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The application of a hierarchical, decision-support system to evaluate multi-objective forest management strategies: a case study in northeastern British Columbia, Canada

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Abstract

Increases in the environmental awareness of global consumers coupled with pressure from regional stakeholders has forced forest managers to demonstrate the potential implications of forest management activities for a broad range of indicators. This paper describes the construction and application of a hierarchical decision-support system for evaluating multi-objective management options for a 288,000 ha forest in northeastern British Columbia. The decision-support system includes a stand-level model, a forest estate model, a habitat model and a visualization model. A set of criteria and indicators, developed in conjunction with a public advisory committee, were used to identify key economic, ecological and social objectives. Indicators include volume harvested, gross profit, active road density, ecosystem carbon storage, age-class distribution, patch-size distribution, snag density, visual aesthetics and backcountry recreation area. A natural disturbance baseline and two alternative harvest strategies that include natural disturbance are projected and assessed with the decision-support system. The first strategy represents a dispersed harvesting approach in which cut blocks are limited to sizes <60 ha. The second strategy represents an aggregated harvesting approach in which a range of cut block sizes (up to 2000 ha) and shapes is created that more closely follows the distribution of openings generated from natural disturbance events in the region. Spatial and temporal changes in each indicator are presented and evaluated for the harvest strategies, and compared to the natural disturbance baseline where appropriate. The application of the decision-support system for strategic analysis of management options is discussed, including a review of the importance of representing the impacts of natural disturbance and the benefits and risks associated with the use of visualization techniques for presenting results to stake holder groups.
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1. Introduction

Forest ecosystems are increasingly viewed as resources that must be managed for a wide range of

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ecological, economic, and social values. Accordingly, management paradigms have shifted from those focused on sustaining levels of resource extraction from forest ecosystems, dominant in the industrial forest era, to those focused on sustaining the ecosystems that provide these resources (e.g. Thomas, 1995; Rauscher et al., 2000). This holistic approach to forest management, commonly referred to as 'ecosystem management', requires that we respect the hierarchical nature of forest ecosystems (O'Neill et al., 1986; Kangas et al., 2000) in developing sustainable forest management strategies. In other words, we can no longer focus strictly on the management of individual trees or stands, but rather we must also consider stands in the context of the landscapes in which they exist. Moreover, the multi-resource nature of modern forestry demands that managers assess the potential impacts of their decisions on a broad range of forest attributes related to biodiversity, timber production, carbon storage, recreation and other values. Given the complex spatial and temporal relationships that often exist between these attributes and the lack of data and general knowledge about the nature of their interactions, this can be a challenging task (see, e.g. Galindo-Leal and Bunnell, 1995). Not only must managers attempt to unravel these complex problems, but, if they are to maintain their 'social license' to harvest, they must also communicate their intentions and possible outcomes to public and consumer groups in a way that can be readily comprehended (Sheppard, 2000).

The pervasive movement towards integrated resource or multi-objective management at the landscape scale necessitates the development of new decision-support systems (DSSs) designed to accommodate the spatio-temporal complexity associated with the development and evaluation of alternative management scenarios. Bunnell and Boyland (2002) suggest that DSSs serve at least four broad purposes: (1) aiding research, (2) guiding management, (3) conveying knowledge, and (4) facilitating a public evaluation of management tradeoffs. The ultimate goal of a DSS, as stated by Rauscher (1999), "is to amplify the power of the decision makers without usurping their right to use human judgment and make choices."

In developing and applying sustainable forest management plans, DSSs are most effective when implemented within an adaptive management cycle (after Walters, 1986; Rauscher, 1999) including a well-defined set of indicators, monitoring systems, and mechanisms for feedback from researchers, industry, and stakeholder groups (see Fig. 1). The DSS plays a critical role in this process by:

(1) highlighting potential conflicts between competing management objectives,
(2) providing a common, science-based framework for stakeholders to evaluate the potential consequences of specific management options,
(3) conveying knowledge about the long-term dynamics of forest ecosystems, and
(4) providing guidance for the monitoring process by projecting expected trends in selected indicators.

At the heart of DSSs are models or modelling frameworks designed to project and/or interpret the consequences of different management activities. DSSs designed to address issues at multiple spatial and temporal scales have increasingly employed a framework of hierarchically linked or nested models (e.g. Li et al., 2000; McGregor Model Forest, 2001; Lamas and Eriksson, 2003; Kazana et al., 2003; Nelson, 2003a). The hierarchical structure facilitates problem analysis across different planning levels (i.e. tactical versus strategic) by allowing for the addition of complexity where warranted and necessary (Lamas and Eriksson, 2003; Nelson, 2003a). Moreover, the modular approach allows for increased flexibility within a DSS as it facilitates the use of different models to address specific problems or ecosystem types (Li et al., 2000).

Common components of modelling frameworks developed for multi-objective forest management include stand-level growth and yield or vegetation dynamics models, forest-level harvest schedulers, and a wide range of habitat suitability models (see Guisan and Zimmermann, 2000). The validity of a modelling framework for addressing multi-resource management questions is dependent not only on the capabilities of the individual models within the framework but also on the nature of the links that are created to facilitate communication between models. For example, forest planners are commonly faced with the problem of trying to drive habitat suitability models with standard output from growth and yield models (e.g. basal area and stem volume) that is often only weakly correlated with key habitat elements (e.g. snags, coarse woody debris, non-crop species, etc.).

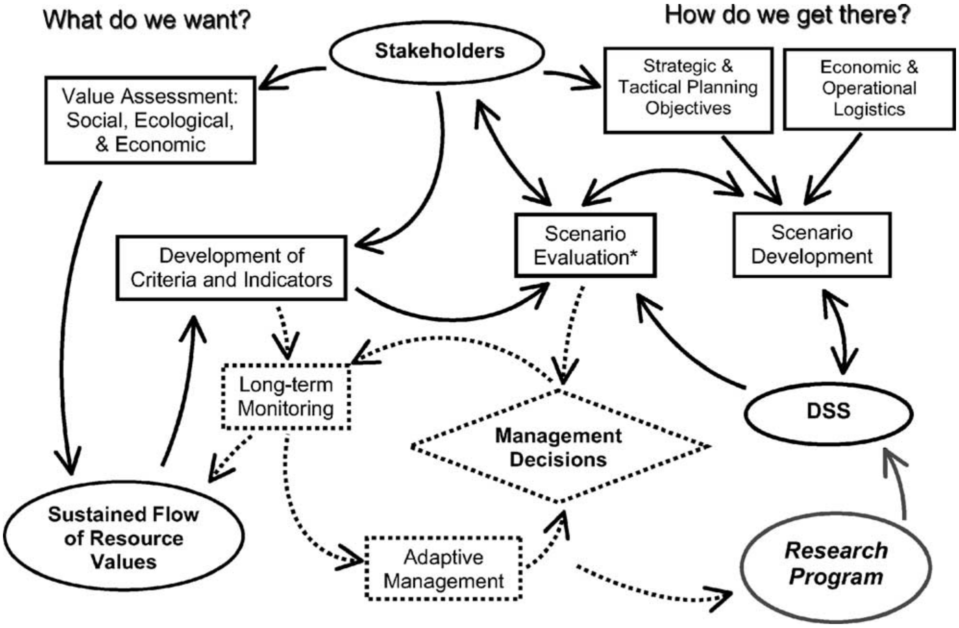

Fig. 1. An illustration of the role of the DSS in supporting the decision-making process in development and implementation of a sustainable forest management plan. The DSS provides a method for evaluating the potential impacts of alternative management scenarios on indicators of identified forest values. The symbol (*) denotes that it is essential that experts familiar with the ecosystems in question and the assumptions and limitations of the DSS be involved in the scenario evaluation process. Once decisions have been implemented, their impacts can be monitored as part of an adaptive management cycle (dashed lines) that provides feedback on the effectiveness of past management decisions and on the quality of the projections made by the DSS. This information is used to guide further research.

This type of problem typically stems from an inappropriate extension of models originally developed for timber production analysis to multi-objective analysis (Kangas et al., 2000). Another problem inherent in creating links between different models is that they often operate at different spatial and temporal scales. Bugmann et al. (2000) identified errors in scaling as a pervasive problem among modelling efforts where stand-level models were extrapolated up to landscapes.

To provide a level of confidence for the use of DSSs in the public evaluation of tradeoffs, it is essential that the core models/frameworks are constructed on scientifically credible foundations (Kangas et al., 2000) and that the data resources used to drive them (inventory data, habitat suitability relationships, etc.) are reasonably reliable (Eid, 2000; Bunnell and Boyland, 2002). It has also been suggested that given our general lack of field experience with many of the silvicultural systems employed under ecosystem management and the uncertainty associated with natural disturbance regimes and changing climate, models which incorporate some level of causality and/or understanding through the representation of key ecological processes are better suited for this purpose than models driven predominantly by empirical relationships (Korzukhin et al., 1996; Johnsen et al., 2001). Still, it is clear that both empirical and mechanistic models will be required to address the broad range of needs for decision support.

In this paper we describe the development and application of a hierarchical, multi-objective, DSS developed within the Faculty of Forestry at the University of British Columbia. The DSS, referred to as (UBC-FM) was designed to aid forest managers in assessing the potential impacts of management scenarios on a range of indicators. A case study is presented in which the UBC-FM modelling framework was applied to evaluate strategic-level management options for a 288,000 ha forest management unit in northeastern British Columbia. A set of indicators, developed in conjunction with the industry partner and a public advisory committee (Section 3.2), was used both to identify sub-areas within the management unit with the potential for meeting specific landscape-level management objectives and as a basis for evaluating alternative scenarios. Two alternative harvesting strategies and a natural disturbance baseline with no harvesting were subsequently formulated and assessed with the decision-support system.

