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Article

Striving for Sustainability and Resilience in the Face of Unprecedented Change: The Case of the Mountain Pine Beetle Outbreak in British Columbia

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Abstract: A massive insect outbreak in the public forests of central British Columbia (Canada) poses a serious challenge for sustainable forest management planning. Tree mortality caused by natural disturbances has always been a part of wild and managed forests, but climate change is accentuating the uncertainty around such losses. Policy responses to accelerate overall timber harvesting levels to prevent further tree mortality and to aggressively salvage value from dead wood before it deteriorates can be disruptive and even counter-productive in the long run. Current alternatives are to strategically redirect existing timber harvesting quotas to the most vulnerable areas, minimize overall uplifts in cutting activity, prolong the period over which harvested timber can be processed, avoid the harvesting of mixed species stands or those with good advance regeneration, employ more partial cutting or “selective logging” techniques, and relax standards for acceptable species and inter-tree spacing during post-disturbance stand recovery. At the same time, careful attention to species composition and evolving landscape risk profiles may facilitate adaptation to anticipated climate change and reduce vulnerability to future disturbances. Harvest levels must be set conservatively over the full planning horizon if it is important to assure continuity of the timber supply with few disruptions to regional socio-economics and less stress to ecosystems. Broader lessons in sustainability include the option to emphasize persistence, continuity and flexibility over the long term, though at the expense of maximized production and full resource utilization in the short term.

Keywords: climate change; even flow; forest disturbance; forest policy; insect outbreak; salvage logging; sustainable forest management; timber supply

1. Introduction

The concept of sustainability has implications of constancy or predictability that may be at odds with the realities of many biophysical and socioeconomic systems. Over a short period of time, natural disasters, changing economic conditions, political or technological revolutions, and even the more subtle surpassing of critical thresholds or “tipping points” can negate the relevance of well-intentioned, carefully devised long-term plans for a sustainable future. Sustainable forest management is deeply rooted in the principles of long-term planning for sustainability. As a discipline, and with reference to one recent challenge in particular, it may offer some guidance in how to react and adapt when confronted with dramatic unanticipated change, and how such disruptions can be the incentive for promoting adaptive resilience as well.

The current outbreak of mountain pine beetle (*Dendroctonus ponderosae*) in British Columbia, Canada (B.C.), has affected more than 16 million hectares of forest land [1]. Responding to the “perfect storm” of abundant mature pine on the landscape (as a result of widespread fires from 1880 to 1920, effective fire suppression policies, and little logging of pine until the 1970s) coupled with warming winter temperatures, this outbreak has been growing since the mid-1990s. The mountain pine beetle is a native insect, part of the natural disturbance regime of lodgepole pine (*Pinus contorta* var. *latifolia*) forests. Outbreaks have occurred in the past, but the rate of spread and the severity of the current outbreak appear to be truly unprecedented [2].

Forest managers at first responded with sanitation harvesting designed to control infestations. Efforts eventually shifted to salvage operations to recover commercial timber before fiber value deteriorates, though sanitation efforts continue on the edges of the outbreak. Allowable rates of cut have been repeatedly increased on provincial Crown (public) land in order to facilitate such sanitation and salvage activities [3,4]. The outbreak and the accelerated logging mobilized in response are having marked impacts on ecosystems, the forest products industry, regional economies and communities [5]. Yet there may be opportunities presented by this so-called natural disaster, prompting us to evaluate forest policy options and prevailing forest practices as the forest recovers in the context of a changing climate. It is the objective of this discussion paper to suggest ways in which forest disturbance impacts can be reduced, ameliorated, or even taken advantage of to promote more resilient forests and a more sustainable long-term future for the forest sector. There may be lessons garnered from this experience that also have applicability to sustainable resource management in general.

2. Sustainability in the Face of Loss

A minimum basis for sustainable forestry is that timber harvesting should not proceed at a rate greater than that at which the forest is able to regrow the wood volume that is being extracted. This concept is perhaps forestry’s greatest legacy to civilization, seeding the notion that rates of resource consumption must not exceed the ability of the system to replace what is taken, as explicitly articulated in management plans that can span a century or more [6]. Different forest management models emphasize sustainability at different spatial scales (stand, landscape or region), but the goal of sustaining timber productivity in perpetuity is not in question. “Sustainable forest management” extends the principles of sustained yield forestry to a wide range of non-timber forest values (e.g., water, wildlife, recreational opportunities) as well [7,8]. Not only are forest values expected to be maintained over time, essentially reaping the “interest” without compromising the “capital” associated with forest assets, but there is also the widespread expectation that those forest values will exhibit continuity (such as an even flow of timber) over time [9,10]. That is, sustainability means there should be no prolonged gaps in the provision of forest goods and services; one cannot over-exploit the resource in the hope that it will recover “eventually” and still claim the mantle of sustainability. The goal of achieving a non-declining and evenly flowing timber supply is intended to ensure employment and community stability, as well as environmental integrity [11], although declining timber supplies are frequently accepted during the period of converting any high-volume old-growth forest to faster growing plantations [12]. A commitment to an even flow of values is implied, if not explicitly stated, in the 5th criterion (on multiple benefits to society) for sustainable forest management originally endorsed by the Canadian Council of Forest Ministers in 1995, namely that “forests must continue to provide the flow of wood products, commercial and nonmarket goods and services, and environmental and option values over the long term” [13]. Krcmar and van Kooten [11] assert that an even flow of timber “… is the bedrock of public forest policy in Canada.”

