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The economics of salvage harvesting and reforestation in British Columbia's mountain pine beetle-affected forests

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Canada

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Abstract

British Columbia's mountain pine beetle salvage and reforestation decisions involve a wide range of complex social, economic, and ecological trade-offs. In this report, we summarize the current treatment options in beetle-affected areas and outline the many costs, benefits, and risks associated with managing beetle-killed stands. We then demonstrate some important economic aspects of this issue by comparing the discounted costs and benefits of treatment choices under different sets of post-outbreak assumptions. The economic case for salvage harvesting is clear where the activity is profitable, and where post-salvage stand regeneration outperforms stand regeneration in the absence of salvage. However, low-value stands with a positive outlook for natural or advance regeneration may generate greater stand value when left unsalvaged. Where salvage harvesting is not financially feasible, rehabilitation appears to be profitable only on sites with high productivity, low treatment costs, and a poor outlook for natural regeneration. Given the range of site productivities typical in the BC Interior and typical reforestation costs, few sites meet these criteria.

However, forest-level timber supply impacts and non-timber benefits must also be considered, which may justify rehabilitation on a wider range of sites. Partial cutting may be another treatment option in some stands with significant volumes that are unaffected by mountain pine beetle. The discounted future returns from the residual overstorey (including non-timber benefits) largely determine whether this harvesting system is preferable to immediate clearcutting. Candidate sites for partial cutting typically have adequate salvage volumes to pay for any costs associated with the initial stand entry, such as road construction. Where the pine component of the stand offers little short-term profit, it may be more profitable to defer harvesting altogether, allowing beetle-killed trees to decay on the stump.

Résumé

Les décisions prises par la Colombie-Britannique relativement à la récupération du bois endommagé par le dendroctone du pin ponderosa et au reboisement des peuplements ravagés résultent de la prise en compte de nombreux enjeux sociaux, économiques et écologiques complexes. Dans le présent rapport, nous passons en revue les différent traitements possibles dans les régions infestées et décrivons les nombreux coûts, avantages et risques associés à la gestion des peuplements ravagés par le dendroctone. Nous examinons ensuite certaines dimensions économiques importantes de la question en comparant les coûts actualisés et les avantages des traitements possibles dans le cadre de divers ensembles d'hypothèses post-infestation. L'argument économique en faveur des coupes de récupération est clair là où cette option est rentable et où le rendement de la régénération est meilleur après récupération qu'en l'absence de récupération. Toutefois, les peuplements de faible valeur présentant un bon potentiel de régénération naturelle ou préexistante peuvent évoluer vers des peuplements de plus grande valeur si aucune coupe de récupération n'y est pratiquée. Dans le cas où une coupe de récupération n'est pas financièrement envisageable, la remise en état semble une option rentable seulement si le peuplement visé affiche une productivité élevée et si les coûts des traitements et les possibilités de régénération naturelle sont faibles. Étant donné la variabilité qui caractérise la productivité des sites dans l'Intérieur de la Colombie-Britannique et les coûts habituels du reboisement, peu de sites satisfont à ces critères.

Toutefois, les impacts sur l'approvisionnement en bois à l'échelle de la forêt et les avantages non ligneux doivent aussi être pris en compte et peuvent justifier la décision de procéder à la remise en état d'un plus large éventail de peuplements. La coupe partielle peut être une autre option de traitement valable dans certains peuplements comportant d'importants volumes de bois non endommagé par le dendroctone. Les revenus futurs actualisés qu'on croit pouvoir tirer de l'étage dominant résiduel (incluant les avantages non ligneux) déterminent en grande partie si ce mode d'exploitation est préférable à une coupe à blanc immédiate. Les peuplements se prêtant à une coupe partielle contiennent normalement des volumes de bois récupérables suffisants pour compenser les éventuels coûts d'aménagement de voies d'accès au peuplement (p. ex. chemins forestiers). Lorsque les volumes de pin comportent un faible potentiel de profits à court terme, il peut être plus rentable de ne pas intervenir et de laisser les arbres tués par le dendroctone se décomposer naturellement.

Summary

In stands with significant mountain pine beetle (MPB) mortality, forest managers face a range of choices including clearcut harvesting, partial cutting, various rehabilitation strategies, and non-intervention. These choices involve many long-term costs, benefits, and risks, some of which can be assessed through economic analysis. After reviewing the context for this issue, we provide case studies that span the more likely stand-level problems faced by decision makers. All analyses are conducted from the perspective of the landowner (i.e., government) rather than the user of the resource (i.e., licensee). The insights from the case studies form a basis to answer three core questions:

Are some stand types better left unsalvaged? What economic/silvicultural assumptions produce higher stand values when salvaging is foregone?

- The economic case for salvage harvesting is clear where the activity is profitable, and where post-salvage stand regeneration outperforms stand regeneration in the absence of salvage.
- However, low-value stands with a positive outlook for natural or advance regeneration may generate greater stand value when left unsalvaged.
- This may be more likely where: 1) advance regeneration is expected to release and provide sufficient stocking following pine mortality; 2) the subsequent stand is expected to be of substantial value; and/or 3) significant damage to the advance regeneration is expected if salvaging occurs.

In areas that cannot be salvaged, is reforestation a profitable investment?

- From a purely financial perspective, rehabilitation appears to be profitable only on sites that have high productivity, low treatment costs, and a poor outlook for natural regeneration.
- Given the range of site productivities in the BC Interior and typical reforestation costs, few sites meet these criteria. However, forest-level timber supply impacts and non-timber benefits must also be considered, which may justify rehabilitation on a wider range of sites.

Does partial cutting make sense economically?

- Forest managers must decide if the benefits of retaining live merchantable volumes outweigh the opportunity costs of foregoing larger immediate revenues.
- In most areas, this depends on the outlook for growth in the residual stand and on the value of these volumes for mid-term timber supply.
- Depending on the up-front costs and volumes available at the initial stand entry, it may be more profitable on some sites to defer harvesting altogether and leave salvage volumes to decay on the stump.
- This may be especially true of stands that require significant road development or other up-front costs.

Although our case studies assume that timber management is the dominant source of costs and benefits, we emphasize that non-timber values such as wildlife habitat, recreation, water, visual quality, and cultural values must also be considered. These values will weaken many cases for salvaging/rehabilitating, but may strengthen others, especially where the presence of dead pine poses safety or fire risks.

Many assumptions and uncertainties are involved in the analyses we present. Further research into some key topics could help reduce uncertainty and support forest management decisions surrounding forest health and salvage harvesting of lodgepole pine forests. These topics include fire risks from dead pine, impacts on non-timber values, market-related issues, the shelf life of dead pine, and the performance of residual overstoreys and advance regeneration in post-MPB stands.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae,* Hopkins) (MPB) is creating widespread change in British Columbia's (BC's) Interior pine forests. Although the MPB has always been a natural agent of forest renewal in BC (Taylor and Carroll 2004), the current outbreak is unprecedented in scale and is expected to kill roughly 70% of BC's mature pine inventory (Walton 2009). Factors that led to the epidemic include an abundance of mature pine, a lack of cold winters that normally reduce beetle populations, and hot dry summers that stressed trees and increased their vulnerability (CFS 2005). While the infestation may cause a wide range of social, ecological, and economic impacts for decades, some of the most immediate effects are being felt by the industries that rely on interior forests as a source of raw materials.

Over the past several years, the excess of dead pine has led to a large-scale reorientation of BC Interior timber harvesting towards salvage operations. These operations are attempting to capture timber volumes before decay reduces or eliminates the economic value of affected stands. The salvage program also aims to re-establish productive stands that will help provide future timber supplies. Timber harvesting activity increased significantly as the salvage effort gathered momentum; however, harvesting has declined more recently due to weak forest product markets. Going forward, harvest rates will continue to be driven by markets, but will also be constrained as operable salvage areas are depleted or become increasingly subject to decay. As these areas recover, MPB-affected forests may eventually be capable of supporting pre-epidemic harvest rates. However, it will be many decades before timber supplies fully recover from the epidemic.

In addition to the site-specific operational challenges of salvage harvesting, forest managers responsible for directing salvage programs face many larger-scale tradeoffs and uncertainties. While rapid salvage harvesting may ensure timber values are captured in the short-term, a surge in timber output can reduce prices and increase the magnitude of the subsequent supply decline, putting strain on forest-dependent communities. Spreading salvage activity over a longer timeframe carries risks, as "shelf-life" (the time in which dead standing pine remains usable) is both variable and uncertain (Byrne et al. 2005). Less aggressive salvaging could result in losses of volume or value if shelf-life estimates turn out to be shorter than expected..

To further complicate the situation, some beetle-killed stands contain a healthy juvenile understorey with potential to provide the next generation of forest cover (Burton 2006; Coates et al. 2006). Salvaging the mature overstorey may lead to unavoidable damage to the understorey and require reforestation expenditures. Fire hazards resulting from a widespread overstorey of dead pine add another dimension to the problem (Kaufmann et al. 2008), and may pose risks to the future development of stands, to other values such as recreation, or may even create risks to public safety or infrastructure in certain areas.

Values other than timber must also be considered, as large-scale salvage harvesting (and associated road development) can adversely affect the ecology and hydrology of forested landscapes (Lindenmayer et al. 2004, 2008). Leaving some beetle-killed forest unsalvaged (both within and outside of salvage blocks) is a key strategy to mitigate these impacts, as is avoiding harvesting non-pine species during the salvage period (Bunnell et al. 2004; Eng 2004; Snetsinger 2005; Klenner 2006; Lindenmayer et al. 2008). The latter strategy may also preserve stocks of timber that can help sustain forest industries and associated communities after salvage harvesting by delaying or reducing the magnitude of subsequent timber supply reductions. Furthermore, mixed stands may be managed under a multiple-entry system, first harvesting the dead or vulnerable pine component while leaving non-pine volumes for future use, to ease mid-term timber supply shortages.

Strategies to avoid non-pine harvesting do have limits. Some mixed stands may be well-suited to partial cutting treatments that target only beetle-killed stems, while in other areas avoiding non-pine stems may be difficult, costly, or silviculturally inappropriate (Martin et al. 2005). This leaves forest managers with difficult choices to make when candidate stands for salvage also involve a significant "by-catch" of unaffected trees. Is it better to harvest these stands now while the pine component can be used, or is it better to accept some volume losses so unaffected trees are available for future use? Other considerations may make a strict avoidance of non-pine volumes impractical. Some manufacturers rely heavily on species other than pine, particularly those in the value-added sector. While constraining non-pine harvesting can help to minimize overall timber supply fluctuations, some individual firms may then face difficult consequences.

Harvesting as a response to large-scale natural disturbances can also be controversial. During the 1980s, harvesting associated with outbreaks of spruce beetle (*Dendroctonus rufipennis* [Kirby]) in BC led to concern over the scale of salvage areas and prompted considerable public debate. More recently, the benefits of salvage harvesting in Oregon have also been debated (see Baird 2006; Donato et al. 2006a, b; Newton et al. 2006; Stokstad 2006).

Clearly, many complex factors influence the timing, location, and scale of salvage operations. This report examines the issue from an economic perspective and demonstrates some of the complexities involved with optimizing the economic value of a resource that is subject to both rapid change and uncertainty. The goal of this report is to outline the structure of the economic problem at the stand level, and to demonstrate or discuss many of the costs, benefits, and risks associated with managing beetle-killed stands. While forest-level models and timber supply forecasts can provide more detailed predictions of product mixes, forest growth, outbreak behaviour, and landscape conditions (e.g., BCMFR 2007; Walton 2009), this report demonstrates how economic factors affect the salvage harvest decision. Key lessons from this analysis are of interest to forest managers, policy makers, and stakeholders both in the current beetle epidemic and in other large-scale forest disturbances.

2. Literature Review of the Economics of Forest Disturbance and Salvage Harvesting

Previous studies have looked at the economics of timber in the presence of natural disturbance. We do not attempt to provide an exhaustive review of the entire body of literature on this topic, but instead give an overview and a few particularly relevant examples. These studies can be grouped into four categories:

1) assessing damages and optimal levels of forest protection (e.g., Sparhawk 1925; Vaux 1954; Brown and Boster 1978);
2) examining the effects of catastrophic and routine forest disturbance on the timing of stand-level harvests and values (e.g., Martell 1980; Reed 1984; Reed and Errico 1985; Englin et al. 1999);
3) examining the effect of salvage harvesting on timber market dynamics (e.g., Holmes 1991; Prestemon and Holmes 2000, 2004, 2008); and
4) assessing impacts on timber supply and profitability at the forest or landscape level (e.g., Van Wagner 1983; Reed and Errico 1986; Martell 1994; Boychuck and Martell 1996; Armstrong 2004). Each group of work offers insight on the factors relevant to economic decisions surrounding forest management and natural disturbances at both the stand and forest scales. Table 1 summarizes major findings from these studies.

Table 1. Literature relevant to economics of large-scale salvage harvesting and disturbance.