2. Description of modelling framework

2.1. Modelling approach: philosophy, structure and functional components

The UBC-FM modelling framework was conceived within the Faculty of Forestry at the University of British Columbia as a means to unite a variety of independent models and associated research programs focused on various aspects of forest ecosystem management. The intent was to develop an integrated DSS that could be used to help forest managers cope with the complex decisions that must be made in the face of multi-objective forest management. The model framework was created by linking the individual models within a hierarchical structure that facilitates the transfer of data between models through common databases. The models within the framework can be broken into two functional groups: (1) those focused on the projection of forest attributes and conditions under specific management and disturbance regimes, and (2) those focused on interpreting both temporal and spatial changes in forest conditions resulting from the projection models (Fig. 2).

2.1.1. Stand-level simulation (FORECAST)

FORECAST (Kimmins et al., 1999) is an ecosystem-based, stand-level, forest growth simulator. The model was designed to accommodate a wide variety of harvesting and silvicultural systems in order to

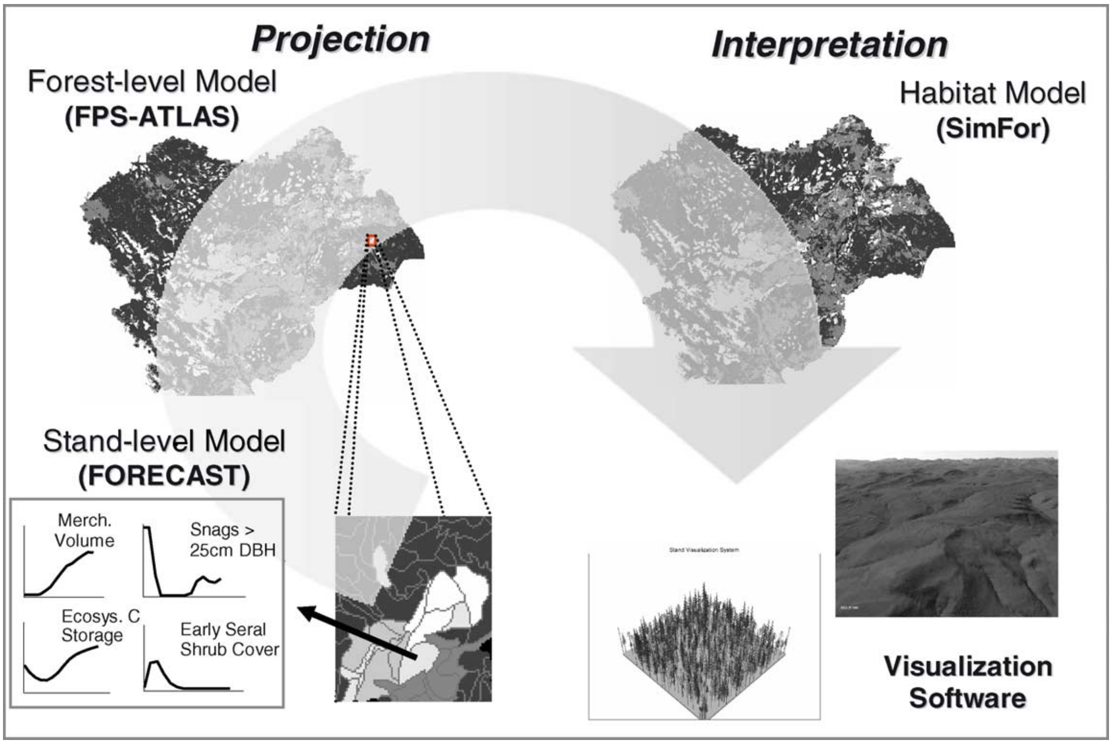

Fig. 2. A schematic illustration of the University of British Columbia Forest Management DSS (UBC-FM). The principal flow of information within the modelling framework is in the clockwise direction beginning with projection of management and disturbance events and moving towards interpretation in the context of selected indicators.

compare and contrast their effect upon forest productivity, stand dynamics, and various biophysical indicators of non-timber values. The model uses a hybrid approach whereby local growth and yield data (often from locally calibrated empirical growth and yield models) are combined with other data to derive estimates of the rates of key ecosystem processes related to the productivity and resource requirements of selected species. FORECAST uses derived measures of decomposition, nutrient cycling, light competition, and other ecosystem properties to simulate forest growth and ecosystem dynamics under changing management and environmental conditions. Growth and yield in complex stands is based on a simulated partitioning of limited resources (light and nutrients) among species and age cohorts. The biological properties of individual species, as defined by the input data, determine their relative competitiveness for limited resources. The ability of FORECAST to project the development of stand attributes related to both timber and non-timber values in an integrated system provides a strong foundation for the UBC-FM modelling framework.

2.1.2. Forest-level simulation—harvest scheduling (FPS-ATLAS)

FPS-ATLAS (Nelson, 2003b) is a spatially explicit, forest-level simulation model designed for harvest scheduling. In a given time step, the model grows the forest for a specified period, implements natural disturbance regimes (if so desired), and then simulates a harvest. These steps are repeated until the desired planning horizon is reached, which typically requires several rotations. The forest is comprised of stand polygons, and each of these are linked to a series of age-dependent attribute tables, such as the merchantable volume/ha, provided by the stand-level model FORECAST. Harvests are controlled by setting volume production targets for each time period, setting harvest queue priorities and implementing constraints such as seral stage limits and adjacency rules. The representation of natural disturbance within FPS-ATLAS is described in Section 3.4.2. FPS-ATLAS is also capable of simulating transportation activity on a road network. In addition to harvest outputs such as area and volume treated, the model also produces a list of the current status of every polygon in every time period that is used by other models in UBC-FM (e.g. habitat, visual).

2.1.3. Interpretation of habitat suitability (SIMFOR)

SIMFOR Version 3.0 (Daust and Sutherland, 1997) is a decision-support tool designed to help managers and researchers evaluate the impacts of forest harvesting scenarios on landscape and habitat indicators. The primary objective of SIMFOR is to evaluate general trends in selected indicators of forest structure and function through space and time. SIMFOR combines harvesting plans with projections of forest attribute development to predict habitat occurrence and to measure landscape pattern. Using this approach, SIMFOR may be used to evaluate the response of forest vegetation to harvesting treatments or natural disturbance events, and to calculate potential landscape and wildlife habitat conditions.

In the context of the UBC-FM modelling framework, SIMFOR imports, from FPS-ATLAS, a list of polygons with specified treatments or natural disturbance events according to a particular harvesting/disturbance scenario. This list of treatments is subsequently assessed within an aging routine to determine future patterns in seral stage and stand structural conditions. Stand structure is represented by the abundance of selected habitat attributes, which are provided as input from the stand-level model FORECAST. By matching wildlife species requirements with these habitat attributes, SIMFOR estimates species-specific habitat suitability. In addition, the software uses spatial relationships to project simple landscape metrics: seral stage, patch-size and edge characteristics.

2.1.4. Interpretation of visual impacts and communication of results through visualization

The CALP visualization system (Cavens, 2002) was developed at UBC's Collaborative for Advanced Landscape Planning to link output from the projection and interpretation models within the UBC-FM modelling framework, in order to facilitate the creation of visual representations of proposed alternative forest management plans. To accomplish this task, model outputs must be concatenated, parsed and eventually reinterpreted such that information may be extracted and used by a standard rendering package. The strength of this approach is that the CALP visualization system can be adapted to accept information from any relevant model and can produce output for many different rendering engines. In this case, World Construction Set (WCS) was used as the rendering engine because of its ability to handle large numbers of elements typically necessary to produce near photo realistic visualization of forested landscapes. The three-dimensional visualization of output from the UBC-FM modelling framework serves three primary functions: (1) it allows the researchers involved in model development and application to identify inconsistencies in scale and patterns associated with the linkage of the various components within the modelling framework, (2) it helps to communicate spatially and temporally complex model results to stakeholder groups through the use of familiar visual references, and (3) it provides a method to evaluate the potential visual impacts associated with alternative management options.

3. Application of the modelling framework to the study area in northeastern BC

3.1. Site description

To evaluate the potential of UBC-FM for evaluating multi-objective forest management options, the modelling framework was applied to a management subunit called Block 4 which exists within Tree Farm License (TFL) 48, managed by Canadian Forest Products Ltd. TFL 48 is located in northeastern British Columbia near Chetwynd and spans from the east slopes of the Rocky Mountains down into the foothills and eastward into the southeastern edge of the boreal plains (Fig. 3). In addition to fiber production, other important resource uses within TFL 48 include oil and gas exploration, trapping, hunting, motorized recreation and an evolving eco-tourism industry. Conflicts between public groups interested in access to remote sites and those interested in wilderness are common. The area also has significant value to several First Nations.