With these principles and expectations in mind, how do forest planners deal with recognized risks and losses from agents such as forest fires, insect outbreaks, and other agents of tree mortality? These disturbances have always been visible threats to the reliable planning and delivery of timber value, so forest protection (e.g., fire suppression) has a long history as part of forest management [6]. In recognition of some inevitable losses to fire, insects and diseases, estimates of sustainable harvest levels are usually adjusted to “give Nature her cut,” by considering the average level of annual losses observed historically, before determining how much can be logged [10,12,14]. But true catastrophes, in which some large proportion of the inventory is lost, require a recalculation of what subsequent harvest levels can be sustained, and often precipitate a redirection of management, processing, and marketing efforts [15].

The mountain pine beetle outbreak in British Columbia is not a unique example of catastrophic disturbance in managed forests. Eastern Canada has dealt with repeated outbreaks of the spruce budworm, *Choristoneura fumiferana* [16]. Large areas of the boreal forest burn every year, although much of this area is not part of the managed estate scheduled for timber harvest [17]. Hurricanes make regular landfall in the southeastern United States, where strong winds can decimate forests in a matter of hours [18]. Exotic pests have also taken their toll on North American forests: from chestnut blight (*Endothia parasitica*) in the early 1900s through to the emerald ash borer (*Agrilus planipennis*) today [19].

Not all “disasters” or “game changers” faced by forest managers constitute loss of standing timber. Widespread regeneration failure caused nationwide concern in Canada [20] and in Finland [21] in the 1980s. Entire nursery crops can be destroyed by harsh weather or mismanagement before seedlings are even planted. Young plantations are also subject to damage as a result of disease [22]. Such problems cause significant shortfalls in the rate at which timberlands are renewed and able to replace the volume of wood that is being harvested, meaning that if such failures are not remedied, sustainable harvest levels eventually must be curtailed accordingly. Market disruptions and changing social values (e.g., shifting forest management from commodity production to biodiversity protection) can similarly threaten the continuity of forest harvesting. For example, forest management in national forests of the United States Pacific Northwest underwent a sea change when protection of the Northern Spotted Owl (*Strix occidentalis caurina*) and its old growth habitat took precedence over lumber production in the mid-1990s [23]. Non-timber forest values too can be disrupted by reduced logging activity when sustainable forest management depends on timber harvesting and marketing to pay for road construction, local employment, habitat enhancement or ecosystem restoration. A reduced level of U.S. housing starts along with the rapid appreciation of the Canadian dollar between 2004 and 2008 reduced lumber prices to levels that made many Canadian sawmills and associated woodland activities no longer economically viable [24], showing that dependence on a single market is also a threat to sector sustainability. Whether due to insect outbreaks or loss of markets, many rural and forest-dependent communities across Canada are now experiencing reduced forestry activity and an uncertain future. Are there ways to avoid such disruptions to forest management plans, economic activity, livelihoods and communities? What can be learned from previous forest disturbances or other drastic shifts in management direction?

3. A Place for Salvage Logging

One widespread response to the sudden death or damage of mature timber is to salvage the wood as quickly as possible. The logic of the argument is that the wood should be harvested before it loses economic value due to the activity of wood-boring insects and fungi [25,26]. Large quantities of dead and fallen trees, rapidly drying out and accumulating on the ground, are further perceived to be a fire hazard [27,28]. When insect pests survive or propagate in the dead trees (as is the case for spruce beetle, *Dendroctonus rufipennis*, or the mountain pine beetles in trees attacked in the previous year), it is imperative to destroy those broods, usually through log processing or burning, before pest populations explode [29,30]. It is also argued, especially in the case of damaged even-aged stands, that the forest needs to be regenerated as rapidly as possible, for which the removal of logs and debris is usually a prerequisite.

Natural disturbance events vary in size, severity, and frequency, but invariably open up the forest canopy and free resources, thereby facilitating the regeneration of plant communities and diversifying the landscape [31]. Well-studied examples such as the Mount St. Helens volcanic eruption of 1980 and the Yellowstone forest fires of 1988 show that ecosystem recovery can be rapid where biological legacies (*i.e.*, surviving trees, snags and logs, patches of intact vegetation, seed banks in tree crowns or in the soil) remain intact [32]. Consequently, efficient timber salvage, which results in the widespread removal of most biological legacies and tends to further damage elements of an already disturbed ecosystem, can result in severe ecological impacts [33,34]. Such impacts can include accelerated erosion and sedimentation in streams, and the loss of vertical structure (standing live and dead trees) important for perches and nests [34,35]. Salvage clearcutting tends to damage the tree seedlings that had established before or soon after the natural disturbance, and the resulting slash may increase rather than decrease the risk of wildfire [36]. It has been projected that carbon release stemming from the mountain pine beetle outbreak will be exacerbated by salvage logging [37]. Salvage operations after wildfires and insect outbreaks are becoming so widespread that naturally disturbed, unsalvaged forests, and the flora and fauna associated with such habitats, are now rare in many parts of the world [38-41].

For reasons of economic and silvicultural efficiency, as well as safety concerns, clearcutting remains the standard harvesting system employed for salvage logging, even though it is unusual for all trees in a stand being salvaged to be dead or damaged. Consequently, there is considerable “by-catch” or the unnecessary removal of green trees as part of salvage operations. In the case of mountain pine beetle outbreaks in British Columbia, only 37% of the affected forest areas have historically consisted of pure (>80%) lodgepole pine [42]. This means that many healthy trees (including many which experience growth release in response to the beetle-initiated death of neighbouring pine trees [43,44]) are being removed from locations where they are most needed to provide critical habitat elements and critical timber supply for use after the insect outbreak.

