NRC Research Press

ARTICLE

Diversifying managed forests to increase resilience

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Abstract: In British Columbia, Canada, a recent epidemic of mountain pine beetle (*Dendroctonus ponderosae* Hopkins, 1902) caused widespread forest mortality. This epidemic was due in part to the changing climate, and damage from pests and diseases is expected to increase in the future. Therefore, we used a historical retrospective approach as a proxy to evaluate management options on reducing the forest health damage that may occur under a future changing climate. We assessed two landscape-scale strategies, intended to increase tree species diversity, for the response in ecosystem resilience and compared the results with the business-as-usual strategy. The assessment was based on simulation modelling of the Merritt Timber Supply Area for 1980–2060. We applied a strategy to increase the harvest of the most dominant tree species, plant more diverse species, and increase natural regeneration. This strategy resulted in greater ecological resilience (higher diversity and growing stocks), higher harvest rates, and higher, more consistent net revenue over time than the business-as-usual strategy or the strategy that only employed a diversity of planting. A sensitivity analysis indicated a high level of robustness in the results. Our study showed that it may not be necessary to compromise economic viability to reduce forest health risks and consequently improve socio-ecological resilience.

Key words: resilience, adaptation, climate change, forest management, temperate forests, mountain pine beetle, landscape ecology, economic analysis, timber supply.

Résumé : En Colombie-Britannique, au Canada, une épidémie récente du dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopkins, 1902) a causé de la mortalité très répandue dans les forêts. Cette épidémie était due en partie au changement climatique et les dommages causés par les insectes et les maladies devraient augmenter dans l'avenir. Par conséquent nous avons eu recours à une rétrospective historique comme substitut pour évaluer les options d'aménagement susceptibles de réduire les dommages à la forêt qui pourraient survenir éventuellement à cause du changement climatique. Nous avons évalué deux stratégies à l'échelle du paysage visant à augmenter la diversité des espèces d'arbre pour augmenter la résilience de l'écosystème et nous les avons comparées à la stratégie courante. L'évaluation a été réalisée à l'aide d'un modèle de simulation de « Merritt Timber Supply Area » de 1980 à 2060. Nous avons appliqué une stratégie consistant à accroître la récolte des espèces d'arbre les plus dominantes, à planter une plus grande diversité d'espèces et à favoriser la régénération naturelle. Avec le temps cette stratégie a engendré une plus grande résilience écologique (plus grande diversité et plus de matière ligneuse sur pied), des taux de récolte plus élevés et un revenu net plus important et plus régulier que la stratégie courante ou qu'une stratégie se limitant à diversifier les plantations. Une analyse de sensibilité indiquait que les résultats avaient un haut degré de robustesse. Notre étude a montré qu'il est possible de réduire les risques pour la santé de la forêt et conséquemment améliorer la résilience socio-écologique sans nécessairement compromettre la viabilité économique. [Traduit par la Rédaction]

Mots-clés : résilience, adaptation, changement climatique, aménagement forestier, forêts tempérées, dendroctone du pin ponderosa, écologie du paysage, analyse économique, approvisionnement en bois.

1. Introduction

Forest health surveys show that pests, drought, and disease are common events in forests. A changing climate is expected to contribute to increased losses of timber through a variety of forest health agents, although the uncertainties are high as to where problems will develop and the degree of mortality or growth loss (Woods et al. 2010; Haughian et al. 2012). British Columbia (B.C.) has recently experienced a catastrophic epidemic of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins, 1902) that resulted in widespread mortality and a high degree of damage to the timber stocks. By the end of 2012, the beetle affected approximately 181 000 km^2 of forest to some degree, and over half of all pine in the province was estimated to be killed. The mountain pine beetle epidemic was the result of the large area of susceptible host of mature lodgepole pine (*Pinus contorta* Douglas ex Loudon) and climate change (an absence of extreme cold weather events that limited beetle populations in the past (Taylor et al. 2006)). The projected severe reductions in harvest rates over the next decade are already having economic and social consequences of mills closing, increased unemployment, and decreased tax revenue to the provincial government (Special Committee on Timber Supply 2012). Given the relevance of past, present, and future forest health risks to B.C.'s forests, an important question is: what forest management strategies might be effective, biologically and economically, to address potential impacts of climate change?

Managing for ecological resilience has been proposed as a way to counter some of the negative impacts of climate change on the supply of ecological goods and services (Millar et al. 2007; Rist and Moen 2013). In B.C., the theoretical framework for understanding and managing forests under climate change draws on ecological

Received 13 March 2014. Accepted 7 July 2014.

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Published at www.nrcresearchpress.com/cjfr on 9 July 2014.

resilience science (Campbell et al. 2009). In their framework and in our study, we have adopted the Walker et al. (2004) definition of resilience: "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks". In this theory, systems can respond to disturbance(s) in two distinct ways: either with resilience, growing along similar pathways as prior to the disturbance, or by reorganizing themselves into a qualitatively different form. Folke (2006) summarizes the application of resilience theory to socio-ecological systems in which ecosystems and landscapes affect and are affected by management practices and institutions. This kind of integrated system seems applicable to forestry in that ecosystems and landscapes are relied on by society for timber, wildlife, water supply, recreation, etc. and are affected by resource extraction and other management activities. One potential indicator of ecosystem resilience is biological diversity, when it also indicates functional redundancy in key ecological processes that creates resilience (Folke et al. 2004). However, diversity is not the only component of resilience (Ives and Carpenter 2007). Biological diversity can contribute to resilience through an insurance or bet-hedging effect by buffering the temporal variability of productivity and increasing productivity over time (Yachi and Loreau 1999). Empirical studies support this insurance hypothesis and show that mixed stands of species and silvicultural techniques that foster complexity lower the impacts of disturbances and reduce productivity losses in permanent sample plots (Liang et al. 2007; Paquette and Messier 2011) and in experimental treatments (Griess and Knoke 2011). However, from the perspective of forest managers, it may not be clear how this science can be applied at either the stand or landscape scale. Furthermore, we found few studies that assessed how effective management actions may be over various spatial and temporal scales (Quijas et al. 2012; Temperli et al. 2012).

Numerous forest management strategies to adapt to climate change, including increasing resilience, have been proposed (Spittlehouse 2005; Puettmann et al. 2009) or explored in recent modelling work (Seidl et al. 2011; Steenberg et al. 2011). Operational and policy application of these strategies in B.C. has been slow for a number of reasons. Impediments to action include the lack of tools to aid operational analysis and decision making (Spittlehouse 2005), cultural barriers (Puettmann et al. 2009; Hagerman et al. 2010), assumed higher economic costs, and policy barriers (Howlett 2009; Hagerman et al. 2010). Therefore, an objective of this study is to evaluate the economic trade-offs between the status quo and a selection of alternative strategies aimed at maintaining and enhancing forest diversity and resilience.

