Estimating the impacts of harvest distribution on road-building and snag abundance[1]

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Abstract: Various patterns of harvest in forests influence the length of road and number of stream crossings required. Snags are removed directly by harvesting, but they are also removed along road and opening edges to ensure worker safety. To assess the potential impacts of rate of harvest and pattern of harvest in an old-forest-dominated montane landscape, we developed a spatially explicit landscape dynamics model, which includes submodels for snag removal, harvesting activities, and access management. The model assesses the amount of new road construction and number of streams crossed by new roads, as well as changes in snag density and configuration across the landscape over a time horizon of several decades, in response to various harvesting patterns. We estimated that a dispersed 40-ha cutblock harvest pattern required about one-third more kilometres of new road over a 50-year period and removal of up to 70% more snags per hectare of harvest for safety purposes, compared with a harvest pattern based on natural-patch size distribution. Each 20% increase in stand-level retention resulted in a roughly equivalent increase in new road required. Up to eight times as many snags were removed per hectare of harvest for safety purposes at a stand-level retention of 70% than at a stand-level retention of 10%. The model appears to be an effective tool for determining the future impact of various harvest-pattern options on a number of important indicators of ecological impact.

Résumé : Les patrons de coupes forestières ont une influence sur la longueur du réseau routier et le nombre de traverses de cours d'eau à construire. Les chicots sont éliminés lors de la récolte dans le bloc de coupe mais doivent également être enlevés le long des routes et en bordure des blocs afin d'assurer la sécurité des travailleurs. De façon à évaluer les impacts potentiels du taux de prélèvement par la récolte; et du patron de coupe dans une vieille forêt dominée par une topographie montagneuse, nous avons développé un modèle spatial d'analyse de la dynamique des paysages qui inclut des sous-modèles pour l'enlèvement des chicots, les activités de récolte et la gestion de l'accès. Le modèle évalue la quantité de nouveaux chemins à construire et le nombre de traverses de cours d'eau pour chaque nouveau chemin; il évalue aussi le changement de densité des chicots et la configuration du paysage sur un horizon temporel de plusieurs décennies en fonction de différents patrons de coupe. Nous avons estimé qu'un patron de coupe constitué de blocs dispersés de 40 ha nécessitait approximativement un tiers plus de kilomètres de chemin sur une période de 50 ans et permettait d'enlever pour des raisons de sécurité jusqu'à 70 % plus de chicots par hectare récolté comparativement à un patron de coupe basé sur la distribution de la dimension naturelle des peuplements. Chaque augmentation de 20 % dans le taux de rétention lors de la coupe entraîne une augmentation approximativement équivalente des nouveaux chemins requis. Jusqu'à huit fois plus de chicots par hectare récolté étaient enlevés à des fins de sécurité avec un taux de rétention de 70 % comparé à 10 %. Le modèle qui a été développé semble être un outil efficace pour déterminer l'impact futur de différents patrons de récolte sur plusieurs indicateurs importants d'impacts écologiques.

[Traduit par la Rédaction]

Introduction

Broad characteristics of natural disturbance dynamics — such as spatial extent, frequency, severity, and heterogeneity — are used as a basis for forest management policies directed toward maintaining biological diversity in many forest types (Booth et al. 1993; BCMOF and BCMELP 1995; Harvey et al. 2002). An underlying assumption of this management paradigm is that forest-dependent biota are adapted to the ecosystem characteristics and landscape patterns created by natural disturbance regimes (Hunter 1993; Bunnell 1995; DeLong and Tanner 1996; Bergeron and Harvey 1997; Angelstam 1998; DeLong and Kessler 2000). We expect that species and ecosystem functions should be more re-

