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Effects of uncertainties about stand-replacing natural disturbances on forest-management projections

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Abstract

Designing policies for long-term forest management is difficult, in part because ecological processes that drive forest structure and composition interact strongly, both spatially and temporally, with the many values we want to obtain from the forest. Using the Robson Valley in east-central British Columbia as a study area, we developed a spatio-temporal landscape model to assess the effects of uncertainties about stand-replacing natural disturbance regimes on indicators related to the sustainability of forest harvesting and biodiversity. Results show that key timber policy indicators were relatively less sensitive to natural disturbance regime parameters than were the biodiversity indicators of seral stage distribution and tree species composition. The other biodiversity indicator we examined, structural connectivity among old-forest patches, was among those indicators least sensitive to any of the parameters we varied. Other timber supply indicators—including non-recoverable losses, and volumes and areas disturbed—were the most sensitive to both the particular natural disturbance agent chosen and to the parameters describing its behaviour. Projections of a range of scenarios for present and alternative natural disturbance and management regimes for the study area show that most indicators varied from less than 1% up to 93% from the value of the present management/disturbance regime. Generally, three alternative management policies had weak-to-moderate capabilities of reducing effects of natural disturbances. Despite the range of uncertainties explored, the results provided little indication that, at the scale of the whole study area, current timber-harvesting targets are not sustainable over the long term. However, our findings highlight the lack of knowledge about the future, particularly about changes in climate, resulting in significant uncertainty about the future condition of the forest and about future forest-management opportunities.

KEYWORDS: *natural disturbance, spatial landscape model, modelling, forest management, forest-management planning, ecosystem management, biodiversity, indicators, climate change, British Columbia.*

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Introduction

Applying ecosystem management concepts on publicly owned forested lands in Canada requires that forest managers include the following objectives in their plans: maintain an economically viable timber supply and current "levels" of biological diversity, achieve visual quality objectives, maintain high recreation potential, and maintain high water quality (Mitchell *et al.* 2002). In attempting to achieve these objectives at local and (or) regional scales, forest managers must make decisions in the face of substantial uncertainty. Some of this uncertainty is related to a lack of information about the current structure and function of forested ecosystems, to an inability to predict changes in ecosystem dynamics, and to unknown changes in future forest-management regimes (Harvey *et al.* 2002). While historical variation in these factors may be known to some extent, future conditions may not resemble past conditions. In addition, the effects of interactions between management activities and ecosystem dynamics may be completely unknown.

Natural disturbance regimes in British Columbia vary widely among geographic regions and forest types. In east-central British Columbia, the frequency of disturbances in the forests found in the Robson Valley vary widely depending on topography, tree species composition, stand age, and regional climate (Hoggett 2000; Eng *et al.* 2001; Fall and Sutherland 2001; Hoggett and Negrave 2001). Natural disturbances in the area include wildfires; outbreaks of defoliating insects, bark beetles, and other insects; and occasional windthrow events. Often these events are patchy in their effects—for example, fire severity varies within an event, which can result in remnant patches of trees or vegetation (Delong and Tanner 1996). Disturbances can interact in space and over time. For example, patches and partially disturbed stands left after wildfires can be further modified over time by low-severity disturbances such as defoliating insects, tree heart rot, and root diseases (Lewis and Lindgren 2000). Some disturbances occur very infrequently, perhaps only a few times per century; information about the local and regional effects of these disturbances on forest ecosystems can thus be limited even though their influence on landscape patterns can be substantial (Turner *et al*. 1994; Palik *et al.* 2002).

Even within a single management unit, such as a Timber Supply Area, the effects of uncertain natural disturbances are difficult to account for in forest-management planning. Many primary forest-management policy drivers, such as the allowable annual cut, are defined relative to the state of the timber-harvesting land base, yet the state of the forest that will not be harvested interacts with the harvestable portion of the land base to determine sustainability of all resource values. Because natural disturbances potentially affect all forested stands, they can significantly alter indicators related to the sustainability of forest harvesting and other values. In addition, significant impacts of global warming are already discernable in meta-analyses of the seasonal and population dynamics of plants and animals (Root *et al.* 2003). Because natural disturbances are strongly linked to climatic drivers (Clark 1988; Heyerdahl *et al.* 2001), it is likely that disturbance regimes will also shift as a consequence of climatic trends.

Our objective in this study was to evaluate what effects uncertainties about infrequent, high-intensity, stand-replacing, natural disturbance regimes might have on strategic forest-management projections in the Robson Valley. The projection tools used for this analysis were spatially explicit models of forest stand dynamics (managed and natural) and disturbances developed for the Robson Valley Enhanced Forest Management Pilot Project (EFMPP[1]) (Eng *et al.* 2001; and see description below about the Robson Valley Landscape Model). Due to the spatial and temporal scales involved, the use of spatially explicit models of landscape dynamics to address issues such as these is increasing (e.g., Boychuk and Perera 1997; Andison 1998; He *et al.* 2002b). We report results for two primary sources of uncertainty:

1. current attributes (frequency, size, number, etc.) of infrequent, high-severity, stand-replacing, natural disturbance events, including fires, and outbreaks of both western hemlock looper (*Lambdina fiscellaria lugobrosa*) and mountain pine beetle (*Dendroctonous ponderosae)*; and
2. likely changes in the future attributes of disturbances as a result of environmental factors such as climate change, or as a result of management factors such as changes in forest-harvesting policies.

[1] The EFMPP is a co-operative effort between the B.C. Ministry of Forests; B.C. Ministry of Water, Land and Air Protection; B.C. Ministry of Sustainable Resource Management; Forest Renewal BC; the forest industry; and the academic community. Its goal is to establish new, or to enhance existing, forest-management processes or tools by utilizing the expertise and experience of other EFMPP sites, model forests, academia, and researchers. For further background, refer to: *http://www.for.gov.bc.ca/hcp/enhanced/robson/efmpp/index.htm*

Unless otherwise specified, our analysis considers the study area as a whole, and does not present separate results for the timber-harvesting and non-timber-harvesting portions of the study area.

Methods

Study Area

The study area for this analysis was the 1.2 million hectare Robson Valley Timber Supply Area located in the eastern portion of central British Columbia. The area is both topographically and ecologically diverse, containing four biogeoclimatic zones (Interior Cedar-Hemlock, Sub-Boreal Spruce, Engelmann Spruce–Subalpine Fir, and Alpine Tundra) and sixteen subzones (Meidinger and Pojar 1991). The Timber Supply Area contains a diversity of tree species. Various areas are dominated by spruce *(Picea engelmannii* and *Picea glauca*), subalpine fir (*Abies lasiocarpa*), western redcedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*), with smaller components of Douglas-fir (*Pseudotsuga menziesii)* and deciduous species. The area also comprises a diversity of wildlife habitats[2] and a wide variety of land uses, including forestry, recreation, protected areas, and private lands (B.C. Ministry of Forests 2000).