It would not violate the principles of sustainable forestry to redirect pre-determined (sustainable) harvest levels to salvage trees killed or damaged by natural agents. Impact on biodiversity and ecosystem services can be minimized if relatively high levels of canopy retention are assured, as recommended in guidelines issued by British Columbia’s Chief Forester [45]. High levels of overstory and green-tree retention are especially important for mitigating salvage impacts where managed forest (recent clearcuts, homogenous second growth, and new salvage areas) cover large contiguous areas of land [34]. Another consideration is the overall disturbance regime currently prevailing in the landscape: Where forest stands naturally disturbed by insects, fire or windthrow are rare, intervention by salvage operations is less appropriate [34].

4. What about Forest Restoration?

Many silviculturists and restoration practitioners suggest that their skills are needed to help “repair the damage’ after natural disturbances. This position may not recognize a distinction between ecological disturbance and ecological degradation. Most indigenous flora and fauna are evolutionarily adapted to natural agents, frequencies and severities of disturbance and are capable of recovering on their own, while degraded ecosystems (often, but not always, a consequence of human activities) may not recover in a reasonable period of time without human assistance [39,46-48]. The concept of degradation, too, has an implicit ranking of values at its core: A degraded forest might have superlative grazing values, while (conversely) rangeland can be degraded through forest ingrowth and subsequent shading. So all remediation and restoration activities must identify some desired ecosystem state as their goal, recognizing that there may be several alternative natural or potential states to the ecosystem being managed [49].

In the case of the mountain pine beetle outbreak and most other forest insect disturbances, mortality is limited to one or a few species of obligate host tree species. Depending on the complexity of forest composition and structure, a wide range of tree species and tree sizes (collectively known as “secondary structure”) may survive the insect outbreak [43]. Even though many lodgepole pine trees are found in even-aged fire-origin stands, pre-logging surveys conducted in central British Columbia reveal that between 40% and 60% of pine stands have high densities of tree seedlings and saplings in the understory [50,51]. In other words, half of these forests are *not* “dead” (even if just talking about trees, to the exclusion of other plant and animal species) in the wake of the pine beetle, and require no assistance to regenerate. Conversely, half of the pine-leading stands in central British Columbia appear to be less than fully stocked with advance regeneration. Natural regeneration in such stands is likely to be lengthy and spotty, largely dependent on the dispersal and germination of tree seeds after moss-dominated forest floors break down [52]. Such areas with poor prospects for the release or natural regeneration of trees are logical priorities for artificial regeneration. From a conservation biology perspective, however, beetle-killed or severely burned forests with delayed tree regeneration also contribute important habitat diversity to the landscape [34,40].

In many cases, there is healthy natural vegetation, including trees, surviving and thriving on the site of forest disturbances caused by wind, ice storm or insects. That vegetation may or may not consist of species desired by the forest industry. Conversion of such sites to conifers or other desired crop species is better referred to as "rehabilitiation" rather than "restoration" [50]. Given that almost all of B.C.'s lodgepole pine dominated forests originated after widespread crown fires, true restoration (*i.e.*, back to even-aged, densely stocked lodgepole pine forests) would similarly require the use of stand-replacing fire [53]. There has been widespread discussion and a few pilot projects (especially in provincial and national parks, but also on commercial forest lands) to use prescribed fire as a tool to control mountain pine beetle populations, renew the forest, and restore forest age-class structure to a more natural state [53-55]. However, if the climate is changing as the evidence now indicates [56], do we really want to restore the forest to a composition and structure that arose in response to conditions prevailing more than a century ago? Alternatively, if climate change projections are not sufficiently reliable and precise to design future forests [57], perhaps the best we can do is facilitate the natural adaptation of forest ecosystems to changing conditions.

5. Bridging the Timber Supply Gap

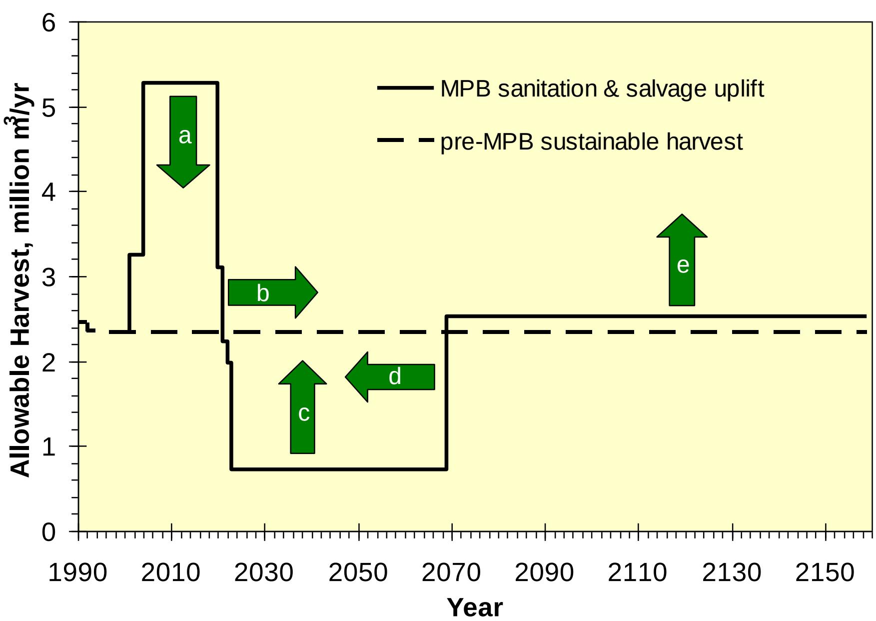
Salvage logging can be a useful management tool in a multiple-use forest, so long as considerable residual structure is retained, as recommended elsewhere [45,58-60], and if it is conducted in landscapes where naturally disturbed early-successional habitats are plentiful [34], preferably without increasing the rate of harvest to unsustainable levels. But what are the consequences, and some mitigative alternatives, if society decides to harvest some of tomorrow's timber supply today? The principle of even-flow sustained yield and the basic concepts of sustainable forestry advise caution in boosting harvest levels above the long-run sustained yield [12]. While it may be economically optimal to draw down timber stocks to in order to pay for infrastructure, or to accumulate growing stock rather than process wood products under unfavourable market conditions [12,13,61], even-flow sustained yield is nevertheless desired for reasons of employment stability and community well-being. It may yet turn out that the biggest impact of the mountain pine beetle outbreak to the fabric of British Columbia is not the number of trees killed by the insect, but disruptive spikes and lulls in the rate of logging.