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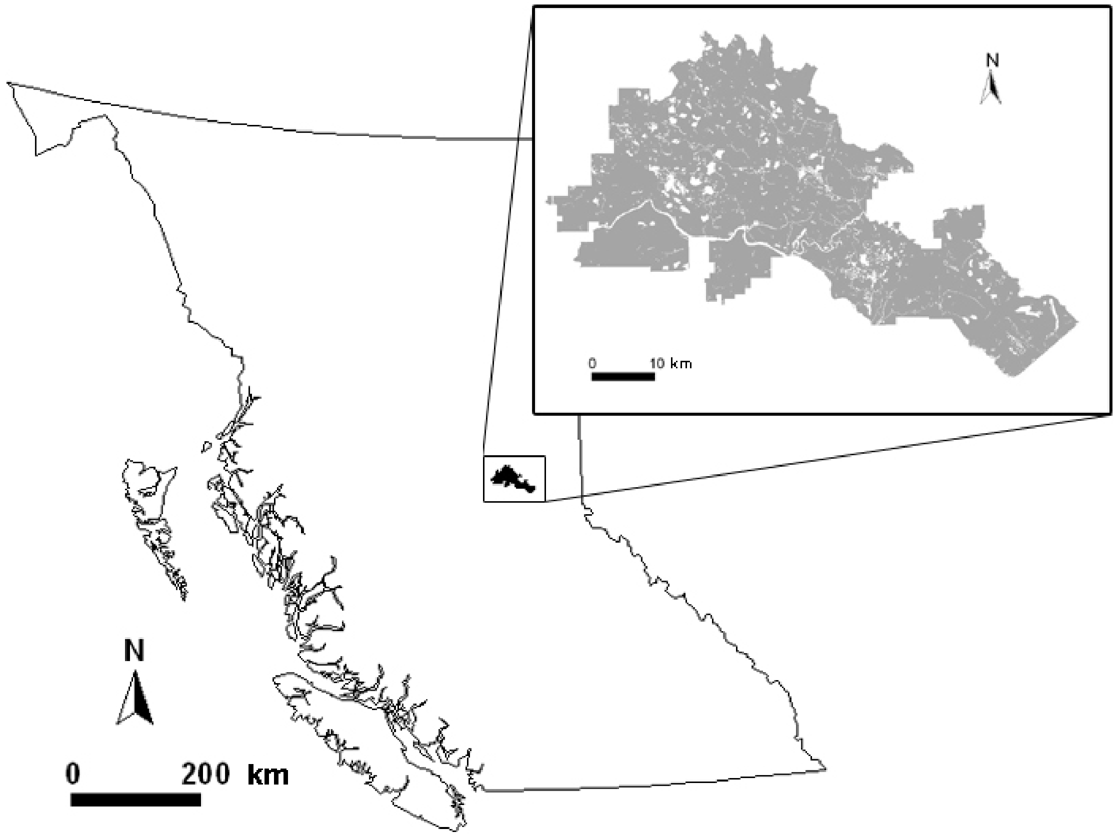
Fig. 1. Location of the tree-farm licence (TFL 30) study area (inset) in British Columbia.



silient to the ecological changes associated with forest management activities if the pattern and structure created by these activities resemble those of natural disturbance events.

For forests managed under the sustainable forest management paradigm, key indicators related to conservation and maintenance of biological diversity, soil, and water quality are densities of roads (Dempster 1998), stream crossings (Dempster 1998), and snags (Bunnell 1997; Dempster 1998). A number of ecological benefits are expected to result from harvesting patterns that emulate particular patterns of natural disturbances, such as the patch size of wildfire (DeLong and Tanner 1996; DeLong 2002). Among these benefits are (*i*) reduced road densities, in comparison with the three-pass dispersed-block model currently used in many areas (DeLong and Tanner 1996; DeLong 2002); (*ii*) reduced numbers of stream crossings (DeLong 2002); and (*iii*) increased retention of tree snags.

Three-pass dispersed, mid-sized (40–80 ha) block clearcut harvesting has been used in British Columbia for the past few decades and is still being used in areas where there is a lack of further direction from a higher level plan. In addition, stand-level retention has received considerable attention for management of the mountain ecotype of the woodland caribou (*Rangifer tarandus* subsp. *caribou* Gmelin) (Stevenson et al. 2001) and in the temperate rainforests of British Columbia (Mitchell and Beese 2002).

We developed a fine-resolution, spatially explicit landscape dynamics model that includes submodels of harvesting activities, access management, and snag dynamics and removal, to predict the possible effect of various harvest patterns on amount of new road construction, number of stream crossings required, and level of snag depletion. This model assesses these indicators across the landscape over a time horizon of several decades. We use this model to test the hypothesis that harvesting in a pattern that approximates natural wildfire will result in reductions in the roads and stream crossings required and in snag loss, in comparison with other harvest patterns.

Materials and methods

Study area

We focused our analysis within a tree-farm licence (TFL 30), held by Canadian Forest Products Ltd. and situated about 50 km east of Prince George, British Columbia, on the McGregor Plateau and western slopes of the Rocky Mountains (Fig. 1). The study area consists of two main biogeoclimatic units: the very wet Sub-Boreal Spruce (SBSvk) and the Misinchinka variant of the wet, cool Engelmann Spruce Subalpine Fir (ESSFwk2) (DeLong 1996; DeLong et al. 1994). Forest stands are generally dominated by hybrid white spruce (*Picea glauca* (Moench) Voss × *Picea engelmannii* Parry ex Engelm.) or subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), with small, localized upland areas at lower elevations dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), paper birch (*Betula papyrifera* Marsh.), and trembling aspen

Table 1. Estimate of initial snag distribution by biogeoclimatic unit and seral stage (S.C. DeLong, unpublished data).

