

# A Dynamic Bioeconomic Analysis of Mountain Pine Beetle Epidemics

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Abstract: In this paper we develop a bioeconomic model of timber harvesting that includes dynamic interactions between mountain pine beetle (MPB) and a lodgepole pine forest with a disaggregated size structure. The model is used to investigate the consequences of alternative public management strategies on forest dynamics in the presence of MPB outbreaks. Management practices similar to those commonly practiced are shown to increase the severity of MPB cycles. Centrally coordinated forest management can eliminate MPB cycles and lessen the impacts of MPB outbreaks with only small reductions in the long-run stock of adult trees.

JEL Codes: Q57, Q23, C61

Keywords: mountain pine beetle; cycles; stock externality

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## Introduction

The mountain pine beetle (MPB) is a native species of the Rocky Mountain ecosystem. Historically, endemic levels of bark beetles have performed an important ecosystem service by removing older and less vigorous trees from the forest, causing two to five percent mortality per year.<sup>2</sup> However, MPB populations periodically surge to epidemic levels, threatening to kill vast tracts of western forests.<sup>3</sup> Recent aerial surveys show that the current MPB epidemic now covers more than 4.5 million acres in the western United States; larger in size and severity than any previous recorded outbreak. In Canada the MPB epidemic is even greater, covering more than 33 million acres, an order of magnitude larger than any previous recorded MPB infestation (Fountain 2008).

The adverse impacts of pine beetle epidemics to the timber and recreation industries are well documented (Holmes 1991; Samman and Logan 2000; Patriquin et al. 2007; Phillips et al. 2007). Projections for the current epidemic include a \$2.5 billion decrease in manufacturing activity, a loss of 27,000 direct jobs, and a loss of \$250 million in government stumpage and royalty revenues in British Columbia alone (Abbott et al. 2008).<sup>4</sup> However, MPB epidemics have less obvious impacts as well. Recent research shows that these outbreaks are occurring in new habitats that will disrupt established ecosystems (Logan et al. 2003). In addition, the current MPB epidemic may be contributing to global warming as the boreal forests of Canada have now been converted from a carbon sink to a carbon source (Kurz et al. 2008).

In order for endemic MPB populations to transition to a landscape-level outbreak, two requirements must be satisfied. First, there must be a sustained period of favorable weather over

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<sup>2</sup> See Amman and Cole (1983) and Samman and Logan (2000) for an extensive treatment of MPB biology.

<sup>3</sup> In the northern Rocky Mountains, MPB outbreaks have been reported with some regularity since the early 1900s. Forest insect survey records indicate four to five significant outbreaks in western North America over the last century (Taylor and Carroll 2004).

<sup>4</sup> These estimates are based on a 25% reduction in available wood fiber.

several years (Safranyik 1978). Winter temperatures influence MPB populations directly through survival while drought indirectly impacts populations by lowering host-tree resistance (Carroll et al. 2004). Second, there must be an abundance of susceptible host trees (Safranyik 1978; Raffa 2008). Dense stands of susceptible host trees combined with a homogenous forest structure increase the risk of landscape-level MPB epidemics (Safranyik and Carroll 2006). Conventional wisdom appears to implicate climate change and a recent sequence of abnormally warm years as the root of the current epidemic (Berg et al. 2006; Logan and Powell 2009). Here, we augment previous research by investigating the role of forest management policies in contributing to MPB epidemics using predator-prey type interactions between MPB and a lodgepole pine forest.

The geographic range of the MPB stretches from New Mexico to California and north into British Columbia. The vast majority of MPB forest habitat in the U.S. is public land administered by the Forest Service for timber and non-timber benefits. However, according to U.S. Forest Service Manual (FSM) section 2404.21, specific forest management decisions (such as harvesting intensity and timing) are often made at the regional, forest or district forest level (USFS 2004).<sup>5</sup> In the U.S., the geographic range of MPB covers six Forest Service regions, 92 national forests, and 336 forest districts. In other words, approximately 434 Forest Service officials possess the authority to initiate harvesting activities throughout the range of MPB in the U.S. alone. In British Columbia, the provincial government oversees the management of public forest lands but delegates most operational management decisions to numerous holders of resource tenures (BCMOFR 2006).

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<sup>5</sup> The maximum level of approved authority for timber sales depends on the level of management. For instance, district rangers possess the authority to initiate commercial timber sales up to 5,000 hundred cubic feet (CCF), forest supervisors up to 50,000 CCF, and regional foresters up to 100,000 CCF (USFS 2004). In addition, each official can appeal up the chain of command to have a timber contract modified or canceled.

An important drawback of localized forest management is that decision makers may ignore the endogenous nature of aggregate MPB risk. An individual forest manager may be capable of exerting a small amount of influence on local MPB populations through silvicultural practices.<sup>6</sup> However, migration from neighboring forest stands limits the ability of local managers to fully control the MPB population and the risk they face.<sup>7</sup> An individual manager has little influence on the landscape-level forest structure which dictates the ability of localized populations of MPB to cause large-scale outbreaks (Raffa 2008). This conjecture is supported by evidence suggesting that localized management is likely ineffective during a mountain pine beetle outbreak (Amman et al. 1988; Preisler and Mitchell 1993). In this way, MPB should be regarded as a common property resource creating a negative stock externality (Smith 1969). Unless all local managers agree to control the MPB populations simultaneously, the stock externality will decrease the incentive for local forest managers to engage in preventative harvesting to control MPB, leading to elevated MPB populations. When management is more centralized and the forest manager acknowledges the endogenous nature of MPB risk, their decisions are able to lessen the risk of future MPB epidemics.

To investigate the consequences of public management strategies on forest and MPB dynamics, we develop a bioeconomic model of timber harvesting which incorporates forest mortality through specification of predator-prey interactions between MPB and a lodgepole pine forest. Given the quasi-public good nature of national forests in the United States and Canada,

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<sup>6</sup> Previous silvicultural research suggests that partial harvests, shorter rotations, and multiple age classes can minimize the amount of MPB-induced mortality in non-outbreak conditions (Cahill 1978; Whitehead et al. 2004). Such prescriptions are based on empirical evidence indicating that higher tree diameter and stand age will increase the likelihood of MPB attack (Amman et al. 1977).

<sup>7</sup> Dispersal from neighboring forest stands can cause MPB populations to grow much larger than local forest conditions would allow. Natural beetle dispersal can cover several kilometers and is largely dependent on host tree availability, wind patterns, and weather conditions during the dispersal period at the end of the summer (Safranyik et al. 1992; Heavilin and Powell 2008). Human-mediated dispersal (such as in cut wood) can cover much farther distances.

management decisions are made to maximize household utility for timber and non-timber benefits. The model is simulated over a 200-year planning horizon to compare three alternative management strategies: 1) baseline passive management without timber harvesting; 2) localized management in which forest managers treat MPB risk as exogenous; and 3) centralized forest management in which managers optimally recognize the endogenous nature of MPB risk. We find that passive and localized management increase the risk and severity of MPB epidemics, and exacerbate associated future echo effects. By considering the effects of forest management on MPB risk, the optimal choices of a central forest manager substantially reduce the size of epidemics and largely eliminate future echo effects. Because localized forest management may be beneficial in many respects not considered in the present analysis, we also consider a potential subsidy which will reconcile localized and centralized decision-making.

## 2. Related Literature

Managing forests in the face of native insect risk has received little attention in the economic literature.<sup>8</sup> Reed and Errico (1987) use stand-level and landscape-level models to assess the effects of MPB on long-term timber supply in British Columbia. However, they assume constant annual infestation rates so that insect dynamics are independent of the forest structure. Reed and Errico acknowledge this potential downfall:

*It should be noted that the models presented herein consider only the effects of pests on the forest and not the effects of forests on the pest. Thus if changes in forest structure have an effect on pest dynamics, the models of this paper may be inadequate.*

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<sup>8</sup> There is a strand of research incorporating endogenous fire risk into models of forest management (Reed 1987; Yoder 2004; Gonzalez-Olabarria et al. 2008; Konoshima et al. 2008). Thorsen and Helles (1998) address forest-management decisions in the presence of endogenous storm risk. These studies find that in spite of substantial fixed costs related to thinning, the optimal solution when risk is endogenous calls for increased harvesting of young trees over the optimal solution when risk is considered exogenous or ignored.