Focus of Literature	Questions Addressed	Findings/Insights
Damage Assessment	What is the appropriate level of forest protection?	The cost of disturbance is the discounted present value of reduced future benefit flows. The forest management context is important in understanding disturbance costs and optimal protection levels. Least-cost-plus-loss is the theoretical optimum control strategy, though this is difficult to establish in practice.
Impact on Rotation Age and Expected Values	How does risk of natural disturbance affect expected stand cutting decisions and values?	When disturbance risks are considered, optimal rotation ages are reduced and overall economic returns from forestry decline. Multiple forest values can lead to ambiguous results.
Salvage Harvesting and Market Dynamics	How does salvage harvesting impact market prices and who benefits and loses?	Increased salvage harvesting reduces timber prices initially, but these rebound after salvaging ends. Consumers gain and producers lose while prices are depressed, but this reverses when prices rebound. There may be an optimal salvage harvesting level that maximizes returns to public lands.
Timber Supply	How can sustainable harvest levels be estimated when disturbance is uncertain? What are the most profitable harvest levels?	The impact of ongoing disturbance on long-term timber supply can exceed the volume of timber directly killed by disturbances. Individual forest estates may vary in their ability to absorb timber supply shocks caused by disturbance. Sustainable harvest rates and long-term profitability also depend on a tolerance to periodic harvest flow disruptions.

The first group of studies on pest and fire disturbances focuses on the optimal level of protection. Determining this amount requires assessing the damage. Minimizing the sum of the expenditures on control plus damages ("least-cost-plus-loss") has long been recognized as the theoretically optimal strategy (e.g., Sparhawk 1925). Subsequent work by Vaux (1954) and Brown and Boster (1978) considered the question of damage estimation within the framework of whole forest systems. These authors assert that the cost of a single event is the discounted present value of its impact on all future benefit flows from the forest, rather than just the nominal value of the timber directly lost in the event. Since harvest schedules can be adjusted and losses spread over time, the economic cost of disturbance can be less than the value of the lost standing timber. However, the magnitude of this difference depends heavily on the type of management regime (ownership, policies, and regulatory constraints). Several authors have also acknowledged that the practical application of a least-cost-plus-loss approach to fire and pest management is limited by data uncertainties, such as the difficulty of estimating actual gains from prevention and control (Davis 1959; Montgomery et al. 1986; Martell 2001).

The second group of studies examines disturbance within the optimal harvesting model originally developed by Faustmann (1849). Although fire disturbance has been the focus of much of this work, a number of basic principles involved may also apply to some insect outbreaks. For example, fire risk has been shown to shorten the economic rotation of a stand and reduce the expected economic returns from harvesting (Martell 1980), effectively adding a risk premium to the discount rate (Reed 1984). However, where opportunities exist for salvage harvesting (Reed and Errico 1985) or where other forest values dependent on disturbance are present (Englin et al. 1999), these effects can be offset somewhat. While this work largely considers risks from future disturbance, it is relevant to post-disturbance stand-level investments such as reforestation.

The US Department of Agriculture's Forest Service has published detailed studies on the impact of large-scale salvage harvesting on market dynamics. Holmes (1991) examined the economic impacts of southern pine beetle (*Dendroctonus frontalis*), demonstrating short-run effects on the economic welfare of consumers and holders of both damaged and undamaged timber. Although these epidemics can provide gains to consumers, producers suffer losses in both damaged and undamaged forests due to price effects caused by the increased supply of salvage logs. The total supply curve shifts outwards, prices drop, and supplies from undamaged stands decline (Figure 1). Prestemon and Holmes (2000) examined a longer time series of price dynamics associated with Hurricane Hugo and demonstrated that short-run price declines associated with salvage harvesting were followed by longer-term price increases due to the increased scarcity of timber. The total supply curve shifts inwards following the completion of salvaging, and holders of undamaged timber enjoy higher prices than before the disturbance (Figure 1). Prestemon and Holmes (2004) examined government intervention in such catastrophes, showing that programs that facilitate salvage harvesting can improve the welfare of consumers and holders of damaged timber, but increase the negative consequences to holders of undamaged timber. Expediency is also an important factor in salvage programs as dead standing timber is subject to reductions in usable volume and quality through decay. Prestemon et al. (2006) estimate delays in post-fire salvage harvesting in the Bitterroot National Forest reduced government revenues by some 25%. Some unique factors that limit salvaging in public forests have also been identified (Prestemon and Holmes 2008). These include:

- greater concern for non-timber impacts;
- greater consideration of the price effects of increased harvesting;
- public perceptions of salvage as a "give-away" to industry and the potential for litigation; and
- institutional limitations, such as an inability to make salvage timber available in a timely manner.

Forest-level models have explicitly incorporated ongoing natural disturbance to demonstrate the magnitude of timber supply impacts (e.g, Van Wagner 1983; Reed and Errico 1986; Martell 1994; Boychuck and Martell 1996; Armstrong 2004) and some models have included salvage harvesting to provide improved projections of long-term forest conditions and profitability (e.g., Klenner et al. 2000; Seely et al. 2004; Peter and Nelson 2005). This body of work underscores the challenge of reconciling the uncertainty of disturbance with the social objective of establishing sustainable levels of commercial forest use. Wagner et al. (2006) propose that such models could be used to determine thresholds of MPB activity that would trigger specific management responses. However, data requirements and uncertainties continue to pose limitations to this approach.

As BC's MPB outbreak has unfolded, models have been developed that attempt to forecast its progress (Walton 2009) and consequent timber supply impacts (e.g., BCMFR 2007). Potential impacts of timber scarcity following the epidemic have also been examined, which likely include a downsizing of the BC Interior forest sector (Schwab et al. 2009). Prices for forest products may even rise somewhat as a result (Abbott et al. 2009), though actual price trends depend on the future state of international forest product markets.

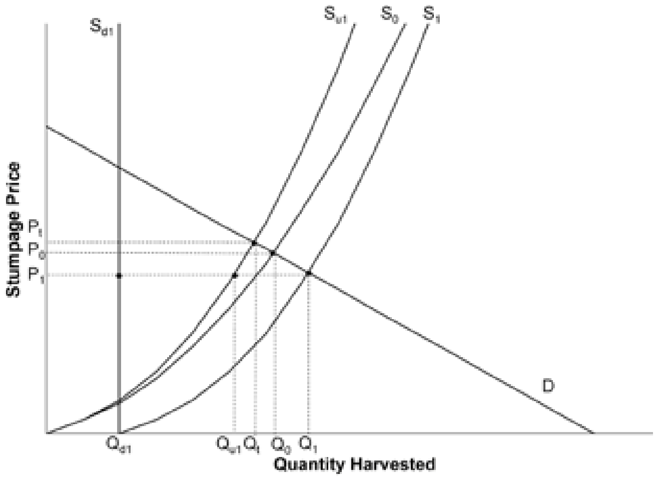

Figure 1. Equilibrium harvest quantities and stumpage prices during large-scale timber salvage. Assuming demand for logs (D) and initial supply (S_0), an initial equilibrium price and quantity occurs at Q_0, P_0. A pulse of salvage harvesting creates a new supply component (S_{d1}) and shifts the supply of undamaged timber backward to S_{u1}, due to a decrease in undamaged timber inventory. Total supply is shifted forward to S_1, as the opportunity costs of supplying damaged timber decrease. This assumes the salvage supply is perfectly inelastic for a positive amount of damaged timber and the forest owner (i.e., the government in the case of public land) is willing to salvage for any non-zero stumpage rate up to this amount. The price of stumpage drops to P_1 and holders of undamaged timber reduce harvesting to quantity Q_{u1} while damaged timber is salvaged at quantity Q_{d1}. Following salvage, prices rise to P_t and holders of undamaged timber increase supply to Q_t. As the salvaged areas recover over the long term, the supply curve eventually shifts back to S_0 and the equilibrium price and quantity returns to Q_0, P_0. Note that if the supply of damaged timber is more price elastic (beyond some threshold Q_{d1}) then the immediate drop in market price of timber would fall below P_1. (Adapted from Prestemon et al. 2006.)

3. MPB Salvage Harvesting in British Columbia

Although harvesting has been used as a tool for managing the MPB for many decades in the BC Interior, as the scale of the current MPB outbreak emerged, selected Timber Supply Areas (TSAs) and Tree Farm Licenses (TFLs) began receiving Allowable Annual Cut (AAC) "uplifts" to facilitate accelerated salvage harvesting of beetle-killed trees. Figure 2 shows the aggregate AAC of 22 TSAs and 15 TFLs[1] in BC's beetle-affected region (locations shown in Figure 3). Since 2001, timber supply (AAC) has risen from approximately 45 million m^3 to over 60 million m^3 [2].

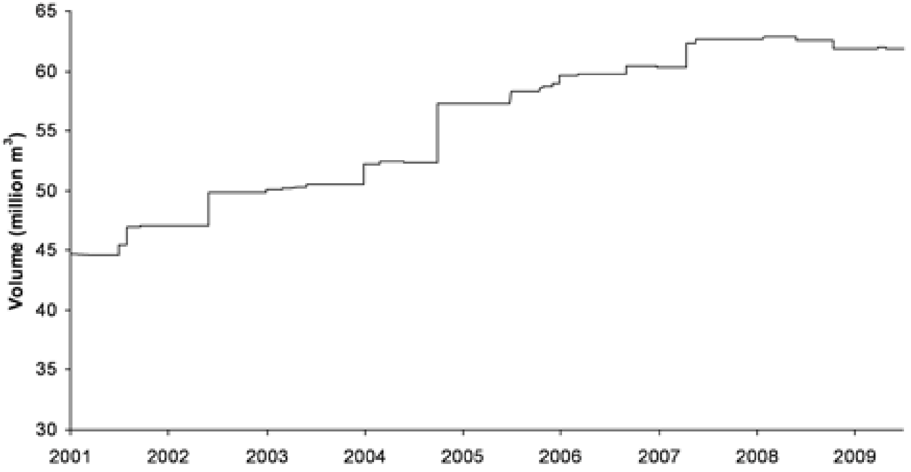

Figure 2. Allowable annual cut in BC's MPB-affected region. (Source: BCMFR AAC Determinations [available online at www.for.gov.bc.ca/hts/aac.htm])

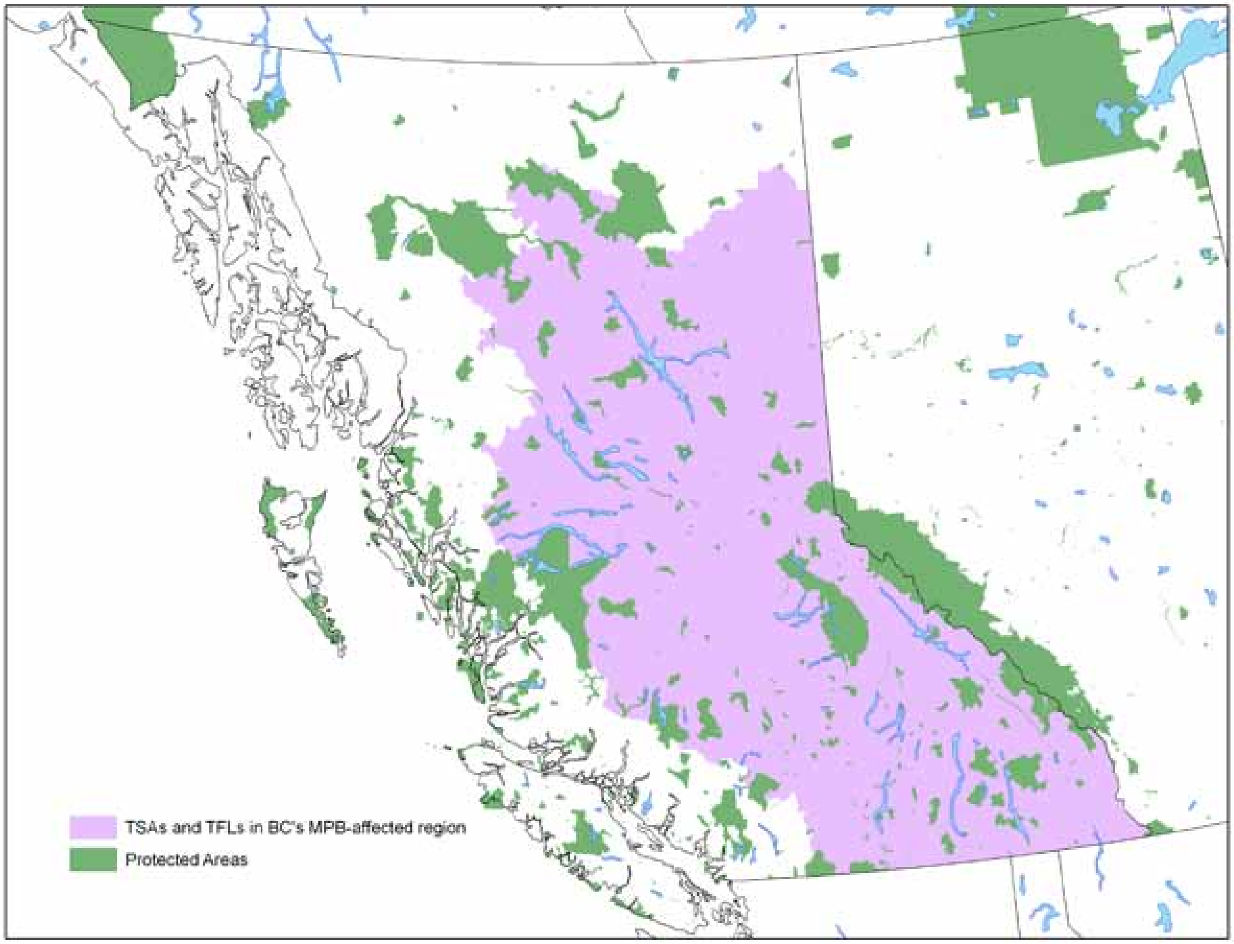

Figure 3. TSAs and TFLs in BC's MPB-affected region.