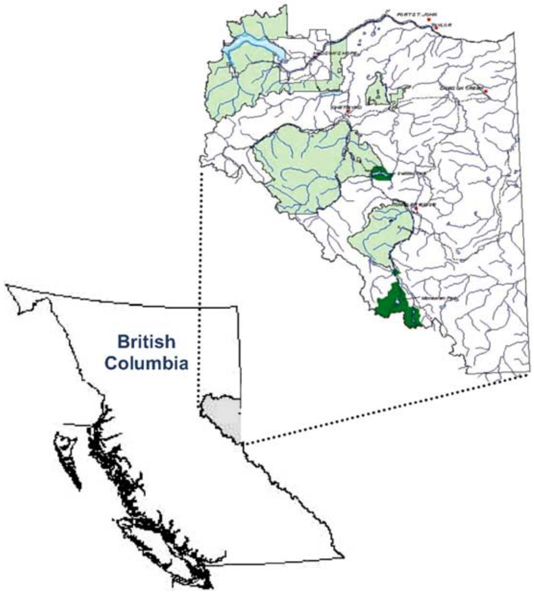

Fig. 3. Illustration showing the location of the 288,000 ha study area within northeastern British Columbia.

Block 4 of TFL 48 represents an area of approximately 288,000 ha in size of which about 75% (216,000 ha) is productive forest land. The primary forest types within the area include the high elevation forests dominated by Engelmann spruce and subalpine fir, mid-slope forests dominated by hybrid spruce, lodgepole pine and aspen, and the boreal foothills and plains dominated by mixedwood stands of white spruce, aspen and lodgepole pine.

Four Natural Disturbance Units (NDUs) have been identified within the study area by DeLong (1998) and DeLong (unpublished report, 2002) (Fig. 4). The units represent disturbance regimes which are described

Table 1
Estimates of pre-fire suppression disturbance rates and patch-size distributions for each of the Natural Disturbance Units (NDU) within the study area

Natural Disturbance Unit	Total area (%)	Disturbance cycle (years)	Patches >1000 ha (%)	Patches 100–1000 ha (%)	Patches 51–100 ha (%)	Patches <50 ha (%)
Boreal Foothills Mountain	32.9	150	40	30	10	20
Boreal Foothills Valley	26.2	120	40	30	10	20
Boreal Plains Upland	22.4	100	70	20	5	5
Wet Mountain	18.5	900	10	60	10	20

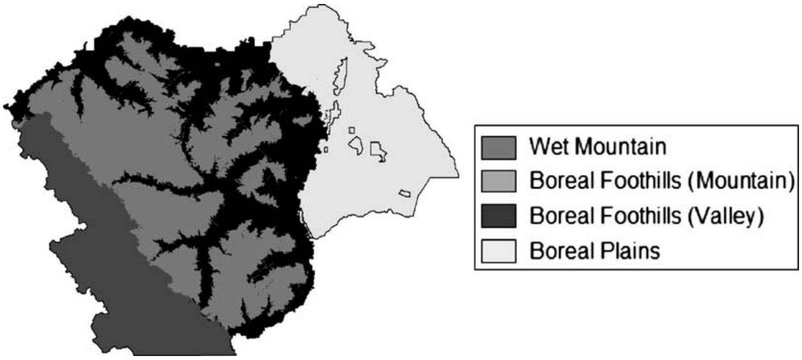

Fig. 4. Natural Disturbance Units (NDUs) in Block 4 of TFL 48.

using estimates of pre-suppression fire return intervals and patch-size distributions (Table 1). Wildfire is the dominant disturbance agent in all of the disturbance regimes, with the exception of the Wet Mountian NDU, where stands are more often subject to endemic levels of various insects and diseases. The Boreal Foothills NDU is dominated by large wildfires, resulting in large patches of even-aged forest. Fire control in this NDU may have slowed the natural disturbance rate, increasing the amount of mature to old forest in areas not subject to timber harvesting, and reducing large areas of fire-origin stands. The Boreal Plains NDU is also dominated by fire with similar patterns to those in the Boreal Foothills, although fires are characterized as being more frequent and much larger.

3.2. Development of indicators for scenario evaluation

Criteria and indicators (C&I) play a critical role in developing and implementing sustainable forest management plans by providing a methodology for defining goals and objectives and for evaluating progress towards those goals. As part of the process of pursuing certification under the Canadian Standards Association (CSA), Canadian Forest Products Ltd. (Canfor) has consulted with a public advisory committee to develop a comprehensive set of C&I to address the concerns of the various stakeholder groups. A representative subset of those indicators were subsequently selected and developed for application within UBC-FM. This subset was designed to provide an integrated suite of indicators that would allow for an assessment of the potential impacts of management alternatives on economic, ecological and social values within the management area. Fig. 5 illustrates the relative relationship of each of the selected indicators with respect to the three broad value categories. Details for each indicator are provided in Table 2.

3.3. Application of the FORECAST model

To construct a stand-level database for use as a foundation for the UBC-FM modelling framework, it was first necessary to identify the range of site types and conditions that exist within Block 4. Spatial ecological classification data (e.g. Terrestrial Ecosystem Mapping) was used in conjunction with vegetation inventory data to define a series of core site types. Each forest type, in conjunction with a set of silvicultural options (in the case of managed stands), was considered to be a discrete stand unit. A total of 82 discrete stands units were described to represent 'natural' or unmanaged stands within the study area while 52 discrete stand units were created to represent the range of managed stands. FORECAST was then used to create a series of stand attribute curves for each unit including merchantable volume, species composition, stand structure, and carbon storage. These unique stand units were subsequently assigned to individual polygons within the landscape models using a set of criteria including TEM site types, indices of site productivity, and current forest cover. This method of scaling up is a form of direct extrapolation as described by King (1991) and has been shown to be quite accurate as long as a sufficient number of landscape elements are defined (e.g. Bugmann et al., 2000).

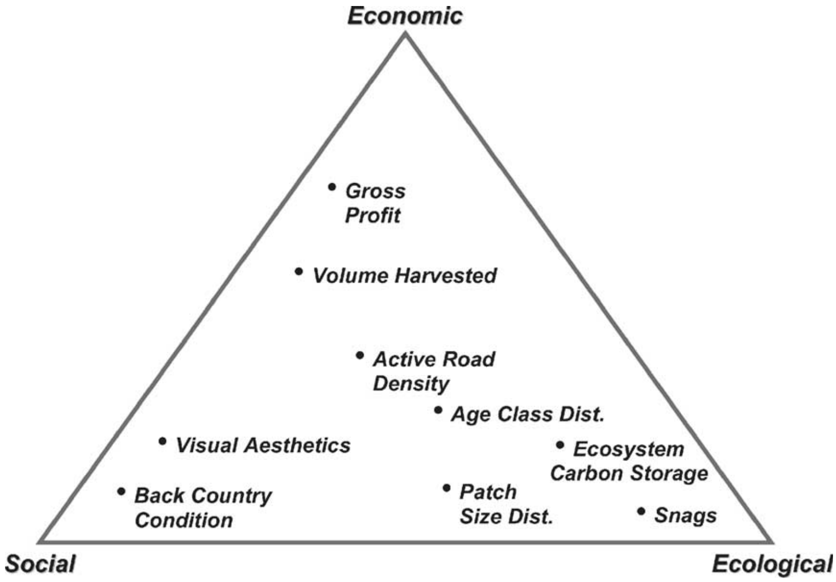

Fig. 5. Graphical representation of the relative relationship between individual indicators employed within the UBC-FM and the three broad forest value categories.

Table 2
A description of the set of indicators used within UBC-FM for the case study analysis of Block 4

Indicator	Description	Units
Volume harvested	Quantification of merchantable volume harvested during each time period through the planning horizon.	m^3
Gross profit	Calculation of the gross profit from logging activities based on estimates of revenue and costs. Costs include: road construction, harvesting, transportation, administration and silviculture. Revenues are based on estimates of values for specific classes of timber and pulp wood.	$
Active road density	Quantification of the length of active road per unit area within the study area. This has implications for public access, harvesting costs, erosion, and wildlife movement.	km ha^{-1}
Ecosystem C storage	Quantification of the total ecosystem carbon (C) storage including above and belowground biomass pools, soil organic matter and forest floor and coarse woody debris. Provides a method for evaluating the effect of management alternatives on the contribution of the study area towards the global C cycle.	Mt C
Age-class distribution	Quantification of area within 40-year age classes. Provides a measure of how the total forest age-class structure is altered by aging, natural disturbance, and harvesting over time.	ha
Patch-size distribution	Quantification of the amount of area within patches of different size classes based on age-class groups. Provides a measure of the effect of harvest and natural disturbance on landscape structure (degree of fragmentation).	ha
Snags	Quantification of the area into discrete classes based on the number of large snags (>25 cm dbh) per hectare. Calculated separately for deciduous trees and conifers. Functions as a medium filter indicator for the maintenance of wildlife habitat resources and biodiversity.	% of total area
Visual aesthetics	Qualitative evaluation of the visual consequences associated with different management alternatives, based on generated visualisation images.	na
Backcountry condition	Quantification of the area into discrete Recreation Opportunity Spectrum (ROS) classes based on intensity of management activity. Used to evaluate the implications of timber harvest activity on backcountry condition.	% of total area

3.4. Application of FPS-ATLAS for simulation of landscape management scenarios within a natural disturbance regime

Utilizing the stand-level database prepared with FORECAST, FPS-ATLAS was used to examine two alternative landscape management scenarios and a baseline natural disturbance scenario in which there was no harvesting or fire suppression. The dispersed harvesting scenario was designed to represent the status quo, regulation-based forest management practices in British Columbia which include green-up and adjacency standards that result in many small blocks distributed across the timber-harvesting land base. In contrast, the aggregated harvesting scenario allowed for blocks up to 2000 ha in size and used a distribution of block sizes based on that established for each NDU as shown in Table 1. The primary goals of the aggregated harvesting scenario were: (1) to create a range of patch sizes that more closely resembles natural conditions by concentrating harvesting in particular areas and leaving relatively larger patches of undisturbed forest and (2) to reduce road construction and the length of active road. The details of the scenarios including data preparation, representation of natural disturbance regimes, etc. are described in the following sections.