The present timber-harvesting land base[3] is 213 383 ha (17.3% of the Timber Supply Area). Most stands (86%) in the timber-harvesting land base have never been harvested. Fires, western hemlock looper (WHL), and mountain pine beetle (MPB) are the frequent, stand-replacing, disturbance agents (B.C. Ministry of Forests 2000). Approximately 57% of the trees in the timber-harvesting land base inventory are over 140 years of age with the oldest stands being dominated by cedar and hemlock (B.C. Ministry of Forests 2000). Most timber harvesting in the Robson Valley Timber Supply Area is conducted according to a clearcut silvicultural system, and sites are restocked by planting, usually three years after the completion of harvesting activities. In the most recent Timber Supply Review, the allowable annual cut was set on a declining scale starting with 602 377 m^3 for the first decade and ending with 340 000 m^3 for the seventh decade (B.C. Ministry of Forests 2000). The average annual non-recoverable timber volume losses (NRL)—due to insect pests (principally western hemlock looper, but also mountain pine beetle, two-year cycle budworm, spruce weevil, spruce bark beetle, and balsam bark beetle), root diseases, windthrow, and fires—are currently assumed to be 57 031 m^3/yr (N. Stromberg-Jones, Stewardship Forester, B.C. Ministry of Forests, Clearwater, B.C., pers. comm., November 2001).

Description of the Robson Valley Landscape Model

For this analysis, three types of spatio-temporal submodels in the Robson Valley Landscape Model[4] were implemented. All submodels operate at a spatial resolution of 6.25 ha (250 × 250-m cells) and for a time horizon of 250 years, which matches the horizon of the Timber Supply Review. The general features of the submodels relevant to this analysis are:

1. ***Timber-harvesting submodel.*** We implemented a relatively simple spatial forest-harvesting model that uses strategic harvesting rules included in the Timber Supply Review. The submodel is driven by a target harvest request (the allowable annual cut) and a cutblock size distribution, and it is constrained by the access development pattern and various policies. The harvest request is expressed as area (ha/yr), not volume, because adherence to a strictly volume-based target leads to increasingly unrealistic and unstable model results as deviations from the harvest order used in the Timber Supply Review increases. When the assumptions (parameters) are equivalent to those used in the Timber Supply Review, the differences between these two methods of modelling the allowable annual cut are minor. Hence, using an area-based allowable annual cut facilitates comparison of results with the Timber Supply Review base case.
2. ***Tree growth and species succession submodel.*** Inventory type groups (ITG) in the forest cover inventory represent tree species by the combination of leading and secondary species. We identified three broad types of inventory type groups in the Robson Valley area: early seral, mid-seral, and late seral. In the Robson Valley Landscape Model, probability tables specify the likelihood that a particular inventory type group shifts to a different state given its

[2] The study area supports three wildlife species of particular concern to forest managers: mountain caribou (*Rangifer tarandus)*, grizzly bears (*Ursus horribilis)*, and mountain goats (*Oreamnos americanus*).

[3] Timber-harvesting land base: the portion of the total area of a management unit considered to contribute to, and be available for, long-term timber supply. The timber harvesting land base is defined by specified assumptions about how timber management and silviculture are to be done.

[4] More details about the design of the Robson Valley Landscape Model and the individual submodels are provided in Eng *et al.* (2001).

age, its biogeoclimatic subzone, the management or disturbance regime that has influenced it, and the residual influence of the previous stand (Fall 2001). The probability tables are parameterized based on current patterns of tree species representation within 40-year age classes stratified by biogeoclimatic subzones. This empirical approach likely captures broad variations in growing conditions, and historical stand-level responses to disturbances at all scales. It does not distinguish between effects of natural disturbance regimes, forest-management activities (e.g., planting), or other anthropogenic disturbances on successional trends, although obvious human influences (e.g., broad-scale planting of spruce on cedar-hemlock sites) were removed after we sought the expert opinion of local ecologists.

3. ***High-severity natural disturbance submodels.*** Three empirical submodels in the Robson Valley Landscape Model were used to project stand-replacing natural disturbance events: a wildfire submodel, a western hemlock looper submodel, and a mountain pine beetle submodel. The key parameters for these disturbance submodels are:
    - mean and standard deviation of the number of disturbance events in the study area per year,
    - mean and standard deviation of the extent (hectares) of each disturbance event (all submodels),
    - annual probability of initiating an outbreak in the study area (mountain pine beetle and western hemlock looper submodels),
    - probability of an outbreak continuing for the current year,
    - probability of minimum susceptibility of an outbreak to occur, and
    - probability of tree mortality occurring given cumulative defoliation (western hemlock looper submodel only).

Some other natural disturbances do occur in the study area, but these are not included because they generally occur at a spatial scale smaller than that simulated by the Robson Valley Landscape Model (e.g., landslides or windthrow) or are related to endemic (rather than episodic) agents that are seldom if ever stand-replacing (e.g., root diseases or spruce beetles). The effects of these disturbances are assumed to be reflected in the volume tables used by the forest growth submodel.

Geographic information system data for the Robson Valley Landscape Model included maps of topography, biogeoclimatic zones and subzones, forest inventory information, and management zones; all were rasterized to a 6.25-ha resolution. Other data included yield tables, management constraints, and parameter values specifying natural disturbance regimes.

All submodels were implemented using the SELES spatio-temporal landscape modelling environment (Fall and Fall 2001). Unless otherwise specified, all analyses presented here were conducted over the 250-year time horizon on 10 iterations of the model per scenario.

Indicators

We examined a selection of key indicators used in forest-management decisions and generated by the Robson Valley Landscape Model, and these were classed into three groups (Table 1). These indicators also provide some key information required for assessing broad-scale forest ecosystem status, and are partial surrogates for landscape-scale monitoring of the long-term sustainability of forest values in these groups.

Because the "true" ranges of parameter values are unknown, we evaluated three values for each individual parameter.

Analyses

Sensitivity Analysis

Changing the natural disturbance parameters for each submodel in turn changes the *disturbance regime* to which the forest-management system (including forest growth and succession dynamics) and management policies (e.g., the harvesting submodel) respond. Because the "true" ranges of parameter values are unknown—and, therefore, are uncertain—we evaluated three values for each individual parameter: its current estimated value (empirical estimates are described in Fall and Sutherland 2001, and in Sutherland *et al.* 2002), a decrease of 25% of that estimate, and an increase of 25% of that estimate, for a total range of variation of 50% of the empirical estimates. Only one disturbance parameter was varied at a time; all others were held at their current empirical value.