The actual volumes harvested in these areas increased in response to the uplifts, though market conditions have more recently led to a decline in harvesting. Figure 4 shows annual rates of timber harvesting in approximately this same region, broken down by lodgepole pine versus other tree species. The total volume harvested rose from approximately 47 million m^3 in 1998 to nearly 60 million m^3 in 2005, and the proportion of pine in the total harvest rose from approximately 40% to over 60%. By 2008, harvesting had declined back to approximately 45 million m^3 per year, though the proportion of pine has remained in excess of 60% since 2005.

Within the Montane Cordillera ecozone (which covers an area that is slightly larger but roughly corresponding with that shown in Figure 3), pine-leading forests cover over 10 million ha and approximately 33% of the total forest area (CFS 2009). The predominance of pine within this region varies considerably and in particular, some forests within the "Interior Wet-belt" and high-elevation areas contain little or no lodgepole pine. Pousette and Hawkins (2006) estimated that in the Prince George TSA, stands with greater than 70% pine contain approximately 280 million m^3 of merchantable volume, which accounts for some 40% of the current merchantable volume in the TSA. These stands are considered the most vulnerable to the beetle: it is estimated that 200 million m^3 of it could be killed by the end of the outbreak. However, pine also occurs in many stands dominated by other species, and Pousette and Hawkins (2006) estimate that the Prince George TSA contains roughly 30 million m^3 of pine volume dispersed through stands containing less than 50% pine. Estimates for the William's Lake TSA (BCMFR 2006a) show similar patterns of lodgepole pine occurrence. Stands with greater than 70% pine account for 115 million m^3 of merchantable volume (110 million m^3 of which is pine), while a further 11 million m^3 of pine volume is dispersed through stands with less than 70% pine.

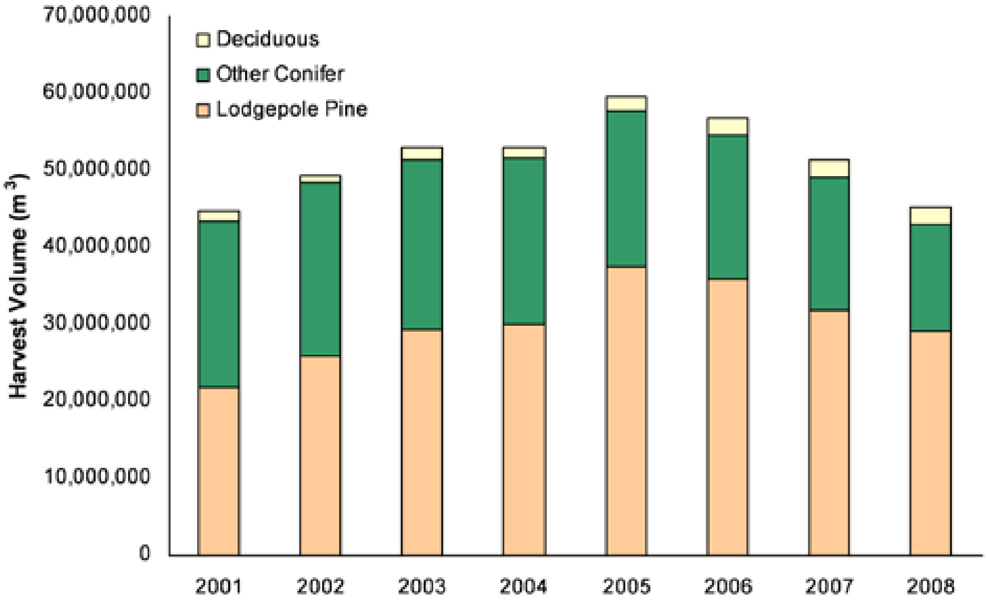

Figure 4. Timber Harvesting in BC's MPB-affected region. Harvest volumes reported for the Southern Interior Forest Region, plus the Mackenzie, Peace, Fort St. James, Prince George, Vanderhoof and Nadina Forest Districts. (Source: BC Ministry of Forests and Range Harvest Billing System www.for.gov.bc.ca/hva/hbs/). Although this area roughly corresponds with the area for which AACs are shown in Figure 2, harvest volumes in Figure 4 include those from Woodlot Licenses and private land, and so are not directly comparable with AACs in Figure 2. The Bulkley TSA is also excluded from the volumes shown in Figure 4.

Despite the apparent predominance of vulnerable pine-dominated stands in BC's Interior, much of this area is unlikely to be salvaged, even with aggressive salvage strategies. Existing forest legislation requires that harvest units be designed to protect sensitive ecosystems and retain some forest cover across the overall landscape. Retaining some standing trees within harvest blocks is also a standard requirement in operational plans. In particular, reserves in riparian areas (adjacent to major streams, lakes, and wetlands) are now a well-established requirement in harvest planning. Under BC's *Forest Planning and Practices Regulation,* in-block retention levels must average at least 7% (as measured by averaging all blocks harvested by an agreement holder within a one-year period) as well as a minimum of 3.5% of the area of each individual block. (Individual companies may use alternative strategies for wildlife tree retention if they are part of an approved Forest Stewardship Plan.) As salvage harvesting gathered momentum in BC, Eng (2004) made a series of recommendations to encourage more tree retention in stands: at least 10% retention (by area) in blocks smaller than 50 ha; 10%–15% retention in blocks 50–250 ha; 15%–25% retention in blocks 250–1000 ha; and 25% retention or more in blocks larger than 1000 ha. These recommendations were endorsed in a December 2005 letter from BC's Chief Forester, which provided further strategic direction to promote the retention of forest structure at both the stand and landscape level. Regional or district-specific guidelines also exist that provide other guidance, such as minimum distances between retention areas (e.g., Klenner 2006; Cariboo-Chilcotin Land Use Plan Biodiversity Conservation Strategy Committee 2005). A recent study (FPB 2009) found that these guidelines have been followed within new harvest openings, although in areas where salvaging has combined with past harvesting to create very large openings, retention levels may still be lower than recommended.

At the landscape level, other constraints also exist to ensure that old forest remains in commercial forest areas. In some areas, regional land-use plans or other higher-level plans specify these constraints. Where such planning has not taken place, BC's Non-Spatial Old-Growth Order (BCMFR 2006b) establishes default targets for old-growth retention in each of the province's landscape units, and the age at which forests are considered "old" is defined for each biogeoclimatic zone within generalized natural disturbance types (NDTs). For example, in most NDT 3 (forests with frequent stand-replacing disturbances), forest stands older than 140 years are considered oldgrowth, and old forest retention targets range from 7%–21% (depending on the biogeoclimatic zone and the level of "biodiversity emphasis"). The order also recognizes the challenges associated with maintaining landscape-level old-growth inventories in some areas due to "forest health or catastrophic events" (such as MPB) and requires recruitment strategies that re-establish old-growth areas in a timely manner.

Furthermore, parks and protected areas limit commercial forestry and most other industrial development from large areas of BC's forests. Special management zones are also significant in BC, allowing some limited commercial activity but with a strong priority on the conservation of non-industrial values. Currently, parks cover more than 13 million ha in BC (roughly 14% of the landbase) and special management zones cover an even greater area (Forestry Innovation Investment 2009). According to Environment Canada (2006), 16.5% of the Montane Cordillera ecozone (BC and Alberta) is under some form of protected status.

4. Reforestation in British Columbia

In BC's public forests, reforestation is required virtually everywhere commercial timber harvesting takes place. Reforestation is part of the wider field of silviculture, which encompasses *"The theory and practice of controlling the establishment, composition, growth, and quality of forest stands to achieve the objectives of management."* (Forestry Canada 1992, p.53). Even-aged management initiated through clearcutting[4] is the most common silvicultural system in BC, largely due to its operational efficiency and the reliability with which productive conifer stands can be established in clearcut areas. Economics, forest health considerations, simplicity, and tradition have also contributed to widespread use of the system. Particularly in the BC Interior, the parallelism between clearcutting and stand-replacing natural disturbances has provided a strong basis for its ongoing use, given the natural role of stand-replacing fires in many interior forest ecosystems.[5]

Other even-aged silvicultural systems are sometimes employed in BC, such as shelterwood or seed-tree systems (where mature trees are left standing to provide shelter for shade-requiring tree species or as a seed source for natural regeneration). Uneven-aged management (i.e., single-tree selection or group selection) is also practiced in some ecosystems, especially where this strategy mimics natural stand-level dynamics (e.g., interior Douglas-fir stands). Partial-cutting systems may also target one or more species within mixed species stands. For example, in areas affected by MPB, partial cutting has been used to remove vulnerable or already infested pine trees, while leaving non-pine species to provide future harvest volumes (e.g., Nishio 2009).

Since 1988, holders of major public forest tenures[6] in BC have been responsible both operationally and financially for reforestation within their operating areas, and are required to ensure harvest areas are stocked within a specified time, normally within 3–6 years (Weetman and Mitchell 2005). Furthermore, operators are also required to ensure that areas meet "free-growing" standards within a specified time (normally within 8–20 years) (Weetman and Mitchell 2005). Free-growing generally refers to stands that are fully stocked with commercially valuable species and which have grown above the height of surrounding vegetation. Free-growing standards and deadlines are established according to region-specific guidelines published by the BC Ministry of Forests and Range (e.g., BCMoF 2000) and are formalized within individual forest development plans and site plans. As newly established stands develop towards free-growing, stand tending may be required to prevent overstocking or to suppress competing vegetation. Regular field surveys are conducted following stand establishment to assess whether such intervention is needed. Before reforestation obligations can be considered met, field surveys are required to empirically demonstrate that stands have indeed met free-growing criteria.

The costs associated with producing a free-growing stand are estimated in the BC Ministry of Forests and Range's Interior Appraisal Manual (BCMFR 2008). Costs are estimated for 156 ecosystem types in BC, and range from as little as $28/ha in the Ponderosa Pine biogeoclimatic zone to as high as $2765/ha in the very wet cold subzone of the Engelmann Spruce–Subalpine Fir zone (ESSFvc). Hawkins et al. (2006) reported recent reforestation costs on two study sites in the BC Interior under a variety of site preparation options. Total costs (site preparation, seedling and planting costs) ranged from $1050/ha to $2042/ha (in 2000 Canadian dollars). Recent estimates of wildfire rehabilitation costs in the southern BC Interior by J.S. Thrower and Associates Ltd. (2005) also provide some useful reference points. They estimated site preparation costs at $475/ha-$962/ha and basic planting costs at $770/ha-$1294/ha, with variation depending on slope and distance from roads. Snag falling, when required, added $100/ha to over $1000/ha depending on slope, distance from roads, and snag density.

In addition to the legal obligation to establish a free-growing stand, forest companies also have other incentives to promote prompt and vigorous regeneration. "Green-up" is a common requirement that constrains harvesting in stands until regeneration in adjacent cutovers has reached 3 meters in average height. In visually sensitive areas, areas of important wildlife habitat, or community watersheds, green-up requirements may be stricter (BCMoF 1999). The performance of regenerated stands is also considered in timber supply analyses, and has a direct impact on estimates of sustainable rates of timber harvesting. In what is known as an "allowable cut effect," improvements in plantation performance can allow for immediate harvest rate increases in volume-regulated forests (Schweitzer et al. 1972; Binkley 1980).

In clearcut areas, the principal methods of reforestation include tree planting, natural regeneration, or a combination of both. Natural regeneration or planting may be facilitated through site preparation involving the use of fire, machinery, chemicals, or manual treatments to modify vegetation, slash, or upper soil horizons. Direct seeding may also be effective in some situations (Thompson 2006), though its use in BC is rare. Natural regeneration is more commonly used in stands managed for western hemlock or lodgepole pine. Given the right conditions following harvesting (i.e., adequate seed supply and favourable seedbed conditions), the reproductive characteristics of these species allow for prompt and widespread natural regeneration. Still, planting is often preferred due to its reliability in terms of the reforestation obligations of public forest tenure holders.

In addition to planting and natural regeneration, existing understorey trees (known as advance regeneration) may also contribute to stand regeneration. However, in many cases, advance regeneration may be considered unsuitable due to the presence of decay agents, the expectation that harvesting will cause unavoidable damage, or doubts that residual trees will "release" after long periods of stagnation under the pre-existing canopy. Weetman and Mitchell (2005) summarize current acceptability guidelines for advance regeneration in BC by biogeoclimatic (BGC) zone. Of the 16 species considered across 11 BGC zones, only the Ponderosa Pine BGC zone and Interior Douglas-fir BGC zones contain species (ponderosa pine and Interior Douglas-fir) that are considered "usually acceptable." Other species including interior spruce (white spruce, Engelmann spruce, and their natural hybrids) and subalpine fir are considered "sometimes acceptable" across a wide range of ecosystems. In general, the success of advance regeneration in meeting reforestation obligations depends on: (1) abundance, quality, and distribution prior to harvest; (2) avoidance of damage during harvest and post-harvest treatments; and (3) the ability of advance regeneration to adapt and survive following overstorey removal (Herring and McMinn 1980; Puttonen et al. 1997; Parish and Antos 2005). Weetman and Mitchell (2005, p.414) advise,

"Use of advanced growth gives assurance of species composition, is cost-effective, saves time by telescoping the location, and produces trees with small juvenile cores....foresters should consider whether the preferred species are present, the health, vigour and size of the advance regeneration. Smaller trees typically release better than larger trees. Trees that are growing faster in height before harvest typically show better release than slower growing trees."