Across the southern and central interior of B.C. (consisting of 20 timber supply areas affected by the beetle outbreak), the allowable annual cut (AAC) was increased from 37.6 million m^3/yr to 54.6 million m^3/yr (a jump of 45%) in order to salvage this value before it is no longer economically viable to do so [4]. In the Vanderhoof and Quesnel Forest Districts, with large expanses of pure lodgepole pine forest, allowable cutting levels were more than doubled from their pre-outbreak levels.

This means that much of the timber inventory that had previously been slated for logging in the coming decades is instead being harvested over just a few years.

The "uplift" in permissible harvest rates is popular with sawmills and logging contractors, but can last only 5 to 15 years, after which it is anticipated there will be a precipitous "falldown" in logging opportunities (Figure 1). This falldown is largely due to a gradual deterioration in the wood quality of beetle-killed trees, although this "shelf life" varies with climate, site, end product, manufacturing efficiency, and market conditions. With such a loss in useable timber stocks, it is inevitable that sustainable levels of harvesting would have to be adjusted downward after the pine beetle outbreak, especially in timber supply areas heavily dependent on pine trees. Part of the falldown, however, is in compensation for the harvest uplifts that will have already consumed the wood originally scheduled for future harvest. The falldown is projected to last for several decades, because most second-growth forests in the B.C. Interior will not be sufficiently mature to harvest for another 30 to 50 years [62], and some of the more intensively managed lodgepole pine plantations have been attacked too, though younger than generally considered susceptible to mountain pine beetle [4]. This gap in the forest age class structure, already in existence before the pine beetle outbreak and exacerbated by beetle-induced mortality and salvage uplifts, constitutes a dearth of mature forest habitat and ecosystem services as well as mid-term timber supply.

Figure 1. Scenario 1 of three alternative timber supply projections for the Quesnel timber supply area in central British Columbia [63] showing allowable harvest levels prior to the mountain pine beetle (MPB) outbreak, associated uplifts in the AAC and the subsequent falldown trough. Potential strategies for decreasing the impact of the falldown and increasing the mid-term and long-term timber supply include: (a) not having such a large uplift in harvest rates; (b) prioritization of salvage operations to harvest pine stands with shorter shelf life first, and perhaps storing harvested logs under sprinklers or snow; (c) use of partial cutting or deferring logging in mixed-species stands; (d) protection of advance regeneration during logging, and thinning or fertilizing juvenile stands; and (e) reformulation of stocking standards to accept broadleaf species and clumped regeneration.



New businesses have formed, logging contractors have bought additional machinery, and sawmills have put on extra shifts to handle the increased volumes of wood made available at the peak of the pine beetle outbreak [64-66]. Figure 1 indicates a dramatic drop in forestry activities projected to start a decade or two after uplifted harvest rates began, reflecting the completion of (economically feasible) salvage operations in the wake of the pine beetle well before most second-growth stands (first planted in the 1970s and 1980s) will have reached rotation age [4,62]. During this mid-term gap, forest products manufacturers and logging contractors will have to depend on the harvesting of spruce (*Picea* spp.), subalpine fir (*Abies lasiocarpa*), interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and broadleaf species such as paper birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*), and black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) in order to survive. Mature stands of those species are not evenly distributed throughout the BC Central Interior. In practice, many businesses in the forestry sector are expected to move elsewhere or close shop [67].

It is useful to view mitigation and remediation of the mid-term timber supply gap as an exercise in the promotion of sustainable forest management. There are several tactics that can be employed, most of which are applicable to forest management after insect outbreaks and perhaps other disturbances. As portrayed in Figure 1, efforts can be made to shorten the temporal span of the mid-term gap and the depth of that mid-term trough. Such tactics can be employed individually, but may further influence each other's efficacy if applied collectively. They largely depend on improved knowledge of the forest and its ecological dynamics.

Firstly, the post-outbreak falldown need not be so steep if the uplift were not so great in the first place (letter a in Figure 1). Given the lumber markets and access limitations prevailing at the time, actual harvest levels in the Quesnel timber supply area during 2005 to 2009 ranged from 63% to 82% of the AAC [63]. This means that the magnitude of the post-uplift falldown will not likely be as great as it might have been. One scenario presented in the discussion paper accompanying the Quesnel timber supply review, recently released by the B.C. Forest Inventory and Analysis Branch [63], suggests immediately dropping the AAC to match the greatest annual level of actual harvest, thereby softening projections for the magnitude of reductions in industrial activity.