The sensitivity of model outputs (indicators) to this range of variation in natural disturbance submodel parameters was assessed. We first calculated the mean value obtained for each indicator over the length of the projection for each parameter value. Proportional sensitivity (s_i) was then calculated as:

$$s_i = \frac{\delta i}{\delta p}$$

where: δi = the maximum observed change in the value of each indicator *i*, and δp = the maximum observed change in the value of each parameter *p.*

Statistics for proportional sensitivity were calculated for each natural disturbance regime parameter that we varied. Using these proportional sensitivity statistics, we then examined the patterns in sensitivity of each indicator in relation to those of other indicators. Larger values of proportional sensitivity represent greater responses in an indicator relative to a unit change in a parameter value. Greater sensitivity in indicators is a signal of increasing uncertainty in the projected results due to uncertain knowledge (Morgan and Henrion 1990).

Analysis of Disturbance Regime by Management Option Scenarios

In co-operation with a broad-based stakeholder planning team that included research scientists, a community advisory group, planners from the provincial and federal governments, and forest industry representatives, we developed a series of "what-if" scenarios based on expected changes in four alternative natural disturbance regimes and we developed a set of five alternative forest-management options. When combined, these resulted in 18 different scenarios that were "reasonable" to project (Table 2). These included a "Reference Scenario" (the present disturbance regime and present management regime) and a Timber Supply Review base case scenario as defined in the *Robson Valley Timber Supply Area Analysis Report* (B.C. Ministry of Forests 2000). The Timber Supply Review base case scenario follows, as closely as possible, the assumptions of the *Timber Supply Area Analysis Report*. In that process natural disturbances are not explicitly modelled, but an attempt is

TABLE 1. Forest-management indicators used to assess the probable ranges of outcomes under natural disturbance regime and management assumptions

Group	Function	Indicator
Timber	Economic, resource allocation	• Volume harvested (m^3/yr) • Area harvested (ha/yr) • Total growing stock (m^3) • Non-recoverable loss (m^3/yr, by mortality source) • Volume salvaged (m^3/yr)
Biodiversity	Ecosystem representation at coarse-filter and fine-filter scale; assessment of landscape planning targets (e.g., B.C. Ministry of Forests and B.C. Ministry of Environment 1995)	• % area in each seral stage • Mean % composition by inventory type group by decade • Mean distance of links in the minimum spanning tree[a] of old-forest patches[b] • Patch size distribution[c] of old-forest interior
Visual quality	Recreation objectives, quality of life	• Area in age classes by visual quality objective type

[a] A minimum spanning tree is the set of shortest inter-patch links to join all patches of a similar type together into one connected component. The mean minimum spanning tree distance is the mean length of these links (which include all nearest-neighbour links). For more details, see Urban and Keitt (2001).
[b] This includes old forest (> 250 years old) surrounded by disturbed or harvested forest, as well as non-forested areas.
[c] The Forest Stewardship Council Certification Standards (FSC 2002) define these patch size classes: 0 ha, 0–1 ha, 1–50 ha, 50–200 ha, and > 200 ha.

TABLE 2. Number of scenarios analyzed for each disturbance regime, by management option combination

Natural disturbance regimes	Management options: No management	Present management	Change in fire suppression	Aggressive salvaging	Anticipatory harvesting
No disturbance		1 (Timber Supply Review base case)			
Present regime	1[a]	**1[b] (Reference Scenario)**	2	1	1
Increased mountain pine beetle		1		1	1
Climate change	4	4			

[a] Although a reconstruction of the Robson Valley landscape without human intervention was beyond the scope of this project, one method of determining the boundaries of landscape condition without management is to project forward the forest state without harvesting, which would form one edge for the "envelope" of possible outcomes.

[b] This scenario represented the "core" of the analysis. The results of other scenarios were compared against this one.

made to include their effects on timber supply through an *a posteriori* process of calculating losses to timber supply resulting from disturbances (B.C. Ministry of Forests 2000). Note also that eight of the scenarios were based on various possible projections of climate change (Table 2).

Natural Disturbance Regimes

Four alternative natural disturbance regimes were defined (Table 2):

1. **No disturbance events (one scenario).** Forest dynamics were unaffected by explicit natural disturbance submodels. Effects of disturbances are reflected only in the non-recoverable loss assumptions of the harvesting submodel. This was combined with the present forest-management regime, thus effectively matching all of the ecological and management assumptions of the Timber Supply Review base case.
2. **Present natural disturbance regime (six scenarios).** Submodels for stand-replacing disturbance dynamics (fires, western hemlock looper, and mountain pine beetle) were enabled and run according to the present empirical parameter estimates for the study area.
3. **Increased mountain pine beetle attack (three scenarios).** While reliable data from Forest Insect and Disease Surveys (FIDS) (Natural Resources Canada 1996) about the spatial dynamics of some pest outbreaks (i.e., western hemlock looper) are generally limited to the post–1960s period (N. Borecky, Research Technician, Canadian Forest Service, Victoria, B.C., pers. comm., October 2001), it is clear that, historically, both endemic beetle activity and periodic outbreaks of mountain pine beetle of greater than 10 000 ha do occur throughout the province of British Columbia, and thus create cumulative areas of mortality up to 450 000 ha (Wood and Unger 1996; Wong *et al.* 2003). It is therefore likely that larger and possibly more frequent mountain pine beetle outbreaks occur than are suggested by the empirical parameters extracted from FIDS. To assess the effects of this possibility, we created a mountain pine beetle disturbance regime where the probability of a new mountain pine beetle outbreak occurring was increased by 30%. In addition, once an outbreak was underway, we increased the annual probability of new outbreak patches occurring by 20% and increased mean patch sizes by 30%.
4. **Climate change (eight scenarios).** We based our climate change scenarios on the predictions of the Canadian Global Climate Model 2 (Canadian Institute for Climate Studies 2002) and of Flannigan *et al.* (2002) in *Climate Change Implications in British Columbia: Assessing Past, Current and Future Fire Occurrence and Fire Severity in British Columbia*. Specific predictions for the next 100 years in the Robson Valley area include: (i) a temperature increase of 1–4.5°C in winter and 1.5–4°C in summer, (ii) up to a 40% increase in winter precipitation,[5] and (iii) longer dry periods in summer.

[5] Predictions for summer precipitation are less consistent and range from a 30% decrease to a 30% increase.

TABLE 3. Range of multipliers applied to individual natural disturbance regime parameters for simulating possible effects of climate change on disturbance regimes

Disturbance type	Mean no. of new disturbance patches per year	Mean size each disturbance patch	Annual probability of disturbance initiation	Annual probability of disturbance continuation	Probability of tree mortality
Fire[a]	1.2	1.2	—	—	—
Mountain pine beetle[b]	1.1	1.2	1.2	—	—
Western hemlock looper[c]	0.9–1.1	0.7–1.3	0.7–1.3	0.8–1.3	1.0–1.3

[a] In general, the fire season is expected to start earlier in the spring and end later in the fall (Flannigan *et al.* 2002), while changes to fire ignition frequency and spatial intensity of fires are very uncertain.

