic) are largely independent of each other, and so present distinct opportunities to adapt management activities.

The summertime dispersal range of adult beetles determines the rate of spread of a beetle outbreak. For example, the current outbreak was instigated in part by hot, dry summers in 1997 and 1998 that allowed the beetles to disperse over very long distances – giving them a significant foothold and precipitating the dramatic population explosion that has followed. Hot, dry summer weather compounds the beetle problem by leaving lodgepole pine stands drought stressed and therefore more susceptible to successful attack. Interestingly, the switch to cool, wet summers over the last three years has not made management of the beetle any easier. While conditions have reduced the rate at which the beetles spread, the weather has also interrupted the seasonal synchrony of the beetle's life cycle. A consequence of this change is that beetles now fly throughout summer, with different populations synchronized differently. At endemic levels this disruption to the beetle life cycle, coupled with the relative abundance of available water, would likely increase tree resistance and reduce larvae survival. However the sheer number of beetles now flying ensures that successful attacks continue to occur. Furthermore, the late termination date of beetle flight delays the field work necessary to map out new attack areas, develop operational plans and, in particular, complete sanitation logging.

Accurate or even improved summer climate forecasts could benefit beetle management activities by allowing managers to allocate resources more efficiently. Hot, dry summers contribute to the rapid spread of beetles, but they also synchronize the beetle's lifecycle to the seasonal cycle. In these summers it is safe to remove timber in early- and late-summer – when adults are not emerging. In these conditions large-scale sanitation logging is advisable since it is safe, recovers timber value, and is at least nominally effective in reducing beetle population growth. In contrast, when summer conditions are wet the seasonal synchrony is lost but the rate of spread is slowed substantially. In these conditions it would be beneficial to target the small patch and individual brood trees. Since dispersal will generally be relatively local, efforts to control smaller population centers will be on average more effective than during years with longer-range dispersal. Because timber is not normally removed in these operations (trees are normally burned on site or treated with MSMA) there is less risk of inadvertent spread of beetles during transport. Harvest operations should target salvage wood – trees that have been abandoned by beetles but have not lost all commercial value to the bluestain fungus.

The greatest limitation to making use of climate information in this manner is the generally poor predictability of summer climate. Summertime variability does not appear to be strongly linked to the dominant modes of ocean-atmosphere variability (e.g. PDO, ENSO, NAM), and the mechanisms that lead to variability are consequently poorly understood. Furthermore, the majority of research efforts are focused on wintertime climate – suggesting that improved summer forecast models will not be available in the near future.

In contrast to this pessimistic assessment, there are substantial opportunities to incorporate winter forecasts into beetle management strategies. Beetle outbreaks end when one of three climatic conditions cause substantially increased mortality rates:

1. Severe cold outbreaks that occur outside of the main winter months (Figure 2).
2. Sustained winter temperatures below -40°C.
3. Mid-winter warm intervals (minimum temperatures above +5°C) followed by sudden cold outbreaks (maximum temperatures below -20°C).

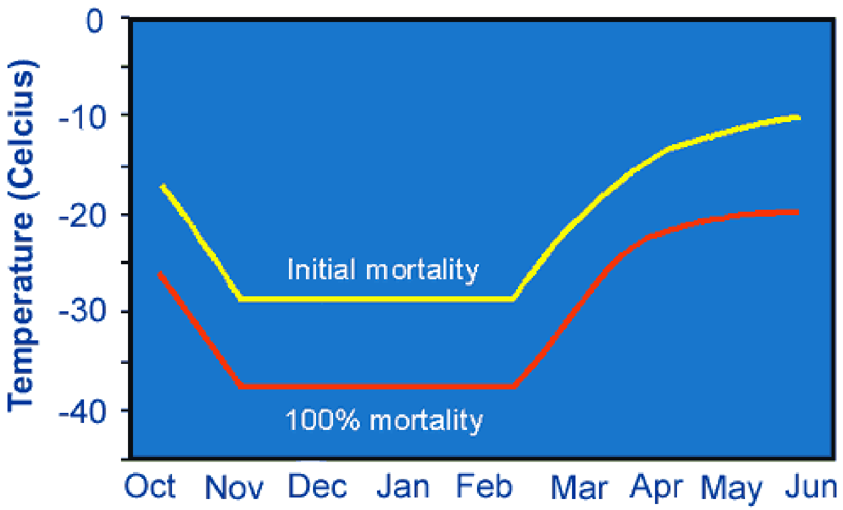

Figure 2. Average beetle mortality thresholds as a function of season. The upper line indicates the minimum temperature at which beetle larvae begin to die. When under bark temperatures reach the threshold indicated by the lower line 100 percent mortality occurs. (from Canadian Forest Service, Natural Resources Canada)