Secondly, the socioeconomic disruption associated with inevitable decreases in logging and milling activities will be softened if the transition out of uplift mode can be made more gradual (letter b in Figure 1). Such a graduated reduction to the AAC for the Quesnel timber supply areas is presented in another scenario offered in Forest Inventory and Analysis Branch discussion papers [63].

Other means of prolonging the harvest of useable wood are also being explored. Pine stands can be ranked in the order they are expected to undergo checking (longitudinal cracking associated with drying) and the onset of stem-rot fungi. Checking appears to develop more rapidly on very dry or exposed sites (although the wood from such trees can remain structurally sound and suitable for solid wood and pulp processing for over a decade), while root rots and stem rots progress more rapidly under warm moist climate regimes and on wetter sites [68]. Modelling work based on spruce budworm (*Choristoneura fumiferana*) outbreaks in New Brunswick suggests that re-optimized harvest scheduling in conjunction with a focused salvage program can offset eventual harvest reductions by more than 26% [69]. Logs can be stockpiled dry or under sprinklers in log decks, but they are still vulnerable to deterioration by fungi and wood boring insects. In the past, a glut of dead and damaged wood generated by forest fire, insect outbreaks or wind storms might have been rapidly harvested and then stored in lakes and ponds in order to prevent its deterioration before it could be milled [70], but such practices have unacceptable impacts on aquatic ecosystems [58]. One alternative, already being practiced in Scandinavia and Quebec, is to stockpile logs under snow [71]. Using such techniques, the supply of damaged timber to processing facilities can be prolonged, but log storage does not reduce the ecosystem impacts of accelerated logging.

The by-catch problem associated with clear-cut harvesting (both at sanitation and salvage stages, and accentuated by the degree of uplift) results in an unnecessary depth to the post-uplift trough in timber supply, as shown in Figure 1. Solutions (letter c in Figure 1) are to retain stands, or portions of stands, that will be economically viable through the mid-term trough. This can be accomplished using more partial cutting, selectively logging the dead and dying pine from mixed stands, leaving mature and windfirm Douglas-fir or clumps of spruce and fir trees to harvest in the decades after the pine is gone. Given the risk of windthrow to newly exposed trees that had grown up in dense stands, and the operational and economic realities of modern mechanized logging practiced on the bulk of B.C. forest lands, such "selective logging" might more practically be implemented on a coarse stand by stand basis. If forest licensees queue the harvesting of beetle-affected stands according to the proportion of mature pine in each stand, the transition to green-tree harvesting from salvage harvesting will be more gradual, with the remaining mixed stands (having significant non-pine volumes) making a valuable contribution to the mid-term timber supply [4]. This prioritization is possible on the basis of existing forest inventory information, but can conflict with short-term imperatives (which tend to prevail in a tight economy) to harvest stands with the greatest net value, typically those with the largest total volumes, regardless of composition, at the shortest distance from processing facilities. One might question the harvest scheduling priorities and thresholds used in forest planning further: What if the default assumption was to defer stands with more than a given non-pine volume (e.g., 120 m^3/ha, as per some timber supply modelling scenarios [63]), rather than assuming that stands with greater than that volume of mature lodgepole pine would be available for salvage? It would be useful to have such proactive plans and guidelines in place before major disturbances occur, and before operators have spent borrowed money on capital equipment; this would help avoid crisis management and would minimize socioeconomic disruption [34].

The mid-term timber supply gap can also be shortened (letter d in Figure 1) by protecting the advance regeneration of non-pine species found in many stands. This can be achieved through careful logging, or as for mixed stands, simply by leaving stands having well developed understories unsalvaged for the time being. These saplings and poles of spruce and fir can represent 40 to 60 years of growth, essentially constituting well-established second-growth stands that are being destroyed by current clear-cut logging practices [72]. Griesbauer and Green [73] describe several studies in which the advance regeneration released by insect outbreaks contributes merchantable volumes of conifer timber within a few decades. Deferring stands with significant amounts of secondary structure from logging during the period of timber salvage may constitute an important means of bridging the mid-term timber supply gap [3,43] and sustaining a continuity of all forest values in the face of this insect outbreak. The feasibility and potential profitability of this sort of careful logging has been documented [74].

Finally, it is worth reconsidering what constitutes acceptable forest regeneration on public land in British Columbia. Because the current forest products industry in B.C. is dominated by the processing of conifers for softwood lumber and pulp production, it is generally only conifers that are identified as preferred and acceptable species for use in forest regeneration. In addition, growth and yield projections for second-growth stands are based on the assumption that such stands are even-aged and consist of a single crop species [75]. Stocking surveys and free-growing surveys usually don't count deciduous trees, nor many of the conifers found in dense natural clusters. Yet mature canopy trees with less than optimal inter-tree distances are commonly found in natural forests. A natural abundance of broadleaf tree species led to their role as the primary feedstock for several large forest products enterprises in neighbouring Alberta [76], and fast-growing poplars are increasingly in demand for bioenergy production [77]. Diverse stand composition and structure also has tremendous habitat benefits, especially to a large number of migratory songbird species, many of which are in decline [78]. A reformulation of these survey standards and the recognition of useful broadleaf species as part of the timber supply and habitat supply would recognize larger areas of naturally regenerating forest as being adequately stocked [50,73]. With more liberal definitions of acceptable tree species and stocking criteria, the falldown trough may not be so prolonged as current projections would suggest. Should suitable hardwood products and markets be developed, long-term sustainable harvest levels may be even greater (letter e in Figure 1) than currently estimated.