[b] Outbreaks of mountain pine beetle are expected to increase in the future, largely because of decreased probability of late fall frosts occurring with sufficient intensity to kill larvae in infested trees (L. Safranyik, Emeritus Research Scientist, Canadian Forest Service, Victoria, B.C., pers. comm., 2002).

[c] Projected impacts of climate change on western hemlock looper are quite uncertain. Warmer and drier springs and summers may increase the growth and survival of larvae as well as increase the influence of pathogens on eggs and larvae (N. Borecky, Research Technician, Canadian Forest Service, Victoria, B.C., pers. comm., October 2001).

Based on these projections, the specific implications of expected trends in the frequency and severity of disturbances are difficult to determine. Because both temperature and precipitation influence natural disturbance regimes, we developed a range of scenarios to reflect different effects that climate change might have on the disturbance types we modelled (Table 3). To simplify the modelling, we assumed that no long-term trends in parameter values existed over the time horizon. That is, mean effects of climate change were set to a constant value for the time horizon.

In general, estimated effects of climate change were independent of disturbance agents. That is, we did not model possible interactions between agent dynamics in response to climate change.

Management Options

We examined five alternative management options:

1. **No harvesting.** By "turning off" forest harvesting we gained insight into the effects on the model indicators of natural disturbance dynamics alone.
2. **Present management.** Forest management was conducted using the same rules and assumptions as in the current Timber Supply Review base case.[6]
3. **Altered fire suppression.** Robson Valley Forest District staff indicated that fire suppression in this area is most successful on small and medium fires. Therefore, we assumed that the most likely scenario for achieving increased fire suppression was to reduce the size of fires by 50% for fires of 25 to 500 ha. In contrast, a decrease in fire suppression increased the sizes of this same range of fires by 50%. We also explored, in less detail, the effects of assuming all fires could be controlled.
4. **Aggressive salvaging.** In response to the tree mortality that occurs as a result of a disturbance event, we simulated a switch in harvesting effort from a preference for green-tree harvesting to a preference for salvaging merchantable dead wood.
5. **Anticipatory harvesting.** This was defined as a preferential harvesting in stands with an increasing degree of susceptibility to mountain pine beetle (Shore and Safranyik 1992) and western hemlock looper. The specific attributes that define stand susceptibilities to these disturbance types are: mountain pine beetle (tree species, stand age, and biogeoclimatic subzone); and western hemlock looper (biogeoclimatic subzone, stand age, elevation, and tree species).[7] We modelled a 2% increase in annual probability of harvest with each percentage increase of susceptibility (which effectively targets these stands as they become highly susceptible to

[6] Outlined in B.C. Ministry of Forests 2000. See Fall and Sutherland (2001) for details on how the Timber Supply Review base case is implemented in the Robson Valley Landscape Model.

[7] See Fall and Sutherland (2001) for details.

outbreak). Anticipatory harvesting rates were applied equally to stands susceptible to either mountain pine beetle or western hemlock looper.

Unless otherwise specified, comparisons are relative to the present disturbance and present management regimes (i.e., the "Reference Scenario").

Results

Uncertainties in Natural Disturbance Submodel Parameters

We examined projected patterns in tree species composition as a consequence of post-disturbance succession, relative to the current assumption (no succession) in the Timber Supply Review base case (Figure 1). Despite considerable uncertainty in the successional pathways likely to be followed by stands in the Robson Valley following disturbance, we found two strong differences between the two types of projections. The natural disturbance regimes project a significantly larger component of deciduous stands (primarily aspen) and a significantly smaller component of lodgepole pine than are projected in the Timber Supply Review base case.

Outputs were most sensitive to parameter values that specified the mean numbers and sizes of natural disturbance events that occurred in each year (Table 4). Because fire is the most dominant disturbance agent in the Robson Valley, the model is most sensitive to variation in the parameters for the fire regime. We found the results to be slightly less sensitive to large-scale (regional) parameters that specify the periodicity of outbreaks for mountain pine beetle and western hemlock looper. Further, the results are generally less sensitive to fine-scale (stand-level) factors in determining where outbreaks are likely to occur (with the exception of a minimum susceptibility threshold), and in determining the consequences for tree survival (at least for western hemlock looper).

We also examined the sensitivity of individual model indicators to variations in each model parameter (Figure 2). For all natural disturbance submodels in the Robson Valley Landscape Model, many indicators of timber supply were more sensitive to variation in disturbance submodel parameters than were biodiversity indicators, with the exception of seral stage distribution. The most sensitive timber supply indicators were those directly