Several economic studies have examined forest management treatments with an operationally relevant focus. For example, Andreassen and Øyen (2002) estimate financial returns of forest management practices at the stand level and include the value of the initial harvest in addition to the value of subsequent rotations. Hawkins et al. (2006) examine the economic value of a variety of site preparation methods on two forest stands in the Interior of British Columbia. They found that a short-term focus on cost minimization led to lower values over the longer term. Both of these studies reflect a predominant focus of analysis at the stand level. Moving the analysis to the scale of a forest landscape rather than the stand level mimics the actual management and operational environment facing land owners and users and more closely reflects the decision set facing operations managers. For example, Schou et al. (2012) modelled the forest response and resulting economic values of strategies to transform an even-aged monoculture forest into a near-natural forest in Denmark. This approach provided a flow of timber from multiple stands and evaluated various stand dynamics and adjacency interactions that would not be addressed at the stand level. None of the studies reviewed for this paper, however, undertook a retrospective analysis that included an actual catastrophic disturbance and altered past management practices through modelling.

We used a historical retrospective study of the management of a real insect epidemic to evaluate the effectiveness of alternative management options on current and future species diversity and supply of timber within a forest management unit. We expect that a more diverse forest will lower future risk and, in doing so, provide a more secure investment opportunity and improved and more consistent financial returns. Three strategies were assessed: business as usual (BAU), increased diversity through reforestation, and proactively decreasing the area occupied by a high risk species through harvesting, as well as increasing diversity though reforestation. We assessed the effectiveness of these management strategies over time. Effectiveness was estimated using survivorship during a mountain pine beetle outbreak, harvest rates after beetle outbreak, species diversity indices, and discounted revenues and costs for 1980–2060.

2. Methods

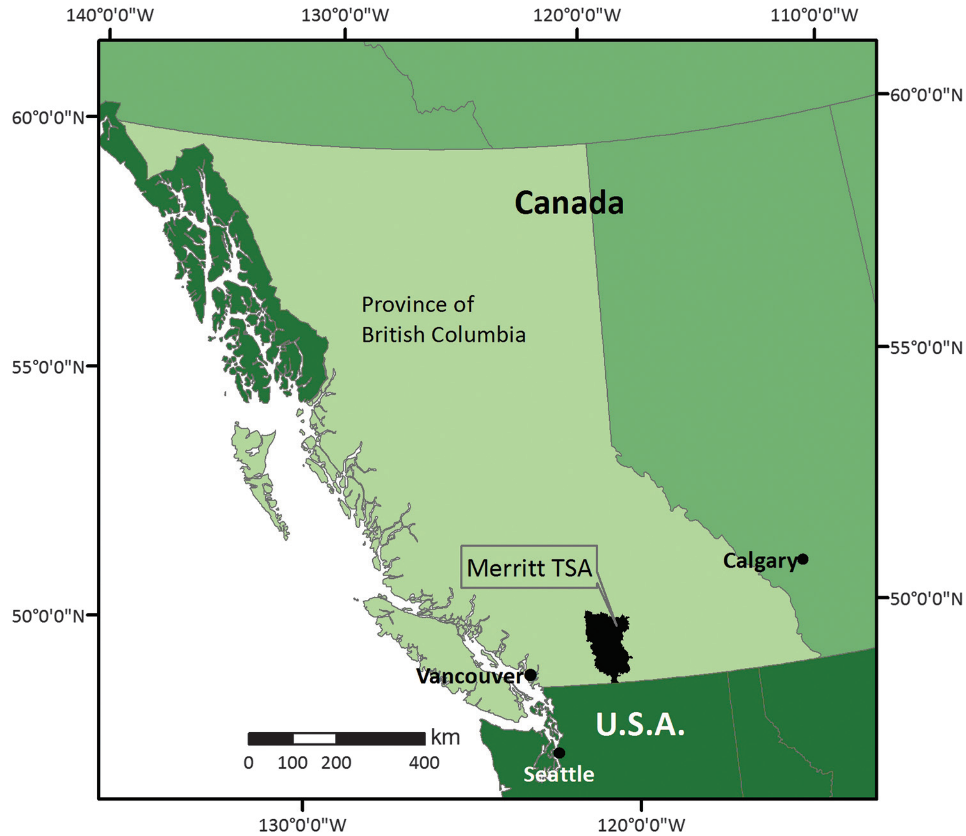
2.1. Study area

We selected the Merritt Timber Supply Area for this project because it had significant damage by the mountain pine beetle, it is a landscape with a low diversity of tree species, and it shows evidence of planting monocultures of lodgepole pine in recent decades (Supplementary Table S1[1]). However, lodgepole pine is not the only option, given the site conditions. A number of other species are commercially viable, and therefore more diverse stands could potentially be generated through reforestation (Lloyd et al. 1990). A timber supply area (TSA) is a management unit designated by the government of B.C. to practice integrated resource management principles, and they are the primary unit for the allowable annual cut (AAC) determination.

The 11 300 km² of the study area (Fig. 1) encompasses mountainous terrain and steep river valleys of the Cascade Mountains in the western portion and the flat Thompson Plateau in the eastern portion. The forests are largely coniferous, dominated by lodgepole pine, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and interior spruce (*Picea engelmannii* × *glauca*). Other abundant or commercially valuable tree species are Englemann spruce (*Picea engelmannii* Parry ex Engelm.), paper birch (*Betula papyrifera* Marshall), ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson), mountain hemlock (*Tsuga mertensiana* (Bong.) Carrière), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), trembling aspen (*Populus tremuloides* Michx.), western larch (*Larix occidentalis* Nutt.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don). Productive forest covers about 914 700 ha (81%) of the TSA (Supplementary Table S2[1]) and 686 500 ha are in the timber harvest land base (THLB) — the portion of publically owned forest where harvesting is expected. Grasslands with sagebrush and open-growing ponderosa pine, the alpine, and forested areas not available for harvest are outside the THLB. Severe or very severe damage was recorded in over half of the 90 years of annual forest health surveys in the study area (Supplementary Table S1[1]). The climate of the forests has a mean annual temperature of 1.8–6.9 °C and mean annual precipitation of 380–2720 mm (Supplementary Table S2[1]). Annual temperature has increased by about 1 °C in the last 60 years and is projected to increase by a further 2–4 °C over the century, accompanied by drier summers (Fettig et al. 2013). This will likely result in an increase in natural disturbance frequency or severity (Sturrock et al. 2011; Haughian et al. 2012).

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2014-0146.

Fig. 1. Overview map of the study area, Merritt Timber Supply Area (TSA), in south-central British Columbia.