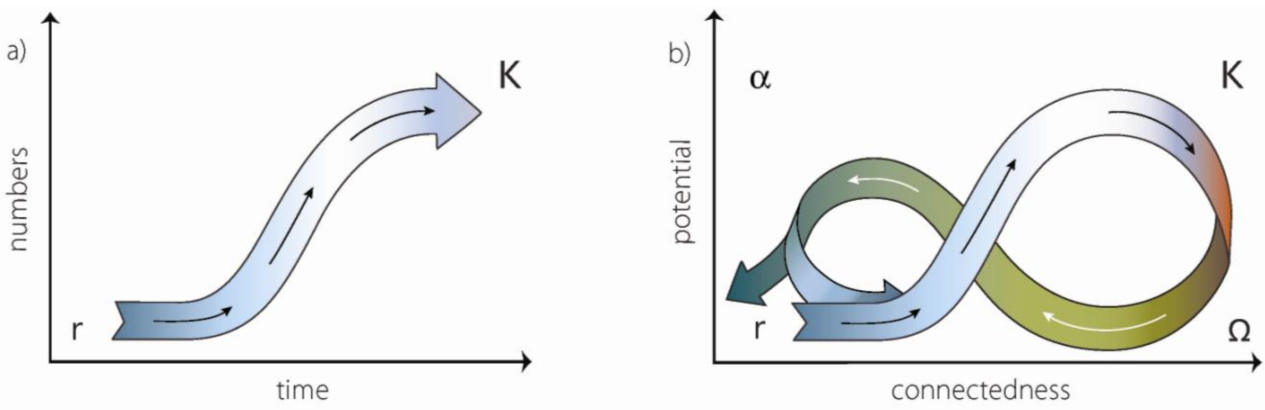
In summary, one challenge after catastrophic forest disturbances is to strategically assess what should and should not be harvested in the short and medium term, in order to create the most favorable timber supply and habitat supply forecast possible. There appear to be areas that will produce economically viable timber volume earlier if they are harvested soon and promptly regenerated than if they are left unharvested, just as there are other areas that will produce economically viable volume earlier if they are not harvested immediately. It is understandably difficult to identify and project those responses across an imperfectly known forest estate and over an economic surface that is changing unpredictably. Hence it is essential to regularly recalculate sustainable harvest levels and harvest scheduling priorities, and not just in disturbed forests.

6. Sustainability through Resilience

Though revolutionary, the vision of sustainability is also a peculiar human invention, perhaps one that is only attainable in a qualitative sense. Sustainability implies a constancy or a degree of expected control (or at least equilibrium) that is rarely seen in natural or human systems. Furthermore, we may not wish to sustain (read "freeze") all activities or all conditions at their current levels, or indeed at any given pre-conceived level [13]. That which does not change through evolution tends to change through revolution; regardless, we can be assured that change is universal. Trees grow, stands mature, and ecosystems undergo succession until relatively short-lived disturbance events cause mortality and in so doing free up space for new growth. Similarly, cultures develop, leaders come and go, regimes change, and societies rise and fall, though hopefully with some institutional memory and legacies from *l'ancien regime* so that the same mistakes aren't repeated. These cycles of growth, development and disruption can be recognized throughout natural and human spheres, and constitute the core of panarchy theory (see www.resalliance.org), a synthetic approach to understanding the great cycles of ecological and human systems [79,80].

We are used to the dichotomy between *exploitation* and *conservation*, and expect sustainable development to somehow strike a balance. But *release* and *reorganization* are just as essential to the full cycle of adaptive renewal, thereby conferring survival, resilience and future sustainability. The adaptive cycle (Figure 2) can be viewed as an expansion of the r and K notations of Lotka-Volterra population growth equations and the associated r- and K-adapted strategies exhibited by some species [81,82]. By extension, one can now recognize adaptive value to traits and scenarios associated with growth, survival and fitness during periods of disturbance and chaos as well as those associated with population (or economic) expansion and stability. Starting with the familiar logistic growth curve, one sees some species and processes thriving under conditions of widespread resource availability, so populations and activity increase at rate r, then level off at some (supposedly stable) carrying capacity K. Different traits confer survivability during the period of disturbance and resource release denoted Ω, and during the "backloop" of system reorganization, α. The cycle then starts anew, but often with different players, different inter-relationships, and different strengths and weaknesses for taking advantage of the forthcoming opportunities for growth and then stability, and for coping with the disturbance and chaos that eventually will emerge again.

Figure 2. (a) Classic representation of logistic growth, with exponential growth proceeding at rate "r" until resources become limited, so that populations must level off at some carrying capacity "K." (b) Extension of logistic growth behaviour to represent the adaptive cyclic dynamics fundamental to natural and human systems, in which "r" denotes growth and exploitation of abundant resources, "K" denotes conservation, competitiveness, niche specialization for stabilization, "Ω" denotes release and new opportunities through disturbance, and "α" denotes recovery through reorganization (adapted from [79]).



If rapid dispersal, colonization, and competitive abilities contribute to r-adapted strategies, and conservation and recycling of resources, niche specialization, and longer-life-spans constitute K-adapted strategies [82], what are the hallmarks of Ω- and α-adaptation? It is easy to interpret the massive die-off of pine trees across the interior of British Columbia as representing the collapse of a mature system, rapidly moving large areas of land into an Ω state, whereas before they had been in various stages of successional development (r) and near-climax old growth (K). As economic activity associated with the forest products sector is curtailed over the next decade or two, the socio-economics of many forest-dependent businesses, communities, and families will likewise undergo collapse or rationalization.