Treating MPB risk as exogenous misses a potentially important feedback from forest management policies to MPB outbreaks and long-term MPB populations.

A more complete specification of MPB risk includes both endogenous and exogenous components. Exogenous factors such as weather influence the frequency of MPB outbreaks while endogenous factors such as forest structure determine the severity of MPB outbreaks. Although forest managers cannot fully control future outbreaks, they can take actions to lessen the probability and severity. To the best of our knowledge, no previous models have incorporated endogenous insect risk into a model of forest management.

Our integrated bioeconomic model specifies a predator-prey relationship between MPB and lodgepole pine. Previous work by economists incorporating predator-prey relationships have focused on optimal harvesting of either the predator, prey, or both (Hannesson 1983; Ragozin and Brown 1985; Wilen and Brown 1986). Thus, predator and prey populations are largely determined by the market value of the population(s) being harvested. Additional research has incorporated non-market values of stocks (Tu and Wilman 1992; Kaplan and Smith 2001; Finnoff and Tschirhart 2003). Our model is novel in that the prey (trees) provides both market and non-market benefits which must be balanced.

Similar to the problem of MPB control, the economic pest-management literature has focused on the optimal management of plant populations which sustain an economically damaging pest population (Hall and Norgaard 1973; Feder and Regev 1975). This research evaluates centralized and decentralized pesticide application intended to minimize losses in crop production. Results indicate that a central planner will acknowledge production externalities associated with pesticide application and predator population dynamics, which naturally control pests. Bhat et al. (1993) incorporate the presence of diffusion externalities in the control of

migratory pest populations. They find that unilateral action results in less control and an elevated level of damages compared to collective action by all landowners.

### 3. Integrated Bioeconomic Model

The integrated model involves a resource-based economy where social welfare depends on economic activity unrelated to the resource, exploitation of the resource and the quality of the resource *in situ*. The model is dynamic and time set in discrete annual increments  $t$  to match the univoltine nature of the MPB lifecycle. MPBs typically emerge from a tree, reproduce, lay new eggs, and die over the course of a few weeks at the end of the summer. The eggs develop within the tree over the winter and emerge from the tree approximately one year after the initial infestation. This biological timing provides the foundation for the development of the model.

#### 3.1 Economic behavior

Labor  $L$  is allocated to the production of a composite good  $Q$  or to timber products  $T$  to maximize household utility,  $U$ . Utility is a function of both produced goods and the quality of the forest given by the stock of living adult trees  $A^H$  that provide non-consumptive benefits such as recreation, amenity values, and ecosystem services. For tractability, annual utility of the representative household is given by:

$$U(Q_t, T_t, A_t^H) = \ln(Q_t) + \alpha_T \ln(T_t) + \alpha_N \ln(A_t^H). \quad (1)$$

$T$  can be produced through harvests of live adult trees  $h^A$  or harvests of dead (salvage) trees  $h^S$ .

The household is willing to substitute adult harvests for salvage harvests at a constant rate of  $\eta < 1$ :

$$T_t = h_t^A + \eta h_t^S, \quad (2)$$

to reflect that salvage products are less desirable (de Steiguer et al. 1987; Holmes 1991).

Household labor endowments are fixed over time and normalized so that  $L = L_t^Q + L_t^A + L_t^S = 1$  units of labor are annually allocated between the production of the composite commodity ( $L_t^Q$ ) and the production of timber products ( $L_t^A$  and  $L_t^S$ ). Production of  $Q_t$  is directly proportional to labor inputs:  $Q_t = L_t^Q$ . Harvesting of adult and salvage timber requires labor and depends on harvestable stock according to Schaeffer harvesting functions:

$$h_t^A = \rho L_t^A A_t^H \quad (3)$$

$$h_t^S = \rho L_t^S S_t^H \quad (4)$$

where  $\rho$  is a scale parameter measuring the efficiency of harvesting activities. The stock effect in the Schaeffer harvesting function is a simple way of accounting for complex spatial considerations inherent in timber harvesting. For instance, fewer trees in the forest will result in longer distances to transport logging equipment into the forest and drag felled trees back to logging roads.

### 3.2 Lodgepole pine forest dynamics

Lodgepole pine (*Pinus contorta var. latifolia*) is a major forest species from Colorado to northern Canada and a primary target of MPB.<sup>9</sup> Following Heavilin and Powell (2008), the forest is assumed to be homogeneous<sup>10</sup> and divided into three size classes: seed base ( $X$ ), young trees ( $Y$ ), and adult trees ( $A$ ).<sup>11</sup> Each size class is measured in trees (or seeds) per acre. The laws of motion for the beginning-of-period density in each size class are given by:

<sup>9</sup> See Koch (1996) for more information on lodgepole pine ecology.

<sup>10</sup> The laws of motion therefore apply at the stand or landscape level.

<sup>11</sup> Young trees have a diameter at breast height (DBH) less than 8 inches. Although young trees have less defensive mechanisms and could provide enough nutrients for the larvae to develop, they seldom provide enough clearance in the phloem for larval development. Adult trees are characterized by a DBH 8 inches and larger. While adults have

$$X_{t+1} = (1 - \delta_X)X_t + b_Y Y_t + b_A A_t \quad (5)$$

$$Y_{t+1} = (1 - \delta_Y)Y_t + \delta_X X_t \quad (6)$$

$$A_{t+1} = (1 - d - \pi_t)A_t + \delta_Y Y_t - h_t^A. \quad (7)$$

Each period, a proportion ( $\delta_X$  and  $\delta_Y$ ) of the seed base and young trees mature to the successive size class. Contributions to the seed base are made by the young and adult size class at rates  $b_Y$  and  $b_A$ . Only adult trees are considered viable for commercial harvest  $h_t^A$  and susceptible to natural mortality (at rate  $d$ ) or MPB-induced mortality (at rate  $\pi_t$ ).<sup>12,13</sup>

The probability a lodgepole pine will die from MPB is determined by the interaction between the number of MPB attacking the tree and the level of tree resistance (Li et al. 2005; Heavilin and Powell 2008; Raffa 2008).<sup>14</sup> Berryman et al. (1985) define the probability of a successful attack on a lodgepole pine as

$$\pi_t = \frac{B_t^2}{B_t^2 + a^2}, \quad (8)$$

where  $B_t$  is the number of MPB per acre and  $a$  is a measure of the natural ability of susceptible trees to defend against MPB attack.<sup>15</sup> The healthier the tree, the more beetles are required for a successful attack and the larger the assumed value of  $a$ . The function is characteristic of the type

the strongest defenses against MPB attack, they are large enough to house egg galleries and act as an ample nutrient source (Heavilin et al. 2007).

<sup>12</sup> For simplicity we assume the volume of usable wood from adult trees is constant regardless of DBH differences.

<sup>13</sup> The effect of fire suppression efforts on MPB populations has been well documented (Safranyik et al. 2001). For simplicity, we abstract from the impacts of fire on forest and MPB dynamics. We do not feel this is a strong assumption given the success of fire suppression efforts on public lands.

<sup>14</sup> Successful attacks have two major consequences. First, females lay eggs with each individual laying in excess of 100 eggs. Larvae emerge from hatched eggs and spend the majority of their lifecycle inside the tree. The larvae construct feeding galleries in the phloem or inner bark of the tree. These galleries eventually girdle the tree by cutting off nutrient exchange between the roots and the tree. Second, MPB also carry blue stain fungi (*Ophiostoma clavigerum* and *O. monitum*) which interrupt water translocation, lower wood moisture content, and weaken defense mechanisms (Kim et al. 2003). Effects of the fungi coupled with damage to the inner bark and phloem eventually lead to tree death.

<sup>15</sup> Heavilin and Powell (2008) demonstrate that equation (8) works well at replicating actual data on beetle attack dynamics at a landscape-level.

III functional response in predator-prey interactions (Holling 1959)<sup>16</sup> and characterizes species exhibiting threshold dynamics such as MPB (Raffa and Berryman 1983).