In the Merritt TSA, approximately 27% of pine volume was killed by the beetle between 1999 and 2012. The AAC was increased from 1.45×10^6 $m^3 \cdot year^{-1}$ to 2.8×10^6 $m^3 \cdot year^{-1}$ in 2005 in response to the beetle epidemic (Supplementary Table S1[1]). The AAC is a regulated cap on harvest levels which may or may not be reached by logging companies. The forecasted timber supply is expected to drop substantially by 2023. The socio-economic analysis for the most recent timber supply forecast estimated that a decrease in harvest of 1×10^6 $m^3 \cdot year^{-1}$ would reduce employment by 651 person-years within the area and 799 person-years provincially (Supplementary Table S1[1]).

2.2. Ecosystem modelling

We used simulation methods similar to those used to determine the AAC (maximum harvest rates) and silviculture strategies for the majority of forests in B.C. One key difference was that timber supply analyses typically assume a constant low rate of nonrecoverable losses due to natural disturbances, while episodic disturbance impacts may be incorporated on an ad hoc basis. Instead, we used a historical retrospective approach by starting the simulations in 1980 to leverage a climate change impact in the form of the mountain pine beetle outbreak (Taylor et al. 2006). We started the simulations in 1980 because that was the earliest date for which there was reliable data on harvest volume by species and area planted by species. Furthermore, it provided a substantial time period (20 years) before the beetle outbreak for the alternate management strategies to be simulated and their effectiveness against the beetle assessed.

We ran the simulation from 1980 until 2060 to allow the tree species regenerated in the first few decades to become merchantable (>50–70 years of age) before the end of the projection. However, there is uncertainty with the future decades because the simulations do not include future natural disturbances or the impacts of a changing climate on growth and mortality. Therefore, we did uncertainty analyses as described later. Simulation of the growth and development of the trees, impact of the mountain pine beetle, spatial harvest scheduling, and impact of harvesting, planting, and natural regeneration was done with Critical Analysis by Simulation of Harvesting, version 6.21 (CASH6) (Carson 1995).

CASH6 is a deterministic model with the resolution of the polygons in the forest inventory. The forest inventory for the Merritt TSA contained 59 452 polygons with a minimum size of 0.5 ha, maximum size of 453 ha, and mean size of 15.3 ha. The model uses aspatial and spatial geographic approaches to land base and inventory definition to adhere as closely as possible to the intent of forest cover regulation on harvesting (e.g., a minimum percentage of old growth is aspatial, regrowth requirements are spatial). CASH6 can simulate the impact of overlapping forest cover objectives on timber harvesting and resultant forest development. In these analyses, simulations were done in discrete time steps (decades). The model projects the development of a forest, allowing the analyst to impose different harvesting or silviculture strategies on its development, to determine the impact of each strategy on long-term resource management objectives that incorporate all integrated resource management considerations.

The growth and yield input values to CASH6 were derived from the Variable Density Yield Prediction (VDYP 7) model (Brierley 2008) for naturally regenerated stands and Table Interpolation for Stand Yields (TIPSY, version 4.2) (Di Lucca 1999) for planted stands. These growth and yield models are used in many aspects of forest planning and management in B.C.

Simulating the forest dynamics starting in 1980 required a forest inventory that reflected 1980 conditions, but that dataset was not available. We rolled back a circa 1990 inventory using fire, mountain pine beetle, and harvest spatial datasets from 1980 (T. Salkeld, personal communication, 2011) to create the 1980 forest inventory (Supplementary Table S3[1]). Within the Merritt TSA, each forest inventory polygon was classified as either "natural" or "disturbed". For stands disturbed between 1980 and 1989, the predisturbance stand characteristics were assigned to the disturbed stands based on their neighbours (43 415 ha or 3.8% total). We determined standing volume for the 1980 forest inventory (Fig. 2) using the VDYP 7 model (Brierley 2008).

Aerial overview surveys were used to estimate the impact of the mountain pine beetle and create input to the simulation modelling (Supplementary Table S1[1]). Each strategy received the same input of the cumulative impact from 1999 to 2010 and was applied by the model over three decade time steps (1990–1999, 2000–2009, and 2010–2019). Based on the survey data, over 95% of the forested area was affected between 2000 and 2009. Mortality classes were as follows: low (5% pine killed), moderate (20% pine killed), severe (40% pine killed), and very severe (100% pine killed). We assumed that wildfires were absent, suppressed, or harvested immediately after the fire. These assumptions are consistent with other timber supply analyses done in B.C. and simplified comparisons between strategies.

We developed harvest schedules for input to the CASH6 model using historical datasets for the decades between 1980 and 2009. For 2010–2060, we estimated the highest possible harvest rate that the growing stock in each strategy could support while meeting provincial regulations and management objectives. One assumption greatly influenced the future harvest rates: all future decades were required to have the same rate of harvest. This is a common, although not universal, assumption in harvest modelling.

The main output from each analysis was a projection of the amount of future growing stock given a set of growth and yield assumptions, planned levels of harvest, and silviculture activities. Growing stock is defined as standing stocks of green, merchantable volume (operable volume above minimum harvest age by species). Species richness, the Berger–Parker dominance index, and the Shannon diversity index were used as indicators of diversity (Magurran 1988). The Shannon diversity index is a combined indicator which integrates the number of species and the relative abundance. Higher values indicate higher diversity. We also used the Berger–Parker Dominance index which is the volume of the most common species to the total volume. Higher values reflect a lack of evenness of abundance among species.

2.3. Management strategies

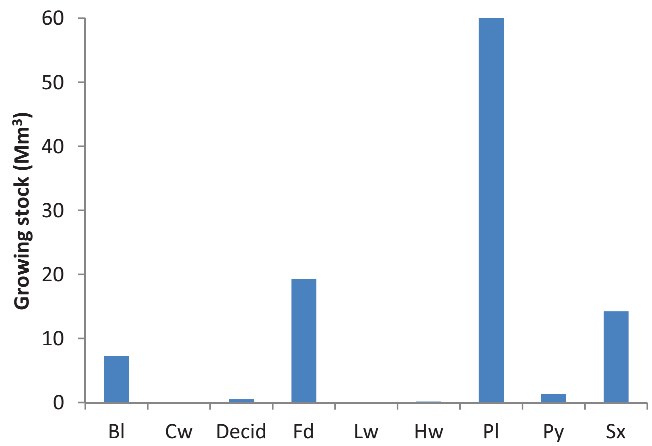
We assessed different harvesting and regeneration strategies relative to BAU (Supplementary Table S4[1]). Current and historical practices specific to the Merritt TSA defined the BAU as primarily clear-cutting and planting with pine. We developed the alternative strategies based on their potential to increase tree species diversity, reduce the area of lodgepole pine host trees before the outbreak of mountain pine beetle in the 2000–2020 decades, and reduce the risk of forest health damage to regenerated stands and logging revenue in the middle of the 21st century. In addition, we required all strategies to be compatible with the current regulations and standards governing forest management in B.C. The focus of the management strategies is on the THLB because that is where the vast majority of activities take place and where intervention is most likely to occur. Outside the THLB, B.C.'s forests are used for recreation, cultural ceremonies, aesthetics, wildlife habitat, conservation, etc. Some replanting of naturally disturbed areas may occur in special cases but they are not included in this study. The proportion of the harvest as lodgepole pine was based on either the historical records or the availability of mature lodgepole pine on the landscape, depending on the strategy.