Research into the viability of advance regeneration has shown encouraging results (e.g., Herring and McMinn 1980; Navratil et al. 1994; DeLong 1996; Puttonen et al. 1997; Parish and Antos 2005); however, understanding of the long-term performance of advance regeneration across the full range of BC ecosystems is still far from complete.

4.1 Silvicultural Options in MPB Stands

A considerable body of literature on silvics, silviculture, and reforestation in BC examines these topics in light of the current MPB outbreak. While salvage areas will likely continue to regenerate successfully and predictably under the basic silviculture obligations of forest licensees, the future development and yield from unsalvaged stands is less certain, and is currently a major topic of interest. For example, Kimmins et al. (2005) suggest that on some sites (typically those with poor productivity), future stand trajectories may be fairly predictable, while on others (typically richer sites) outcomes may vary widely and may be much more difficult to predict. Understorey conditions also play an important role. In beetle-killed stands with well-established understoreys, shrub or herb cover may dominate for long periods following pine mortality, impeding tree regeneration (Kimmins et al. 2005). In general, future stand trajectories depend on factors that include ecosystem type, initial stand conditions (including those in the understorey), the degree of beetle-induced pine mortality, and the presence of seed sources (Kimmins et al. 2005; Mitchell 2005).

Using the stand-level model SORTIE-ND, Coates and Hall (2005) simulated post-beetle stand development in several stand types. Results demonstrated that natural regeneration in pine-dominated stands may be heavily constrained by seedbed limitations and shading from residual dead-standing trees (in contrast to regeneration in fire-killed stands where most of the overstorey needles and fine branches are destroyed and optimal seedbeds are prepared during the fire). However, stands with a residual spruce overstorey or advance regeneration were predicted to release well following beetle infestations. Coates and Hall (2005) also suggest that if left unsalvaged, these stands may develop quickly enough to provide medium-term timber supply (in the next 10 to 50 years). The authors recommend that salvage harvesting in mixed-species stands should avoid damaging residual non-pine trees, or that salvaging in these stands be avoided altogether. When under-planting was simulated in pine-dominated beetle-killed stands, survival improved when planting was delayed until understorey light conditions improved. However, the authors note that safety concerns and increased understorey brush may make delayed underplanting impractical. An estimated 40% or more of pine-dominated stands in the Northern Interior could contain enough advance regeneration to allow for adequate post-beetle stocking (Burton 2006; Coates et al. 2006). However, Griesbauer and Green (2006) caution that reliance on advance regeneration may result in clumpy and/or patchy stocking in many areas and that much of the advance regeneration is dominated by subalpine fir, which is typically considered less favourable for timber production. They also conclude that the long-term consequences of these conditions must be carefully weighed against the costs of silvicultural treatments that aim to manipulate the stocking or species composition of unsalvaged stands. Rakochy and Hawkins (2006) also noted that worker safety must be carefully considered before applying silvicultural treatments to unsalvaged stands.

More recent studies (Astrup et al. 2008; Vyse et al. 2009) confirm that many unsalvaged areas will likely regenerate to subalpine fir, and that substantial regeneration delays may occur in stands without advance regeneration, due to unfavourable seedbed conditions and overstorey shading. In other areas, repeated MPB attacks in the past have helped to create multi-age stands that will have fewer regeneration concerns (Axelson et al. 2009).

Mitchell (2005) reviewed regeneration techniques with specific reference to areas that may be left unsalvaged after the current beetle outbreak. Some key issues found in Mitchell (2005) include:

- Favourable seedbed conditions are required for natural regeneration, although these may not exist in unsalvaged stands unless fire subsequently occurs or until dead trees begin to topple over. The time required for trees to topple is mostly driven by the effects of light, temperature, wind, and moisture conditions on rates of bole decay. Trees may fall in as little as three years, but in some areas they may not begin to fall for a decade or more. This may exceed the time in which seed from the dead pine remains viable, limiting the success of natural regeneration.
- Douglas-fir, spruce, and subalpine fir advance regeneration may also release in unsalvaged areas, although advance regeneration is not present in all stands. Stands lacking advance regeneration are typically pure or near-pure pine stands. If fire does not occur in these stands after the beetle infests them, they may only regenerate slowly and at low densities. If these stands are not salvaged, restoration work may be needed if prompt regeneration is desired.
- Overall, natural regeneration is the most cost-effective regeneration method, though cost-effectiveness depends on the need to remove the overstorey, the need for site preparation, and the risk that fill-planting or other stand-tending activities will be required. Direct seeding may also be a cost-effective method, although this depends heavily on germination success.
- Where overstorey removal is required for restoration, this may be achieved through mechanical means (e.g., using feller-bunchers or by toppling, crushing, and/or piling with other machinery) followed by site preparation (e.g., drag-scarification or disc trenching). Costs and feasibility vary widely depending on the size of the area to be treated, accessibility, terrain, and stand conditions.
- Prescribed burning may also be used to treat unsalvaged stands. This treatment will have the added benefit of releasing pine seed from serotinous cones, allowing for natural regeneration. However, seed from non-pine species (and presumably any new germinants or advance regeneration) will likely be destroyed. Prescribed burning may not result in adequate mineral soil exposure, and complete stocking may not always occur.

Mitchell (2005) concludes by suggesting that a range of strategies will be required in unsalvaged areas, from leaving stands to natural processes, to more intensive interventions that include residual tree removal, site preparation, planting, or direct seeding.

However, Burton (2006) argues that in most cases restoration work in unsalvaged MPB areas is not needed for ecological reasons and that even where timber management objectives predominate, calls for restoration work may be largely misguided. In particular, we may do more harm than good if stands with residual non-pine volumes are replaced with younger lodgepole pine plantations, which will do little to mitigate medium-term timber supply shortages and furthermore, may set the stage for future epidemics. Pearce (2005) points out that while spruce is generally preferable for reforestation, some pine reforestation will be prudent given the shorter rotations on which pine plantations can be managed. Pearce (2005, p. 30) acknowledges that *"Further studies are needed to define the best mix of species to balance reforestation/rehabilitation costs, mid- and long-term timber supply needs, and pest management goals."* Clearly, there is a need for further exploration of the issue of salvaging, rehabilitation, reforestation, and the associated economic tradeoffs at both the stand and landscape level.

Based on the above, Table 2 summarizes the major assumed benefits, risks, and tradeoffs associated with choosing to salvage/rehabilitate beetle-affected areas versus leaving them to natural processes.

Table 2. Benefits, risks, and tradeoffs associated with salvage/rehabilitation versus no-treatment in MPB stands.

Issue	Salvage/Rehabilitate		No Treatment	
	Assumed Benefit	**Risks or Tradeoffs**	**Assumed Benefit**	**Risks or Tradeoffs**
Regeneration Timing and Stocking	Prompt regeneration and full stocking are highly likely.	If advance regenerationis present, this may be destroyed during salvage, increasing the time required to produce the next merchantable stand.	Stocking with naturals of a desirable species, especially if rapid stand breakup or fire creates site conditions that facilitate regeneration.	Regeneration may be delayed by shading or unfavorable seedbed. Regeneration density may be too low or clumpy. Advance regeneration may be at risk from fires due to the overstorey of dead pine.
Species Composition and Future Stand Resilience	Establishment of a diverse and resilient future stand with a high probability of providing long-term timber values. Seed provenance and species choices may even promote resilience to future climate change.	Even-aged stand may be vulnerable to future forest health concerns, especially if lodgepole pine is the only viable species choice under post-harvest site conditions.	Natural or advance regeneration is diverse and is mostly non-pine, creating a productive and resilient stand.	Extensive fires may create large areas of vulnerable pine monocultures. Natural or advance regeneration in areas not burned may consist primarily of less desirable species such as subalpine fir.
Non-timber Benefits	Risks to non-timber benefits are minimized through careful planning and access management. Risks to some non-timber benefits from fire may even be reduced through well-planned salvage harvesting.	Operational constraints, the need for extensive road development or a rushed approach to planning, may create risks to the maintenance of non-timber benefits. Widespread losses of stand-level structure and an accelerated shift towards young, even-aged stands may compromise non-timber benefits.	Natural processes in post-beetle stands will minimize risks to non-timber benefits. Roadless areas of dead pine will transition towards a regenerated state at varying rates, providing diverse stand structures and habitats that deliver multiple ecological and social values.	Elevated fire risk in untreated stands may lead to extensive fires that create risks, such as further reductions to the area of late seral forest on the landscape.
Timber Supply	Ensures site continues to contribute to long-term timber supply. Successful avoidance of advance regeneration or non-pine overstorey may provide critical mid-term timber supply.	Newly established even-aged stand may do little to mitigate mid-term timber supply shortages. Significant by-catch of unaffected trees may exacerbate future timber supply fall-down.	Successful release of advance regeneration or non-pine overstorey which provides critical mid-term timber supply. At a minimum, natural regeneration keeps site productive for long-term timber supply.	Regeneration may be inadequate, clumpy and/or consist of less desirable species with little long-term timber supply benefits.
Profitability and Costs	Profitable timber harvest which offsets regeneration and access costs, and avoids costly future interventions.	Low or negative profits due to poor markets, degraded timber or expensive access. Additional harvest volumes may negatively impact already over-supplied and depressed timber markets.	Avoids harvesting in marginally profitable stands, and avoids expensive rehabilitation treatments in stands with a capacity to naturally regenerate.	Expensive future silvicultural interventions may be required due to clumpy or inadequate stocking or undesirable species composition. Operational and safety issues due to dead standing timber may make future treatments more costly or infeasible.

In pine-leading stands with heavy beetle-induced mortality, the choice is essentially one between clearcut harvesting with retention or leaving the stand to natural processes. In mixed stands, partial cutting strategies may also be employed that involve dispersed removal of pine from mixed species stands or small patch harvesting of scattered groups of dead trees. Several significant areas of uncertainty exist with the outcomes associated with these choices. For example, the presence and performance of advance regeneration may play a major role in the time required to reach a regenerated state. Where advance regeneration is insufficient, the timing and density of natural regeneration in the absence of harvest is another key area of uncertainty. The future development and yields from all stands are subject to uncertainty. However, stands originating from traditional harvesting or a "two-pass" system in mixed stands likely have the least long-term uncertainty.

Salvage strategies are primarily aimed at recovering timber values, although hazard mitigation and the maintenance of long-term site productivity may also be important objectives.[7] For example, a pine-only removal treatment with no subsequent overstorey removal may be prescribed in stands where non-timber objectives predominate, and the removal of pine is primarily aimed at reducing risks. Fire risks to timber and/or non-timber values in beetle-affected stands must also be considered, and may represent another important motivation for salvaging. Furthermore, prescribed burning has been suggested as an alternative to harvesting where fire hazard mitigation is required, but where harvesting is impractical for economic or environmental reasons (Lindenmayer et al. 2008).

In BC, recent experience suggests that beetle-killed stands are more vulnerable to long-distance spotting and crown fires. Subsequent decreases in crown fuel continuity during stand break-up will reduce this risk, at the same time increasing potential surface fire intensity and flame length (Taylor and Lavoie 2008; Harvey and Duffy 2008). Furthermore, Kaufmann et al. (2008, p.9) point out, *"…fire intensities under these conditions could cause high mortality of young trees that survived or regenerated after the mountain pine beetle attack. If widespread fire mortality occurs before trees have matured to cone production age, rapid re-establishment of lodgepole pine on this site is less likely."* Although the magnitude of these risks in beetle-killed stands is difficult to quantify, it does seem reasonable to conclude that some elevated risks from pine mortality will occur.

5. Economic Evaluation of Stand-Level Salvage Harvesting Decisions

Economic evaluation of stand-level salvage decisions range from simple to complex depending on stand characteristics and the scope of values considered. From a purely economic perspective, the management strategy that generates the greatest net value (benefits minus costs) is the best strategy. However, in practice, uncertainty regarding management outcomes or the difficulty of evaluating many non-timber benefits (e.g., ecosystem services, social values, or maintenance of traditional land uses) confounds the analysis. Even in the absence of uncertainty and un-priced values, evaluating the problem solely from a timber management perspective can involve several tradeoffs between current stand values and future values. Given the variety of stand conditions and the numerous tradeoffs, there is no single guideline but instead a range of physical and economic conditions within which one management strategy will likely be favoured.