Although it is difficult to identify separate Ω-strategies and α-strategies, a number of traits repeatedly emerge during the backloop of ecological and social system dynamics [79]. Survival strategies that have proven successful during times of upheaval include the abilities and willingness to:

- tolerate low resource availability, and live with less for a while;
- move in space, or switch functional roles;
- experiment, innovate, and adapt;
- be plastic, flexible, exploratory and adventurous, embracing the possibility of a wide range of potential solutions;
- retain institutional memory, the knowledge and legacies of structures and approaches that had been useful during past upheavals;
- retain or build effective networks of communication and information exchange.

In the context of the post-beetle regional economy and landscape, we may see these generalities expressed in the form of the following scenarios for resilience:

- businesses and households with lower consumption and lower debt loads are more likely to survive;
- logs are being transported across traditional timber supply boundaries in an effort to maximize the processing of beetle-killed timber; many businesses and households will be exploring work opportunities outside the region or outside the forestry sector;
- it is a time to experiment with the establishment of a wider range of tree species, and forest companies are trying to develop and market new wood-based products;
- the rules, regulations and guidelines constraining how the future forest "ought to" look could be relaxed, so that a number of alternative futures (in terms of composition, structure, and configuration) can be entertained;
- efforts are being made to retain the legacy of some dead trees and some dead stands as specialized habitat and as lessons from which to learn about patterns of stand recovery; non-pine regeneration is being retained where feasible, as those seedlings and saplings may be the bridge to the next generation of forest … maybe one even better adapted to a changing climate;
- much residual forest will be left unsalvaged in continuous networks, to facilitate the survival and migration of biodiversity, not only in recovering from the mountain pine beetle outbreak, but also in adapting to climate change; networking through knowledge exchange and idea sharing throughout the region also will help communities pull through.

Whereas those principles all apply to coping with system collapse once it is under way, it might be preferable to prepare, or even plan, for system reorganization without the trauma of collapse. This is a subset of more general planning for an uncertain future or dealing with risk. Strategies for planning under conditions of uncertainty are similar to those taken for granted in business and financial circles, namely to avoid, reduce, transfer, accept (absorb), or even capitalize on risk [83]:

- diversify your portfolio of assets and marketable services;
- "cast a wider net," spreading risk geographically;
- understand the probabilities and trends;
- avoid risk-prone products, processes, and areas; and
- optimize survival, persistence, and resilience, rather than productivity and profit.

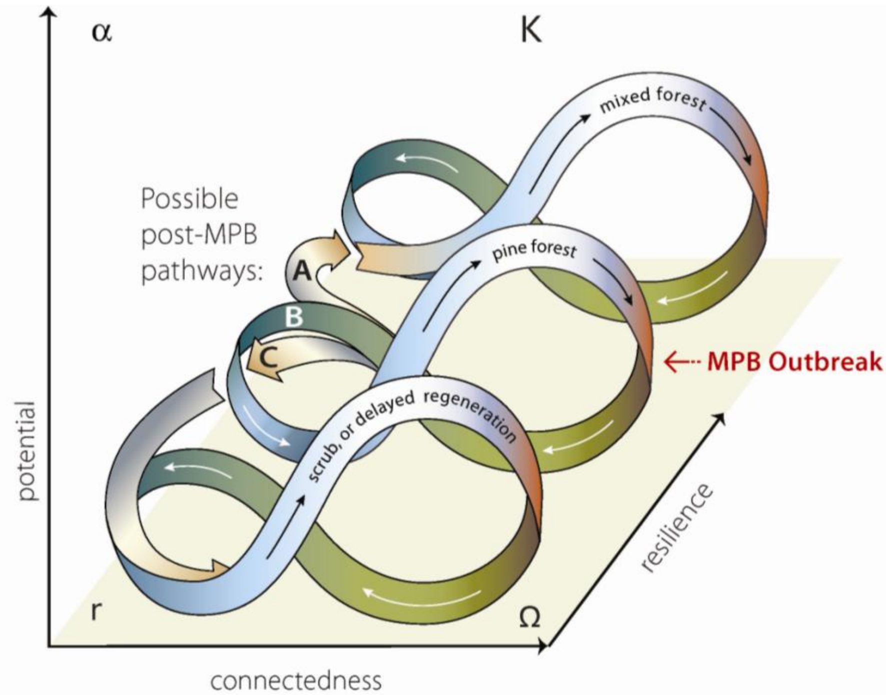
Diversification is a common theme in addressing the potential for system collapse and traumatic change. In economics as in ecology, if the objective is maximized persistence rather than maximized productivity, then diversification (of products, markets, and in the supply chain, for example) must be part of the game plan. Cautious planning is also called for, avoiding approaches that promise optimized returns or big pay-offs, but with greater dependence on a set of required conditions and hence greater sensitivity to disruption.

7. Planning for Resilient Forests in a Changing Climate

The mountain pine beetle outbreak also constitutes a weather warning, announcing in no uncertain terms that a warming climate is a reality and has socio-economic as well as ecological consequences. The beetle outbreak in B.C. is now widely cited as a concrete example of climate change impacts [56]. With winters becoming milder and summers moister in much of the province [84], and with wildfire management policies and landscape fragmentation largely constraining the propagation of large wildfires in the region, the conditions under which today's lodgepole pine forests established (pathway B in Figure 3) are vanishingly unlikely to recur, so we can expect quite a different ecosystem to develop at some time in the future. By being prepared to manage beetle-affected forests in the backloop of ecosystem reorganization, we have the opportunity to facilitate the development of better adapted and more resilient forests.