2.3.1. Business as usual (BAU)

For the 1980–2009 period (three decades), the model simulated the same volume and species obtained through clear-cut (90%, on average) and partial cut (10%, on average) harvest as described in the B.C. Forest Service records (Supplementary Tables S1 and S4[1]). The volume harvested increased by 128% from the 1990–1999 to the 2000–2009 decades because of government policy to harvest as many of the pine stands as possible. Pine increased from 39% of the harvest in 1980–1989 to 89% in 2000–2009. For the fourth and future decades, we determined the maximum harvest rate that could be achieved within normal, regulatory constraints.

The regeneration assumptions for the BAU strategy followed the current timber supply analysis report with 91% of the harvested area being replanted, primarily with pine (Fig. 3; Supplementary Tables S1 and S4[1]). There were 93 different growth strata described based on their climatic conditions, soil type, current species, and site index. Assumptions about the exact species composition and density of seedlings and, therefore, yield curves depended on the growth strata. In stands in which natural regeneration of subalpine fir was expected based on the growth strata, we included simulated ingress of subalpine fir.

Fig. 2. Growing stock volumes by species on the harvestable areas of Merritt Timber Supply Area in the 1980 inventory. Units are in millions of cubic metres (Mm^3). Bl, subalpine fir; Cw, western redcedar; Decid, deciduous species; Fd, Douglas-fir; Lw, western larch; Hw, western hemlock; Pl, lodgepole pine; Py, ponderosa pine; Sx, interior spruce.



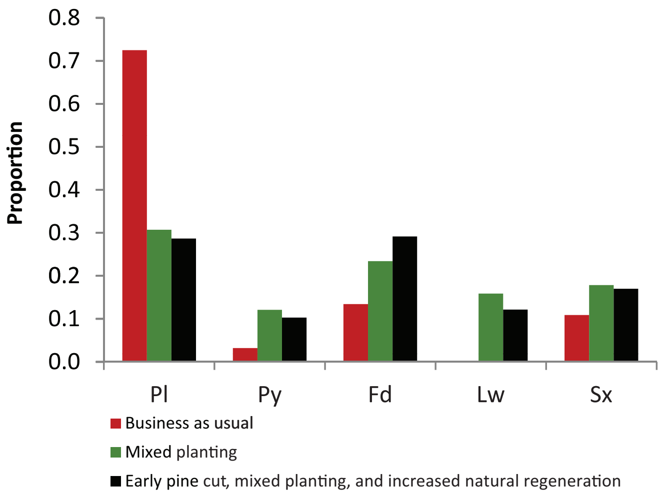
2.3.2. Mixed planting (MP)

The 1990–2009 harvesting strategy was the same for MP as for BAU, but reforestation was different. Rather than using data from current planting practices, this strategy simulated mixed planting starting in 1980 to increase species diversity following harvest. We simulated planting six species (vs. five) with greater evenness of abundance than BAU. The planting assumptions took into account stand conditions, current standards, regulations, and what can be expected to thrive in a clearcut (Fig. 3; Supplementary Table S4[1]).

2.3.3. Early pine cut, mixed planting, and increased natural regeneration (EMR)

For this strategy, the model preferentially allocated the harvest volume for the first three decades to pine (93% of the volume, on average). Consequently, this simulation left, where possible, the nonpine species in mixed-species stands through a greater amount of partial harvest compared with BAU (15%, on average, vs. 10%). On clear-cut sites, the regeneration in this strategy followed similar assumptions as the MP using six species for reforestation with greater evenness than BAU. In addition, the amount of natural regeneration was increased to 25% on appropriate growth strata (Fig. 3; Supplementary Table S4[1]).

Fig. 3. Regeneration management strategies by proportion of area assigned to different species. Pl, lodgepole pine; Py, ponderosa pine; Fd, Douglas-fir; Lw, western larch; Sx, interior spruce.



2.4. Economic analyses

The CASH6 model also provided a discounted cash flow assessment of the harvesting and replanting strategies. The model is able to incorporate cost and revenue data and reflect other operational characteristics such as cycle time, silviculture method, slope, and species of interest. The model generated revenue and cost flows and thereby net present value (NPV) over the simulation period and annually. These calculations are another means to compare management approaches in addition to the ecological output. The analysis is at the landscape level, assumes that the land is treed, not bare land, and is situated within an actively managed forestry setting; subsequently, the analysis includes discounted cash flows of harvesting activity in years 1 through 80.

Total harvesting costs were broken into harvesting, hauling, overhead, and silviculture categories. Harvesting costs differentiated by slope classes provided a proxy for harvest method by silvicultural type (Supplementary Table S5[1]). We applied a 10% increase for the costs of partial harvesting and a fixed hauling cost based on cycle time (Supplementary Table S6[1]). The cycle time estimate consisted of loading, hauling, weighing, unloading the harvest, the return time from road closest to a cut block to the closest mill, and unavoidable delays. A map of isomers of cycle time from primary processing facilities was developed using cutting permits in each harvest unit, detailed road and highway spatial datasets, highway haul costs, and local knowledge (Thomae 2006).

Reforestation cost estimates for clear-cut replanting were sourced from log cost appraisal information for determining stumpage (Supplementary Table S1[1]). These costs were applied by growth strata and varied by strategy based on differing species composition and regeneration type (planted or natural regeneration). For the BAU strategy, we used log cost appraisal estimates (area-weighted mean was $\$972 \cdot ha^{-1}$, Canadian dollars used throughout) (Supplementary Table S1[1]). The MP and EMR strategies have an increased diversity of species planted so we estimated the associated higher silviculture costs by using relative seedling costs in the 2012 market (area-weighted means were $\$1005 \cdot ha^{-1}$ and $\$691 \cdot ha^{-1}$, respectively). Log prices were 2003–2011 means by species or species group (Supplementary Table S7[1]). Because these log prices were means, they may not fully reflect actual log prices paid by processors. The analysis also assumes that the product mix remains the same over time.