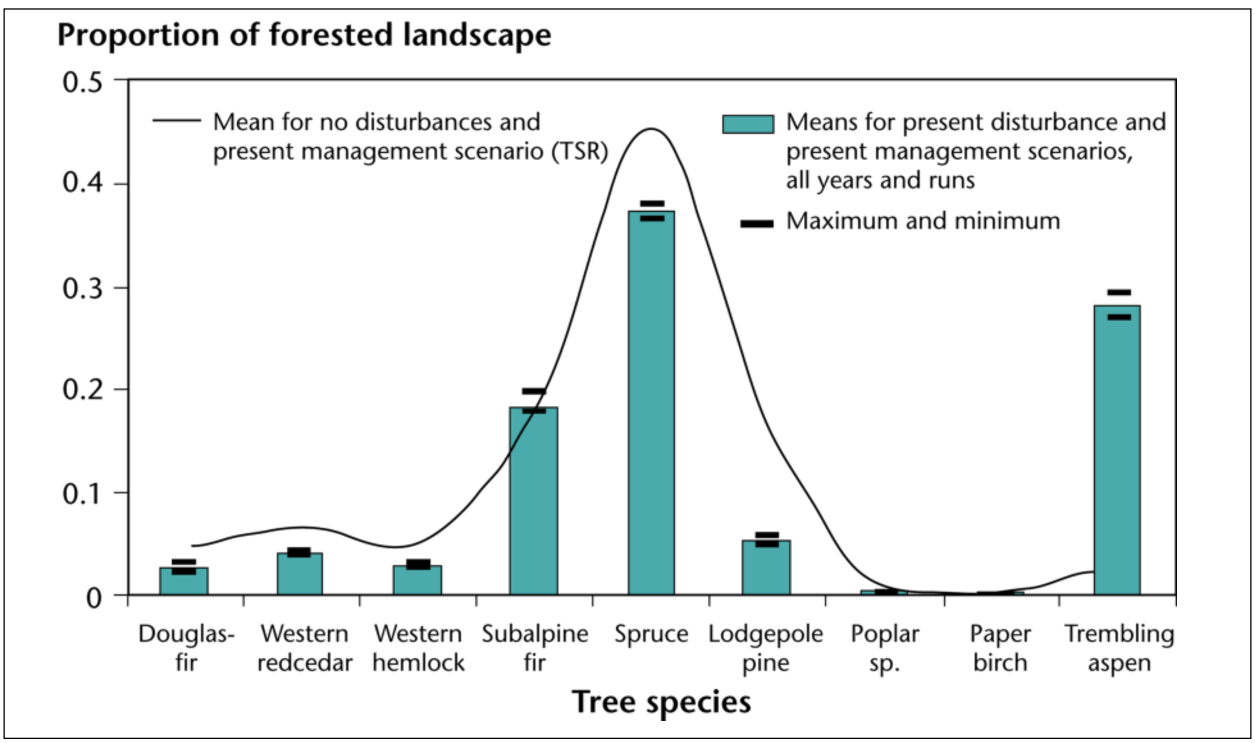

FIGURE 1. Projected tree species abundances, assuming ecological succession occurs (teal bars) and does not occur (black line).

TABLE 4. Proportional sensitivity to variation in the natural disturbance model parameters over all model indicators

Parameter	Natural disturbance model		
	Fire (mean ± SD[a])	Mountain pine beetle (mean ± SD[a])	Western hemlock looper (mean ± SD[a])
Mean no. events per year	0.348 (± 0.276)	0.189 (± 0.232)	0.151 (± 0.248)
Mean extent of events (ha)	0.240 (± 0.250)	0.172 (± 0.172)	0.232 (± 0.127)
Probability (outbreak initiation)	—	0.134 (± 0.252)	0.133 (± 0.072)
Probability (outbreak continuing)	—	—	0.057 (± 0.074)
Minimum susceptibility for outbreak	—	—	0.158 (± 0.242)
Probability (tree mortality)	—	—	0.089 (± 0.012)

[a] Standard deviation of results for each parameter over all runs.

related to consequences of disturbance such as annual non-recoverable losses for each disturbance submodel—particularly those non-recoverable losses attributed to mountain pine beetle and western hemlock looper. Other indicators of disturbance (i.e., area disturbed in the timber-harvesting land base and volumes salvaged) were also relatively sensitive to variation in disturbance submodel parameters. Effects of uncertainty in disturbance submodel parameters on key policy indicators of sustainability of timber supply (e.g., growing stock[8] and annual volumes harvested) were relatively minor even when associated with variation in the fire submodel's parameters.

Generally, biodiversity indicators tended to be less sensitive to variations in model parameters than timber supply indicators. Indicators of the distribution of seral stages were most sensitive to variation in mean extent of each disturbance event and the number of disturbance events per year regardless of disturbance type. Structural connectivity and species composition indicators were relatively insensitive to either natural disturbance submodel type or to the range of variation in model parameters.

Uncertainties in Disturbance Regimes and Management Policies

The matrix of disturbance regime and management factors we modelled (Table 2) can be considered as a broad outline of the plausible future for strategic forest management in the Robson Valley. Across the combinations of disturbance regime and management options we examined, most indicators (assuming forest harvesting would continue to occur) varied less than 15% on average from the mean value observed in the Reference Scenario, with average values for non-recoverable loss due to western hemlock looper being 93% more than the Reference Scenario (Table 5). However, some scenarios created much more extreme deviations from the Reference Scenario in some indicators. For example, two disturbance-related indicators—non-recoverable loss for western hemlock looper and proportion of lodgepole pine—deviated over 200% from their Reference Scenario value (Table 5). Generally, we found the annual non-recoverable loss due to western hemlock looper was projected to be less than the current non-recoverable loss assumption for the study area (6588 m^3/yr).[9]

We examined the patterns of areas disturbed and volumes killed by disturbance events in more detail (Figure 3). The scenarios that elevate the probability of one or more natural disturbances occurring without compensatory management policies are also the scenarios that increase both the area and volume affected by natural disturbances relative to the Reference Scenario. In particular, all of the climate change scenarios substantially increased the extent and impact of disturbances—including mountain pine beetle attack—beyond those of any other scenario. In terms of long-term timber supply, the projected average volume of growing stock under the climate change scenarios was between 7.5 and 11% less

[8] Defined as the volume estimate (m^2) for all standing timber at a particular time (B.C. Ministry of Forests 2000).
[9] All scenarios except climate change (average = 2199 m^3/yr, maximum = 3500 m^3/yr).