In evaluating the problem from a timber value perspective only, there are five key ingredients to consider. First is the proportion of mature pine in the stand: if the entire stand is dead mature pine, then the decision rests on the value of the dead timber and land value (Land Expectation Value). The proportion of living mature pine is another possible factor: if part of the stand is living (and is expected to remain so), then the option of partial harvesting presents itself. Third, the stand may contain other mature commercial species, in which case partial cutting or leaving the stand for a future clearcut harvest are possible options. Additionally, the stand understorey may have advance regeneration of commercially valuable species. In this case, consideration of the future value of this component of the stand must be included in the calculations. Finally, in the context of continuous forestry, the value of the land in forestry must also be considered. If the land has another possible and higher valued use, such as in agriculture, the land value associated with this alternative activity may be used in the analysis.

In summary, analysis of the economic benefits and costs of salvage-reforestation options may include the following sources of value:

1. Dead pine
2. Live pine
3. Other live and merchantable mature species
4. Live and merchantable species in the understorey
5. Land (including value in another land activity)

The structure of the stand can largely determine the scope of management options that will likely need to be evaluated.

Pure pine stand

Evaluating the salvage and reforestation decision on a commercially mature stand of pure pine that is 100% dead simply involves calculating the stumpage value of the dead standing timber and the land value. If the timber and land value exceed the value of the stand left un-harvested, then salvage the stand. The difficult part of this problem is to determine the value of the stand if left unharvested. If the standing timber value is negative (due to the dead stand depreciating), it still may be optimal to harvest the stand if the land value is sufficiently high or if current stand conditions constrain its ability to regain its productive capacity, such as sites of very high productivity situated close to processing centres. The data required to conduct this analysis include: log values, harvesting costs (including transport costs if evaluated at a mill instead of at the stand), land productivity, discount rate, and harvest wait time in the case of a no-harvest decision.

The problem is to calculate the benefits and costs for each management option and then choose the one with the greatest net benefits. Mathematically, the calculation is

Equation 1

$$\mathrm{B} = \max\left\{ S_S + W^*\,;\ \frac{S_L + W^*}{(1+r)^t} \right\}$$

where S_S is the value of salvaged dead timber (price of salvage logs minus harvesting costs times volume), S_L is the value of the stand left unsalvaged and harvested later at time *t, r* is the discount rate[8], and *W** is the land expectation value (LEV)[9]. The largest value within the curly brackets is the optimal salvage and reforestation strategy (B). If the first term in the brackets is larger than the second, then salvage the stand; if the second term is larger, then leave it intact.

Mixed stand

If other mature species are present, or if some of the pine survived, the analysis is more complicated due to the option to partially harvest the stand.

The basic options are:

1. Harvest the entire stand (one pass, both pine and non-pine)
2. Harvest the dead timber and harvest the rest later (two passes)
3. Leave the stand and wait for future harvest (one pass, though dead pine may have little or no commercial value)

Mathematically, the analysis can be expressed as

Equation 2

$$\mathrm{B{=}max}\left\{ S_s + W^*\,;\ S_{sp} + \frac{S_0 + W^*}{(1+r)^{t^*}}\,;\ \frac{S_{S0} + W^*}{(1+r)^{t^{**}}} \right\}$$

where S_{sp} is value of salvaged dead timber using partial-harvesting methods, S_o is the value of live mature timber harvest, S_{so} is the value of the dead and live mature timber, and multiple * indicate various optimal values of harvest time (t).. The largest value within the curly brackets is the optimal salvage and reforestation strategy.

Advance regeneration in understorey

If we consider a stand where advance regeneration in the understorey exists, the options are similar to the mixed stand case above, except the time between partial harvests is likely to be greater and the expected growth and yield are more uncertain.

The basic options are:

1. Harvest the entire stand (one pass, with value from dead pine only)
2. Harvest the dead timber now and then harvest the advance regeneration later (two passes)
3. Leave the stand until advance regeneration reaches merchantable age, then harvest stand, including all original overstorey (one pass, though dead pine may have little or no commercial value)

Note that advance regeneration under option (2) may perform poorer than under option (3) if significant logging damage occurs or if residual live trees do not adapt well post-harvest. Alternatively, option (2) could enhance the advance regeneration if there is minimal logging damage and overstorey removal facilitates advance regeneration release. Option (1) assumes that advance regeneration is destroyed during harvest and future rotations require planting. However, future rotations under options (2) and (3) could be established by using a subsequent cohort of advance regeneration. Mathematically, the analysis can be expressed as

Equation 3

$$\mathrm{B{=}max}\left\{ S_s + W^*\,;\ S_{sp} + \frac{S_{ar} + W^*}{(1+r)^{t^{**}}}\,;\ \frac{S_s + S_{ar} + W^*}{(1+r)^{t^{***}}} \right\}$$

where S_{ar} is the value of advance regeneration. Again, the largest value within the curly brackets is the optimal salvage and reforestation strategy.

Mixed species overstorey and advance regeneration

If the stand is mixed species and has advance regeneration, the scope of management options expands again. The options are likely to be:

1. Harvest entire stand now (one pass)
2. Harvest dead timber now and harvest other mature (and any advance regeneration that may have reached merchantable size) later (two passes)
3. Harvest dead timber and other mature trees now and harvest advance regeneration later (two passes)
4. Harvest dead timber now, harvest other mature trees later, harvest advance regeneration in a final harvest (three passes)
5. Leave the stand until advance regeneration reaches merchantable age, then harvest, along with any remaining pre-existing mature timber (one pass)

Options (1) and (2) assume that advance regeneration is destroyed during harvest and future rotations require planting. However, future rotations under options (3), (4), and (5) could be established by using a subsequent cohort of advance regeneration.

It is clear that the more structural components in a stand, the more management options there are and the richer the economic evaluation. To get a better sense of the practical weight of the components of the salvage-reforestation decision in the context of the BC Interior and the current MPB outbreak, three case studies are presented: a stand with advance regeneration in the understorey, a stand with negative standing timber value, and a mixed stand. Unless stated otherwise, all analyses are conducted from the perspective of the landowner, not the user of the resource, and only account for timber-related values.

Equation 4

$$B=\max\left\{ S_s + W^*; S_{sp} + \frac{S_o + S_{ar} + W^*}{(1+r)^{t^*}}; S_{sp} + S_{op} + \frac{S_{ar} + W^*}{(1+r)^{t^{**}}}; S_{sp} + \frac{S_{op}}{(1+r)^{t^{**}}} + \frac{S_{ar} + W^*}{(1+r)^{t^{***}}}; \frac{S_{so} + S_{ar} + W^*}{(1+r)^{t^{****}}} \right\}$$

where S_{op} is the value of live and dead mature timber of the original stand overstorey harvested by partial cutting methods. Again, the largest value within the curly brackets is the optimal salvage and reforestation strategy. Note that the values of S_{sp} and S_{op} can vary among each option in proportion to the care taken to not compromise S_{ar} (and there may even be constraints to S_{sp} so as not to compromise S_o under the deferral options).

5.1 Scenario 1: Salvaging MPB-killed Pine with Understorey Advance Regeneration

Assume there is a pine stand containing advance regeneration that has the capacity to release and develop into a merchantable stand following MPB mortality. A planted stand on the same site will also develop into a valuable stand, but initial growth will be slower due to the time required for early stand development that involves little merchantable increment. Figure 5 shows the merchantable volume over time that might be expected from these two regeneration pathways on the same site.

Although the planted stand produces a larger volume of timber over the long term, the stand of released advance regeneration yields higher merchantable volumes until approximately Year 90. However, now assume that the existing overstorey also has some salvageable volume, but this volume is subject to decay. Assuming an initial merchantable overstorey salvage volume of 300 m^3/ha, and a straight-line decay function spread over 20 years, the available volume in this stand would decline initially, but then recover as the advance regeneration grows. In this stand, we assume there is a choice to be made between salvaging and planting, or allowing the existing overstorey to decay, releasing the advance regeneration for a future harvest. The relative merits of each choice depend on the expected yields from the overstorey, advance regeneration, and planted stand, but also on costs and expected revenues from current and future rotations. Discount rates also influence the decision. Initially we assume that salvage timber sells for \$5/m^3, all other harvested timber sells for \$20/m^3 (i.e., harvests from advance regeneration or planted stands), and that there are no costs associated with bringing the stand into production (i.e., planning, harvest, and reforestation costs are borne by an operator who is willing to pay our assumed stumpage rate after covering these costs)[11]. Furthermore, we assume all costs and revenues are discounted at 3%.

Under these assumptions, the value of the bare land itself is approximately \$448.63/ha (based on an infinite series of planted stands managed on a 72-year rotation). The existing volumes present on the site have a current value of \$1500/ha, which, along with the site value, give a total NPV of \$1948.63 when salvaging is chosen. On the other hand, if we choose not to salvage, the advance regeneration will yield a harvest that will be worth approximately \$2940/ha in 58 years.

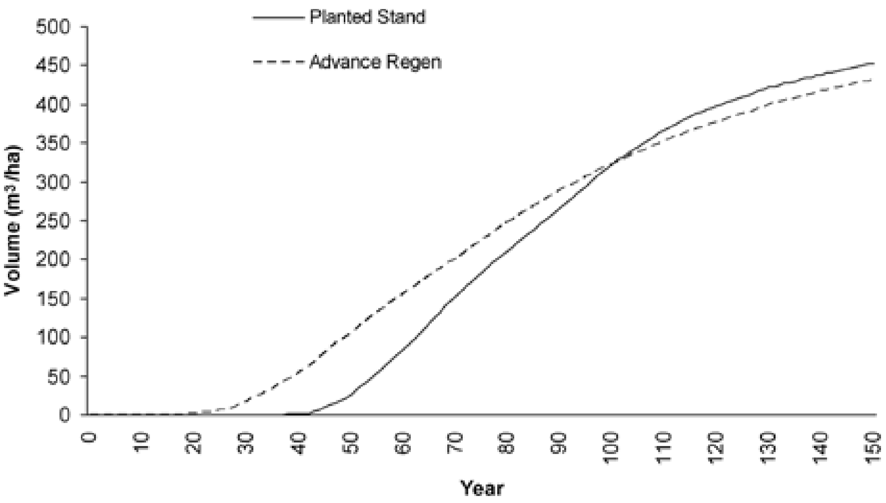

Figure 5. Expected yield for advance regeneration and planted stands on a hypothetical site. Yield data obtained from BC Ministry of Forests and Range's TIPSY software (BCMoF 2005) based on spruce stands on a pine site[10] with site index (SI) 15. Advance regeneration is assumed to develop as if it were a 35-year-old natural stand that initiated at 1000 stems/ha. The planted stand is assumed to initiate at 1600 stems/ha.

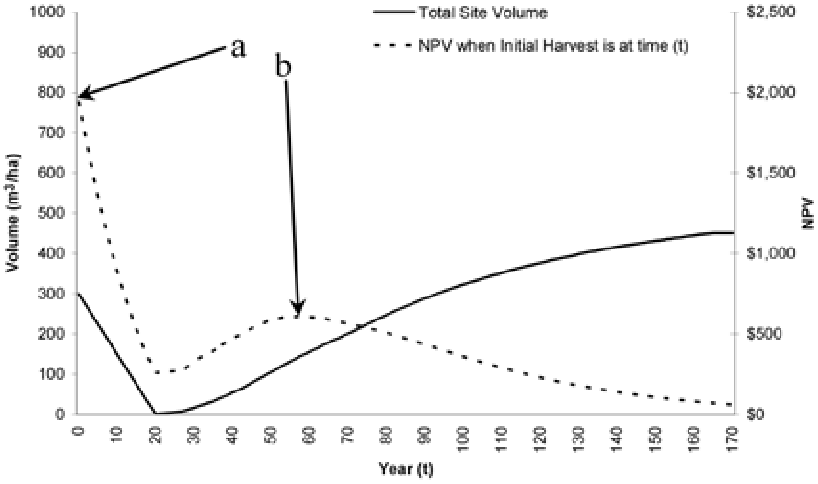

Figure 6. Stand volume (left-hand scale) and net present value (NPV) (right-hand scale) of a hypothetical site (300 m^3 of initial salvage volume) across a range of initial harvest years. Point (a) indicates the optimal time to salvage; point (b) indicates the optimal time to harvest advance regeneration. Salvage harvesting is the optimal choice in this scenario.

However, when discounted back to the present, the advance regeneration along with the value of future planted stands are worth approximately $610.19/ha. Under these assumptions it is more profitable to salvage the stand and forego the future yields from the advance regeneration. Figure 6 illustrates NPV across a range of initial harvest years, including the optimal time of salvage (Year 0) and the optimal time to harvest advance regeneration if the salvage volumes are foregone (Year 58).