Cahill (1978) establishes a positive relationship between MPB populations and forest density.<sup>17</sup> However, the relationship involves a one-year lag as adult MPBs emerge from the tree a year after initial infestation. MPB density at time  $t$  is therefore a function of the density of successfully attacked trees at time  $t-1$  and fecundity<sup>18</sup>,  $\varphi$ :

$$B_t = \varphi(\pi_{t-1}A_{t-1})^\nu, \quad (9)$$

where  $\nu$  is a curvature parameter. Equations (8) and (9) capture the recursive nature of the MPB population.

The final forest category is salvage timber. Timber is commercially viable after being killed by MPB, but recovery volumes typically decay over time. The degree of decline in recoverable volume depends on moisture, oxygen, temperature, and the amount of insect damage (Dobie and Wright 1978; Plank 1984; Fahey et al. 1986). We approximate the evolution of salvage timber using a geometric declining function that depends on recoverable volume decay ( $\theta$ ), natural and MPB-induced mortality from the adult stock, and the amount of salvage harvesting ( $h_t^S$ ):

$$S_{t+1} = (1 - \theta)S_t + (d + \pi_t)A_t - h_t^S. \quad (10)$$

The structure of equations (7) and (10) imply that growth and mortality occur prior to timber harvesting. Thus the density of adult and salvage trees responsible for growth and

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<sup>16</sup> Type III predation arises when the predator becomes more efficient as prey densities increase. An example would be a predator that responds to chemicals emitted from the prey and in turn increases search activity. This type of behavior corresponds to the behavior of female MPBs that emit pheromones to attract mates once a suitable host has been found (Samman and Logan 2000).

<sup>17</sup> An obvious reason for this relationship is that more trees lead to greater MPB reproductive potential. A second less obvious reason is that greater forest density translates into increased competition for sunlight and nutrients. This increased competition decreases host tree defenses and increases the probability of successful MPB attack.

<sup>18</sup> Fecundity refers to the potential reproductive capacity of a population. In this instance, MPB fecundity refers to the number of new beetles produced from a successfully attacked tree.

mortality will differ from the density available for timber harvesting. A fraction of the adult stock at  $t$  succumbs to either natural or MPB-induced mortality  $(d + \pi_t)A_t$  and moves to the salvage stock. The remaining fraction survives and combines with new growth  $\delta_Y Y_t$  to provide harvestable adult stock:  $A_t^H = (1 - d - \pi_t)A_t + \delta_Y Y_t$ . Likewise, the fraction of the salvage stock that does not decay  $(1 - \theta)S_t$  combines with natural and MPB-induced mortality to create harvestable salvage stock:  $S_t^H = (1 - \theta)S_t + (d + \pi_t)A_t$ . A portion of the harvestable stock may be harvested and the remainder forms the adult and salvage stock at the beginning of period  $t+1$ .

### 3.3 Forest management

Under passive management there is no economic control of the ecological system and no harvesting occurs. In this case the dynamics solely represent interactions between MPB and the forest. Household utility is thus only a function of (constant) composite good production and the stock of live adult trees. In contrast, under localized and centralized management harvesting decisions influence the ecological system. Each year the forest manager decides how many adult and salvage trees to harvest given the preferences of households, the stock of trees, and the MPB population.<sup>19</sup> There are direct tradeoffs to the consumer between harvesting live and salvage trees given the rate of substitution between adult and salvage timber. There are also indirect tradeoffs with harvests of adult trees as they provide timber products yet sacrifice amenity values and reduce contributions to the seed base.

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<sup>19</sup> In this way the lodgepole pine forest is treated as any other ecosystem that produces renewable resources. Thus optimal time paths of timber harvesting are determined using a similar approach as in the fisheries literature (Clark 1990). This approach allows managers to partially harvest the forest while harvesting the entire stand is allowed as a corner solution. Models of forestry management typically assume that it is optimal to harvest the whole stand at discrete time intervals (Faustman 1849; Pressler 1860; Ohlin 1921; Samuelson 1976).

### 3.3.1 Localized forest management

Due to the nature of MPB dispersion and the scale of the manager's jurisdiction, local harvest decisions are made *as if* they have no measurable impact on the overall MPB population. This management scenario captures, within the confines of the model, the real-world problem facing Forest Service district managers who oversee local areas which may differ from the landscape scale of MPB habitats.

The local forest manager solves the following problem:

$$\max_{\{h_{t+j}^A, h_{t+j}^S\}_{j=0}^{\infty}} \sum_{j=0}^{\infty} \beta^j U(Q_{t+j}, T_{t+j}, A_{t+j}^H) \quad (11)$$

where  $0 \leq \beta \leq 1$  is the discount factor. The problem in (11) is solved subject to linear technology condition (2), ecological equations of motion (5) – (10), initial conditions for stocks,

$$Q_t + \frac{h_t^A}{\rho A_t^H} + \frac{h_t^S}{\rho S_t^H} = 1, \quad (12)$$

$$h_t^A \geq 0 \text{ and } h_t^S \geq 0 \quad (13)$$

while ignoring the impact of individual harvesting decisions on the probability of successful MPB attack:

$$\frac{\partial A_{t+2}^H}{\partial \pi_{t+2}} \frac{\partial \pi_{t+2}}{\partial B_{t+2}} \frac{\partial B_{t+2}}{\partial A_{t+1}} \frac{\partial A_{t+1}}{\partial h_t^A} = 0. \quad (14)$$

Assuming an interior solution, the first-order condition requires adult harvesting to proceed until:

$$NB_t^A = \beta \{ NB_{t+1}^A (1 - d - \pi_{t+1}) + NB_{t+1}^S (d + \pi_{t+1}) \} + \beta^3 \delta_X \delta_Y b_A NB_{t+3}^A, \quad (15)$$

and salvage harvesting until

$$NB_t^S = \beta (1 - \theta) NB_{t+1}^S \quad (16)$$

where  $NB_t^A$  and  $NB_t^S$  are the marginal net benefit of an adult and salvage tree at time  $t$ .<sup>20</sup> It is important to note that localized forest managers do not ignore MPB. Each forest manager optimally responds to changes in MPB risk but treats this risk as exogenous.

Equation (15) reveals both direct and indirect impacts of adult harvesting. The left-hand side of (15) represents the present net benefit of harvesting an adult tree while the right-hand side represents the future costs. Harvesting an adult tree produces a direct net benefit in period  $t$ . However, harvesting an adult tree in period  $t$  means that tree is not available to provide utility for timber and non-timber benefits in period  $t+1$  and will increase the cost of harvesting other trees in future periods through the stock effect. The opportunity cost of harvesting an adult tree in period  $t$  is an expected value because the tree may be killed by MPB (with probability  $\pi_t$ ) or natural causes (at rate  $d$ ) before next period's harvesting decision. In addition, harvesting a live tree in period  $t$  eliminates the tree's contribution to the seed base.

Salvage harvesting follows a standard renewable resource rule. Equation (16) states that harvesting should occur until the marginal current net benefit of salvage timber equals its marginal future net benefits. As expected, increases in the rate of decay and the discount rate speed up the rate of salvage harvest.

### 3.3.2 Centralized forest management

Under centralized forest management a single manager internalizes the effect of aggregate MPB risk. As such, the centralized manager optimally responds to MPB-induced mortality but also seeks to manipulate future mortality due to MPB through additional harvesting of adult trees. Assuming local and central authorities have the same information and equal

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<sup>20</sup> A more detailed representation of the first-order conditions for adult and salvage harvesting under localized management can be found in Appendix A.

ability to adjust policies<sup>21</sup>, the optimization problem facing the centralized forest manager extends that of the local manager to acknowledge the endogenous MPB risk. In this case, the optimal adult harvesting rule is given by:<sup>22</sup>

$$\begin{aligned}
& NB_t^A + \beta^2(NB_{t+2}^A - NB_{t+2}^S) \frac{\partial A_{t+2}^H}{\partial \pi_{t+2}} \frac{\partial \pi_{t+2}}{\partial B_{t+2}} \frac{\partial B_{t+2}}{\partial A_{t+1}} \frac{\partial A_{t+1}}{\partial h_t^A} \\
& = \beta\{NB_{t+1}^A(1 - d - \pi_{t+1}) + NB_{t+1}^S(d + \pi_{t+1})\} + \beta^3 \delta_X \delta_Y b_A NB_{t+3}^A. \quad (17)
\end{aligned}$$

In contrast to (15), equation (17) includes a second term on the left-hand side, which captures the positive production externality of current adult harvesting. Harvesting adults in period  $t$  reduces hosts in period  $t+1$ , in turn reducing the number of MPBs and beetle-induced mortality in period  $t+2$ :

$$\frac{\partial A_{t+2}^H}{\partial \pi_{t+2}} \frac{\partial \pi_{t+2}}{\partial B_{t+2}} \frac{\partial B_{t+2}}{\partial A_{t+1}} \frac{\partial A_{t+1}}{\partial h_t^A} > 0. \quad (18)$$

The value of this reduction in beetle risk depends on the difference between the net benefit of a live and salvage tree two periods hence  $(NB_{t+2}^A - NB_{t+2}^S)$ . When the difference between the value of a live and salvage tree is high, the benefits of manipulating MPB risk under centralized management are also high. The effect of the positive externality, all else constant, is to increase the level of harvesting (through increased allocations of labor to adult harvesting) under centralized management in comparison to localized management.