Downscaled climate change projections predict major geographic shifts in the locations of the bioclimatic envelopes that appear to constrain the distribution of diverse forest types in British Columbia [85]. Large portions of the B.C. Central Interior are expected to become drier and more suitable for Douglas-fir and western larch (*Larix occidentalis*), while northeastern portions are projected to become wetter and more suitable for interior white spruce (natural hybrids of *Picea engelmannii* and *Picea glauca*), subalpine fir, and even inland rain forests of western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*). Although there are important uncertainties in the specifics of climate change projections and species distribution modelling [57], the trends are consistent and these species are already found in the understory of some pine-dominated stands. Where this is the case, or where forest managers can strategically select species or seed sources that will be suitable for reforesting harvested lands under both current and expected conditions [86], such forests can be expected to have a jump start on maintaining forest cover that is better adapted to the new climate (pathway A in Figure 3). Indeed, the mountain pine beetle and focused salvage logging can have the effect of breaking the "biological inertia" [87] of mature pine trees that have been holding sites for a century or more, and that might otherwise be expected to delay the establishment of trees better adapted to current and future climates. Although lodgepole pine exhibits a wide range of climatic tolerances, juvenile stands are now succumbing to some rusts and fungal diseases never before prevalent [22]. We now may have the opportunity to facilitate a more diverse and resilient forest than if the outbreak had not occurred. This opportunity may be one of the "silver linings" in the clouded future of unprecedented change [31].

Figure 3. Alternative recovery trajectories and associated adaptive cycles in the wake of a mountain pine beetle (MPB) outbreak in lodgepole pine forests. Forest stands can develop into a more resilient mixed-species forest (pathway A) if there is abundant advance regeneration of spruce, fir and other tree species, or if post-logging silviculture establishes seedlings of diverse species and origins. Re-establishment of a new pine forest (pathway B) requires forest fire, or logging followed by the establishment of lodgepole pine from scattered cones or planted seedlings. Forest regeneration can be indefinitely deferred or inhibited by shrub growth (pathway C) in situations there is little or no advance regeneration, and where no fire, harvesting or silviculture occurs.



8. Summary and Conclusions

The current mountain pine beetle outbreak in British Columbia is an example of a natural disturbance that has rapidly grown from causing the mortality of small groups of trees, to killing entire stands, to converting whole landscapes and disrupting the economy over a large region. For all its ecological and economic impacts, the mountain pine beetle outbreak need not be considered an unmitigated disaster. Boreal, sub-boreal and temperate forests are highly resilient, have recovered from dramatic disruptions in the past, and will likely do so in the future. At the stand and landscape level, lodgepole pine forests have experienced similar (even multiple) outbreaks in the past and have naturally recovered over a matter of decades [44,88]. Contrary to calls for disaster relief, a more careful inspection of the forest reveals that the forest is not dead, for most of the affected area consists of mixed stands, with other species able to maintain forest cover and probably respond positively through growth release. Unfortunately, most forest inventories do not extend to the understory, so research and modelling is needed to get the full picture of the extent of secondary structure, but it is estimated that about half of pine-leading stands in central B.C. are stocked with trees that will survive and thrive in the wake of the pine beetle [50]. This little insect and its impacts have reinforced the message that better inventories of the full complement of forest resources and a better understanding of their dynamics are needed.

A policy response to accelerate timber harvesting to salvage as much wood as possible after natural disturbances may need to be reconsidered [33], especially after mixed-severity fires or storm damage, or in mixed-species stands after pest outbreaks. Outbreaks such as those of the mountain pine beetle also provide the opportunity and incentive to reform a wide range of other forest policies [15]. Salvage logging has a place, primarily through the redirection of existing harvest levels in landscapes already rich in young seral stands initiated by natural disturbances. Increasing harvest levels above those determined to be sustainable in the long run means, by definition, that an accentuated falldown must follow if sustainable harvesting is to be achieved in the future. The greater the increase in the rate of logging, the steeper, deeper, or more prolonged the falldown trough or mid-term timber supply gap will be. Indeed, where mixed stands and industrial clearcutting practices predominate, salvage logging can make the situation worse by harvesting large numbers of green trees that have survived the insect outbreak and could provide valuable timber and habitat when and where it is most needed.

It is now well established that biological legacies and residual structure are key to ecosystem resilience and continuity, especially after large-scale disturbance [32]. It is critical that an ample number of live and dead standing trees be retained for wildlife habitat, and that forest understories are protected to allow rapid recovery and readjustment of the ecosystem. Where we do intervene, however, we now have the opportunity to design forests that are more diverse and more resilient to climate change, pest outbreaks and other unforeseen challenges that are sure to follow.

The strategy of diversification also provides a key lesson for forest products companies and communities: It is wise to avoid dependence on a few species, a few commodities, and a few markets. In a rapidly changing world, it is better to spread risks as much as possible, and to be flexible enough to embrace the inevitable changes rather than fight them with outdated paradigms of "command-and-control" that ultimately are at odds with the forces of nature. The mountain pine beetle has reminded us that it is more important to plan for survival than for maximum growth, and that continuity is important in any strategy that aspires to sustainability. That old sustained yield goal of a non-declining even flow of timber, inherited from classical forestry, provides a useful template for ecological and socioeconomic continuity. Because such stability is ultimately unattainable, however, perhaps it is time for forest managers to embrace adaptive resilience as a means of incorporating the unplanned disruptions of eco-social systems.

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