The appropriate discount rate depends on ones' expectation of risk and the attractiveness of the investment over the long term. A review of the literature on forestry investment analyses indicates a wide range of discount rates from 1% to 9.75%. A higher discount rate is often used when evaluating projects associated with high uncertainty (Miller and Park 2002). Our analysis was based on discount rates of 1%, 3%, and 5%. These lower rates reflect an intergenerational perspective, longer term planning time horizon (Roumboutsos 2010), and the possibility of additional public goods benefits that may result from a more diverse and resilient forest, as described in the Discussion. These benefits would add value in the latter stages and reduce the effect of discounting on the timber-related revenue streams. Given the inherent uncertainty, results from a range of discount rates are presented.

2.5. Sensitivity analyses

There are many sources of uncertainty in projections of the future. Uncertainty in growth and yield projections can be quite large because of natural variability, forest health damage, and ingress of unexpected trees through seed dispersal. When modeling forest management at the landscape scale, these are compounded by forest inventory uncertainties (Bernier et al. 2010), multiple objectives, variability in costs and other economic values, and disturbances (Nelson 2003). Considering the uncertainty in VDYP7 and TIPSY, we arbitrarily decided to test the effect of using a ±20% change in Douglas-fir productivity. It had the largest single-species increase in volume between BAU and EMR, and therefore, the results would be most sensitive to productivity in this species. This uncertainty could also account for productivity changes that may result from planting improved stock and assisted migration (Aitken et al. 2008).

We also conducted log value sensitivity analysis to determine how a change in the price of logs would affect the NPV outcome of the management strategies, given the changes in species harvested over time. The initial simulation held the price of logs constant over time, but prices will change and some species may become relatively more valuable over time. This sensitivity analysis also gave an indication of the risks associated with a change in prices. High and low values were assumed to be ±20% of the original log values (Supplementary Table S7[1]), reflecting variability in mean monthly log values over the 2003–2011 period. Variability, in terms of the percentage of the standard deviation to the mean, was 12%–21%, depending on species.

3. Results

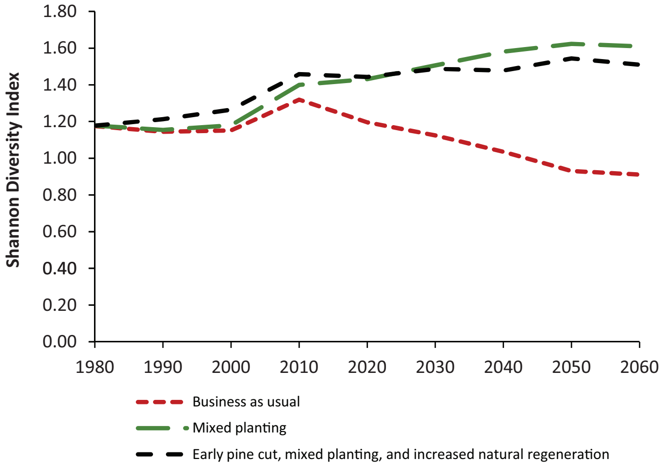
3.1. Biophysical analyses

The biophysical analysis considers the impact of management practices on properties of the forest. Examination of key indicators, including the Shannon diversity index, the Berger–Parker dominance index, standing volume of merchantable trees, species harvest rates, and age class distribution, all reveal potential impacts of different strategies.

3.1.1. Diversity

The number and relative abundance of species must be examined together to understand diversity. The number of tree species remained at 10 for all of the management strategies. The 1980 inventory of the THLB had its volume heavily concentrated in lodgepole pine, a Shannon diversity index (H) of 1.18 (Fig. 2), and a Berger–Parker dominance index of 0.59. Over two decades, the EMR strategy increased H to 1.26 before the mountain pine beetle epidemic (Fig. 4). Removal of lodgepole pine through logging and mortality due to the beetle in 2000–2009 decreased its relative abundance, thus increasing diversity in all strategies during that decade. Over the future decades, the BAU strategy lowered the diversity of the landscape to an H of 0.91 and dominance value of 0.7. In contrast, MP and EMR increased the diversity on the landscape, with H reaching 1.61 and 1.51, respectively, by 2060, and dominance indices at about half of the BAU value. Pine was the most abundant species in all strategies over all time steps.

Fig. 4. Shannon diversity index for the species in the harvestable area for each management strategy.



We also considered the impact of different management strategies within the context of the whole forest, i.e., the THLB and outside the THLB. The simulated harvesting and regeneration activities affected 0.3%–1% annually of the whole forest in the Merritt TSA (56%–62% total over 80 years). For this larger forest, the Berger–Parker dominance index started at 0.52 in 1980 (data not shown). By 2060, it was 0.57 for BAU, 0.32 for MP, and 0.34 for EMR. Although the difference between the BAU and alternative management was not as large as on the THLB alone, the new strategies were effective at increasing the diversity and, therefore, resilience for the entire forest.

3.1.2. Standing volume and rate of harvest

The growing stock or standing volume of merchantable trees on the THLB is a key determinant of timber flow and is heavily influenced by the harvest rate. We estimated the 1980 growing stock at 104 Mm^3 which declined until 2020 or 2030 (Fig. 5*a*). From 2020 to 2060, the growing stock for the BAU increased more quickly than EMR because BAU had a lower harvest rate compared with the EMR (Fig. 5*b*) and lodgepole pine had a higher growth rate until age 90 compared with spruce or Douglas-fir in this study area. The lower growth rate of the other species also explains the dynamics in MP, with the lowest harvest and rate of growing stock increase from 2020 to 2060. EMR had greater diversity when the beetle hit in 2000–2009 than either BAU or MP (Fig. 4). This greater diversity led to more trees surviving (greater growing stock) through the outbreak and greater stability in the provision of ecological goods and services.