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<sup>21</sup> Assuming similar information at the local and central levels is not unrealistic on public lands where local managers are likely to report to central managers. This assumption may be overly restrictive when local managers are independent entities.

<sup>22</sup> A more detailed representation of the first-order condition for adult harvesting under centralized management can be found in Appendix A.

#### **4. Endemic Steady-State Equilibrium**

The endemic steady state is obtained by solving time invariant versions of (2), (5)-(10), (12), (15) and (16) in the localized case, while (15) is replaced by (17) in the centralized case. Calibrated parameters are displayed in Table 1. Specifics of the model calibration are provided in Appendix B. An endemic steady state is characterized by low MPB density and low probability of successful MPB attack. Each of the passive, localized, and centralized management regimes has a distinct endemic steady state. Table 2 displays the implied values for the variables in the three endemic steady states.

Under the harvesting moratorium of passive management, steady-state MPB populations are significantly higher and utility (welfare) lower than with the two active management approaches. In the absence of other disturbances (such as fire) to naturally thin the forest, there are many hosts. This leads to elevated MPB populations and MPB-induced mortality.

Localized management results in higher MPB populations and lower welfare than centralized management. The difference between localized and centralized management leads to important changes in steady-state forest structure. For instance, adult harvesting is approximately 48% higher when MPB risk is treated as endogenous but only yields a 1% lower long-run stock of harvestable adult trees. Figure 1 illustrates the differences in the steady states. There are two long-run consequences of the (additional) preventative harvesting of centralized management. First, it lowers the MPB risk (from 5.8% to 0.2%), which increases the growth rate for any given stock and increases the carrying capacity. Second, the additional labor allocated to harvesting pivots the harvest function upward, resulting in a large increase in steady-state harvests and a small decrease in the steady-state adult tree stock.

## 5. The Dynamics of MPB Outbreaks

In this section, we consider the dynamic responses to a MPB outbreak. The outbreak is caused by a one-time increase in MPB fecundity that increases the population four times above its steady-state value.<sup>23</sup> The change in fecundity can be interpreted as a transient increase in winter temperatures that raise MPB reproductive capacity or larval survival. The responses in forest and harvesting dynamics under passive, localized and centralized management are contrasted over a 200-year planning horizon. The optimal time path of forest stocks and harvesting are shown in Figure 2.

### 5.1 Dynamics: Passive management

With passive management and no timber harvesting, the initial MPB outbreak has a delayed, cyclical impact on the size distribution of the forest and MPB population, and results in lower levels of welfare (Figure 4). The initial pulse in MPB population leads to a sharp decline in adult trees and a sharp increase in salvage trees. With fewer hosts (adult trees) MPB populations decline and allow for a gradual regeneration of adult trees. The increase in adult trees provides additional reproductive opportunities for the MPB and leads to a secondary spike in the MPB population. The dynamic interactions between MPB and the forest structure repeats with the effects of the original outbreak gradually diminishing over time. The complete absence of harvesting propagates MPB outbreaks over time with substantial “echo effects” which cause cycles in MPB population and the age distribution of the forest. Such cycles are a natural MPB phenomenon and most stark in the case of passive management.

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<sup>23</sup> The change in MPB populations due to exogenous shocks influencing beetle reproductive capacity and larval survival will depend on the population of MPB prior to the shock. Treating the exogenous shock as a percentage increase in MPB populations effectively incorporates endemic (pre-shock) MPB levels.

## 5.2 Dynamics: Localized management

The optimal path under localized management involves harvesting adult trees and intermittent salvage harvesting. Welfare is improved in comparison to that under passive management, yet for most of the time horizon localized management does not perform as well as centralized management (see Figure 4). Although cycles are present, adult harvesting dampens the cycles. The ability of localized management to dampen MPB cycles hinges on household preferences for timber. The more important timber is to households, the more adults harvested and the more MPB cycles are dampened.

The initial spike in MPB causes adult harvesting to immediately rise with a one-year delayed effect on the stock of trees. Initial harvests are driven by one of the indirect cost effects in (15), where harvesting an adult tree today means the tree will not provide timber and non-timber benefits in the future. The high initial MPB stock elevates the future mortality of adults, reducing these opportunity costs. However, the elevated harvests are not sufficient to eliminate the additional MPB induced mortality, so that as the adult stock declines the salvage stock increases. The corresponding relative increase in the productivity of labor in salvage harvesting, encourages a switch from adult to salvage harvests as total timber harvests decline. Adult stocks and harvests decline, pulling down welfare (Figure 4) until the stock of MPB bottoms out. This allows the adult stock of trees to recover and timber harvests and welfare to rise. Of course, as the adult tree stock rises MPB follow and the process repeats.

The cyclical nature of the hosts and pest inherent in the ecological model causes cycles in the marginal benefits and costs of harvesting. However, in comparison to the passive management scenario (with completely natural cycles), locally optimal harvesting works to dampen the cyclical behavior of the ecological system. The stock of adult trees represents the

link between MPB populations and the rest of the forest structure and determines the ability of the ecological model to propagate external shocks to MPB populations. The harvesting of adults reduces echo effects present in the interaction between MPB and adult trees.

### 5.3 Dynamics: Centralized management

Under centralized management, the harvestable adult stock declines slightly after the MPB outbreak and *monotonically* returns to steady state. Here, the extra marginal benefit of adult harvesting shown in (17) provides the incentive for additional harvests to decrease future MPB risk. The higher steady-state level of adult harvesting due to MPB prevention completely dampens forest and MPB cycles. The greater the difference between the marginal net benefit of adult and salvage trees, the greater the degree of preventative harvesting the centralized manager optimally employs and the more MPB cycles are dampened.

As with localized management, the central forest manager initially increases adult harvesting following the outbreak. In addition to the opportunity cost motivations described with localized management, the central manager recognizes that adult harvesting decreases future MPB risk. The combination of reduced marginal costs and increased marginal benefits results in significantly higher levels of adult harvesting. The relatively high levels of adult harvests are maintained over time, to such an extent that MPB stocks continually decline, keeping welfare high (Figure 4).

Interestingly, in contrast to localized management, the central forest manager never harvests salvage trees given the baseline parameters. Salvage trees are only harvested if households view adult and salvage harvests as near perfect substitutes.<sup>24</sup> There are two reasons

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<sup>24</sup> The central manager's decision to not harvest salvage only considers the timber value of salvage and does not reflect potential benefits of salvage harvesting such as fire risk reduction.

for the absence of salvage harvesting. First, centralized management and the smaller endemic level of MPB imply a mere 4% reduction in the harvestable adult stock following the MPB outbreak (by comparison they are cut by nearly 50% under localized management). Such small changes to harvestable stocks and labor productivity do not cause large enough changes in harvesting costs to trigger salvage harvesting. Second, centralized managers are able to manipulate future MPB risk through adult timber harvesting while salvage harvesting presents no such benefit. This additional positive production externality leads to a much higher expected marginal benefit on harvesting adult timber as compared to the localized case. Without cost-effective salvage harvesting, aggregate timber supplies dip almost immediately and remain slightly below steady state over the 200-year simulation.