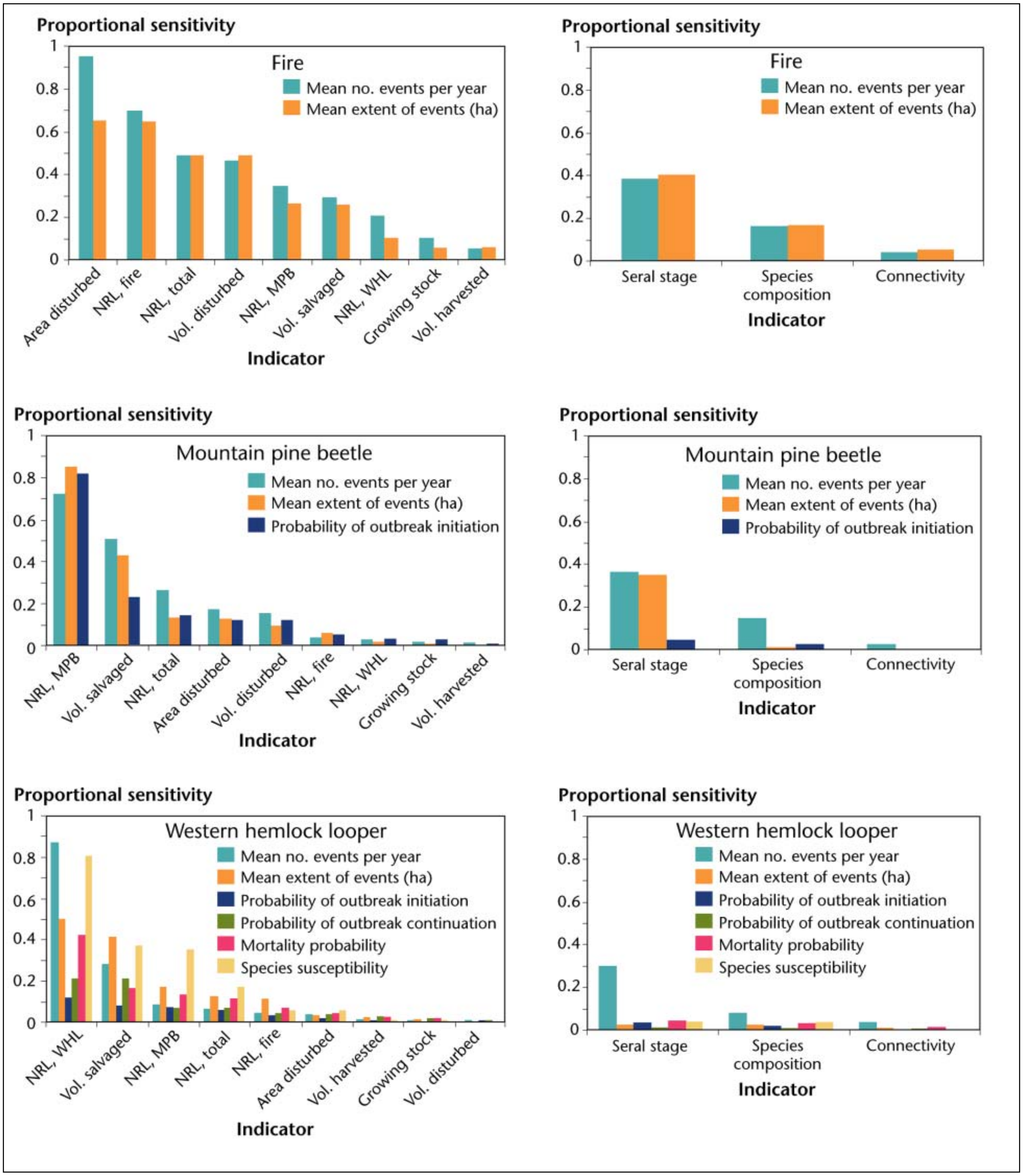

FIGURE 2. Proportional sensitivities of timber supply (left panels) and biodiversity indicators (right panels) to variation in natural disturbance model parameters.

TABLE 5. Projected range of variation observed in all model indicators over all combinations of disturbance regime, by management option, relative to the Reference Scenario[a]

Indicator group	Indicator	% differences from Reference Scenario		
		Mean	Low	High
Timber supply	Volume harvested (m^3/yr)	–3.5	–6.3	+0.5
	Area harvested (ha/yr)	–1.1	–8.4	+0.3
	Total growing stock (m^3/yr)	–2.0	–9.5	+5.6
	Non–recoverable loss, by mortality source (m^3/yr)			
	Western hemlock looper	+93.0	–78. 2	+477.5
	Mountain pine beetle	+11.1	–60.3	+77.5
	Fire	+12.1	–5.1	+28.4
	Volume salvaged (m^3/yr)	–5.6	–100.0	+34.3
Biodiversity	% area in each age class			
	Young	+3.7	–29.8	+17.6
	Mature	–4.9	–22.0	+6.0
	Old	+1.2	–7.3	+31.1
	Mean distance of links in the minimum spanning tree of old-forest patches[b]	–2.4	–12.6	0.0
	Tree species composition			
	Douglas-fir	+3.9	–10.7	+86.0
	Western redcedar	–1.3	–14.6	+45.9
	Western hemlock	+2.8	–12.7	87.2
	Subalpine fir	–2.0	–5.5	–1.5
	Spruce	+0.4	–5.8	+21.8
	Paper birch	+14.6	–3.4	+176.6
	Lodgepole pine	+14.0	–19.6	+247.3
	Poplar sp.	–3.1	–63.4	+9.13
Visual Quality Objective	% area in old forest by VQO zone[c]			
	Protection	–0.23	–7.2	+27.5
	Partial retention	–0.45	–12.7	+24.8
	Modification	+5.1	–4.7	+50.0
	Maximum modification	+2.0	–5.7	+22.7

[a] To simplify interpretation, results from all scenarios with "no management" (i.e., no harvesting) are described elsewhere in the text and are not presented here.

[b] See Table 1 (footnotes) for a definition of this indicator.

[c] The visual quality objective (VQO) zone definitions are, in decreasing order of visual sensitivity: protection, partial retention, modification, and maximum modification.

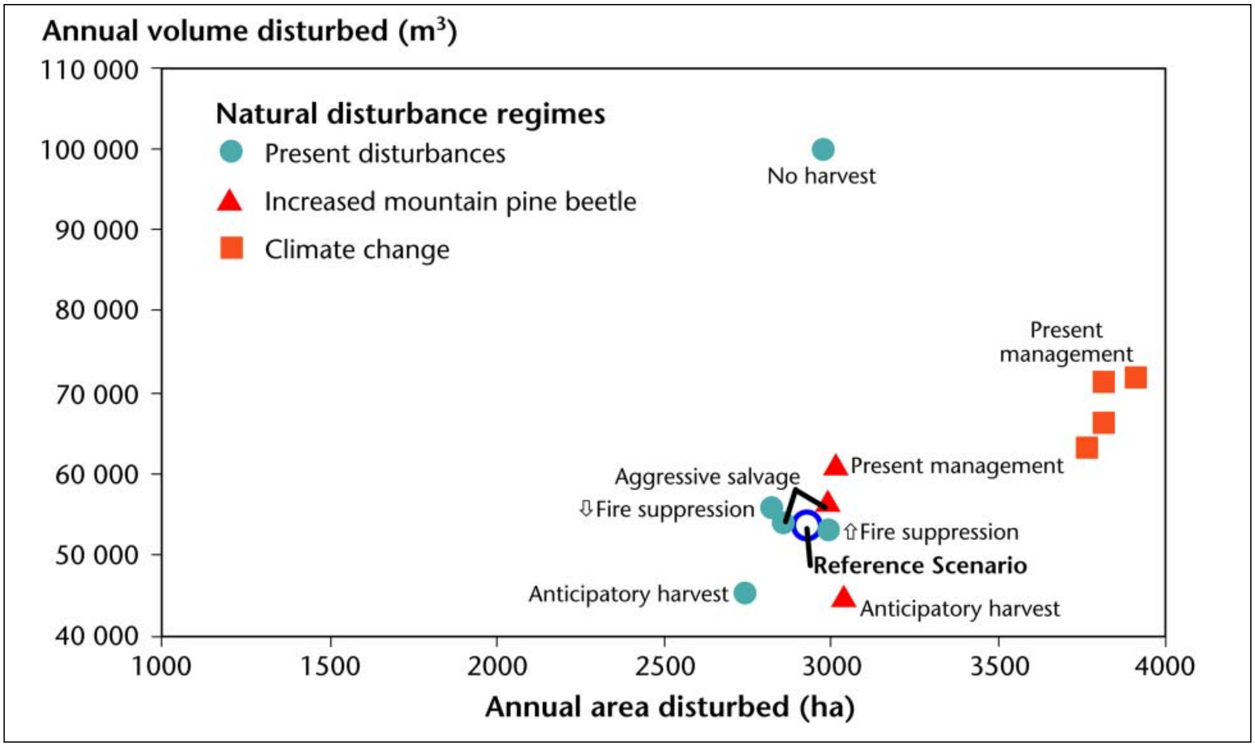

FIGURE 3. Mean outcomes in volumes and areas disturbed in the timber-harvesting land base among the different natural disturbance regimes and management options. Means are averaged across all runs for each scenario. The different scenarios for climate change (squares) result from different assumptions about effects of climate change on western hemlock looper dynamics. Results for climate change scenarios with no management are not shown.

than for the Reference Scenario, although growing stock trends did not demonstrate an irreversible decline (a signal of long-term unsustainability).