As noted above, this solution is sensitive to many of our assumptions. Perhaps the most obvious factor that may vary between sites is the actual volume available for salvage. By examining a range of available initial salvage volumes while holding all other factors constant, we can determine the threshold where salvage volumes are no longer sufficient to make the salvage and plant option the most profitable choice. We can also explore the impact of the price of salvage timber: as it falls, the threshold volume needed to justify

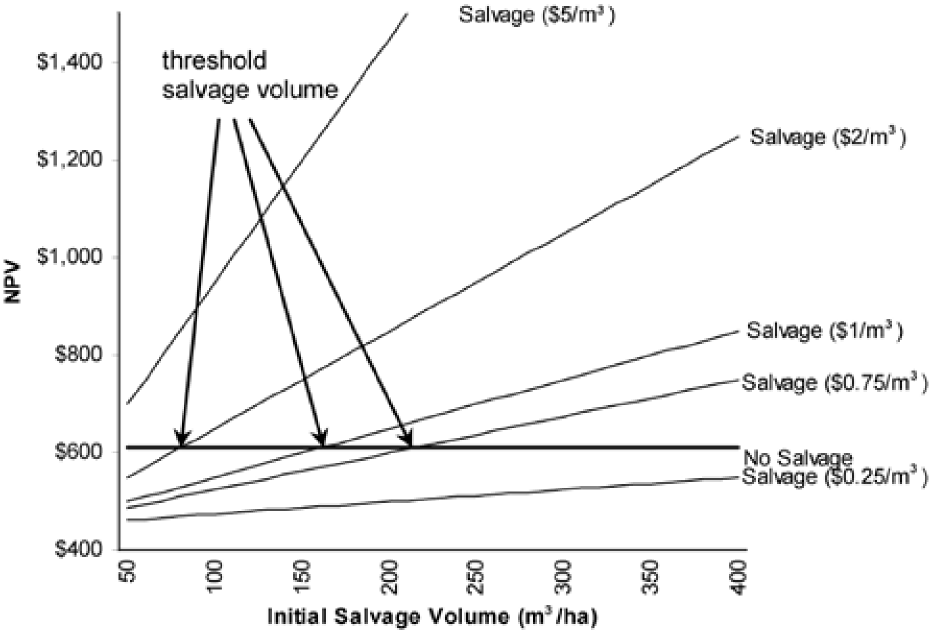

Figure 7. Net present value (NPV) of salvage versus non-salvage across a range of initial salvage volumes and prices for salvaged timber, where the NPV of not salvaging is $610.19/ha.

salvage harvesting is pushed upwards (Figure 7). When the stumpage price of salvage timber is \$5/m^3, any volume within the range we are examining (50–400 m^3/ha) will make salvaging the optimal choice. At \$2/m^3, approximately 90 m^3/ha are needed to make the decision to salvage worthwhile. At \$1/m^3 this threshold rises to approximately 170 m^3/ha, and at \$0.75/m^3, approximately 220 m^3/ha are needed. At \$0.25/m^3 this threshold is pushed beyond the range in Figure 7, to approximately 650m^3/ha.

However, the thresholds demonstrated in Figure 7 hinge largely on our assumptions about advance regeneration performance (Figure 5) and the future revenues that will be available as a result (which we price quite optimistically at \$20/m^3). By delaying the timing of advance regeneration yields, an entirely different picture of this tradeoff emerges. Figure 8 illustrates the effect of an additional 5-year lag in advance regeneration yields. The net present value of the no-salvage option drops to \$526.36/ha, and the threshold volumes required to justify salvaging at \$0.25/m^3, \$0.75/m^3, and \$1/m^3 drop to approximately 320m^3/ha, 100 m^3/ha, and 80 m^3/ha respectively.

This represents an only slightly more pessimistic outlook for the advance regeneration performance than in our base case. Any additional yield reductions would make salvaging the optimal choice at virtually any non-zero stumpage price, as would lowering our expectations for future prices. Conversely, more optimistic assumptions about advance regeneration growth or future prices would widen the range of conditions that make waiting for the advance regeneration the optimal choice. The key point is that the results of an analysis such as this can be highly sensitive to our assumptions about future growth and profitability.

5.2 Scenario 2: Rehabilitating MPB-killed Pine Stands

Where harvesting for forest products is uneconomic (e.g., because access costs are high and/or because timber values have deteriorated), the question shifts from one of salvage to one of rehabilitation. In this situation, rather than receiving positive net stumpage revenues from the treatment, the forest owner (i.e., government) would be required to pay an operator (i.e., licensee or contractor) to access and reforest a stand. Utilization of dead-standing timber may still occur, though this would depend on whether the cost of utilization is less than the cost of alternative means of disposing of the timber on site, such as piling and burning. Dead pine could also simply be left *in situ,* though impacts on planting costs would need to be evaluated and compared with disposal costs. Furthermore, as discussed previously, large numbers of standing or toppled dead trees could pose unacceptable operational constraints or safety hazards. Negative impacts on long-term plantation performance may also occur. On the other hand, the non-timber benefits from these stems could be considerable (Lindenmayer et al. 2008), and these must also be weighed against the costs and benefits of disposal.

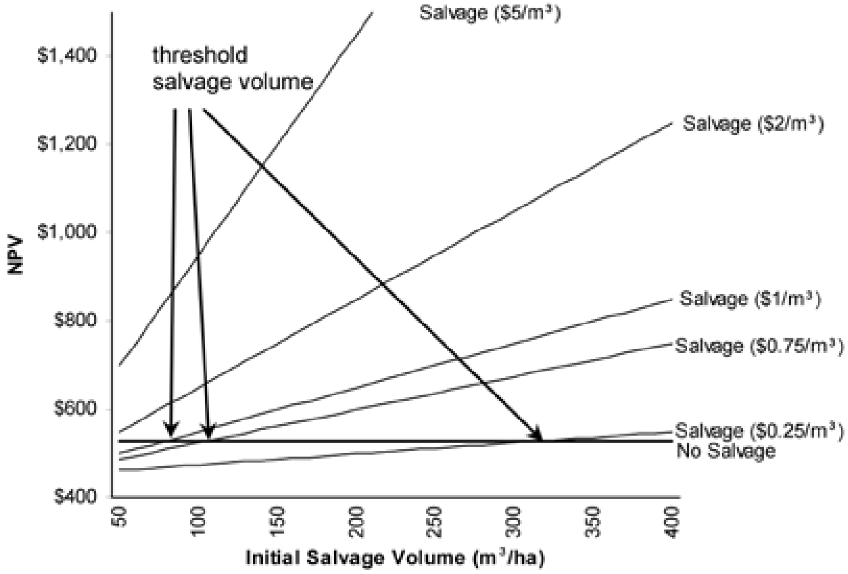

Figure 8. Net present value (NPV) of salvage versus non-salvage across a range of initial salvage volumes and prices for salvaged timber, where the NPV of not salvaging is $526.36/ha.

However, the key issue in any rehabilitation decision would be whether the long-term returns from improved forest growth justify the up-front expenditures. Considering some hypothetical sites again, assume that yields from planted and natural stands follow those shown in Figure 9.

This time, a range of site productivities (site index [SI] 12 to SI 21) are examined. Natural regeneration is assumed to consist of pine[12], whereas planted stands are assumed to consist of spruce (we assume forest managers are compelled to plant non-pine species where possible). Given the same assumptions used in the previous section regarding future prices, and assuming that both natural pine regeneration and spruce reforestation occurs at 1600 stems/ha, Figure 10 demonstrates the maximum expenditures that could be made to achieve the managed stand yields shown in Figure 9, while still breaking even.

Figure 10 shows that, in general, a case for rehabilitation cannot be made unless costs are minimal. When natural regeneration is assumed to consist of 1600 stems/ha of pine that establish after a 5-year regeneration delay (versus 3 years in the planted stand), on SI 21 sites approximately $60/ha can justifiably be spent, although this amount declines with decreasing site productivity. On SI 12 sites only $30/ha may be spent. Beyond these thresholds, the NPV of the planted stand begins to fall below that of the no-treatment option. However, as with our previous example, results rest heavily on our assumptions, perhaps the most significant of which is the assumption that natural regeneration will result in full stocking within a minimal regeneration delay. By examining less optimistic assumptions across the same range of site indices, we can see that the case for rehabilitation becomes stronger. Figure 10 also shows how these thresholds would change if natural regeneration only produces 500 stems/ha of pine (such as might be the case if post-beetle site conditions impede regeneration) or where natural regeneration only produces 500 stems/ha and an additional 10- to 15-year natural regeneration delay occurs.

On SI 12 sites, when only 500 stems/ha of pine are assumed to regenerate naturally, approximately $110/ha could be spent on rehabilitation. This rises to approximately $130/ha where an additional 10-year regeneration delay is assumed. As under our base-case scenario, these thresholds rise with increasing site productivity. On SI 21 sites, approximately $480/ha could be justifiably spent, or $660/ha where an additional 10-year regeneration delay is assumed. Figure 10 shows that, as we become even more pessimistic about natural regeneration, these thresholds continue to rise (e.g., 15-year regeneration delay). Under an absolute worst-case scenario (indefinite lack of regeneration) our maximum break-even expenditures rise to approximately $210, $440, $760, and $1170 on sites of SI 12, 15, 18, and 21, respectively. It is important to emphasize that these amounts are the maximum that could be spent to produce the full managed stand yields shown in Figure 9, and are not optimum levels of expenditure that have been determined through marginal analysis.

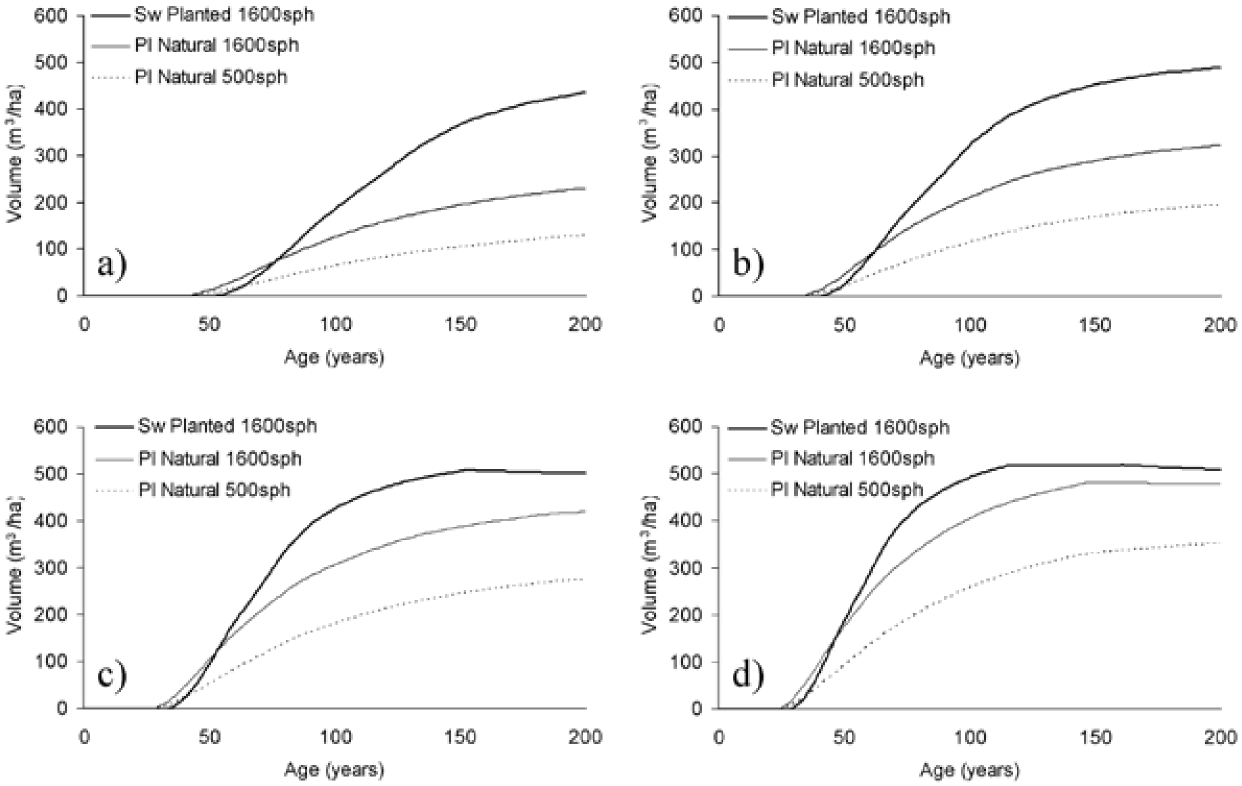

Figure 9. Expected yield for natural regeneration and planted stands on hypothetical sites. Panel (a) SI 12; Panel (b) SI 15; Panel (c) SI 18; Panel (d) SI 21 (See endnote [10] for assumptions used in yield curves). Sw = White Spruce, Pl = Lodgepole pine, sph = species per hectare.

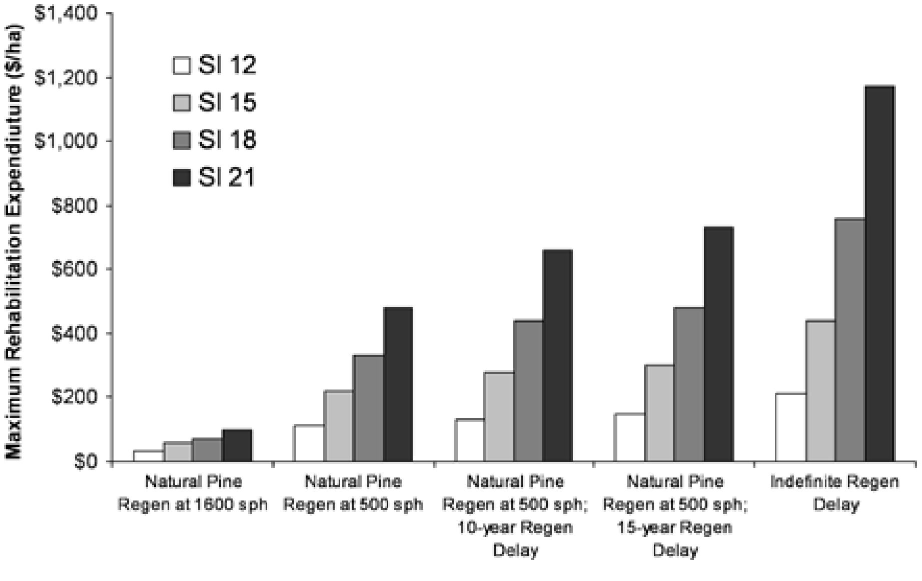

Figure 10. Approximate maximum rehabilitation expenditures that could be justified, based on various natural regeneration (non-rehabilitation) assumptions.