#### **5.4 MPB outbreak severity and duration**

The MPB outbreak increases the probability of successful attack,  $\pi_t$ . While each management scenario is subjected to the same percentage shock, the severity of the subsequent outbreak varies greatly due to differences in endemic MPB levels and initial conditions across scenarios. To illustrate, in reference to Canadian and U.S. Forest Services, outbreaks are categorized as “low”, “moderate”, and “high” severity classes when  $\pi_t < 10\%$ ,  $10\% < \pi_t < 30\%$ , and  $\pi_t > 30\%$ .<sup>25</sup> Because most forest stands exist in a continual state of low severity outbreak, we define outbreak duration as the number of periods the outbreak remains in the moderate or high severity class. The impact of the three management regimes on MPB outbreak severity and duration is shown in Figure 3.

Under passive management, the forest is continually in the midst of a moderate MPB outbreak. In the absence of any other disturbance regime, prime conditions exist for sustaining

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<sup>25</sup> The Canadian and U.S. Forest Services both use a similar classification for aerial and ground survey data.

large MPB populations. Given these high endemic populations, the initial shock causes a high severity outbreak to immediately develop (maximum MPB-induced mortality of 82%) resulting in a forest with a third of the adult trees found in the endemic forest. MPB populations and MPB-induced mortality eventually decline as the beetles exhaust their food supply. The MPB decline is precipitous enough to allow the system to (temporarily) cross into a low severity outbreak. However, over time the system cycles back to its long-run endemic equilibrium (moderate severity).

Localized management produces a steady-state forest which exists in a state of low severity outbreak. This lower endemic MPB population causes a high severity outbreak (maximum MPB-induced mortality of 60.5%) but less severe than under passive management. Over the course of a few years, the outbreak will be reduced to the moderate class but the stock of adult trees will be cut in half. The system then gradually cycles back to its long-run endemic equilibrium but remains in the low severity class.

Unlike passive and localized management, the steady-state forest under centralized management *never* permits a MPB outbreak. The same percentage increase in MPB populations responsible for high severity outbreaks under passive and localized management produces a rate of MPB mortality that is always less than 5%. In fact, the severity of the initial outbreak under centralized management is smaller than the rate of MPB-induced mortality under localized management with no outbreak. The lack of a MPB outbreak is due almost entirely to the preventative nature of the pre-outbreak condition of the forest under centralized management. Perhaps more importantly is the way centralized management limits the ability of the forest structure to propagate the exogenous shock to MPB populations. Specifically, the ability of

central management to increase harvests today to prevent future MPB epidemics leads to monotonic convergence over the entire 200-year planning horizon.

## **6 Implications for Forest Management**

### **6.1 Welfare analysis**

Figure 4 shows the annual welfare improvements of localized and centralized management over passive management. However, the optimality of centralized over localized is temporally specific. Centralized forest management provides significant short-term benefits by reducing the severity of a MPB outbreak. The ability of the centralized manager to look ahead and choose current harvest levels to decrease future MPB-induced mortality results in a much less severe decline in household utility over the early years of the planning horizon. However, there is eventually an interval of time when annual utility under localized management exceeds that of centralized (during a rather large positive swing in adults in the localized cycles). When the welfare differences are considered over the entire 200-year horizon, discounted household utility is approximately 4.4% higher under centralized management.

These welfare gains from centralized management pertain only to MPB risk and do not consider other potential benefits that may arise under localized management. With heterogeneity in households and forested acres, information asymmetries between local and central management are more likely to arise. When faced with these information differences, the central forest manager may be forced to set a constant harvesting quota that equates average marginal benefits and costs. Such a quota would ensure optimal forest management on average but would lead to inefficient harvest levels locally.<sup>26</sup> If this heterogeneity is significant, centralized

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<sup>26</sup> For an in depth investigation of the welfare impacts from localized and centralized standards for transboundary pollutants see List and Mason (2001).

management may result in welfare losses that outweigh the welfare gains achieved from treating MPB risk as endogenous.

## **6.2 Sensitivity analysis**

While ecological parameters were carefully gathered from the relevant literature, there was little guidance over economic parameters. To investigate how the results depend on these parameters, we perform a limited sensitivity analysis. Specifically, we consider two alternative harvest scenarios. First, given the recent national trend away from timber benefits of public forests (see Figure 5), a plausible alternative scenario involves an actively managed forest which is being held primarily for non-timber benefits. This can be captured by a relative increase in  $\alpha_N$ , the preference parameter for non-timber benefits. Second, we consider increases in  $\eta$  (or increases in the salvage harvesting efficiency parameter) which increases the net benefit of salvage harvesting. In response to the devastating wildfires of 2000 and 2002, the U.S. Healthy Forest Restoration Act (HFRA) was passed with the primary goal of expediting the preparation and implementation of hazardous fuel reduction projects on public lands by limiting federally required impact analysis and public review of timber harvesting. The removal of these administrative requirements increase the net benefit of salvage harvests in an effort to encourage the removal of these hazardous fuels as well as recoup timber losses due to fire, insect, and disease.

Changes in economic parameters that cause either increases in non-timber benefits or increases in net benefits of salvage harvesting have two important consequences. First, adult harvesting decreases (causing steady-state levels of adult trees and MPB to increase) creating

more severe but shorter duration MPB outbreaks.<sup>27</sup> Second, the household welfare gains found in centralized management are reduced. The intuition is straightforward. With more trees in the forest and higher endemic levels of MPB, it takes a much larger amount of harvesting to achieve appreciable decreases in MPB-induced mortality. In other words, a given increase in harvesting is less effective at decreasing MPB-induced mortality. Detailed results are shown in Table 3.

The sensitivity results have two important implications. First, the recent trend toward increased non-timber benefits of public land appears to be responsible, at least in part, for increases in MPB outbreak severity. With larger endemic populations, MPB levels during an outbreak will be larger causing a larger percentage of live trees to be killed. Second, attempts to encourage salvage harvesting are likely to have unforeseen consequences. Specifically, they will decrease long-run adult harvesting, increase MPB stocks, and result in more severe MPB outbreaks. As shown in Figure 6, as the net benefit of salvage harvesting increases adult harvesting decreases and MPB stocks increase causing more not less dead salvage trees in the forest.<sup>28</sup> Attempts to mitigate fire risk in the short term may simply exacerbate MPB-induced mortality causing increased fire risk in the long run. If the purpose of encouraging salvage harvesting is to mitigate fire risk, care should be taken to balance this reduction in fire risk with subsequent increases in MPB risk. However, if efforts to encourage salvage harvesting are intended to merely recoup losses in timber value due to fire, insect, and disease, the result could be an increase in MPB risk with more severe MPB outbreaks and little, if any, gains in household welfare.

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<sup>27</sup> The increase in non-timber values also causes a second moderate outbreak twenty years after the initial outbreak. When  $\alpha_N = \alpha_T$ , the echo effects are dampened to such an extent that a second moderate severity outbreak never occurs.

<sup>28</sup> Such unanticipated results that arise through interactions between an ecological and economic system have been termed “ecosystem externalities” by Crocker and Tschirhart (1992).

### 6.3 Internalizing the externality

Localized management is likely to yield numerous benefits which are not incorporated in this analysis. For instance, localized management often reflects heterogeneities in local preferences over forest-based goods. For this reason, it is important to consider potential market-based corrections which will reconcile harvesting decision made at the local and central levels of management. The root of the negative stock externality in our problem is the common property nature of MPB. Unless all local managers agree to control the MPB populations simultaneously, the stock externality will cause local forest managers to engage in less adult harvesting than would otherwise be optimal.

In order to increase the amount of adult trees harvested, one option is to subsidize adult harvesting. By subsidizing adult harvesting, the localized forest manager has an added incentive to harvest more adult trees. If  $\sigma_t$  is the subsidy,  $\sigma_t h_t^A$  is subtracted from the left-hand side of equation (12).<sup>29</sup> The presence of the subsidy works to decrease the cost of adult harvesting. The solution for the optimal adult harvesting subsidy is

$$\begin{aligned} \sigma_t = & \beta^2 Q_t (NB_{t+2}^A - NB_{t+2}^S) \frac{\partial A_{t+2}^H}{\partial \pi_{t+2}} \frac{\partial \pi_{t+2}}{\partial B_{t+2}} \frac{\partial B_{t+2}}{\partial A_{t+1}} \frac{\partial A_{t+1}}{\partial h_t^A} \\ & + \beta \frac{Q_t \sigma_{t+1}}{Q_{t+1}} (1 - d - \pi_{t+1}) + \beta^3 \frac{Q_t \sigma_{t+3}}{Q_{t+3}} \delta_X \delta_Y b_A. \end{aligned} \quad (19)$$

Because the adult harvesting decision is inter-temporal, the subsidy will vary over time in response to the state of the forest. When the subsidy on adult harvesting is set according to equation (19), the localized manager completely internalizes the stock externality and the localized level of adult harvesting will equal the centralized level of adult harvesting.