The management policies investigated in this study had weak-to-moderate capabilities of reducing the effects of natural disturbances. First, under present disturbance parameters, anticipatory harvesting (using indices of stand susceptibility to mountain pine beetle and western hemlock looper disturbance) appeared able to reduce both volume losses (by 15%) and area disturbed (by 9%). Under an increased mountain pine beetle disturbance regime, anticipatory harvesting reduced the volumes lost to disturbances, but it had no effect on areas disturbed, compared with present management for this regime. Second, under the present disturbance regime, aggressive salvaging following disturbances created only minor decreases in both the area disturbed and volume disturbed, compared with the Reference Scenario. In the aggressive salvage regime, the ratio of salvaging to green-tree harvesting increased by an average of 7%. Thus, compared to present management, aggressive salvaging appears to marginally reduce the volume disturbed, but it does not reduce volume disturbed as much as anticipatory harvesting does. Finally, variation in fire suppression had only minor effects on volumes and areas disturbed. However, we caution that the fire suppression results are very sensitive to assumptions about how effective fire suppression activities actually are. Increasing the maximum effectiveness in fire suppression—by assuming that all fire sizes are reduced to 50% of their maximum extent—caused reductions in both volume losses (by 34%) and area disturbed (by 31%) relative to the results shown here.

Note that, compared to the Reference Scenario, the "no harvest" scenario with present disturbances leads to substantially larger volumes lost to disturbance, but with little apparent change in areas disturbed (Figure 3). In part, this is because age is one determinant of species' susceptibility to attack. If the productive portions of the landscape are not harvested, then older age classes of these species accumulate and stand volumes increase, making these stands increasingly susceptible to attack and subsequent mortality. In effect, these natural disturbances "compete" with harvesting for similar types of trees (i.e., older age classes of economically valuable species in the harvestable land base).

Discussion

In this study we used a stochastic spatio-temporal landscape model to explore the question of how uncertainty in natural disturbance regimes might interact with timber supply and other indicators of forest values. Our goal was not to determine the "most likely" future, or identify the "most optimal" planning options for achieving various strategic goals. Rather, by analyzing a wide range of scenarios, we have begun to outline the envelope of uncertainty that exists between the disturbance regimes and the management responses that affect planning objectives. The range of variation exhibited by indicators can be viewed as defining the range of likely uncertainty that forest managers could consider when assessing the "robustness" of any particular management policy. That is, the wider the range of variation exhibited by an indicator, the less certain we are that a particular projected result will actually occur. This degree of variation can also provide direction for selecting indicators for monitoring. Indicators with relatively high variation could help as part of an "early warning" system for detecting signs of departure from the range of natural variability (Attiwill 1994; Landres *et al.* 1999). On the other hand, indicators with low sensitivity are also likely to be more challenging to change via management in short time frames, and hence may be appropriate for monitoring long-term trends.

Overall, our finding is that uncertainties about disturbance effects, and about possible management responses, lead to a wide range of outcomes for a number of indicators presently used for forest-management planning. These uncertainties do not necessarily indicate unsustainable timber or habitat supplies in the long term in this study area, according to present knowledge. We found that the timber supply indicators that are related directly to the disturbances—such as volume salvaged and non-recoverable losses—were typically more sensitive to natural disturbance regime parameters than were biodiversity indicators, particularly species composition and old-forest connectivity. In contrast, the indicators relating to the sustainability of timber supply (i.e., growing stock and volume harvested) were relatively insensitive to variation in the natural disturbance regime parameters.

Generally, the three alternative management policies that we examined possess weak-to-moderate capabilities of reducing the effects of natural disturbances. We found that a policy of undertaking aggressive salvaging after a disturbance had little impact on future disturbances. Anticipatory harvesting is able to reduce the volume disturbed (relative to present management) because the most susceptible stands are also normally the highest volume stands due to their advanced age. These stands are harvested earlier than they would be under present management, and, as a result, they are not "available" for natural disturbances to affect. Benefits from fire suppression are certainly possible, but our projections were very dependent on assumptions about the maximum size and number of fires that can be contained.

These findings are neither surprising nor discouraging for people who use and interpret empirical natural disturbance models such as these. Because the dynamics of our model depend primarily on the dynamics of how disturbance events spread through stands, the sensitivity of results to the number of events that occur per unit of time and to the size of the events are, intuitively, reasonable. Most currently available empirical data on disturbance regimes are converted to frequency and size data; therefore, estimates of these parameters can usually be made for many forest and disturbance types. However, it is difficult to gauge the accuracy of present methods for determining the historical number and extent of infrequent disturbance events (e.g., western hemlock looper), and events that overlap each other (e.g., western hemlock looper and fire in the Robson Valley). Therefore, considerable uncertainty can be introduced into long-term projections due to mapping errors—for example, misclassification of disturbance types or incorrect assumptions around pre-harvest stand age (Wong *et al.* 2003)—or due to uncertainty in the transition probabilities that determine how ecological succession of stand types occurs in response to disturbance. In a partial exploration of this latter question,[10] we found that most indicators were relatively insensitive to uncertainties in ecological succession rules that convert one stand type into another after either management or natural disturbance.

[10] See Sutherland *et al.* 2002 for more details.

Although the background uncertainty, or "stochastic noise," inherent in the degree of randomness built into the model obscures the effects of some management decisions, it generally contributes less to overall uncertainty in indicators than does uncertainty in the ecological relationships we model (e.g., "structural uncertainty" [Walters 1986]). One implication is that the full range of plausible model behaviours and outcomes is unlikely to be accounted for simply by assuming wider ranges of variability in selected model parameters. A second implication is that the consequences of ignoring structural uncertainty in projection models presently used in large-scale forest planning processes[11] are problematic in areas such as the Robson Valley where multiple, infrequent, stand-replacing disturbance types occur.