Biogeoclimatic unit	Seral stage	Age, years	Snags/ha	Percent as large snags (≥15 cm DBH)
SBSvk	Young	0–70	189	73.3
	Mature	70–140	39	41.1
	Old	>140	56	69.1
ESSFwk2	Young	0–70	475	87.6
	Mature	70–140	222	92.1
	Old	>140	114	76

Note: ESSFwk2, Engelmann Spruce Subalpine Fir; SBSvk, Sub-Boreal Spruce.

(*Populus tremuloides* Michx.). Black cottonwood (*Populus trichocarpa* Torr. & A. Gray.) is common along larger watercourses, and black spruce (*Picea mariana* (Mill.) BSP) or lodgepole pine (*Pinus contorta* Dougl. ex Loud.) dominates the wetlands. Because of the wet climate, mean annual precipitation in excess of 1200 mm, and the related long fire-return cycle (estimated to exceed 900 years) (Hawkes et al. 1997; DeLong 1998), the landscape is dominated by stands more than 140 years old.

Model background

We developed harvesting, access management, and snag-removal submodels, which were implemented within the Spatial Explicit Landscape Event Simulator modeling framework (Fall and Fall 2001). We chose a cell resolution of 20 m × 20 m, in an attempt to capture fine-scale aspects of harvesting and access management activities and their impact on snags distributed across the landscape. At this fine resolution, the entire TFL is 2800 rows by 4250 columns, of which just over 4.5×10^6 cells are defined.

As input data for the model, we obtained raster-based digital files containing the biogeoclimatic units (scale), current forest development plan (FDP) blocks, current and planned roads, streams (Terrain Resource Information Management project, scale 1 : 20 000), and vegetation resources inventory (VRI, 1 : 20 000). The VRI data had an associated database from which layers for land cover, species, stand age, stems per hectare, and snags per hectare were extracted. An additional input layer breaks the land base into roughly 40-ha access units, to control dynamic road creation. On the basis of harvest-schedule information and FDPs, we estimated the land available for harvest (the timber-harvesting land base) to be about 141 165 ha. All these data were provided by Canfor, Ltd. Expected distribution of snags per hectare in three size classes (<15 cm DBH, 15–25 cm DBH, and >25 cm DBH) and stems per hectare stratified by biogeoclimatic unit (SBSvk versus ESSFwk2) were available for the area (DeLong et al. 2003). For this project, we focus on snags in the larger two classes, as shown in Table 1 (S.C. DeLong, unpublished data).

Harvesting submodel

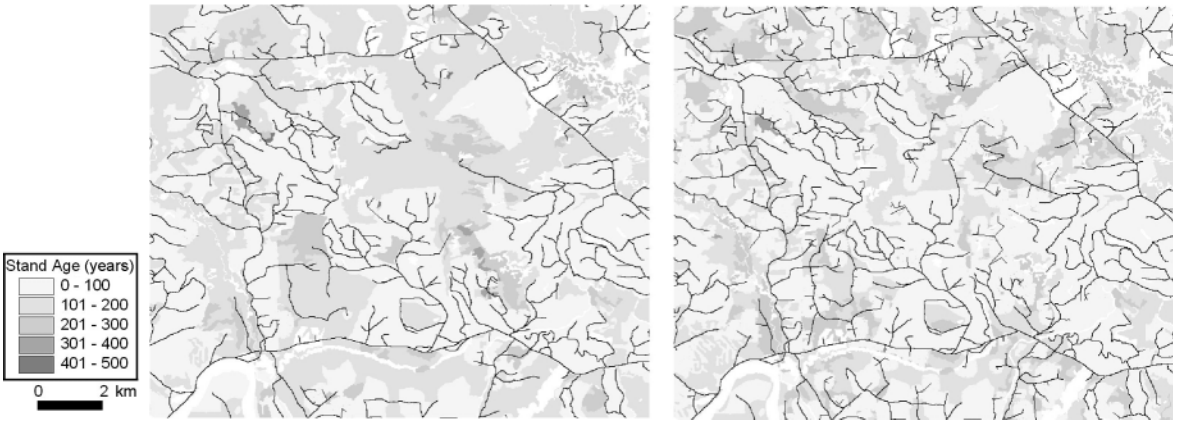
We designed and implemented a fairly simple spatial forest-harvesting submodel that operates at a resolution of 20 m and captures strategic-level harvesting rules. The submodel is primarily driven by a specified harvest target (BCMOF 1996), specified as a constant area harvested per year. We chose a harvest rate of 1% of the timber-harvesting land base per year, which represented a figure intermediate between the harvest rate suggested by the mean minimum harvest age for the area of 165 years (0.61%/year) and that suggested by the current FDP (1.4%/year). We also ran the model at half this rate (0.5%/year) to assess how longer rotation lengths would affect the results.