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<sup>29</sup> For a market-based explanation of the adult harvesting subsidy see Appendix C.

## 7. Conclusions

Interactions between mountain pine beetle and forest management involve an important feedback loop: MPB populations affect forest management decisions and forest management decisions affect MPB populations. When management decisions are localized, stock externalities cause landscape-level MPB populations to be taken as given. This is the scenario currently facing the management of MPB on public forests. MPB populations depend on landscape-level forest structure in the geographic range of MPB. This landscape-level forest structure is determined by the decisions of numerous Forest Service managers and timber tenure holders who each manage a small part of the forest as a whole.

This paper demonstrates how MPB populations are incorporated into centralized and localized harvesting decisions and how these harvesting decisions impact the severity and duration of MPB outbreaks. Using this framework, we characterize and describe an analytical expression for adult and salvage timber harvesting based on the risk of successful MPB attack. Steady-state analysis reveals that centralized management would increase adult harvests by 48% for the purposes of MPB prevention. However, centralized management will only lead to a 1% decrease in the stock of adult trees and a 4.4% increase in welfare for the representative household.

Our primary results concern the ability of forest management to mitigate or exacerbate MPB outbreaks at the landscape-level. Localized management with adult harvesting and intermittent salvage harvesting lessens the ability of the ecological system to propagate external shocks to MPB populations. However, centralized management with higher levels of adult harvesting severely limits this internal propagation mechanism ensuring current outbreaks will not cause future outbreaks. When subjected to identical positive percentage shocks to MPB

populations, centralized forest management results in less severe MPB outbreaks. Because there may be advantages of local decision making not modeled here, we also characterize an analytical solution for the optimal subsidy on adult harvesting that internalizes the MPB stock externality and reduces MPB-induced mortality. In contrast, we illustrate how recent efforts to reduce fire risk by encouraging salvage harvesting on public lands will lower adult harvesting, increase MPB risk, and actually increase long-run fire risk.

In general, adult timber harvesting has a dampening effect on MPB outbreaks. Anecdotal evidence appears to support this conjecture. The longest MPB outbreak on record (18 years) occurred in the 1950s and 1960s during a period of intense timber harvesting (Taylor and Carroll 2004). In contrast, the current outbreak of unprecedented severity is occurring during a time of relatively little timber harvesting (see Figure 5). Given the recent shift toward more passive forest management on public lands throughout the U.S. and Canada combined with historical efforts at fire suppression, we should expect increases in MPB outbreak severity and frequency across the historic range of MPB irrespective of recent climatic changes. In short, while such climatic changes may be responsible for increasing the geographic range of MPB, recent increases in MPB outbreak severity and frequency are in part due to the structure of forest management.

Finally, it is important to note that our results highlight a benefit of centralized management that arises due to landscape-level forest disturbance processes such as MPB outbreaks. When costs and benefits of forest harvesting differ significantly across the landscape, a shift to centralized management may produce welfare losses due to less management flexibility. These welfare losses may overwhelm the benefits of centralized management outlined in this paper. Regardless, these results inform the ongoing debate surrounding the

appropriate level of natural resource management. Furthermore, while our analysis pertains to MPB outbreaks, the results can be generalized to other forest management risks. When faced with controlling forest disturbance processes such as insect infestation and wildfire whose probability and severity are determined by the actions of many, our results indicate that decisions made in an increasingly centralized structure can yield more stable forest dynamics and increase household welfare.

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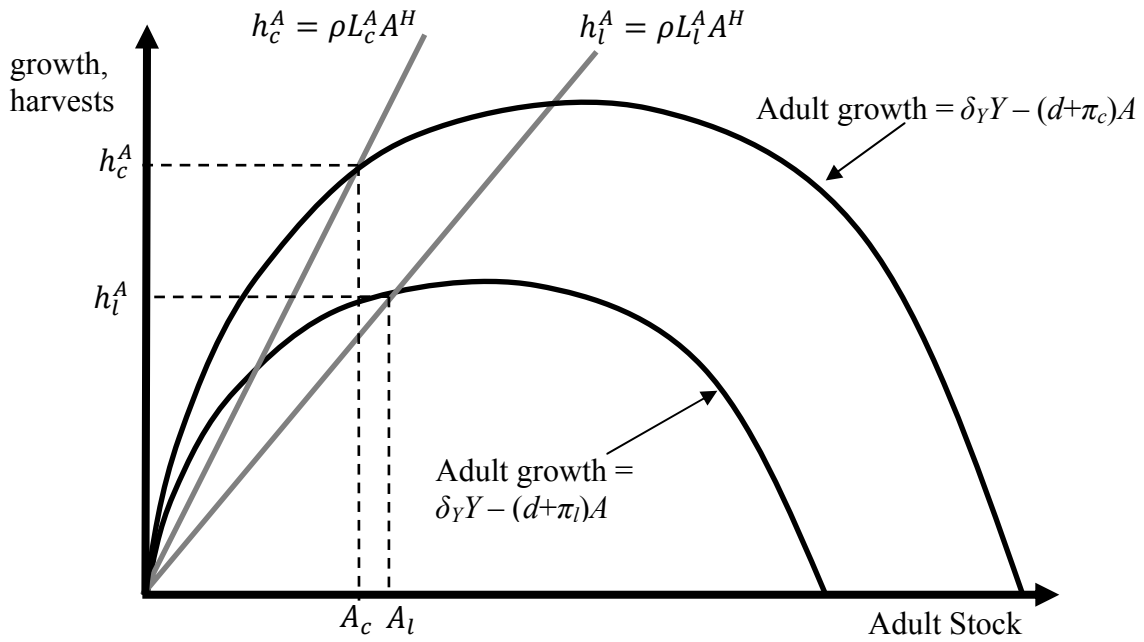


Figure 1. Steady-state levels of adult harvest and adult tree stock under localized ( $l$ ) and centralized ( $c$ ) management where  $\pi_c < \pi_l$