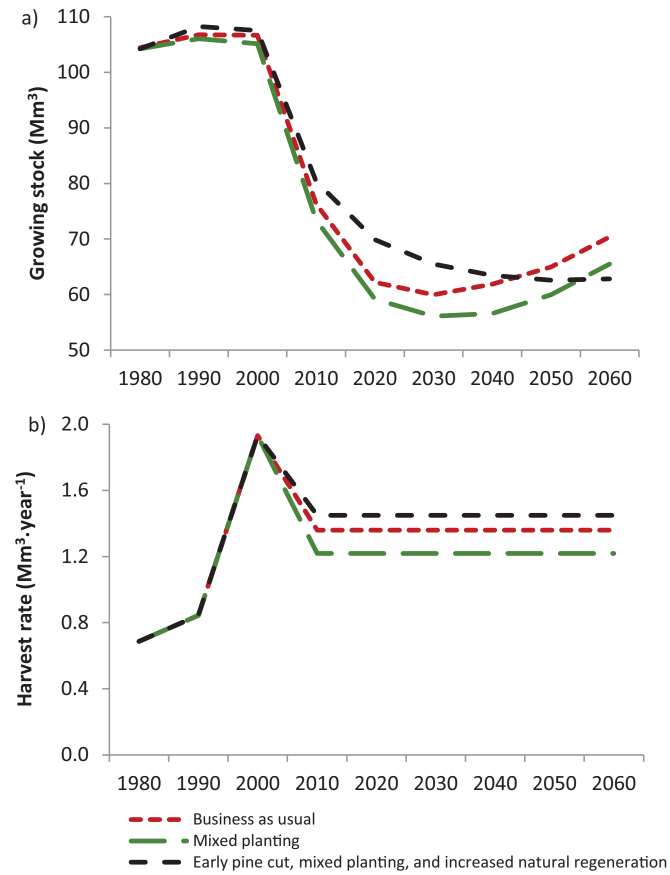
3.1.3. Age class distribution

Old growth forests are one of the nontimber values that are part of the multiple objectives in B.C.'s forest management. Retaining old growth forests is seen as a way to protect habitat, biodiversity, cultural, spiritual, and aesthetic values. We considered the age class distributions for all land (THLB and outside the THLB combined) because old growth (age > 140 years) retention areas may be in either category. There was 12%–14% more old growth in EMR and MP compared with BAU at the end of the simulations (Supplementary Fig. S1[1]).

3.2. Economic analyses

These analyses focused on annual and per-unit discounted net revenues and costs as key economic indicators. Motivations for investing today to benefit from more diverse forests diverge between the owner (the public) and the user (the timber tenure holders). We focused on a 0%–5% discount rate as they are the most relevant to policy makers who consider social values of forests in conjunction with economic returns.

Fig. 5. Growing stock volume in millions of cubic metres (Mm^3) (*a*) and annual rate of harvest volume in millions of cubic metres per year ($Mm^3 \cdot year^{-1}$) (*b*) for each management strategy.



3.2.1. Net present values and annual net revenue

The EMR strategy resulted in the highest harvest rates and NPVs over the simulation period (Table 1). These results were maintained under all discount rates. Under a 3% discount rate, EMR outperformed BAU by 6%. Adopting only a MP emphasis without also targeting species diversity through an early pine cut strategy reduced the NPV by 4%. During the first decade, BAU provided the highest annual net revenue (Fig. 6). EMR had the lowest net revenue in the first decade but accrued higher returns through the mid to late stages of the 80-year simulation. From about 2010 onwards, the discounted net revenue of EMR exceeded BAU by 20%, on average. The higher longer term returns were the result of more growing stock available to support a higher harvest rate and a shift to higher valued Douglas-fir. Surprisingly, despite having more partial cutting, EMR had the lowest harvested area for the first three decades (Supplementary Fig. S2[1]). This was because the model was instructed to preferentially harvest pine leading stands and was able to find high volume per hectare stands to meet the 1980–1989 total volume target, e.g., on average, 208 $m^3 \cdot ha^{-1}$ for EMR and 158 $m^3 \cdot ha^{-1}$ for BAU and MP. Over the simulation period, BAU had 10% of the area harvested by partial cutting, while EMR had 15%.

From 2010 to 2060, the higher valued Douglas-fir under EMR contributed, on average, 25.5% of the total harvest volume, whereas under BAU, Douglas-fir contributed only 14.5% (Supplementary Fig. S3[1]). During this latter portion of the forecast, the total net value of Douglas-fir under EMR exceeded that of BAU by about

Table 1. Net present value by management strategy for 1980–2060 in millions of 2005 dollars*.

	Discount rate			
Management strategy	0%	1%	3%	5%
BAU	1569	1061	574	372
MP	1524	1023	552	359
EMR	**1790**	**1181**	**611**	**380**

Note: Abbreviations for the management strategies are business as usual (BAU), mixed planting (MP), and early pine cut, mixed planting, and increased natural regeneration (EMR).

*Highest value at each discount rate is presented in bold.

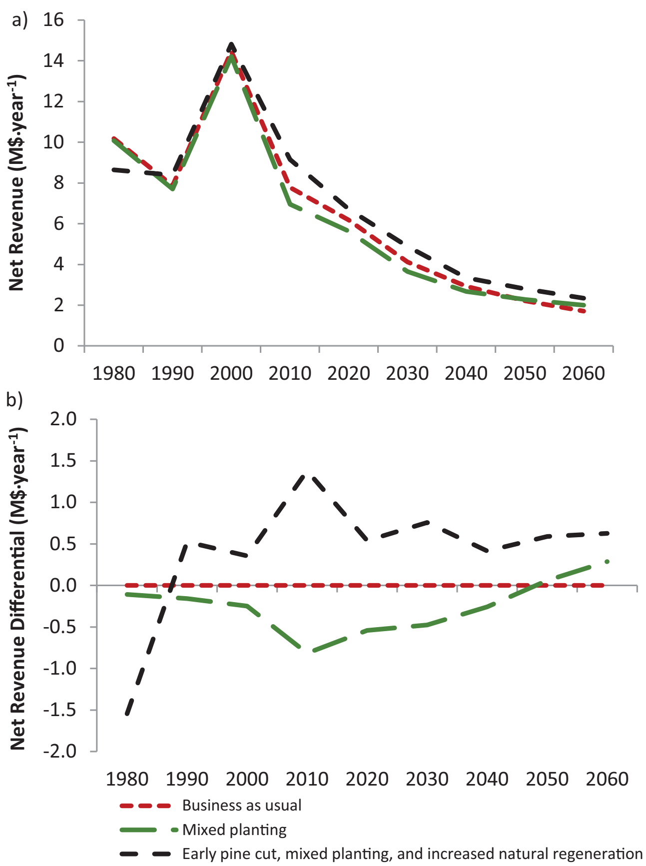


Fig. 6. (*a*) Total annual net revenue and (*b*) annual net revenue differential from business as usual for each management strategy, 1980–2060, discount rate 3%, and constant 2005 dollars. Units are millions of dollars per year (M$·year^{-1}).

85%. MP showed lower net revenue than BAU, driven mainly by higher silviculture costs during the initial 30 years of the simulation and a lower harvest rate after the beetle impact. In terms of recouping the upfront lost revenue, EMR was able to recoup its losses by about 2005, assuming a 3% discount rate.

3.2.2. *Per cubic metre values and costs*

Each strategy uses specific harvest methods and accesses different stands and species at different locations and times. How well the strategy performs in terms of the returns per cubic metre illustrates its success in maximizing the value of the available timber. Per-unit values also provide a clearer link to upstream and downstream markets within a value chain. In terms of the total NPV per cubic metre, EMR provided the highest return only under the 0% and 1% discount rates (Table 2). This result reflected the shift to lower valued pine in the first and second decades and the effect of discounted higher values in the future. MP exceeded

Table 2. Average annual net present value per cubic metre by management strategy and discount rate for 1980–2060 in constant 2005 dollars*.