Under current management practices these climatic events are considered stochastic and unreliable. That is, beetle control is undertaken on the assumption that climatic conditions will remain favorable for continued beetle outbreak. A consequence of this practice is that timber is on average more expensive to extract: longer road networks are often necessary to access remote outbreak locations; harvest units are often reduced in size in order to maximize the number of beetle sites that can be targeted without increasing the volume of timber harvested; more specialists and more expensive equipment (esp. helicopters) are needed to undertake small scale sanitation logging. These approaches are all intended to kill beetles in an effort to slow the rate of spread. In the event that severe cold outbreaks are predictable, though, nearly all of these efforts become extraneous in years when beetle mortality is expected to be high. In these cases human intervention would simply duplicate what nature will take care of itself. By letting climate take care of beetle management in these years, timber harvest operations can focus on more economically valuable and cost efficient harvest operations. Additionally, there will not be pressure to increase the annual allowable cut above sustainable levels, which will reduce the market glut, increasing the expected revenue from the timber that is cut. Lastly, this approach makes more ecological sense as it leaves a greater diversity of patch-types on the landscape while still extracting the same volume of timber.

Recent statistical analyses by Mike Wallace and others have suggested that severe winter cold outbreaks are related to the dominant modes of wintertime variability: notably the Pacific North America pattern and the Northern Hemisphere Annular Mode. These patterns are in turn linked to processes that contain some intrinsic predictability, in particular ENSO and the PDO. Because these severe cold outbreaks occur very rarely, and the economic costs of beetle management are substantially higher than conventional forest practices, climate forecasts do not need to be especially skillful before they will provide tangible economic returns in cost-benefit analyses.

The consequences of acting on climate forecasts that turn out to be incorrect are minimal, making this proposed course of action particularly beneficial. There are four possible scenarios to consider:

1. *A cool, wet summer is forecast but conditions turn out to be warm and dry*. In this scenario managers would have allocated resources to small patch sanitation and salvage logging, and away from large patch sanitation. Given the relative ineffectiveness of large-scale sanitation operations the effect of an incorrect forecast on beetle population size would probably be very small. The economic losses to timber degradation would be slightly higher than under the current strategy, which focuses on large-scale sanitation in all years. Revising harvesting schedules in early summer, when the continuing warm, dry weather makes it clear that beetle reproduction will be synchronized to the seasonal cycle, could offset some of these losses. Salvage logging usually takes place adjacent to active populations, so equipment and people would not need to be moved very far to adjust to the changed forecast. The *Forest Practices Code* has a framework for making very rapid changes to management and working plans for the purposes of beetle management, that would facilitate this procedure.
2. *A hot, dry summer is forecast but conditions turn out to be cool and wet*. Current management practices assume hot dry summers. An incorrect forecast would therefore be no worse than the current practice.
3. *A lethal cold outbreak is forecast but none occurs*. In this scenario harvest operations would be directed towards non-infested timber under the assumption that climate variability would kill large numbers of beetles. Economic losses would occur due to increased losses to beetle and timber degradation. However these losses would not be incurred immediately, but rather passed on to future years in the form of reduced growing stock and an increased proportion of lower quality timber. Indeed, revenue in the year of the incorrect forecast would be

increased due to the higher quality and lower volume of timber harvested. Because the benefits of a correct forecast are realized immediately, but the costs are spread-out over many years conventional accounting procedures "discount" the costs relative to the benefits. Additionally, the burden of incorrect forecasts is spread out over a long time span, making them less damaging.

4. *A lethal cold outbreak occurs when none is forecast*. Current management practices assume that outbreaks will continue. An incorrect forecast would therefore be no worse than the current practice.