3.4.1. Data preparation

Polygons for the forest-level model were generated from GIS overlays of stand types, riparian areas, and a suite of other resource layers (e.g. visual zones, recreation areas, ecological reserves), resulting in 70,777 polygons with an average size of 4.1 ha. In some instances, large and/or sinuous polygons were split into smaller units for better control of harvest projections. Each forested polygon was assigned a discrete stand unit (see Section 3.3), membership in a specific NDU, and membership in various resource layers. A road network used for calculating haul distances and assessing road density was generated with the Computer Assisted Road Projection (CARP) model (Anderson and Nelson, 2003). The network contained 153,000 links that account for approximately 6000 km of projected road.

3.4.2. Representation of natural disturbance

The FPS-ATLAS model includes a natural disturbance module that works in tandem with the harvest scheduler. During each time step, the disturbance module is executed first, followed by the harvest scheduler. Within a NDU, the location of disturbance events is driven by the selection of random seed polygons. If a seed polygon is eligible for disturbance, a disturbance event is initiated, and a patch area target is generated. The disturbance event spreads from the seed to adjacent, eligible polygons. The spread process continues until either the patch-size target has been reached, or there are no more eligible adjacent polygons, or the disturbance rate for the NDU has been reached. Disturbed polygons have their stand unit reassigned to a temporary salvage stand unit (with salvage volumes that represent 70% or the pre-disturbance volume). They are then eligible for salvage by FPS-ATLAS providing no other constraints prevent this. Seed polygons continue to be selected and events initiated until the area target or the target number of events is reached for the period. Finally, the disturbance model re-sorts the polygons by NDU, and places all newly disturbed polygons at the top of the harvest queue. Disturbed polygons that cannot be harvested by FPS-ATLAS (e.g. in the non-harvest land base) are reassigned to an un-managed stand unit, with an age of 0.

3.4.3. Scenario analysis

Details for each of the three simulated landscape-level scenarios (two management and one natural disturbance baseline), are summarized in Table 3. The dispersed harvest scenario used 20-year adjacency rules

Table 3
Summary of the management scenarios simulated with FPS-ATLAS

Scenario	Block size	Natural disturbance rate	Harvest flow target per decade ($m^3 \times 10^6$)
Baseline no harvest	na	Pre-fire suppression	na
Dispersed harvesting	<60 ha	33% of pre-fire suppression	2.43
Aggregated harvesting	40–2000 ha	33% of pre-fire suppression	2.49

while the aggregated harvest scenario used 10-year adjacency. The longer adjacency rule for the dispersed harvest was necessary to ensure the openings remained small. Both harvest scenarios included a constraint to retain 10% of the polygon area as "within block reserves". In the case of the two management scenarios, it was assumed that fire-suppression efforts would reduce historical fire return intervals to 33% of pre-suppression rates (see Table 1). In contrast, pre-suppression rates were used for the natural disturbance baseline. Disturbance patch sizes were drawn from the distribution in Table 1, and large disturbances (>1000 ha) were limited to less than 10,000 hectares for both scenarios.

Each scenario was simulated for 300 years, using 10-year time steps, and, to account for variation due to random disturbance events, each scenario was replicated five times. Harvest priorities were to salvage burned stands first (if salvage criteria are met), and then oldest-first for the remaining stands. The harvest flow target was set to the highest even-flow volume that could be maintained, on average, over the 300-year simulation. Estimates of revenues and costs (roads, harvest, transportation, administration and silviculture) were used to calculate gross profit by decade. The gross profit does not include stumpage and taxes.

4. Results

4.1. Stand-level results

Example output from FORECAST is shown for two of the discrete stand units. Fig. 6 illustrates the simulated development of a natural mixed spruce and aspen stand that originated following a stand-replacing fire within the boreal plains NDU. Fig. 7 illustrates the simulated development of an uneven-aged spruce-subalpine fir stand within the wet mountain NDU that originated following an irregular shelterwood harvest in which most (>90%) of the merchantable stems were removed but advanced regeneration was retained. Under this silviculture system, the retained stems are not harvested until the entire stand reaches

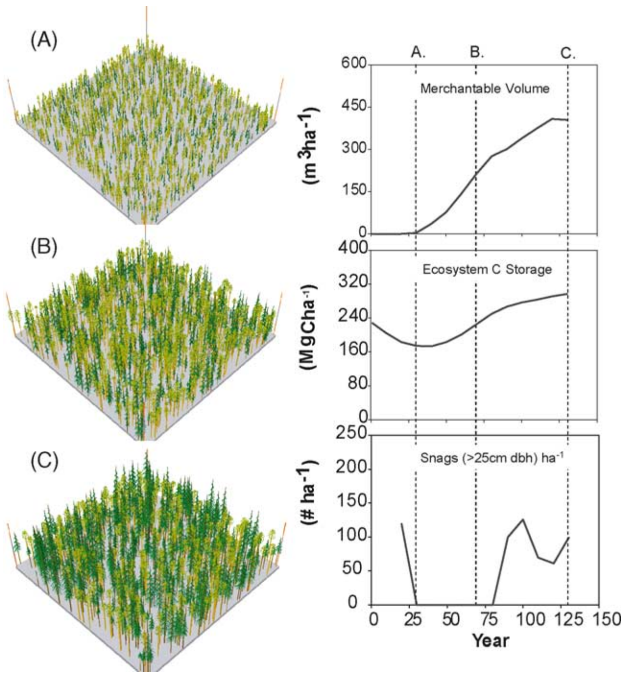

Fig. 6. Stand-level simulation results from FORECAST showing merchantable volume, ecosystem C storage, and large snags for a natural mixed aspen-spruce stand following a stand replacing fire. Images of the stand are shown for three time periods (A) year 30, (B) year 70, and (C) year 130. The lines on the attribute graphs correspond with the time periods for the images.

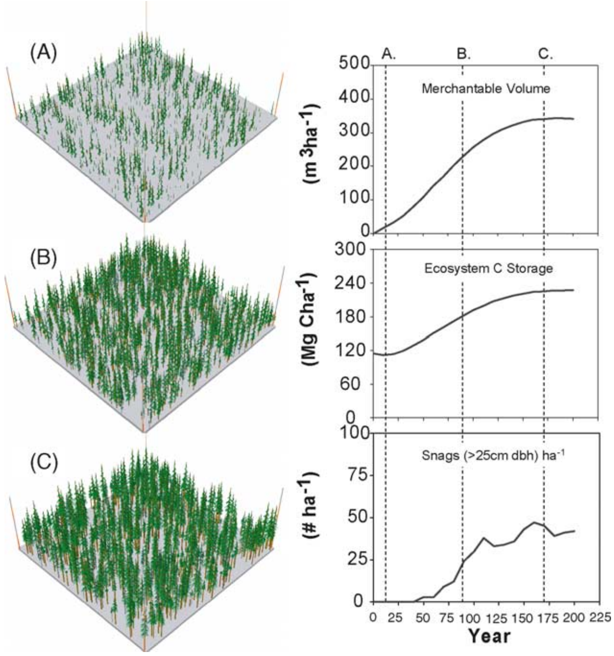

Fig. 7. Stand-level simulation results from FORECAST showing merchantable volume, ecosystem C storage, and large snags for a managed spruce-subalpine fir stand in the wet mountain NDU following harvest using an irregular shelterwood system. Images of the stand are shown for three time periods (A) year 10, (B) year 90, and (C) year 170. The lines on the attribute graphs correspond with the time periods for the images.

maturity (160–200 years) at which point the process is repeated. To illustrate the integrated nature of the individual stand attributes, the results for merchantable volume, ecosystem C storage, and large diameter (>25 cm dbh) snags are presented in combination with three-dimensional visualizations of the stands at different time intervals (generated using the Stand Visualization System developed by Robert McGaughey of the USDA Forest Service). The initial large population of snags shown for the mixedwood stand (Fig. 6) is the result of a stand-replacing fire that initiated the stand. In the case of managed stands, all snags were removed at the time of harvesting in accordance with local worker safety regulations.