Key Findings for Forest Management

We summarize our key findings as follows:

1. In general, the scenarios we examined had variable impacts on indicators that are typically used in forest-management planning.
2. Expectations about the effects of climate change on disturbance regimes have the largest negative impact on indicators of long-term timber supply. Thus, assumptions about the effects of climate change introduce large uncertainties into long-term projections of the sustainability of forest harvesting.
3. Fire suppression has the possibility of having a significant effect on some indicators, the primary ones being area and volume disturbed. The range of projected effects is very sensitive to assumptions about the effectiveness of suppression, and these assumptions are currently not well documented for the study area.
4. Aggressive salvaging has relatively little effect on the volume disturbed by natural disturbances, although some effects are seen in reducing the area disturbed and increasing the ratio of salvaging to green-tree harvesting.
5. Anticipatory harvesting provides only modest decreases in disturbance effects, has both positive and negative effects on harvest indicators, and negatively impacts long-term growing stock (see Sutherland *et al.* 2002 for more detailed results).
6. Accounting for ecological succession after natural disturbances suggests the long-term tree species composition in the Robson Valley may have a greater deciduous component and a reduced lodgepole pine component than is projected using the Timber Supply Review process. This has implications for future management because pine is a commercially valuable species, and deciduous stands are of high biodiversity value.

Implications for Forest Planning and Management

Forest managers and planners need methods to accommodate the uncertainty that inevitably occurs over long time periods and broad spatial scales (Klenner *et al.* 2000). One goal of our analysis was to explore the range of possible outcomes resulting from the combination of variability in both ecological succession and natural disturbances with uncertainties in future management regimes. This specific analysis can help guide forest managers in the Robson Valley as they make plans that will result in leaving long-term legacies on the landscape. However, we believe that the approach taken here has general applicability for natural resource management over extensive spatial scales. Obtaining a better understanding of the sensitivity of planning assumptions to uncertainties in disturbance and landscape dynamics will assist in evaluating the "robustness" of the land-use scenarios developed through other processes, such as timber supply analyses, land-use planning round tables, or optimization processes.

This study has highlighted several key issues that have some general applications in assessing options for long-term forest management. First, the mean number and extent of each disturbance type had a substantial effect on indicators. Obtaining better estimates of the shape of the probability distribution of these parameters is clearly a key issue in improving our ability to project future forest conditions. Second, various indicators respond differently to alternative assumptions about the future disturbance regime and (or) alternative management objectives. For example, doing aggressive salvaging after disturbances reduces both the annual area disturbed as well as the green-tree component of the harvest. Over the long-term, this scenario also shifted the projected tree species composition of the landscape away from lodgepole pine- and spruce-leading stands to hemlock-leading and deciduous-dominated stands. Assessing the effects of this scenario on habitat structure and on single

[11] Such as the Forest Service Simulator (FSSIM) used for timber supply planning in British Columbia (B.C. Ministry of Forests 1997).

species shifts was beyond the scope of this study, but these outcomes illustrate the difficulty of selecting simple management objectives given a variable and a complex natural disturbance regime (Mitchell *et al.* 2002). In reality, it may not be possible to determine management objectives that consistently meet economic, social, and biodiversity targets. It may be more appropriate in the long-term to search for objectives that are relatively robust to uncertainties in knowledge about ecosystem dynamics[12] and that run the least risk of reducing long-term ecosystem function.

Third, we faced a lack of information about the responses of disturbance agents to future changes in the landscape, particularly to climate change. Natural regeneration patterns after disturbances in forests are not well known. Seral stands of lodgepole pine, paper birch, and trembling aspen are generally assumed to establish after fires in montane areas similar to those in the Robson Valley. Subalpine forests that burn usually transform into *Vaccinium* meadows, and tree regeneration appears to be largely unpredictable and only partially correlated with time-since-disturbance or climate because it is also affected by browsing, snow creep, and the duration of the snowpack (Agee and Smith 1984). Effects of climatic changes in montane areas, both in the paleo record and over the last century, are generally characterized by highly complex patterns associated with orography; uncertainty is high due to a lack of observations and to difficulties in accounting for the effects of mountains in climate models (Beniston *et al.* 1997). Local and regional temperature and precipitation patterns influence insect populations, distribution of diseases (Williams *et al.* 2000), and fire frequency and severity (Flannigan *et al.* 2002). Recent evidence suggests that a large number of plant and animal species are already showing significant phenological and spatial range shifts in response to the changes in climate over the last century (Parmesan and Yohe 2003; Root *et al.* 2003). In tightly linked biotic systems such as forests, our knowledge of historical disturbance dynamics may be of limited value in guiding future forest management because of our poor understanding of how climate changes may affect disturbance dynamics.

Our analysis points out some key difficulties in developing robust natural disturbance models for making projections over large areas and long time frames. A fundamental assumption in the modelling approach we used here is that the course of future disturbances will resemble the course of past disturbances. Is this assumption tenable? If it is, then such projections as we present here can be informative in guiding policy making related to forest management. If not, then we may still be highly uncertain of plausible future outcomes in response to changes in disturbance regime or management practices. Other approaches to modelling landscape-level dynamics are similarly vulnerable to this problem (He *et al.* 2002a and 2002b).

Issues of Verification and Validation of Landscape-Scale Natural Disturbance Models in Forest-Management Applications

The ultimate objective of an ecosystem-based management approach in forested areas is to facilitate the application of silvicultural strategies that are compatible with natural disturbance dynamics without compromising the economic or biodiversity goals of forest management. In this context, increasingly, projection and interpretation of natural disturbance dynamics require extensive data analysis and use of spatially explicit landscape models. The utility of such an approach depends on how well these models overcome two common criticisms: (1) such models can seldom be sufficiently verified and validated before they are used in planning, and (2) uncertainties in model relationships renders their projections uninformative over long time frames and broad spatial scales. We define verification as an assurance that the model is implemented as specified, and validation as an assurance of the appropriateness of the model for its intended use (Rykiel 1996). To verify the models, we undertook a range of experimental tests and sensitivity analyses to ensure that the implemented model matched the conceptual model described.[13]

A more difficult problem is the one of assessing the level of certainty one can place on model outputs. Validation is often assessed as the degree to which model output matches an independent dataset (Rykiel 1996). Although very useful, such empirical (or data) validation for a spatio-temporal model is possible only in cases with short time lags in system response or for which suitable replicates exist (e.g., for chronosequence-type

[12] See Hilborn and Walters (1992) for examples.
[13] Data not presented here.

comparisons). None of these points holds for situations involving regional-scale systems and long time horizons such as in our model. In addition, using observational data does not even make sense for assessing hypothetical management alternatives. In the present study, it is more appropriate to rely on conceptual and logical validation (Rykiel 1996) where we view the model as a hypothesis and the model's output as a consequence of the hypothesis; that is, the purpose of the model is to make a clear link between the initial conditions, parameter values, and process behaviour, and the consequences of those assumptions—which are projected via simulation. The use of the model is akin to theorem-proving. The purpose of the model is not to predict the real state of the future forest. Our approach to validation is an extension of verification—which is based on extensive use of sensitivity analyses to ensure that this link between cause and effect can be clearly explained—coupled with cautious inferences from the results.

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