	Discount rate			
Management strategy	0%	1%	3%	5%
BAU	13.51	9.13	4.94	3.20
MP	14.14	9.49	**5.12**	**3.33**
EMR	**14.72**	**9.72**	5.02	3.13

Note: Abbreviations for the management strategies are business as usual (BAU), mixed planting (MP), and early pine cut, mixed planting, and increased natural regeneration (EMR).

*Highest value at each discount rate is presented in bold.

the others beginning at a discount rate of 3%. At a 5% discount rate, MP had a NPV per cubic metre 6% greater than that of EMR. These per cubic metre results differed substantially from the total NPV results in which MP had the poorest performance because of lower harvest rates in the latter portion of the simulation.

In terms of the flow of net revenues per cubic metre over time, EMR provided lower per cubic metre returns in the first decade and generally provided higher returns from 1990 onwards compared with BAU (Fig. 7). From 1980 to 1989, under a 3% discount rate, BAU resulted in a higher NPV per cubic metre followed by MP. The annual per cubic metre NPV of EMR was $2.25 per cubic metre below BAU in the first decade, due largely to the shift in species harvested towards more low-value pine and the higher costs associated with partial cutting. After the beetle impact, both of the alternative management strategies had higher values per cubic metre than BAU because of a larger component of the harvest coming from Douglas-fir, which had a 43% mean price premium over pine.

Rather than maximizing returns on the harvest and sale of logs, a forest manager may seek to minimize the per-unit costs of producing timber as an input into forest products manufacturing. For the first three decades, per cubic metre costs for EMR was about 5% less than BAU (Table 3). Over the remainder of the 80-year time line, per-unit costs for EMR exceed BAU by, on average, about 1.3%. The near-term difference was due mainly to lower silviculture costs as a result of the fewer number of hectares required to maintain the timber supply because EMR required, on average, about 24% less hectares than BAU for the same volume (Supplementary Fig. S2[1]). Beyond 2010, EMR required, on average, about 17.5% more hectares than BAU to produce its greater volume of timber supply, leading to higher total costs for silviculture and harvesting operations.

3.2.3. *Sensitivity and uncertainty analysis*

In this analysis, we evaluated how sensitive the THLB area and the harvest rates were to uncertainty in Douglas-fir productivity. A 20% increase in Douglas-fir productivity led to an 11% increase in the timber supply and a 6.3% increase in NPV for BAU. A 20% reduction in productivity reduced BAU timber supply and NPV by similar amounts (Table 4). In EMR, the timber supply and NPV changed slightly less than in BAU. Regardless, EMR outperformed BAU under both productivity changes, thus there is no change in the ranking under this analysis.

Additional sensitivity analysis of the effects of a plus or minus 20% change in log prices examines the assumption that prices will remain constant, as modelled in the simulation. We included any stand that was above zero net revenue in the forest area available to harvest and excluded any stand that was below. When log prices decreased by 20%, the economic THLB area decreased to 70% of what was assumed in the base simulations (Supplementary Table S8[1]). When prices increased, the economic THLB area increased by 4%. This minor upside indicates that the THLB used in the base simulations was close to the maximum likely to be harvested. The smaller upside potential also reflects the high percent-

Fig. 7. Annual net revenue per cubic metre differential from business as usual for each management strategy, 1980–2060, discount rate 3%, and constant 2005 dollars. Units are dollars per cubic metre per year ($\$\cdot m^{-3}\cdot year^{-1}$).

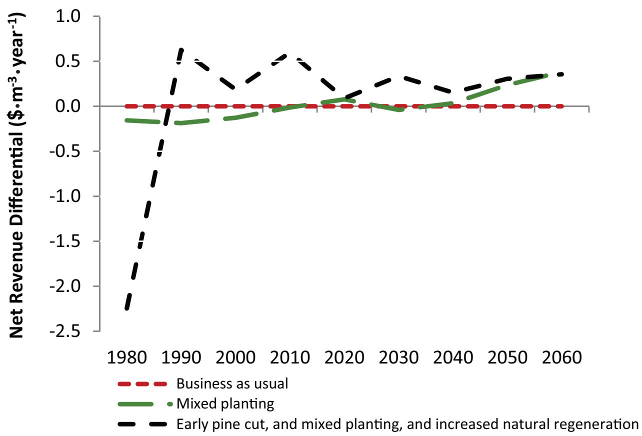


Table 3. Average costs per cubic metre by management strategy and decade for 0% discount rate and constant 2005 dollars*.

	Decade			
Management strategy	1980–1989	1990–1999	2000–2009	2010–2060
BAU	38.6	38.4	36.9	**37.70**
MP	38.8	38.7	37.2	37.97
EMR	**36.7**	**36.1**	**35.7**	38.16

Note: Abbreviations for the management strategies are business as usual (BAU), mixed planting (MP), and early pine cut, mixed planting, and increased natural regeneration (EMR).

*Lowest cost in each decade indicated with bold face numbers.

age of the base THLB to total area. In terms of the volume available for harvest, both BAU and EMR experienced similar harvest reductions as a result of a 20% price decline: –37% and –36%, respectively.

The EMR strategy outperformed BAU under both price changes, mainly as a result of the greater percentage of more valuable Douglas-fir in the harvest and the continued dependence of pine in BAU. For both strategies, the modest gain under the log price increase reflects a capacity constraint, or simply a lack of additional stands that can be incorporated into the THLB. The sensitivity to price indicates far greater downside risk for both strategies. However, the simulation results respond immediately to the price signals, whereas operationally the sector would likely take some time to respond, tending to minimize any losses before closing facilities. The simulation also assumes, the price changes remain constant once in place. Prices will fluctuate as the sector progresses through various economic cycles, thus the price changes in this exercise represent a shift in mean prices versus normal variability. Regardless, one can assume larger downside change than upside change.

4. Discussion

In our study, we explored potential management strategies to achieve resilience to potential future forest health disturbances expected to occur under a changing climate. The resilience of the forest landscapes to pests and disease depends in part on the species diversity and abundance of high-risk species. The lower Shannon diversity index and higher Berger–Parker dominance index for the BAU strategy from 2010 to 2060 indicates lower resilience and potentially greater risks of future severe damage by forest health agents to the timber supply and related forest values. Similar to our BAU results, Schneider et al. (2010) documented that increasing the harvesting rate and focusing the harvesting on pine did not reduce the risks from mountain pine beetle because the regenerated species were the same as the harvested species.