4.2. *Forest-level results*

4.2.1. *Volume harvested, road networks and gross profit*

The temporal pattern in total volume harvested for each of the management scenarios is presented in Fig. 8A. The maximum harvest that could be sustained within the dispersed scenario was slightly lower than that in the aggregated scenario primarily because of the 20-year adjacency rules that were imposed in the dispersed scenario to maintain small patches (see Section 3.4.3). Some of the larger drops in periodic harvest rates near the end of the planning horizon were related to natural disturbance events. While the disturbance rates were held constant across all periods, the random nature of the model sometimes results in a sequence of events that significantly impacts harvest rates over the long-term. The dispersed harvesting scenario, with many small openings spread over a large area, led to a significant increase in road density (Fig. 8B) and total length of active road network (Fig. 8C) relative to the aggregated harvest scenario. Were it not for the salvage logging from natural disturbance events (usually much greater than 60 ha in size), the discrepancy between the two scenarios would have been greater. A comparison of gross profit between the two scenarios (Fig. 8D) shows that the aggregated harvesting scenario had slightly higher profit. The higher profit was the result higher volumes harvested and lower road building costs. Road building costs in the dispersed harvest scenario were parti-

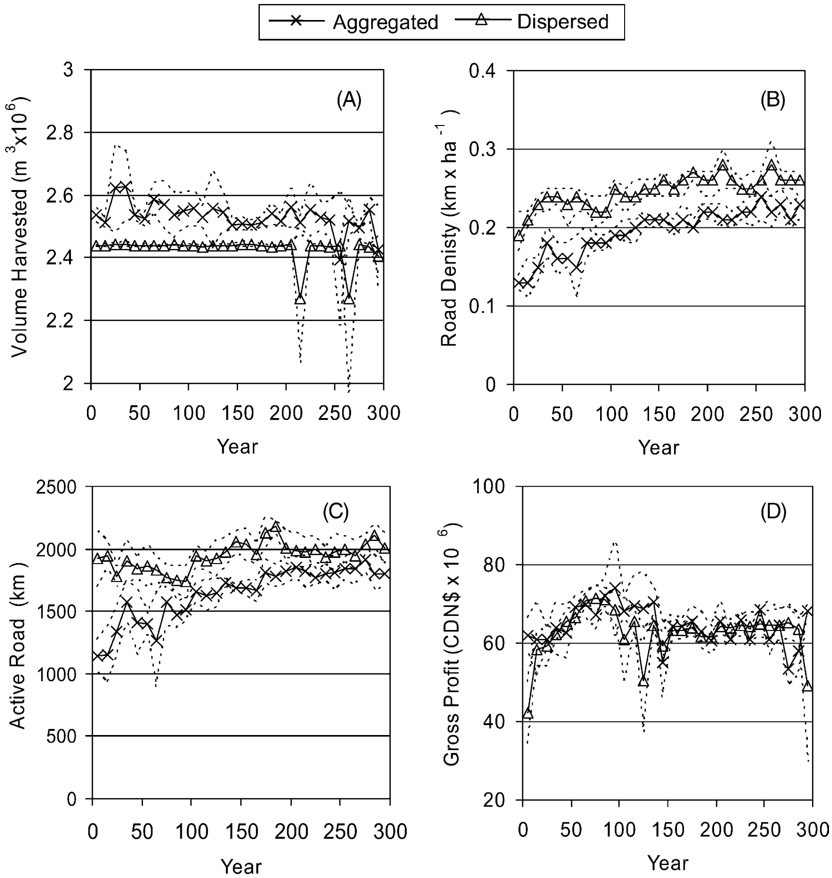

Fig. 8. Simulation results showing averages for (A) total volume harvested, (B) road density in harvested area, (C) length of active road network, and (D) gross profit per unit wood volume harvested for each of the management scenarios in Block 4. The dashed lines represent 95% confidence intervals for the five runs of each scenario.

cularly high in the first few periods when the extensive road network was being established. This translated into lower gross profit early on.

4.2.2. Age-class structure

The effects of the three alternative scenarios on long-term changes in the forest age-class structure are shown in Fig. 9. In all three scenarios, the forest shows a gradual shift from a forest dominated by mid to older stands towards one dominated by young to mid-aged stands. The one exception to this pattern is the increase in the area in the oldest age class in all scenarios. This increase is the result of the accumulation of stands, particularly in the non-timber-harvesting land base within the wet mountain and boreal foothills mountain NDUs, that escape disturbance within the 300-year simulation period. Interestingly, patterns in the age-class structure in the natural disturbance baseline scenario are quite similar to those in the harvest scenarios. While the total area disturbed in the natural baseline scenario was about a third higher, on average, than that in the harvesting scenarios (Fig. 10), the harvest disturbance was focused on older stands while the natural disturbance by fire was age-independent (equal probability for all stands). It appears that these different disturbance regimes tend to converge toward similar age-class structures.

4.2.3. Carbon storage

An evaluation of changes in total ecosystem C storage provides a useful summary of the impact of management on the net transfer of C between the

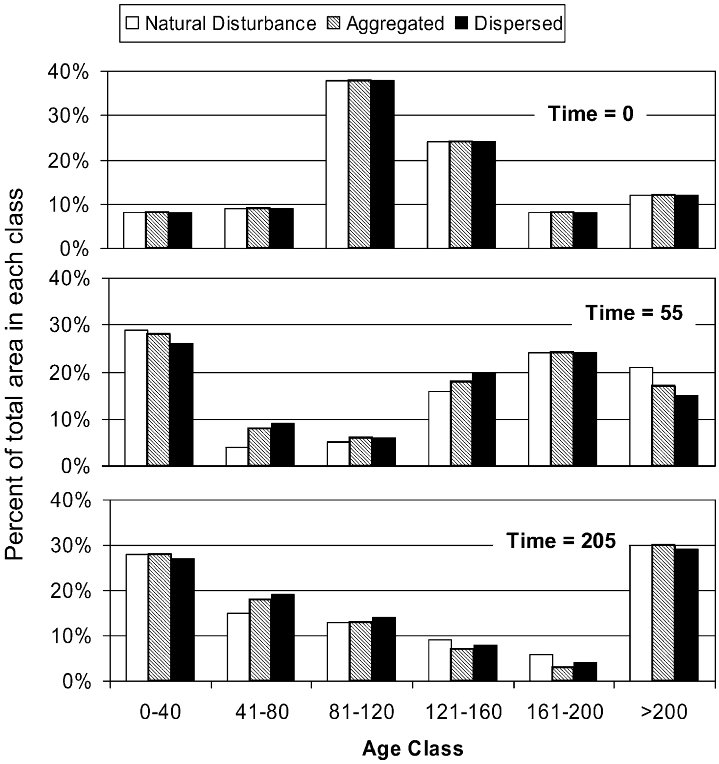

Fig. 9. Simulation results showing age-class distributions for three time periods for all three scenarios. The age-class structure of the forest remains relatively stable for all scenarios after simulation time 205.

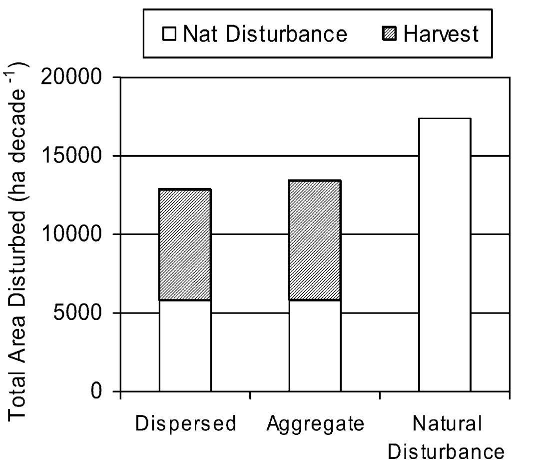

Fig. 10. Average area disturbed during each period for each scenario. Disturbance is separated into harvest and natural (fire) disturbance.

forest ecosystem and the atmosphere. It should be noted that the modelling framework allows for a more complete evaluation of total C storage by ecosystem components including soil, biomass, and dead organic matter pools. For the purposes of this summarized analysis, only total ecosystem C storage was considered.

The implications of the three scenarios for long-term ecosystem C storage are shown in Fig. 11. In all cases, total ecosystem C storage declined gradually during the first 75–100 years of the simulation and then stabilized at approximately 91 and 87% of initial storage for the natural baseline and harvest scenarios, respectively. This pattern of decline is consistent with the general transition of the landscape from an older state to a younger state as described above. As observed in Figs. 6 and 7, the quantity of C stored in a given stand tends to increase with age until the stand reaches a point where C released through respiration is equal to or greater than that sequestered

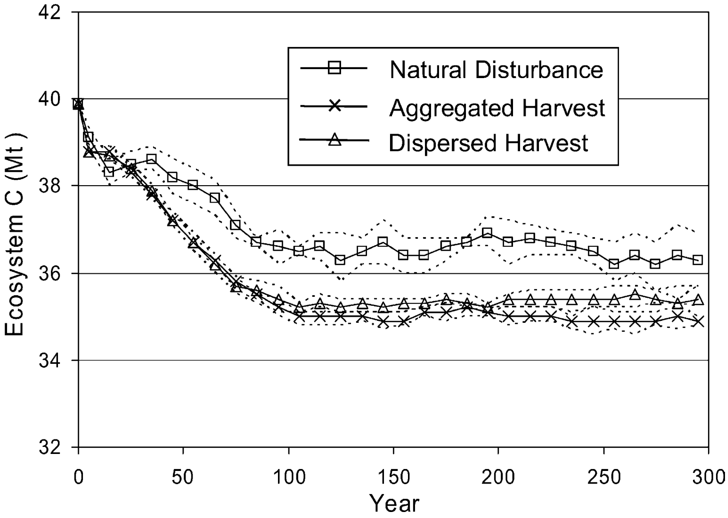

Fig. 11. Simulation results showing average total ecosystem C storage for each of the scenarios in Block 4. The dashed lines represent 95% confidence intervals for the five runs of each scenario.

in new production. Interestingly, the baseline scenario with no harvesting still leads to a decline in C storage. It appears that several decades of fire suppression combined with limited harvesting to date have allowed the forest to mature and accumulate carbon over and above levels prior to fire suppression. Thus, when fire suppression is eliminated, as was the case in the baseline scenario, there is a decline in C storage associated with the increase in fire occurrence.