5.3 Scenario 3: Partial Cutting Mixed Stands with MPB Mortality

Finally, we consider the case where a stand with beetle-induced mortality also contains significant non-pine volumes unaffected by the beetle. We can choose to harvest the entire stand now, choose to harvest the entire stand in the future (likely foregoing the dead pine), or choose to harvest only the beetle-affected volumes now, while retaining non-pine volumes for future harvesting. For example, consider a stand with 250 m^3/ha of merchantable volume, half of which is beetle-killed pine, and the other half is non-pine that will not be subject to shelf-life losses. Under the same assumptions in Scenario 1 (SI 15), the timing of harvests and site volumes that might be associated with these three scenarios are illustrated in Figure 11.

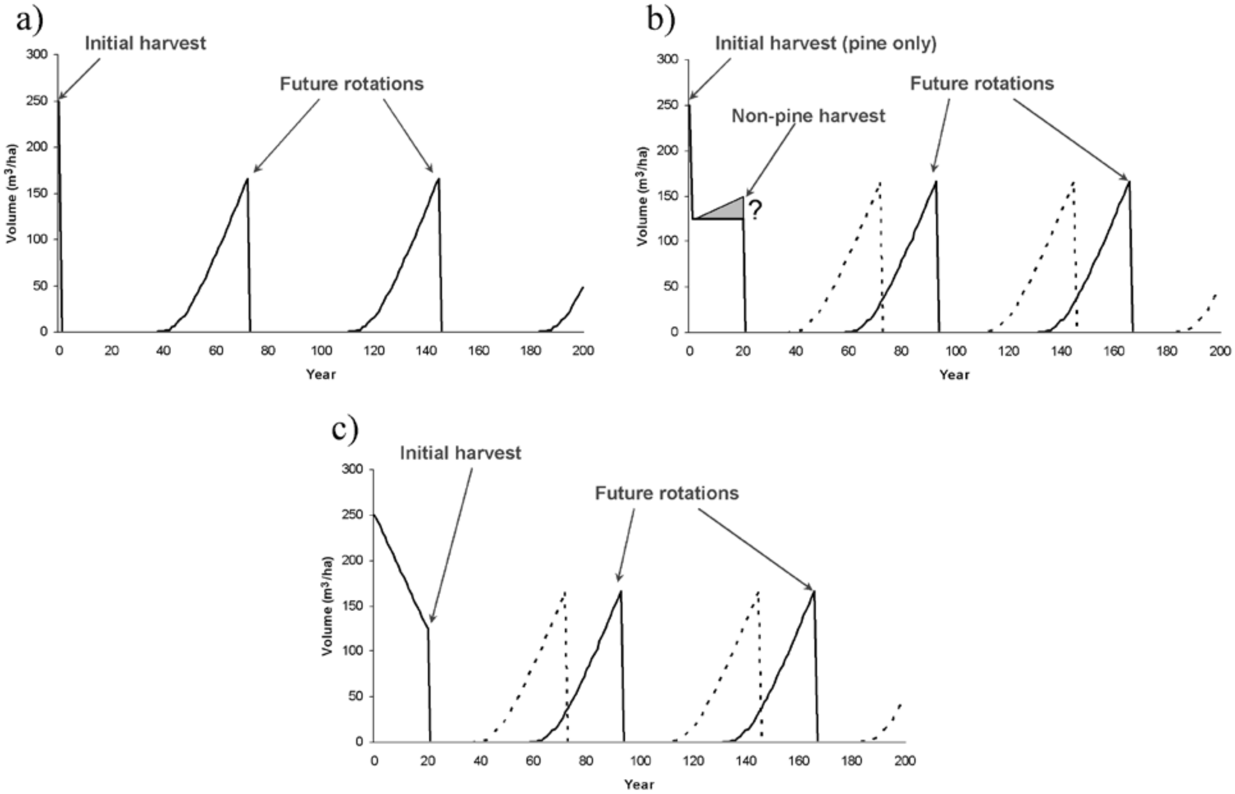

Figure 11. Site volume and harvest timing in a 50% pine stand on an SI 15 site under (a) clearcut/plant at Year 0, (b) pine removal at Year 0 and clearcut/plant at Year 20, and (c) clearcut/plant at Year 20 only. Dashed lines in graph (b) and graph (c) show site volumes from graph (a) for comparison.

After an initial harvest of all volumes on site (Figure 11a), planted stands are established that provide future revenues based on an optimum economic rotation. If only the pine is removed initially, non-pine volumes are available to us in the near future (Figure 11b), and these may even gain more volume through growth (shown by the shaded area adjacent to the question mark in Figure 11b). However, two-pass harvesting may also delay the establishment of future managed stands, unless acceptable regeneration is present and is protected during the final cutting cycle. Finally, harvesting in the immediate term can be foregone altogether (Figure 11c), and the initial stand entry can instead occur once stumpage prices have improved, but when pine volumes may have lost most or all of their merchantable value.

To compare the relative value of these strategies, we present three sets of hypothetical conditions that might occur in the post-beetle era. First, we assume that all volumes (current and future) sell for a \$5/m^3 stumpage price. Secondly, we assume that stumpage prices improve, and after 20 years all volumes (including future rotations) sell for \$15/m^3 [13].

Finally, in addition to assuming increasing stumpage prices, we assume that our stand requires up-front expenditures of $1500/ha by the landowner at the time of the initial stand entry. This assumption is meant to mimic the situation where significant road development is required to gain access to the stand[14], with costs borne by the landowner. For simplicity, we consider only two possible timings for removing volumes in the existing overstorey: now or 20 years in the future. We also assume that the residual stand does not release following pine removal or pine decay, and that regeneration is not established until the time of the final overstorey removal. Under these three sets of assumptions, the net present values of the three strategies are compared in Figure 12.

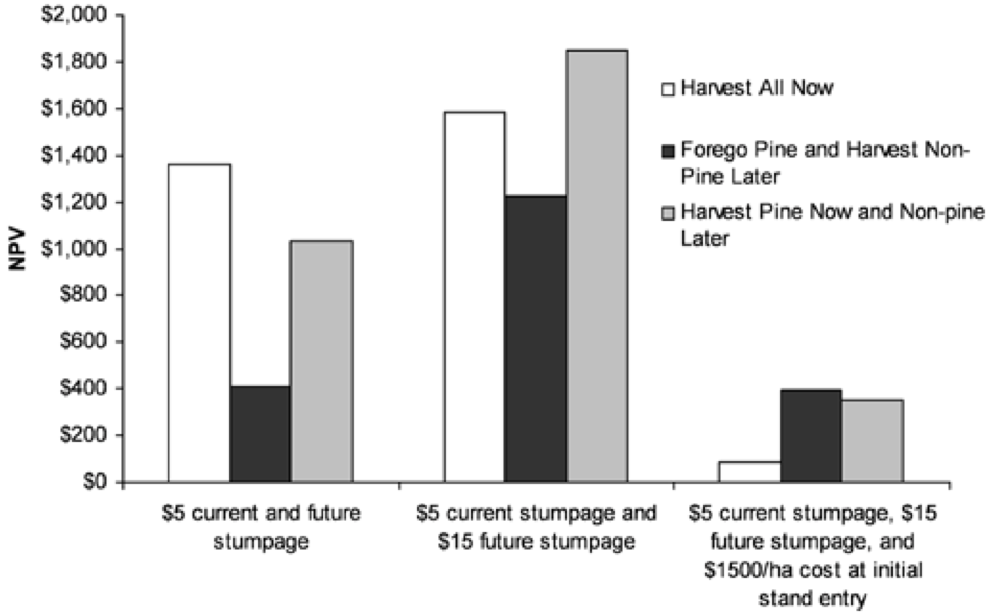

Figure 12. Net present value (NPV) of three strategies in a 50% pine stand on an SI 15 site under various stumpage and cost assumptions.

We can see that when stumpage prices remain constant, "harvest all now" is the optimal choice. Under our second scenario of rising stumpage values, a two-pass harvest becomes supportable. Rising stumpage prices boost the profitability of the "harvest all now" strategy due to the increased value of future managed stand rotations. However, if stumpage prices rise sufficiently, the benefits of leaving the non-pine volume for a future harvest will begin to outweigh the opportunity costs of the delay. Finally, when stumpage values are still assumed to rise, but large up-front expenditures are also required by the forest owner at the time of the initial stand entry, a strategy of foregoing the pine salvage and deferring the initial stand entry becomes the most profitable. Under this final scenario, the benefit of delaying the costs of initial stand entry outweighs the benefits of capturing the pine volumes at $5/m^3.

These examples assume that the non-pine volume is static. Any additional growth would effectively produce the same influence that increasing prices would, boosting future revenues from the residual stand, and strengthening the case for harvesting the non-pine volumes at a future date. Essentially, the future gains required to make two-pass or deferred harvesting preferable depend on our rate of time preference (discount rate) and the length of the delay. Non-timber benefits due to the maintenance of residual forest cover may also strengthen the case for two-pass harvesting. However, many of these benefits would also exist if the initial salvage volumes were simply foregone. The important point here is that high initial harvesting costs (e.g., road development) complicate this tradeoff, and may make deferred harvesting financially preferable to multiple-pass strategies.

6. Discussion

The case studies we have examined illustrate some of the factors to consider when deciding whether to actively manage stands or leave them to natural processes. Obviously, other factors and a great many possible scenarios exist. For example, in our first scenario we could assume that natural or advance regeneration is subject to unique risks, such as increased fire hazard as the dead pine overstorey deteriorates. Forest health concerns such as dwarf mistletoe *(Arceuthobium americanum)*, could affect the regeneration of lodgepole pine exposed to inoculation from residual live pine (Unger 1992). Natural or advance regeneration might consist of less desirable species than those that could be established through planting, or understorey conditions could impede natural regeneration for an extended period (Astrup et al. 2008; Vyse et al. 2009). Inadequate post-beetle stocking may lead to expensive silvicultural interventions. We could also be more optimistic about the potential to use the advance regeneration in the post-salvage stand, and assume that a percentage of the understorey can make a positive contribution to the next rotation. These assumptions would all widen the range of conditions under which salvage harvesting becomes justifiable.

Conversely, more optimistic assumptions about the development and future value of advance regeneration will widen the range of conditions under which salvaging should be foregone. Such stands may be especially valuable in regions facing beetle-induced mid-term timber supply shortages (J. Pousette, BC Ministry of Forest and Range, personal communication, 2010). We have also assumed that planted stands will develop reliably and be of equal or greater value than natural or advance regeneration. However, post-harvest conditions on some sites may leave few species choices other than lodgepole pine, which could be vulnerable to future beetle activity. Dothistroma needle blight *(Dothistroma septosporum)* is yet another risk to lodgepole pine stands, and has recently become particularly serious in northwest BC (Welsh et al. 2009). If natural or advance regeneration is expected to consist of species subject to fewer risks, this once again would strengthen the case for leaving stands to natural processes.

Essentially though, the decision to salvage is clear where recoverable volumes are high, stumpage rates are positive, and managed stands will outperform natural stands. Salvage harvest may not be the best choice where recoverable volumes or stumpage rates are minimal, and where natural or advance regeneration may perform as well as or better than managed stands, or provide important non-timber values.

In stands that are uneconomic to harvest for forest products, the question changes from whether or not to salvage to whether or not to rehabilitate. According to our analysis (section 5.2), the estimated upper cost thresholds that make rehabilitation economically feasible generally fall short of typical costs for site preparation and planting in BC Interior forests (discussed in section 4). The combination of highly productive sites (e.g., SI 21 or higher) and a poor outlook for natural regeneration yields the potential to support adequate returns from rehabilitation investments. However, in addition to basic silviculture costs, rehabilitation treatments in beetle-affected stands might also include costs to develop access for machinery and silviculture crews (roads or trails), or costs to dispose of dead pine. Planning, surveys, and stand tending would also add to the cost of rehabilitation. Even the highest thresholds that we have estimated leave little room for these costs, which suggests that any candidate sites for rehabilitation would also need to be operationally straightforward and have existing developed access.

We observe that stands meeting all of the criteria for rehabilitation (high productivity, low treatment costs, and a poor outlook for natural regeneration) are uncommon. For example, in the Prince George TSA and the TSAs in the former Cariboo Forest Region, only a small fraction of the timber harvesting land base is estimated to have a site index greater than 22 m at 50 years (Figures 13a and 13b).