Selection of forested cells for potential harvest and their relative priorities are determined by two criteria. The distance to nearest road criterion ranks all forested cells with 100% relative likelihood of being selected if they are within 500 m of an active road; and with linearly diminishing likelihood, as distance increases above this threshold, to a maximum distance of 2000 m. The harvest age criterion sets the relative likelihood of selecting forested cells as an increasing function of stand age (specifically, stand age to the power of four, to place a stronger weight on stand age than on access) for cells that are above minimum harvest age for that forest-stand type. The overall likelihood of selecting forested cells is calculated by multiplying the likelihoods of the two criteria (i.e., forming a "nearest–oldest first" relative priority).

Each year, the target number of hectares is harvested in a range of patch sizes, drawn probabilistically from a target patch-size distribution provided by an input table. A block is an amalgamation of 20 m × 20 m cells, consolidated to achieve the desired block size. From a candidate cell, blocks grow by a random selection of nearest neighbour candidate cells until the block size is achieved or the annual harvest target is met. This approach creates blocks with reasonably realistic shapes, without making this aspect of the model overly complicated.

The harvesting model can be run using varying levels of retention within harvesting blocks. Retention is applied probabilistically on a cell-by-cell basis. A specified level of within-block retention defines the probability that each forested cell within that block will remain unharvested during the period of harvest. For example, a retention level of 70% would remove 30% of the area (cells) from the total area in each block. Because of the probabilistic nature of within-block retention, low levels of retention would likely leave behind mostly single unharvested cells (i.e., isolated cells surrounded by harvested cells), whereas higher retention levels would leave both single isolated unharvested cells and larger patches of unharvested cells within blocks. Harvested cells have all snags removed, and their forest stand age is reset to zero.

Fig. 2. Patterning of the road network at year 5 (left map) and year 25 (right map) for the natural-patch scenario (see text) on a randomly selected 210-km^2 section of the study area. Shown are all roads, regardless of type (black lines), and ages of productive forest (gray shading).



Access management submodel

Preprocessing

To create a realistic road system and facilitate the activation of roads to access new harvest units, we created a road-segment network from an input layer of existing and proposed roads. This input layer is the engineered road system for the whole study area and constitutes the main access-road system. When a harvest unit is created, all existing road segments required to access the block are activated. To ensure that all road cells were connected, we used a nearest neighbour diffusion algorithm that spreads from each connected group of road cells to other groups of road cells by the shortest link. We then removed road cells that would not disconnect the network when removed (i.e., redundant cells). The resultant linked network of road cells forms the skeleton for road-traversal algorithms.

Within the road network, specialized cells (nodes) are designated as (*i*) an exit point (a road cell at the edge of the study area); (*ii*) an end point (a road cell at end of the road, i.e., with only one neighbour); (*iii*) an articulation point (a road cell at a fork, i.e., where two or more roads join); or (*iv*) an activation point (a road cell at the boundary between currently active and inactive roads). The nodes were used to extract the road network as a set of "segments", with a segment being defined as all road cells between two nodes. The road network was traversed, starting at the exit points. As the preprocessing proceeds, it keeps track of the last node visited. When a new node is reached, it creates a road segment. If this is an articulation point, then the traversal needs to follow all branches as separate segments. At the end of the process, we produced a map of road-segment IDs and a list (file) of the road-segment start and end points. The entire TFL has 4622 segments, with a mean length of about 25 cells (500 m).

Dynamic access management

In the main model, "spur" roads are created dynamically as cutblocks are created. A spur road is any road required to access a block that is not currently adjacent to an existing or proposed road. They cannot be created a priori for all cases, as the shortest spur for a block may depend on spurs in nearby previous blocks. When a block is being created, each 40-ha access unit with no currently active road access is connected to the road network by simply drawing a straight line between the first cell visited in the unit and the nearest road cell. This nearest road cell may be within the block (e.g., connected to an adjacent access unit), connected to a previously constructed spur in a nearby block, or connected to the main road network. Subsequent spurs may then connect to this spur. Figure 2 illustrates this dynamic method of extending the road network for a randomly selected 210-km^2 portion of the study area at year 25 and at year 5, for comparison, for the natural-patch scenario (see below).

The linking of harvest blocks to the road network may activate inactive road segments or maintain currently active segments. After harvesting is finished, in a year, road segments that are newly activated must be processed to iteratively activate any adjacent segments toward the exit. Thus, starting with a newly active segment, all inactive "downstream" segments are also visited and activated. Any trees and snags are cleared during road construction (including construction of spur roads). In addition, a parameter allows reactivated roads to be iteratively visited to invoke the snag-removal submodel.

After proposed road segments are activated and new spur roads have been created, the distance-to-road information must be updated. This process starts in all newly created or activated road cells. Then this diffusion model spreads outward to forested cells, updating the distance to the nearest road as well as the location of the nearest road cell.