Despite the decline in the baseline scenario, ecosystem C storage remained consistently higher in the baseline scenario relative to the two harvesting scenarios which included fire suppression to 33% of pre-suppression rates. Since the age-class distributions are similar for all scenarios, the primary reason for the greater storage in the natural baseline scenario is that following a fire much of the dead biomass is left on the site; whereas, in the case of harvesting, the majority of the above-ground biomass is removed. Thus, young natural stands tend to store relatively more C in dead organic matter pools relative to their harvested counterparts. The small difference in ecosystem C storage between the two harvesting scenarios stems from the fact that the aggregated harvesting scenario has a slightly greater harvest level. However, if the CO_2 emissions associated with increased road construction and maintenance were included in a C accounting framework, it is likely that the dispersed scenario would result in a greater net emission of CO_2 to the atmosphere.

4.2.4. Snags and patch analysis

Dead and dying standing trees (snags), and downed wood provide wildlife with cover and habitat for breeding and foraging. As such they have been widely recognized as effective, medium-filter indicators for the maintenance of wildlife habitat resources and biodiversity in managed forest ecosystems. The implications of the three scenarios on long-term populations of large diameter (>25 cm dbh) snags were evaluated, since they have been widely shown to be of greater value as habitat (e.g. Bunnell et al., 1999). Individual stands or polygons were assigned one of four snag classes based on the type of tree (conifer; hardwood) and quantity of large diameter snags (2–10 snags ha^{-1}; >10 snags ha^{-1}). The selection of classes was based on evidence “that hardwood and conifer snags are used differently” (Bunnell et al., 1999; Martin and Eadie, 1999; Harestead and Keisker, 1989) and that the quantity per unit area is important for some species. Two to 10 snags per hectare was selected as a cutoff point to differentiate between species that require greater snag densities. Simulation results show that the natural disturbance baseline scenario led to two- to threefold increases in the percent of forested area that contained >10 snags

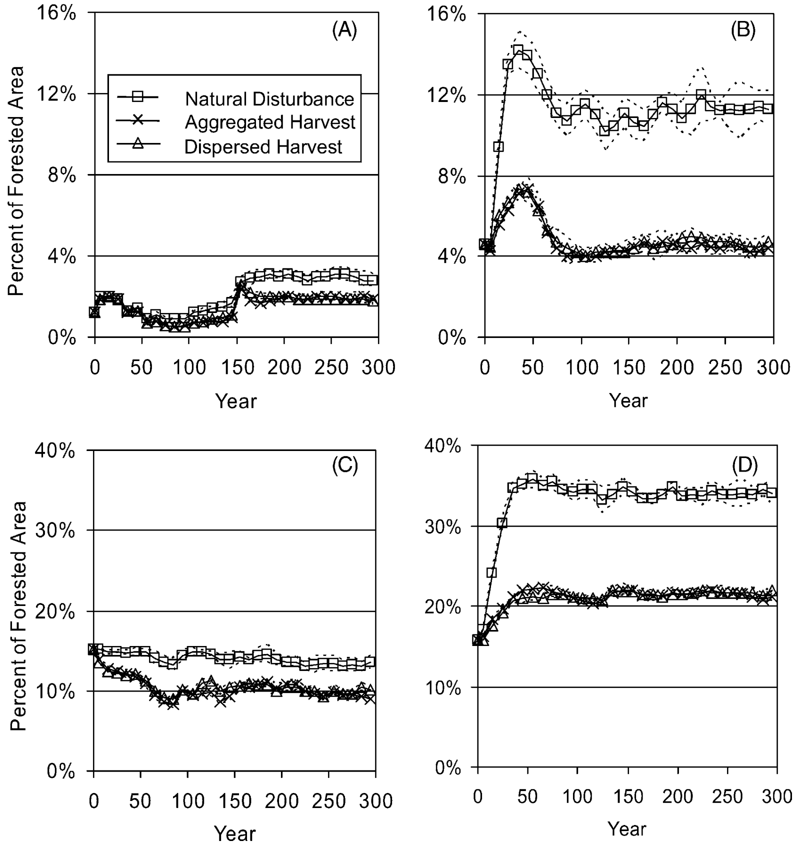

Fig. 12. Simulation results showing averages for the percent of forested area that contains large snags (>25 cm dbh) in the following classes: (A) deciduous 2–10 snags ha^{-1}, (B) deciduous >10 snags ha^{-1}, (C) conifer 2–10 snags ha^{-1}, and (D) conifer >10 snags ha^{-1} for all three scenarios. Notice the difference in scale between panels A–B and C–D. The dashed lines represent 95% confidence intervals for the five runs of each scenario.

ha^{-1} for both conifer and hardwood snags (Fig. 12) relative to the initial condition (time 0). The principal reason for this increase was the increase in fire frequency in the absence of suppression in the baseline scenario which led to an increase in fire originated snags (see Fig. 6 for example). As expected, there were no differences in snag densities between the two spatial harvesting strategies. However, if the simulation had included the removal of snags from road and cutblock edges in accordance with worker safety regulations, the dispersed harvesting scenario, with greater road density and a higher frequency of small patches, would likely have substantially lower snag densities.

The distribution of the total forested area within patch-size classes provides information about the spatial organization or level of fragmentation which may have implications for wildlife habitat. To evaluate the level of fragmentation resulting from the different scenarios, the percent of forested area within different patch sizes was evaluated using the SIMFOR model. Patches were defined based on age classes such that contiguous individual polygons within a particular age class were lumped together. Selected results from the patch analysis are presented in Fig. 13. The natural baseline scenario showed a clear trend toward increased area in large patches (>1000 ha) and decreased area in very small patches (<50 ha). This was predominantly related to the fact that the subareas within Block 4 that had been harvested (in relatively small patches) prior to the time of simulation were converted to larger patches over time via

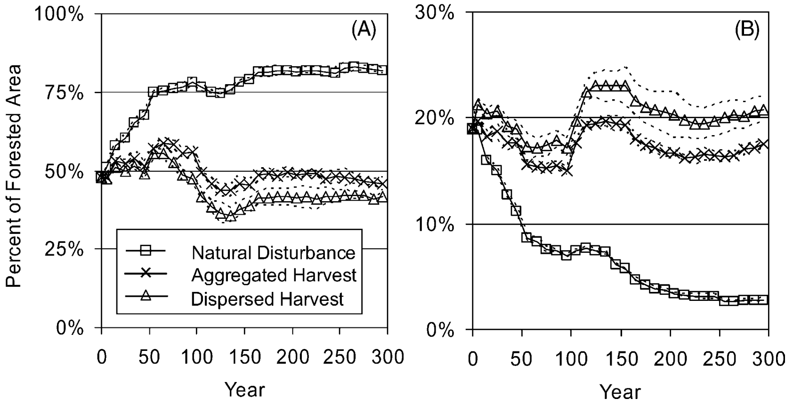

Fig. 13. Simulation results showing averages for the percent of forested area within (A) large patches (>1000 ha), and (B) very small patches (<50 ha) for each scenario. The dashed lines represent 95% confidence intervals for the five runs of each scenario. Notice the difference in scale between panels A and B.

natural disturbance events. Somewhat surprising was the fact that the dispersed harvesting scenario showed only slightly less area in large patches relative to the aggregated scenario. The main reasons for this result were twofold. First, the occurrence of large natural disturbance events within the dispersed harvesting scenario (followed by salvage harvesting where applicable) allowed for the maintenance of large patches where otherwise they would have been reduced. Secondly, the larger patch-size targets within the aggregated harvesting scenario could not always be met due to pre-existing conditions such as uneven age classes prior to harvesting. Examples of changes in the extent and spatial distribution of patches of for the three scenarios are shown in Fig. 14.

4.2.5. *Recreation opportunity analysis*

The maintenance of backcountry condition in areas outside of parks and protected areas can alleviate pressure on protected areas as well as provide primitive settings for some activities that are prohibited in parks (e.g. hunting and motorized use). Maintaining a diversity of recreation opportunity settings also provides managers with the flexibility to respond to changes in recreation demand. Relationships between modeled timber harvesting and outdoor recreation opportunities were evaluated based on a Recreation Opportunity Spectrum (ROS) analysis (Clark and Stankey, 1979). ROS has been recognized as an effective tool for assessing some of the implications of resource management decisions on backcountry condition and associated outdoor recreation opportunities (Harshaw and Sheppard, 2003; Nilsen and Tayler, 1997). Four ROS classes, based on existing British Columbia ROS inventory classes (BC MoF, 1998), were identified and examined for both harvesting scenarios within Block 4. The classes, in order of increasing level of naturalness, were: (1) Roaded Modified (polygons that were within 1 km of operational branch roads and within 1 km of harvest blocks); (2) Roaded Natural (polygons that were within 1 km of a mainline road); (3) Semi-Primitive Motorized (polygons that were ≥1000 ha, and within 1 km of a spur or within block road); and (4) Semi-Primitive Non-Motorized (polygons that were ≥1000 ha and ≥1 km from any road). Because of uncertainties associated with the length of time required to return to 'natural conditions' following harvesting and/or road deactivation, only the first 50 years of simulation were considered. Results are shown in Fig. 15.

The dispersed harvesting scenario showed a more rapid decline in opportunities for semi-primitive, non-motorized recreation activities relative to the aggregated scenario. However, due to the development of road networks, both scenarios appear to lead to substantial reductions in semi-primitive recreation areas within Block 4 relative to current conditions.