Currently, the BC Ministry of Forests and Range uses stand-level internal rate of return calculations to screen and prioritize projects in its "Forests for Tomorrow" program, which aims to mitigate impacts of recent wildfires and MPB through planting and other treatments (FFT 2007). The program also recognizes the need to fund projects that address non-timber impacts, such as hydrological concerns. Furthermore, it considers forest-level timber supply benefits, which can be more complex than are indicated in stand-level analyses (BCMFR 2006c). These impacts will be unique to each management unit, and forest-level modelling is required to evaluate them, which is beyond the scope of our analysis. However, we acknowledge that stand-level analyses such as those we have used in this report may not demonstrate all the potential benefits of silviculture investment, and rehabilitation may be justifiable on a wider range of sites for this reason.

In mixed stands or in stands with only partial beetle-induced mortality, partial cutting may be another strategy that facilitates beetle-killed volumes to be removed, while allowing residual live trees to continue occupying the site. As we have shown, the relative profitability of this strategy hinges on initial harvest volumes and prices, the outlook for future prices, and the capacity of the residual overstorey to release and provide future volumes and value. In addition to a positive outlook for the residual stand, candidate sites for this type of

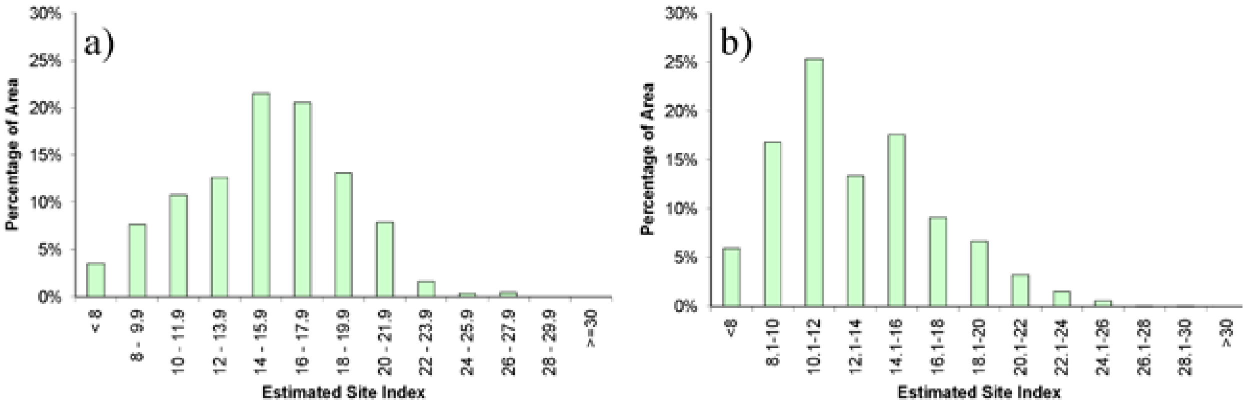

Figure 13. Estimated distribution of site indices on the timber harvesting land base of the (a) Prince George TSA and (b) the former Cariboo Forest Region (Kamloops TSA, 100 Mile House TSA, Quesnel TSA, Robson TSA, and Williams Lake TSA). (Derived from data obtained from J. Pousette, BCMFR, email to B. Bogdanski on 6 August 2006, and from Qiong Su, BCMFR, email to B. Bogdanski on 7 July 2006).

treatment would typically need sufficient salvage volumes to make any initial development costs "pay" for themselves. High initial development costs relative to initial salvage profits weaken the case for this strategy, and if there is still a strong case to be made for delaying harvesting of the non-pine component, salvage volumes may be best left to decay on the stump. However, as with our first scenario, an increase in fire hazard from the dead pine may be another factor that must be considered. Pine-only removal could become justifiable if it is necessary to protect future revenues from the residual stand. Stands managed primarily for non-timber values may even warrant pine removal at an initial loss, if the benefits of ongoing forest cover and the risks from standing dead pine are both considerable.

To summarize, Table 3 provides an overview of the major questions and findings from the case studies, and factors that may influence the treatment choice in each scenario.

Although we have emphasized the importance of considering non-timber benefits and costs, the benefits from carbon storage merit some specific discussion. The contribution of forest carbon sequestration to mitigating global climate change has been cited as a key reason to invest in MPB rehabilitation treatments (e.g., Parfitt 2005). However, the relative carbon benefits associated with treatments in post-beetle stands are complex (Kurz et al. 2008; Kurz 2009). While newly established plantations do sequester carbon, dead organic matter in beetle-killed stands may act as a temporary reserve, slowly releasing carbon to the atmosphere through decay. Salvaging may lead to a more rapid release of some of this carbon, as well as leading to additional emissions associated with forestry operations. However, some carbon will be sequestered long term in forest products and could offset the use of fossil fuels through bioenergy production.

Finally, we emphasize that much of BC's interior pine and mixed pine forests will never be salvaged. The aggressive nature of the recent salvage program has no doubt put pressure on non-timber values such as aesthetics and overall ecosystem function. However, many beetle-affected areas will continue to fall outside of the salvage program due to protected areas, special management zones, riparian reserves, other in-block retention strategies, and landscape-level old-growth reserves and recruitment. Many areas will also be left to natural processes because they are simply uneconomic to harvest, or because of limits to the quantity of beetle-killed timber that markets can absorb.

Table 3. Questions ssked and key findings.

Questions Asked	Key Findings
Does partial cutting make sense economically?	Forest managers must decide if the benefits of retaining live merchantable volumes outweigh the opportunity costs of foregoing larger immediate revenues. In most areas, this depends on the outlook for growth in the residual stand and on the value of these volumes for mid-term timber supply. Depending on the up-front costs and volumes available at the initial stand entry, it may be more profitable on some sites to defer harvesting altogether and leave salvage volumes to decay on the stump. This may be especially true of stands that require significant road development or other up-front costs.
In areas that cannot be salvaged, is reforestation a profitable investment?	From a purely financial perspective, rehabilitation appears to be profitable only on sites that have high productivity, low treatment costs, and a poor outlook for natural regeneration. Given the range of site productivities typical in the BC Interior and typical reforestation costs, few sites meet these criteria. However, forest-level timber supply impacts and non-timber benefits must also be considered, which may justify rehabilitation on a wider range of sites.
Even where we can salvage profitably, are there some stand types that are better left unsalvaged? *What economic/ silvicultural assumptions produce higher stand values when salvaging is foregone*?	The economic case for salvage harvesting is clear where the activity is profitable, and where post-salvage stand regeneration outperforms stand regeneration in the absence of salvage. However, low-value stands with a positive outlook for natural or advance regeneration may generate greater stand value when left unsalvaged. This may be more likely where: 1) advance regeneration is expected to release and provide sufficient stocking following pine mortality; 2) the subsequent stand is expected to be of substantial value; and/or 3) significant damage to the advance regeneration is expected if salvaging occurs.

7. Conclusion

In this report, we summarized the context for salvage harvesting and reforestation in beetle-affected areas of the BC Interior, and some of the economic tradeoffs faced by those responsible for guiding forest management during the outbreak. While we have not specifically determined which stands to salvage, which silviculture strategies to use, and which stands to leave to natural processes, we have demonstrated the structure of the problem and many of the considerations required to make sound decisions. After reviewing the beetle issue and the relevant literature, we summarized the current suite of treatment options recognized in beetle-affected areas, and many of the costs, benefits, and risks associated with managing beetle-killed stands. Our analysis of some hypothetical sites also demonstrates some important aspects of the salvage harvesting decision that involve advance regeneration, rehabilitation, or partial cutting in mixed stands.

Further research would help to improve understanding of some important drivers of decision-making. Growth and yield in beetle-killed stands with residual overstorey or advance regeneration is probably the most significant area of uncertainty, and further work in this area could provide information to guide salvage and reforestation choices. Research into innovative silvicultural treatments may also provide new strategies to overcome regeneration problems in unsalvaged areas, while avoiding the costs of traditional site preparation and planting. Incorporating carbon storage into the types of stand-level analyses we have presented also offers interesting scope for further research. Shelf life, fire risks from dead pine, impacts on landscape values such as water, wildlife and recreation, and market impacts from changing harvest levels are other areas where further research would help inform the salvage issue, and reduce the level of uncertainty in decision-making.

However, uncertainty will likely always be a characteristic of many of these factors. Decisions will need to be made using a combination of the best available data, local knowledge, and professional opinion, but these decisions will inherently be subject to risks. The key point is that decisions on salvaging, rehabilitation, and silvicultural investments should be based on best estimates and evaluations of the potential long-term costs and benefits. While the case for salvaging is obvious across much of the beetle-affected area, some stands are better left without active management. The unique stand characteristics, growth responses to various treatments, forest management objectives, and the value of various benefit flows through time will determine the optimal strategy for each stand.

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9. End Notes

[1] These include the Bulkley, Dawson Creek, Fort St. John, Mackenzie, Williams Lake, Morice, Robson Valley, 100 Mile House, Cranbrook, Invermere, Kamloops, Lakes, Merritt, Okanagan, Prince George, Quesnel, Lillooet, Boundary, Kootenay Lake, Arrow, Golden, and Revelstoke TSAs, along with TFL 3, TFL 8, TFL 15, TFL 18, TFL 23, TFL 14, TFL 48, TFL 55, TFL 56, TFL 42, TFL 35, TFL 49, TFL 5, TFL 52, and TFL 53. Levels of MPB activity and salvage vary widely across these areas, and in some areas (such as BC's Interior Cedar–Hemlock biogeoclimatic zone) MPB mortality is minimal due to the dominance of species other than lodgepole pine.

[2] Not all uplifts are due to MPB salvage. For example, the 2004 Kamloops TSA uplift included 1 million m^3 for MPB salvage and an additional 670,000 m^3 for fire salvage. The 200,000 m^3 uplift in TFL 35 is also due in part to fire salvage. Some areas have also been subject to reduced AACs, which offset the uplifts somewhat. For example, from 2001 to 2004, AACs in the Golden and Arrow TSAs were reduced by 8% and 11%, respectively.

[3] Furthermore, areas under a "low" biodiversity emphasis are only required to meet 1/3 of the prescribed retention targets, unless it can be demonstrated that timber supply impacts will not result from old-growth retention or recruitment.

[4] This involves complete harvesting of the stand and its prompt replacement with trees of uniform age.

[5] "Natural disturbance emulation" is currently a popular approach to managing forested landscapes in BC. See Drever et al. (2006) and Haeussler and Kneeshaw (2003) for recent discussion of this topic.

[6] Major tenures are the Forest License and Tree Farm License, accounting for about 75% to 80% of annual allowable cut from provincial Crown lands. See BC Ministry of Forests and Range, "Timber Tenures in British Columbia: Managing Public Forests in the Public Interest" (www.for.gov.bc.ca/hth/timten/documents/timber-tenures-2006.pdf) for an overview of public forest tenures in BC.

[7] Some of these treatments may also be used to manage beetle outbreaks themselves, to either remove beetle populations from the forest (direct control) or to reduce the susceptibility of forested landscapes to attack (indirect or pre-emptive control) (Shore et al. 2006). Furthermore, individual trees or small patches may be felled and disposed of (e.g., through piling and burning) to prevent incipient MPB population buildup or to address other specific issues or risks, such as public safety in areas of heavy recreational use. However, the focus of this paper is salvage harvesting and post-outbreak reforestation, and the full range of MPB management strategies are not discussed here.

[8] See Chapter 5 of Boardman et al. (1996) for a discussion on determination and choice of the discount rate.

[9] The value of W, land expectation value, is assumed to equal the present value of an infinite series of payments received from using the land for forestry in perpetuity. The value of W depends on harvest age alone if all variables that affect value, such as log values and stand growth and yield, are assumed to remain constant. Mathematically, the land expectation value is

$$W = \frac{S(T) - C}{(1 + r)^T - 1} - C_0$$

where S is stumpage value (= log value - harvest costs), T is the age at harvest, C and C_0 are the recurring and initial stand establishment costs, respectively, and r is the rate of interest. This model assumes that we start with bare land at time zero, and that planting and harvesting occur in the same period. The harvest age, T, that maximizes W is called the optimal rotation age, and is often referred to as the Faustmann rotation due to the original derivation of the solution by Faustmann (1849).

[10] Other assumptions in TIPSY forecasts used in this paper included a 3-year regeneration delay in planted stands; a 5-year regeneration delay in natural stands; Operational Adjustment Factors (OAFs): 15% OAF1 and 5% OAF2 (@100yrs); 12.5 cm pine utilization; and 17.5 cm other conifer utilization. All references to site indices are based on pine height growth in meters at 50 years, and have been converted appropriately where the growth of other species are projected. Currently, the growth and yield of MPB-killed stands with secondary structure (advance regeneration and/or residual overstorey of live trees) is recognized as a major research need (Snetsinger 2005). Our examples do not attempt to address this need, and are hypothetical scenarios for illustration purposes only.

[11] Although controversy exists over whether reforestation should be considered a cost associated with harvesting or whether it should be considered an investment, treating it as a part of harvesting costs is consistent with current public forest management in BC.

[12] Though findings in Astrup et al. (2008) and Vyse et al. (2009) suggest that regeneration in many areas would be more likely to consist of subalpine fir.

[13] It is acknowledged that the costs of harvest may be different in these cases. Under the assumptions in this analysis this would be reflected in lower stumpage prices in the higher cost cases.

[14] Roads often provide access to many stands over the long term as part of a forest-level transportation network. This must also be considered when assigning road development costs to individual cutting units.

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