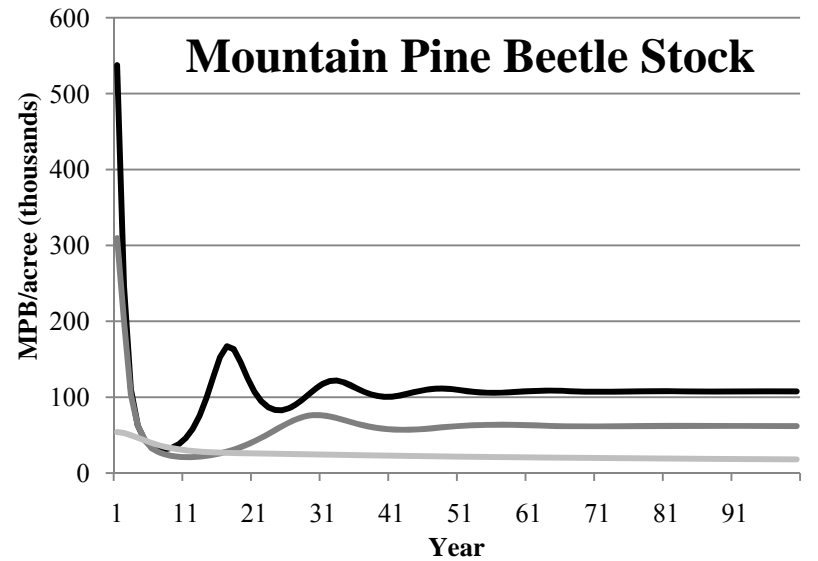
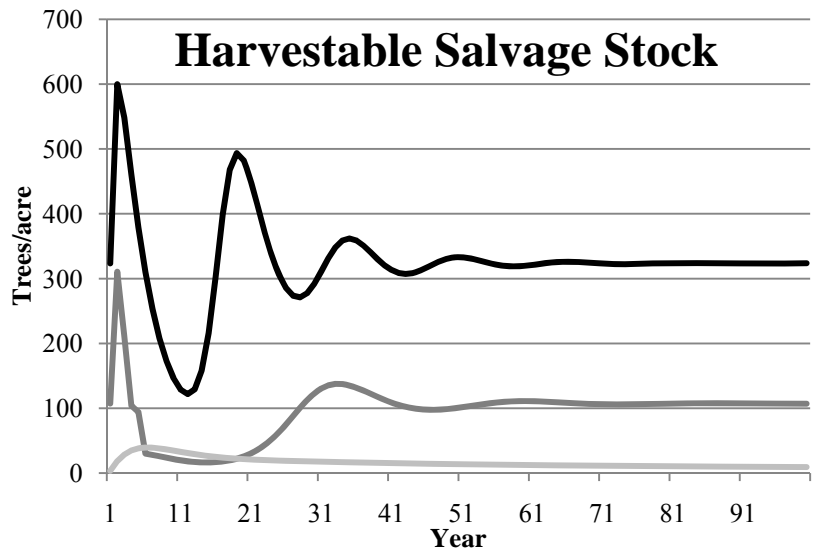
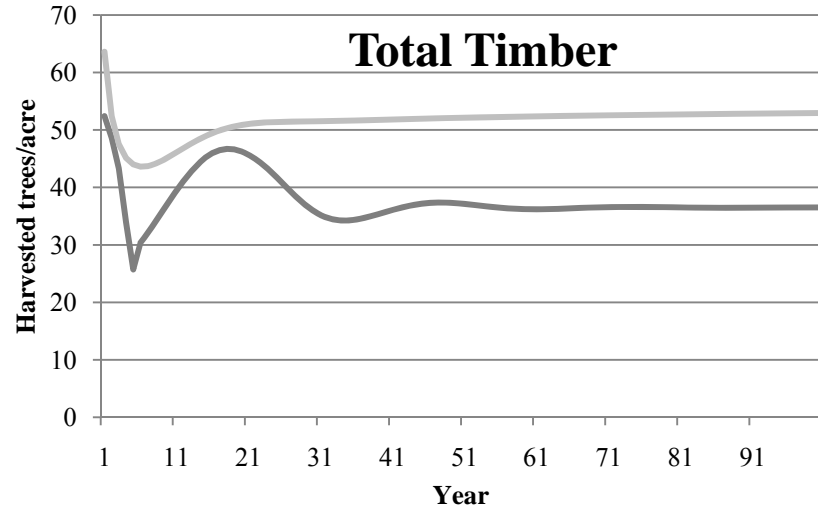
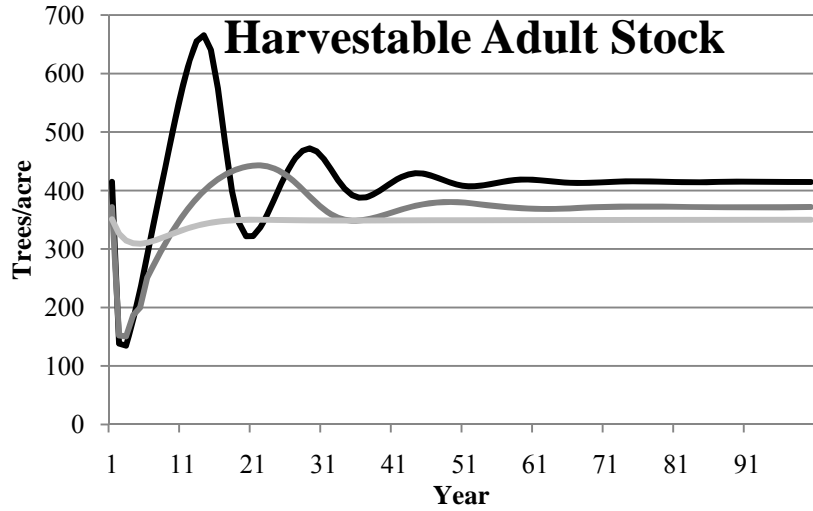


Figure 2. Forest and harvesting dynamics following positive MPB shock in year 1

Passive management     
  Localized management     
  Centralized management

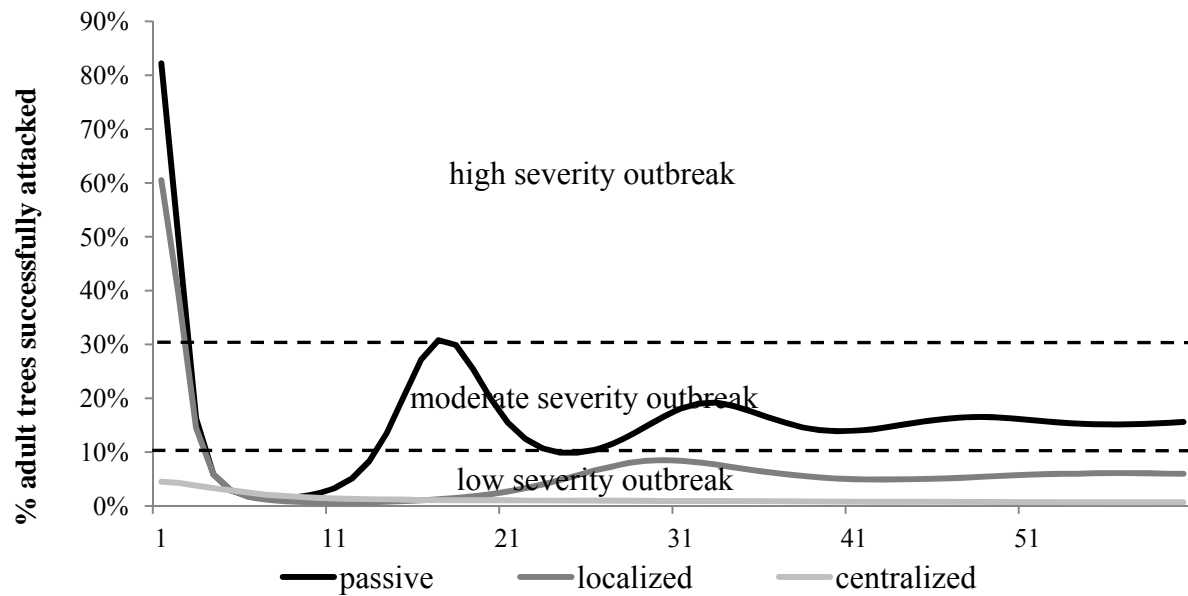


Figure 3. Impact of forest management on characteristics of MPB outbreak

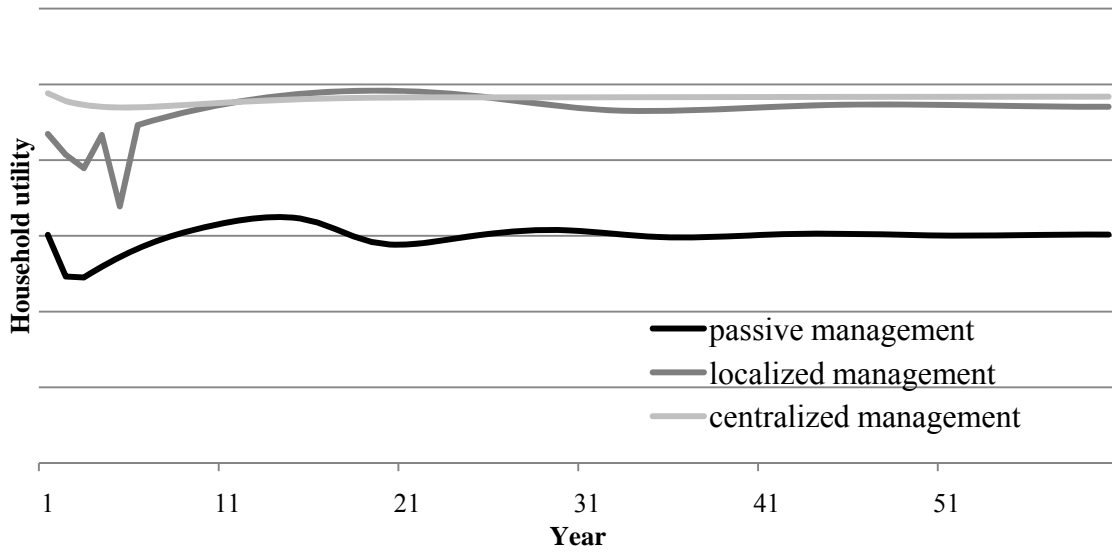


Figure 4. Non-discounted household utility following positive MPB shock in year 1