Snag removal submodel

For modeling purposes, we consider only snags of >15 cm DBH, as these are more ecologically important and more certain to be removed during snag-felling than smaller ones. We modeled snag dynamics using two simple assumptions: (*i*) that natural turnover of snags in the study area is low and in a steady state over the long term; and (*ii*) that the current distribution of snags in unharvested stands is an accurate reflection of the long-term steady-state condition. On the basis of these assumptions, initial spatial distribution of snags for unharvested stands across the study area can be estimated for each cell, either from Table 1 directly or from a combination of the table and the VRI data. For the latter, we don't use the VRI snags per hectare layer directly, as it contains all snags, not just snags of ≥15 cm DBH. Instead, we multiply the number of snags by the portion of snags of >15 cm DBH, as shown in the rightmost column of Table 1. All harvested cells had snags set to zero. Given the short time horizon of the model relative to turnover rates of snags in similar forest types (see Huggard 1999) and given the need to limit model complexity, we did not explicitly model recruitment of snags in this analysis.

Snags are removed as a direct consequence of logging and road construction. This submodel is designed to capture the removal of snags in areas adjacent to cutblocks and roads, to take into account worker-safety regulations (i.e., B.C. Workers Compensation Board (WCB)) for removal of snags. Each year, the cutblock and road cells that were visited are processed, and any snags in adjacent cells are removed. Adjacency is defined by a parameter, with the default being 20 m (i.e., immediately adjacent cells). This approximates the one-tree-length requirement of WCB for snag removal along road rights-of-way and cutblock edges, as most mature trees in the area are 20–30 m in height.

Scenario design and output

We analyzed two landscape-pattern scenarios currently being used in British Columbia. The distinguishing aspects of each scenario as follows: (*i*) dispersed block — has dispersed openings, with areas of ≤40 ha, chosen on the basis of harvest priority (no adjacency constraint), and harvesting used clear-cutting (10% retention);[3] and (*ii*) natural patch — opening size is based on natural-patch size distribution for the area (10%, <40 ha; 20%, 40–120 ha; 60%, 120–960 ha; 10%, 960–1000 ha), and harvesting used clear-cutting (10% retention).[4]

Each scenario was run with a 5-year time step for 50 years and 10 replicates, with output generated every 5 years. Both main scenarios applied harvest rates of 1% and 0.5% of the timber-harvesting land base per year. In each replicate, a new random seed was used to select cells to be harvested and to build blocks. We then analyzed the effect of a range of stand-level retention scenarios (10%, 30%, 50%, and 70%), using the natural-patch landscape pattern and a harvest rate of 0.5%. In all scenarios, access to stands is limited to within 2 km of a road, with a linear decline in preference from 500 to 2000 m. All snags are removed from buffers of 20–34 m width (i.e., adjacent cells, including diagonals) along road rights-of-way and block boundaries. The initial conditions for each run were simply the current landscape conditions (i.e., as per current map layer), including all existing roads and harvest openings.

Outputs of the model include the number of hectares harvested, number of hectares treated (includes in-block retention), number of snags removed by harvest treatments or road clearing, the amount of road created, and the number of streams crossed, stratified by stream type.

Results

The estimated average amount of new road construction required (spurs and mainline) was less for the natural-patch scenario than for the dispersed-block scenario at both harvest rates over the 50 years the model was run (Fig. 3). The largest differences between the scenarios were in the first three or four time periods (i.e., 15–20 years). Only 119 km of extra road was estimated as being required over 50 years to harvest at twice the rate (1%) using the natural-patch scenario, compared with the lower rate (0.5%) in the dispersed-block scenario.

The estimated average amount of new road construction required increased with the amount of retention at the stand level (Fig. 4). For each increase of stand-level retention of 20%, a roughly 20% (16%–21%) increase occurred in the amount of new road construction required over a 50-year period. For the 70% retention scenario, if we assume that stands could be reentered after 35 years (i.e., a reasonable time for a second entry for these stands at this retention level), the total amount of new road construction required is reduced from 1676 km (i.e., total amount required over the 50-year model run) to 1350 km (i.e., total amount required after 35 years).

The number of stream crossings built follows the same trends, and we do not show the results, as they are highly correlated with the amount of road constructed (Pearson r = 0.995, n = 40) in this landscape.

The mean number of snags removed on roads, along road rights-of-way, and along block boundaries per hectare of harvest was higher for the dispersed-block scenario than with the natural-patch scenario (Fig. 5). The differences are greatest over the first 40 years. The indirect loss of snags was sensitive to harvest retention level, with up to eight times as many snags per hectare of harvest being removed for the 70% retention scenario than for the 10% retention scenario (Fig. 6).

Discussion

Our results indicate that the amount of new road construction and number of stream crossings required, as well as the number of snags that are felled to ensure worker safety during harvest operations, are sensitive to harvest pattern at both landscape and stand scales. The model we developed estimates that dispersing 40-ha blocks across the landscape or increasing harvest retention levels results in more roads and fewer snags over a 50-year period than a pattern of harvest based on emulating wildfire does.