4.2.6. *Visual impacts*

A series of images were created for selected viewpoints within the larger study area using the

CALP visualization system. An example of the type of image produced is shown in Fig. 16. Visualisations were used by the study team, presented to the Public Advisory Committee for discussion purposes, and are the subject of ongoing perceptual studies at the Collaborative for Advanced landscape Planning (CALP). Temporal visualization sequences (not shown here) were also created so that visual representations could be viewed side-by-side to allow for direct comparison of the visual effects of one management scenario versus another. In some cases additional data were presented along with these images to allow for integration of both visual and non-visual dimensions so that quantitative results could be assessed in the context of likely visual outcomes of those management actions. This

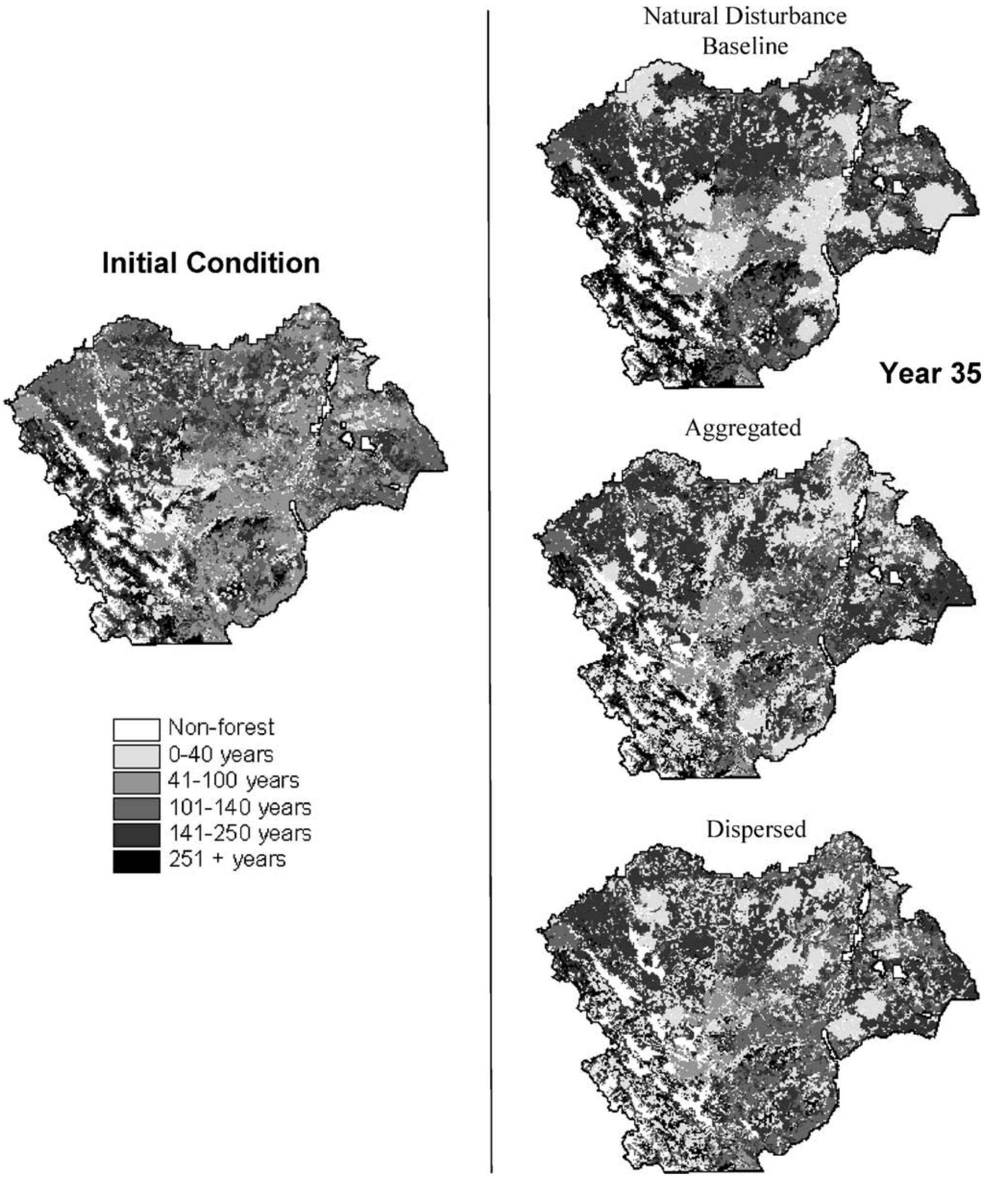

Fig. 14. Spatial distribution of age-class patches for each of the three simulated scenarios showing landscape patterns for the initial condition and simulation years 35, 75 and 155.

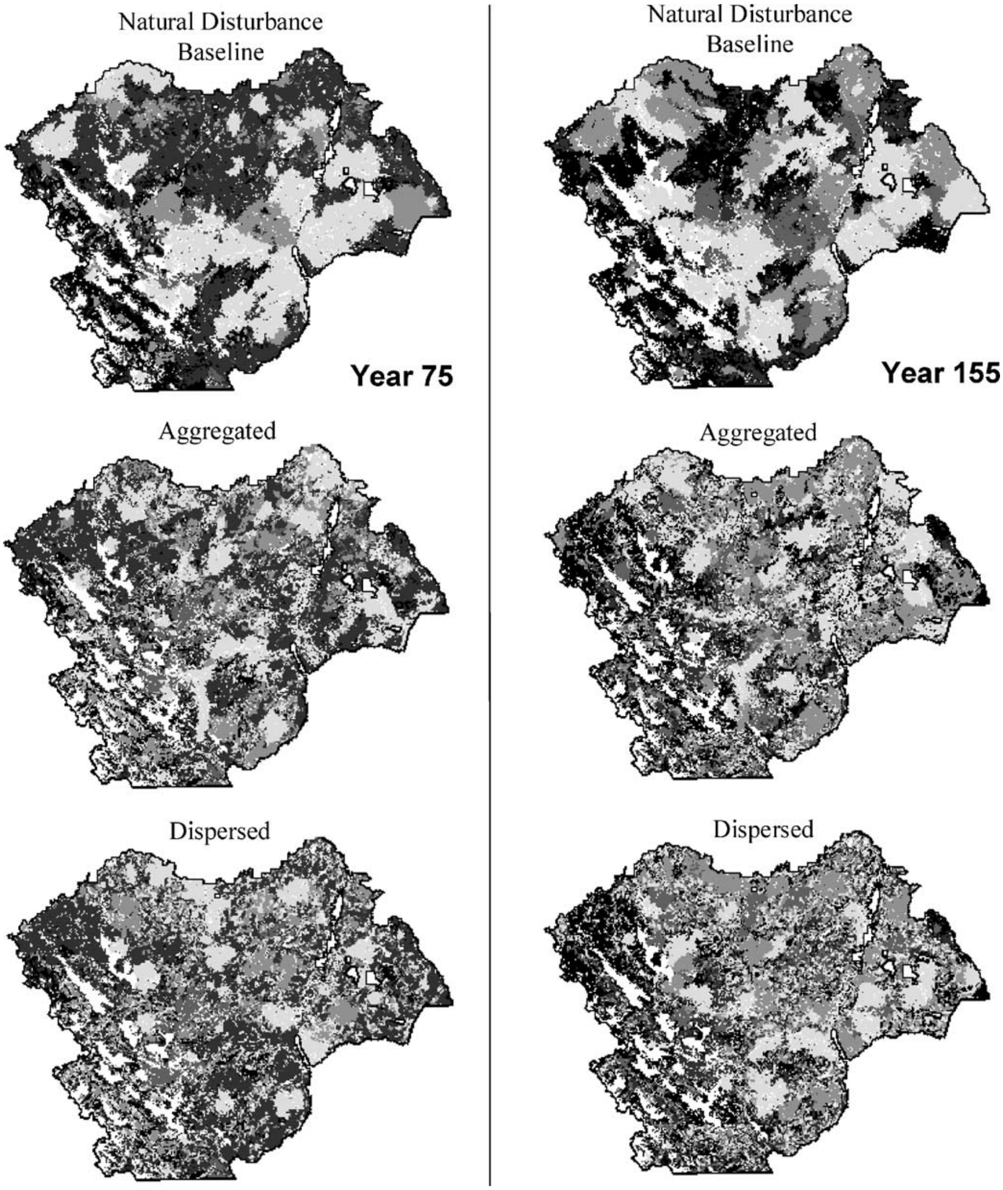

Fig. 14. (*Continued*).

represents a clear advantage over methods where possible visual outcomes are less concretely represented, as these simulated images can be used to evaluate and solicit feedback on possible variants of a given scenario, therefore enabling modifications based on public opinions of proposed alternatives, which would enhance the landscape character resulting from scenario implementation.