In the pine-dominated landscape of our study area, having a management objective to increase diversity was effective in creating greater socio-ecological resilience within two decades, as indicated by greater species diversity, the highest growing stocks, and harvest rates after the beetle impact. These results were surprising because we were unsure before conducting this study whether or not management activities could result in effective change over such a short time period (given the tree species longevities, climate, and large landscape). Also unexpected, the EMR strategy resulted in the highest net revenue over the simulation period, the highest annual net revenue and net revenue per cubic metre starting in 1990, and the lowest costs per cubic metre in 1980–2009. Typically, diversification strategies have poorer economic outcomes (Hildebrandt and Knoke 2011). It is important to note that the EMR strategy employed a variety of forest management tools to achieve an effective outcome: targeted harvesting of a particular species, a different balance of harvest systems, a combination of natural regeneration and planting, and a greater diversity of planted species. However, the less aggressive management strategy — the MP in which we only altered reforestation assumptions — required two decades longer to increase the diversity above the BAU strategy. Therefore, implementing a MP strategy may be effective at increasing resilience over the long term.

Our simulation results confirm the higher long-term harvest rate under a hypothetical resilience-oriented management presented by Rist and Moen (2013). However, in their hypothetical system, there was a trade-off between short- and long-term harvest rates, whereas in our study, the trade-off was in short-term revenue and long-term harvest rates and revenues. Our EMR and MP biophysical results in some ways echo the study by Temperli et al. (2012). They evaluated three management strategies for creating more climate change resilient forests compared with two BAU strategies. The adaptive management objectives were to foster greater structural and species diversity rather than the BAU monoculture. Under a changing climate, timber production was projected to fall dramatically in the latter part of the 21st century due to drought. The reduction in harvest rates was greater and lasted longer under the monoculture approach than under those strategies that increased diversity and fostered drought-tolerant species. One of the key differences between studies was the time required to shift species composition: from 2–4 decades in our study area compared with as much as 70–120 years in Temperli et al. (2012). This difference emphasizes the importance of past and potentially available management practices on affecting change.

Increased species diversity was important to maintain resilience and could result in additional benefits to the forest ecology. For example, the widespread tree mortality caused by the beetle and the surge in harvesting and associated road building has changed the habitat conditions for many wildlife and other species within the Interior of B.C. (Bunnell et al. 2011). Nineteen species at risk can be found in the Merritt TSA, of which five depend upon old-growth habitat. Our results indicate that the management strategies intended to increase forest resilience to forest health damage could also be beneficial in supporting species at risk. Furthermore, the beetle impact led to increased carbon emissions and decreased sinks, resulting in the effected forest becoming a net emitter of carbon to the atmosphere (Kurz et al. 2008). Preventing future epidemics or at least reducing their impacts could therefore mitigate climate change by maintaining biological carbon sinks and storage.

The EMR strategy demonstrated that the portfolio approach to risk reduction would lessen the likelihood of catastrophic losses. A more stable timber supply may also benefit other social and cultural values such as employment and mill openings. These are economic advantages of the EMR strategy, accrued over the longer

Table 4. Harvest rate after beetle impact (millions of cubic metres per year ($Mm^3 \cdot year^{-1}$)) and annual net present value sensitivity to Douglas-fir productivity ± 20%, 3% discount rate, in constant millions of 2005 dollars for business-as-usual (BAU) and early pine cut, mixed planting, and increased natural regeneration (EMR) strategies.

	BAU				EMR			
Douglas-fir productivity	Harvest ($Mm^3 \cdot year^{-1}$)	% from base	Net present value (millions of dollars)	% from base	Harvest ($Mm^3 \cdot year^{-1}$)	% from base	Net present value (millions of dollars)	% from base
–20%	1.22	–10	538	–6.3	1.35	–6.9	575	–5.9
Base	1.36	n/a	574	n/a	1.45	n/a	611	n/a
+20%	1.5	+11	610	6.3	1.55	+7.4	644	5.4

term. However, if the lower valued logs led to lower valued solid wood production, e.g., through a lower volume of peeler logs for the veneer and plywood sector, this could result in an initial reduction in the economic value added or forest-sector gross domestic product (GDP) beyond what we estimated. The strength of the sector would not emerge until the latter part of the simulation period when higher valued species are more abundant. This foregone value in output could lead to reduced spending within local and provincial markets, leading to further declines in output. Thus, while the ability to reduce costs may be an incentive for companies to agree to a program of landscape and species diversity, decision makers need to weigh the opportunity cost against the higher risk of future infestations or other natural disasters associated with a more monoculture approach to forest management.

Our results imply that rather than assuming that climate change adaptation strategies are not practical, forest managers should consider strategies that prioritize ecological resilience as a management objective. A management strategy that distributes the risks across more tree species likely results in a more secure and profitable long-term timber supply. Increasing tree species diversity is not the only way to increase ecosystem resilience: genetic diversity, species diversity beyond just trees, ecosystem and structural diversity (Puettmann et al. 2009), and facilitated migration of populations (Aitken et al. 2008) are others. However, the effectiveness of a strategy such as EMR will depend on conditions in each management units. For example, it may not be effective in areas with high tree species diversity to start with, or areas where reforestation is largely limited to one species because the climate and soils may not be suitable for extensive use by other species. The implications of these results for forest managers will depend on the current tree species diversity, local harvest and reforestation practices, and projections of climate change impacts on forest health in the near term and longer term.

While we must aggressively pursue adaptation strategies, our expectations from our forests must be tempered by the knowledge that management actions to adapt to climate change will have a limited impact at the landscape level even if we can fully put them into effect in the near future. In B.C., we actively manage about 0.3% of the forests area annually. Our results show that management actions may be able to reduce the impacts of an epidemic after only a few decades; however, much of the forest will have to adapt naturally (Spittlehouse 2005; Bunnell and Kremsater 2012).

5. Conclusions

Our analysis reveals that resilience-oriented management strategies may be able to maximize some near-term and many long-term benefits. The BAU strategy underperformed in most situations. However, incorporating only a MP strategy may not result in greater resilience in the near term. The strategy that used both harvesting and regeneration to directly reduce species dominance by removing high risk species in the near term and establish a more diverse stand structure across the management unit fostered ecosystems that are likely more resilient to catastrophic events such as the pine beetle infestation. This management strategy reduced risks, increased resilience, and provided better stability in growing stocks, higher harvest rates in the long term, and higher, more consistent net revenue over time than the BAU strategy. Although uncertainty exists with any modeling exercise, sensitivity analyses indicate a high level of robustness in the results, supporting the management strategy with the objective of more resilient forests.

Acknowledgements

We would like to thank the consultants at Ecora (Kelowna, B.C.) for their capable support for forest ecosystem and economic modelling. The B.C. Ministry of Forests, Lands and Natural Resource Operations funded this project. Amy Law and three anonymous reviewers provided helpful comments on the manuscript.

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