One of the theoretical benefits of harvesting patterns that emulate wildfire is reduced road density. The reduction in new roads required for the natural-disturbance-based harvest-pattern scenario, compared with the dispersed-block harvest scenario, especially over the short term, supports the benefit in this regard hypothesized by DeLong and Tanner (1996). Over the longer term, the road network required would likely be similar, as all areas to be harvested need to be accessed. However, this assumes no change in forest practices. Short-term effects are important, given the possibility that annual allowable cut may be reduced and that innovative ways of reducing roads (e.g., aerial logging systems) may be developed. Negative ecological effects of

[3] Common retention level currently being applied in British Columbia.
[4] Modified from DeLong (1998) to adjust for the 20 m × 20 m pixel size of the model and the 40-ha class size used for the patch-size distribution.

Fig. 3. Estimated amount of new road construction required per 5-year period for the dispersed-block and natural-patch scenario at harvest levels of 0.5% and 1% of the timber-harvesting land base per year. Total kilometres required over the 50 years is shown in parentheses after the legend entry. Results are means of 10 replicates. Range in coefficient of variation is 5.5%–31.1%.

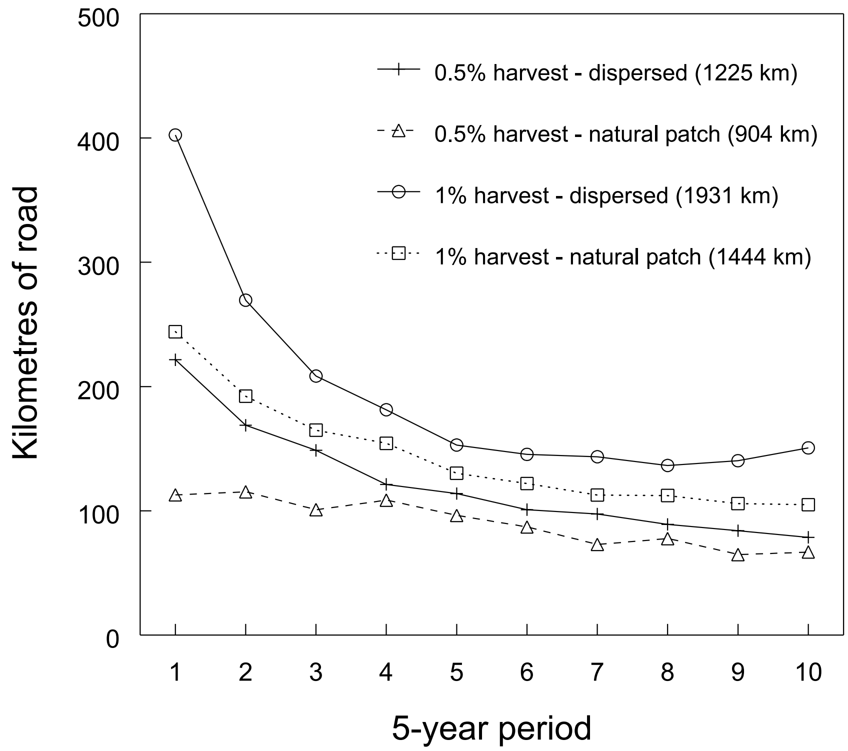


Fig. 4. Estimated amount of new road construction required per 5-year period for four harvest retention levels. Total kilometres required is shown in parentheses after the legend entry. All scenarios harvest 0.5% of the timber-harvesting land base per year. Results are means of 10 replicates. Range in coefficient of variation is 10.3%–31.1%.