INCORPORATING CLIMATE INFORMATION: LONG-TERM SOLUTIONS

The prospect of global climate change over the next several decades has important implications for beetle management in British Columbia. Every credible general circulation model predicts warming for the region, with most models agreeing that the greatest changes will be increases in winter minimum temperatures. Additionally, many of the models predict reduced summer precipitation – leading to increased moisture stress among western forests. While these models do not resolve patterns of variability it does not seem unreasonable to assume that under a climate that is warmer on average the cold outbreaks will also be less severe on average. This scenario implies that beetle outbreaks will typically last longer, and beetle populations will gain access to higher elevation and more northerly forests. This second consideration has some unexpected repercussions, that could have devastating ecological effects: (1) access to higher elevation forests will bring beetles into contact with pine stands that are not ecologically adapted to beetle infestation in the way that lodgepole pine stands are; and (2) access to more northerly pine stands will bring them into contact with a contiguous jack pine forest that has not been exposed to mountain pine beetles at all over their evolutionary history.

In central British Columbia high-elevation forests often contain a significant proportion of whitebark pine (*Pinus albicaulis*) that is separated from the low elevation stands of lodgepole pine by a band of Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*). Laboratory studies have shown that whitebark pine could provide a suitable host for mountain pine beetles, however the current climate is almost invariably too harsh for the beetles to survive. Unlike lodgepole pine, the high elevation pine stands have not co-evolved with mountain pine beetle, and they are not well adapted to episodic disturbance. Mountain pine beetle outbreaks in these forests would be an ecological disaster (from the perspective of a whitebark pine community). Assuming an elevational separation of 1000 m between lodgepole pine and whitebark pine climate would need to warm by an average of at least 6°C to have a significant impact on most whitebark pine communities. This figure is at the upper end of IPCC predictions, and so the potential for mountain pine beetle invasion into these ecosystems cannot be ignored.

Of greater concern is the possibility that mountain pine beetle range expansion will bring them into contact with the distribution of jack pine (*Pinus banksiana*) (see Figure 1). A substantial portion of the jack pine distribution is climatically suitable for mountain pine beetle habitat even without accounting for global climate change. Wide regions without suitable habitat currently prevent beetles from expanding into these forests. Where lodgepole pine and jack pine distributions do overlap, current climate conditions limit beetle survival. A northward expansion of the mountain pine beetle's range, though, would provide access to these eastern forests and would allow the beetle to expand rapidly into jack pine forests. This invasion could have a devastating effect on the ecology of these forests, since they have not co-evolved with the beetles.

The scenarios considered here all imply that climate change will lead to significant expansion of the mountain pine beetle range, and more frequent beetle outbreaks. A consequence of this finding is that the short-term approaches to beetle management that are currently employed by forest managers are unlikely to be successful in the long-run due to their reliance on climate variability to end outbreaks. Assuming that high beetle mortality events will become less frequent in the future it makes sense to shift beetle management energy away from mitigation and into prevention. Current objectives are to mitigate losses until a severe cold outbreak ends the outbreak. If climate variability is unlikely to end an outbreak then this solution cannot succeed. A long-term program of "beetle proofing" forests is more likely to be effective under climate change scenarios.

Several "beetle proofing" strategies have been suggested already: managing for relatively young stands (such as would be expected over most of the landscape where fire is a frequent disturbance agent); managing for lower stand density; and managing for a greater mix of species, including hardwoods and other non-commercial species. These approaches are intended to increase tree vigor, thereby increasing trees' natural defenses against beetle attack. They also increase the landscape patchiness and decrease the density of suitable host trees. Experimental studies have shown that these factors reduce the effectiveness of beetle aggregation, which also increases tree survival rates.

CONCLUSIONS

The current beetle management practices are expensive, ineffective and unsustainable. By incorporating even moderately skillful forecasts into beetle management strategies managers could increase timber revenues without sacrificing growing stock substantially. Additionally, more efficient allocation of resources would allow increases in beetle control efforts per dollar invested. These advances in beetle management are dependent on a climate forecast that is not currently available commercially or academically, but which will likely be available in the near future. Climate change scenarios imply that mountain pine beetle outbreaks will be more persistent and more ecologically damaging in the future. Management agencies need to shift their focus from managing beetles to managing forests if they hope to mitigate potential losses. Given the long rotation length of lodgepole pine (ca. 60 years) silvicultural practices will need to be altered sooner rather than later.

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