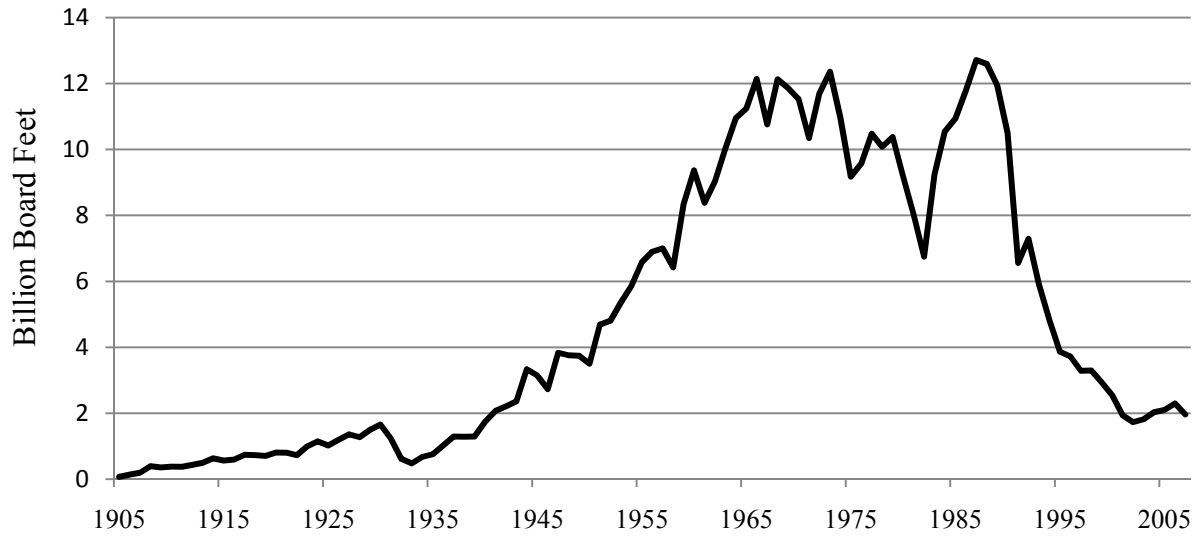


Figure 5. Timber harvested in national forests, 1905-2007  
\*Source: U.S. Forest Service Cut and Sold Reports

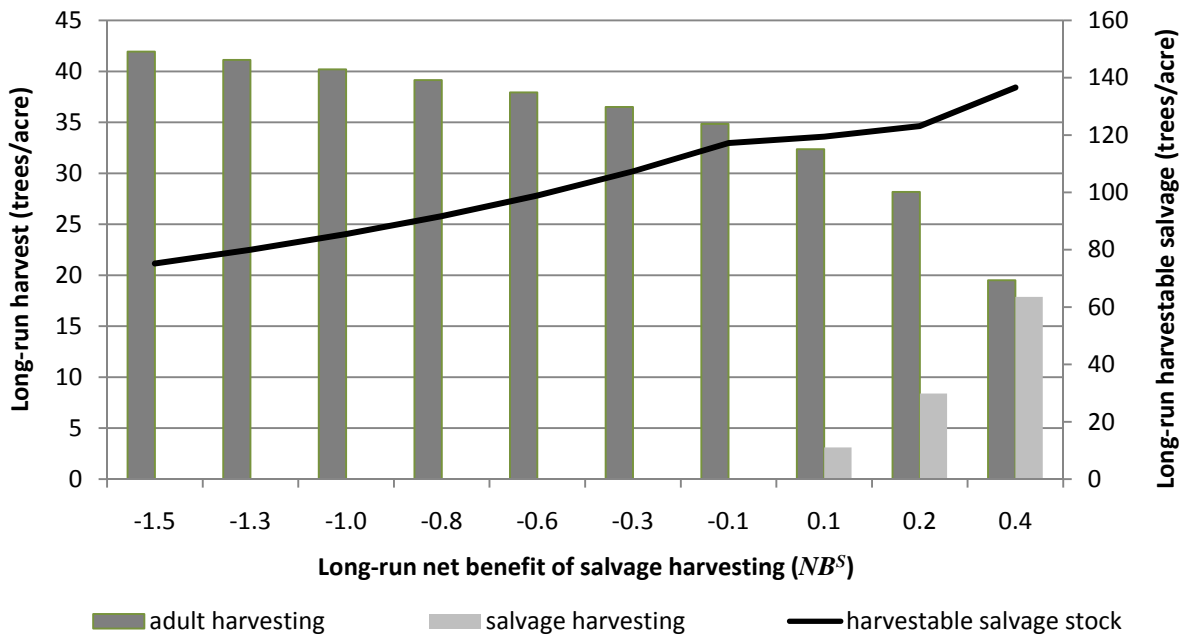


Figure 6. Long-run impacts to timber harvesting and harvestable salvage stocks due to increases in the net benefit of salvage harvest

Table 1. Calibrated parameters

Parameter	Definition	Value
$\delta_X$	Rate of germination of seeds in seed base	0.001
$\delta_Y$	Rate of maturation of young trees	0.004
$b_Y$	Rate of viable seed production in young trees	0.0039
$b_A$	Rate of viable seed production in adult trees	0.0039
$a$	Number of MPB/acre required for a 50% chance of MPB-induced mortality in adult trees	250000
$\varphi$	Average MPB offspring per infested tree	13360
$d$	Rate of natural adult tree mortality	0
$\theta$	Rate of decay in dead, salvage trees	0.2
$\nu$	Rate of decrease in beetle reproduction with increases in beetle-induced mortality in adult trees	0.5
$\alpha_T$	Household preference for timber benefits	0.5
$\alpha_N$	Household preference for non-timber benefits	0.5
$\eta$	Rate at which households substitute adult harvest for salvage harvest	0.5
$\rho$	Harvest efficiency parameter	1
$r$	Discount rate	0.05

Table 2. Steady-state values under various management regimes

Variables	Type of Management		
	Passive	Localized	Centralized
$\pi$	15.60%	5.80%	0.20%
$B$	107,480	61,889	10,809
$X$	64,724	57,975	54,729
$Y$	16,181	14,494	13,682
$S$	323.6	107.3	3.3
$A$	414.9	371.6	350.8
$h^A$	0	36.5	54.1
$L^A$	0	0.09	0.13
$h^S$	0	0	0
$T$	0	36.5	54.1
$Q$	1	0.91	0.87
<i>Utility</i>	3.01	4.71	4.85

Table 3. Effect of alternative harvest scenarios

		Central/local welfare difference	Endemic MPB-induced mortality		Initial outbreak severity	
			Localized	Centralized	Localized	Centralized
Increasing non-timber values	$\alpha_T=0.5; \alpha_N=0.5$	4.40%	5.80%	0.20%	60.50%	4.50%
	$\alpha_T=0.4; \alpha_N=0.6$	1.80%	8.20%	3.70%	69.20%	49.20%
	$\alpha_T=0.3; \alpha_N=0.7$	1.50%	11.00%	6.90%	75.50%	65.10%
	$\alpha_T=0.2; \alpha_N=0.8$	0.90%	13.90%	9.90%	80.20%	73.40%
	$\alpha_T=0.1; \alpha_N=0.9$	0.30%	15.60%	13.10%	82.20%	79.00%
Increasing salvage values	$\eta=0.5$	4.40%	5.80%	0.20%	60.50%	4.50%
	$\eta=0.6$	4.10%	6.30%	0.20%	62.60%	5.50%
	$\eta=0.7$	3.90%	7.00%	0.30%	65.30%	7.20%
	$\eta=0.8$	3.20%	8.20%	0.50%	69.10%	10.40%
	$\eta=0.9$	2.00%	10.60%	0.90%	74.80%	18.00%