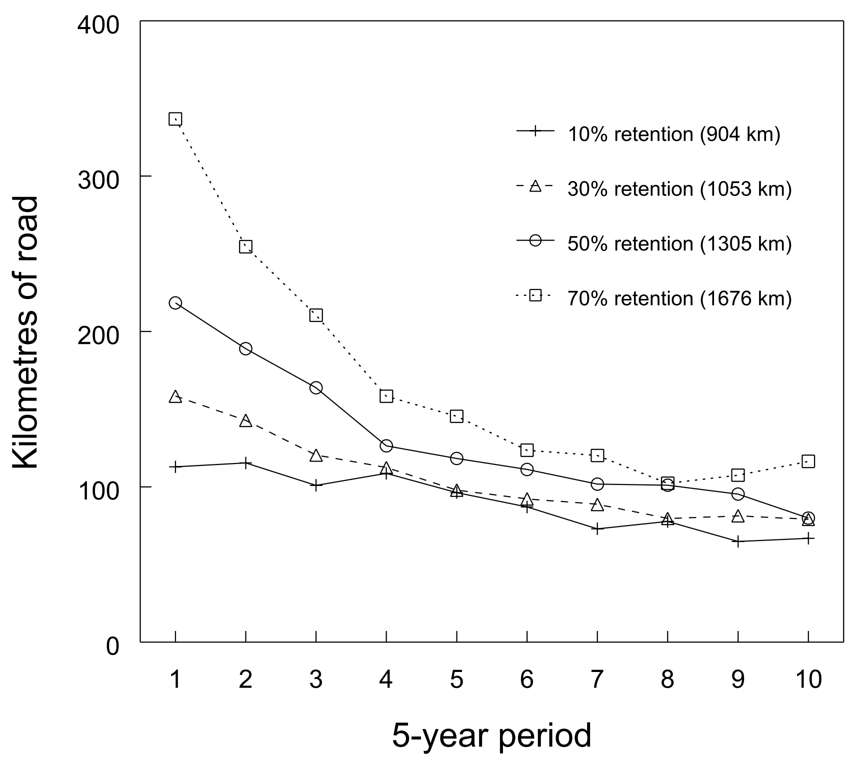
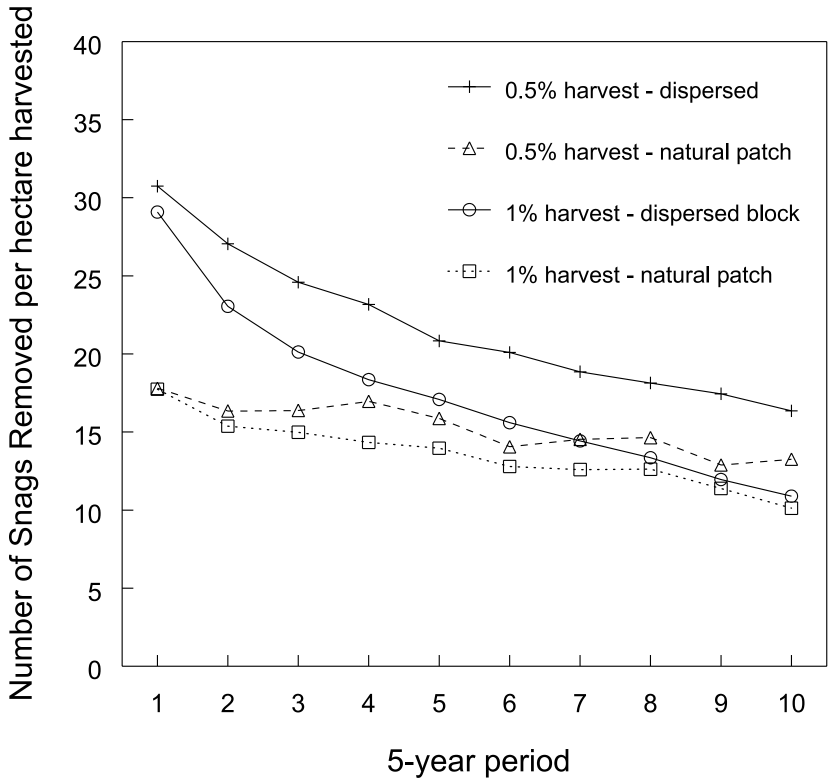


Fig. 5. Indirect loss of snags in terms of number of snags removed per hectare of forest harvested in the dispersed-block and natural-patch scenarios at harvest levels of 0.5% and 1% of the timber-harvesting land base per year. Snag losses include snags cut on roads, along roadsides, and on block boundaries but not snags cut within harvested areas. Results are means of 10 replicates. Range in coefficient of variation is 2.4%–18.5%.

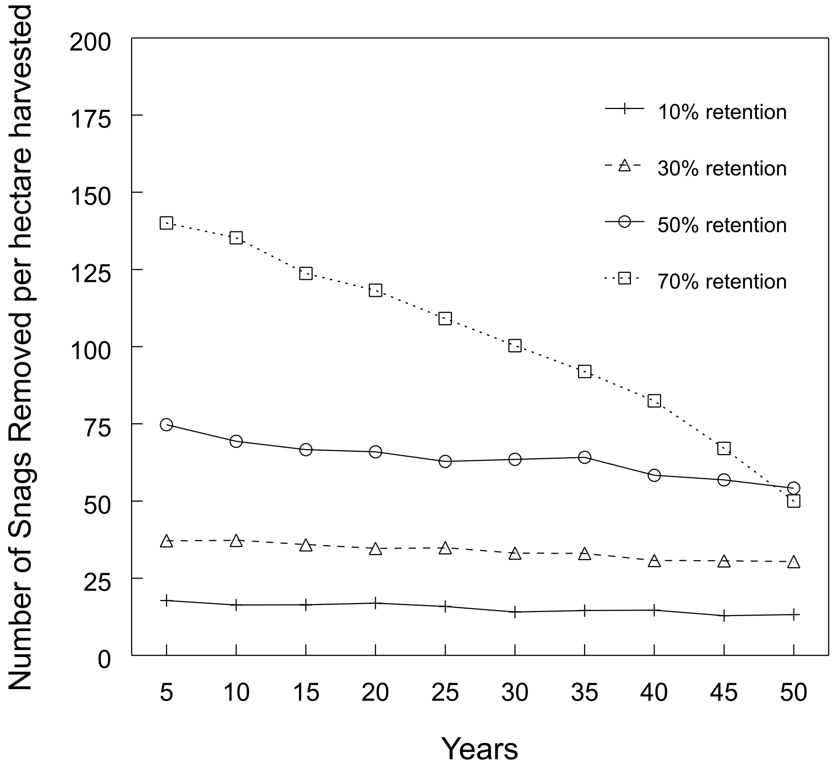


roads are well documented (Forman and Alexander 1998; Trombulak and Frissell 2000) and include mortality related to road construction and collision with vehicles; alteration of the physical and chemical environment; modification of animal behaviour; spread of exotics; and increased use of areas by humans. As much as 90% of erosion and sediment load in nearby streams comes from roads constructed for timber harvesting (Anderson et al. 1976). Increases in road access have negative effects on grizzly bears and wolves (McLellan 1990; Thurber et al. 1994).

New stream crossings are intimately linked to the building of new roads and can significantly impact riparian habitat through their effects on erosion, sediment loading, fish passage, and hydrologic flow. A detailed analysis by Krag et al. (1986) of landslides associated with harvesting on the Queen Charlotte Islands, in British Columbia, indicates that insufficient maintenance of road drainage systems is a major factor in road-related failures. Harvest patterns that reduce the number of stream crossings reduce both the maintenance burden and the risk of failure.

The importance of dead trees and snags to forest biodiversity and carbon dynamics in forest ecosystems has been well documented (Mannan et al. 1980; Bader et al. 1995; Dupuis et al. 1995; Harmon et al. 1986; Kaila et al. 1997; Bunnell et al. 2002). Communities of tree-cavity users are diverse and made up of primary cavity excavators and secondary cavity users and associates (Bunnell et al. 1999). Tree species and length of time for sufficient rot development for excavation of feeding and nest sites in dead and dying trees are primary determinants of the diversity of the snag- and downed-wood-dependent vertebrate community in forests (Bunnell et al. 1999). A study by Everett et al. (1999) indicates that recruitment of snags soft enough to be excavated by cavity-nesting species is a slow process and would often take more than 65 years for thin-barked species such as lodgepole pine, Engelmann spruce, and subalpine fir. Because conifers take longer than most hardwoods to develop rot, commercial forestry may not retain conifers long enough for sufficient rot to develop (Bunnell et al. 1999). Thus, maintaining existing soft snags is important in landscapes where they are being directly removed by harvesting. Reducing additional losses due to snag felling along road rights-of-way and block boundaries is therefore an important consideration. The changes in indirect losses of snags attributed to landscape and stand-level harvest pattern demonstrated by our results suggests that harvest pattern plays a critical role in snag maintenance. The potential value of increasing within-stand-level retention during harvesting needs to be carefully weighed against the apparent corresponding increase in indirect loss of snags over the landscape that we demonstrate. Research is needed to confirm the relative magnitude of snag loss with increased stand-level retention and find innovative solutions to reduce it while protecting worker safety. Losses due to new road rights-of-way could be reduced by restricting high-retention harvesting to areas where good access is already available or by using longer

Fig. 6. Indirect loss of snags in terms of the number of snags removed per hectare of forest harvested for four harvest retention levels. All scenarios harvest 0.5% of the timber-harvesting land base per year. Results are means of 10 replicates. Range in coefficient of variation is 3.4%–18.5%.



yarding and skidding distances to reduce roads within the harvest unit. In addition, review of worker-safety regulations to minimize loss of snags is warranted, as suggested by Huggard (1999).

The model likely overestimates snag removal along road rights-of-way and block edges, as it removes all snags within 20 m, whereas in reality snags are often assessed for risk of falling and removed only if they are deemed hazardous. However the overestimate would be the same for each scenario examined and thus would only effect the absolute differences, and not the relative differences, between the scenarios compared.

The model we developed appears to be an effective tool for estimating the impacts of harvest pattern at landscape and stand scales on some important ecological indicators. We demonstrate that a harvest pattern based on wildfire patch size is superior to the three-pass dispersed-block model in reducing roads, stream crossings, and snag depletion and that increasing stand-level retention results in more roads and fewer snags. Often, the amount of forest harvest is the focus of critical attention for its impacts on the environment. Our results demonstrate that harvest pattern at landscape and stand scales should receive more attention in attempts to reduce the ecological impacts of harvesting.

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