5. Discussion

5.1. Application of UBC-FM for the Block 4 case study

The general intent of the case study presented here was to illustrate the application of UBC-FM to assess alternative spatial harvest strategies for Block 4 and to

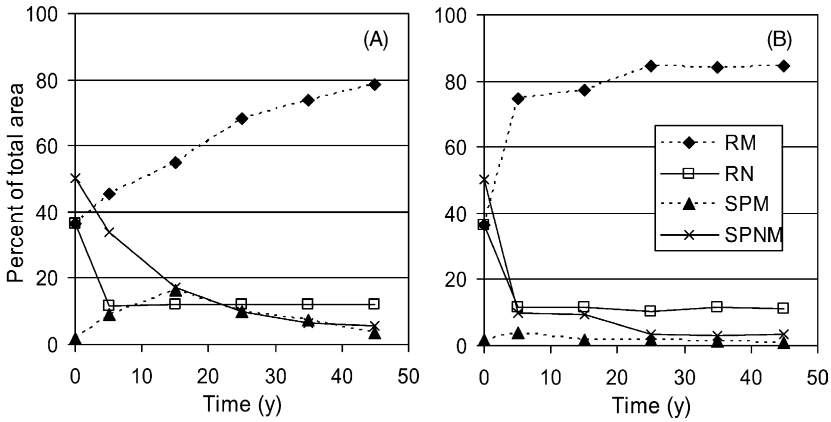

Fig. 15. Recreation opportunity assessment showing the percent of total area in each ROS class for the (A) aggregated and (B) dispersed harvesting scenarios. The ROS classes shown here include Roaded Modified (RM), Roaded Natural (RN), Semi-Primitive Motorized (SPM), and Semi-primitive Non-Motorized (SPNM). A detailed description of the classes is provided in the text. Only the first 50 years of the simulations are shown.

compare them against a natural disturbance baseline. The harvest scenarios were designed to reflect feasible harvest options (dispersed versus aggregated) in the context of a natural disturbance regime. As such, the scenarios were not designed to elicit maximum contrasts between the aggregate and dispersed harvesting methods; this has been the topic of previous work (e.g. Gustafason, 1998; Klenner et al., 2000). As expected, differences between the two harvest scenarios were only observed in indicators that are sensitive to changes in landscape pattern (e.g. road density, gross profit, patch-size distributions, and backcountry condition). In general, the dispersed scenario was less desirable than the aggregated scenario with respect to the amount of active road required, patch-size distributions and short-to-medium term impacts on backcountry recreation opportunities. Since harvest rates were similar and the silvicultural systems applied at the stand-level were identical, long-term patterns in non-spatial indicators including age-class structure, ecosystem C storage, and the density of large snags were indistinguishable between the harvest scenarios. Had different silviculture systems been employed in each scenario, as part of a tactical analysis, for

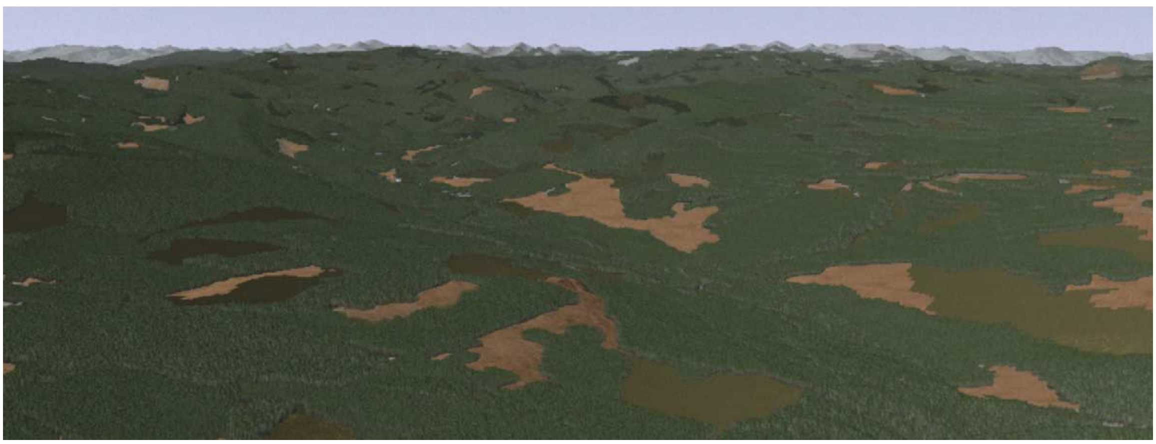

Fig. 16. Aerial oblique visualization of the Highhat Valley within Block 4.

example, larger differences among these indicators would have likely emerged.

The impacts of a natural disturbance regime on indicators were considered from two perspectives. First, each spatial harvest strategy was represented within the context of a superimposed natural disturbance regime (33% of pre-fire suppression rates). Secondly, the harvest scenarios, with natural disturbance rates reduced through fire suppression, were compared to a natural disturbance baseline scenario which was based on estimates of pre-fire-suppression rates.

The incorporation of natural disturbance within the harvest scenarios had a significant influence on landscape patterns (locations, patch sizes and active road networks). This is not surprising since natural disturbance accounted for upwards of 40% of the total area disturbed in each period (see Fig. 10) and since salvage logging was given first priority to meet harvest targets. Overall, the inclusion of natural disturbance caused a general convergence in the landscape patterns (particularly within the non-harvesting land base) towards the patch-size distributions described for each of the NDUs (see Table 1).

The comparison of the harvest scenarios with the natural disturbance baseline yielded both expected and unexpected findings. While it was expected that snag densities and ecosystem C storage would be higher for the natural disturbance baseline, the degree to which they were different and the temporal patterns of change provide a useful reference for the harvest scenarios. In the case of indicators related to landscape pattern, the harvest scenarios led to more fragmented landscapes (as measured by patch-size distributions) relative to the natural disturbance baseline. The patch-size distribution in the aggregated harvest scenario was more similar to the natural disturbance baseline than the dispersed scenario.

One of the more unexpected results was the similarity in the forest age-class structures that developed under the different disturbance regimes. As explained in Section 4.2.2, the higher overall disturbance rates in the natural disturbance baseline scenario were compensated by the fact that the harvest disturbance was focused on older stands. However, because the total area disturbed via natural disturbance was held constant for each period, this convergence is somewhat artificial. In reality, natural disturbance rates tend to fluctuate dramatically from year to year and decade to decade depending on climate conditions, etc. For the purpose of simplification, the rates used in the case study were held constant. The natural disturbance module within FPS-ATLAS is capable of representing a variable (stochastic) disturbance rate. It should be noted that this would typically require a greater number of simulations be completed to determine average long-term patterns in indicators with reasonable estimates of variability.

5.2. Representation of natural disturbance in DSSs

While it is tempting, for the sake of simplicity, to ignore the potential impacts of natural disturbance when developing forest management plans, there is overwhelming evidence that forest management decisions are frequently influenced by natural disturbance events. Whether it be salvage operations following a fire or insect outbreaks, such as the massive mountain pine beetle outbreak presently sweeping through central British Columbia, forest management plans are continually being altered and adjusted in response to natural disturbance. With the onset of climate change, these natural phenomena are likely to increase in frequency. As demonstrated in the Block 4 case study, the inclusion of natural disturbance in a forest planning model can have a significant impact on the outcomes. Moreover, recent literature (Cumming et al., 1998; Gustafason et al., 2000; Klenner et al., 2000; Kurz et al., 2000; Messier et al., 2003) has emphasized the importance of representing the potential effects of natural disturbance within forest planning models. Some specific problems/errors that could result from the exclusion of natural disturbance from a planning model include: (1) an overestimation of the recruitment of old growth (see Klenner et al., 2000), (2) an overestimation of volume available for harvest (particularly problematic in optimization models, e.g. Boyland and Bunnell, 2003), (3) an overestimate of landscape-scale ecosystem C storage, (4) errors in projecting changes in landscape structure (e.g. patch-size distributions), (5) errors in projections of snag and coarse woody debris recruitment and (6) errors in estimating the impacts of management plans on forest age-class structures. In view of these potential sources of uncertainty, it seems risk prone, at best, to exclude the potential impacts of natural disturbance when developing plans for sustainable forest management. Thus, by incorporating natural disturbance regimes within DSSs, we can increase the likelihood of producing plans that are capable of absorbing the effects of natural disturbance.

5.3. Use of a hierarchical structure for an integrated analysis of C&I

To adequately evaluate the tradeoffs that inevitably arise in developing multiple-objective forest management plans, it is necessary to establish sound linkages between indicators of ecosystem function, biodiversity, and social and economic values (Yamasaki et al., 2002). Likewise, the models employed to project the implications of forest management on such diverse sets of indicators must be capable of integrated analyses (e.g. Kangas et al., 2000). However, given the fact that these indicator sets typically span multiple spatial and temporal scales, it is often problematic to represent them within a single model. The use of hierarchical modelling frameworks, in which a series of complementary models are linked either dynamically or through shared databases, provides an effective method for conducting integrated planning analyses (Li et al., 2000; Lamas and Eriksson, 2003; Nelson, 2003a). While the use of shared databases is the simplest approach for linking models, it is not without problems. For instance, when scaling up from the stand to the landscape, the shared database approach can lead to systematic errors in the projection and extrapolation of indicators. Specifically, this type of problem can arise when polygons or discrete stand units, represented within the landscape model, transition from one attribute curve to another (e.g. from a natural condition to a managed condition). While some stand attributes such merchantable volume can easily be reset with stand age, other more continuous attributes such as ecosystem C storage may be subject to significant errors during curve transition. It is possible to minimize such errors by anticipating transition pathways, representing them explicitly in the stand-level model and then building them into the shared database. Alternatively, it may be necessary to create dynamic links between the stand and landscape-level models. Regardless, the hierarchical framework provides an effective system for conducting such analyses.

5.4. Use of visualization in DSSs

While caution must be exercised when displaying visual representations of model output to public groups (to avoid mistaking simulated results for reality), the use of computer generated images represents a powerful tool for delivering complex information to forest stakeholders. Ultimately, investigations of the potential of these technologies to disseminate information to the public and to act as vehicles for evaluation and feedback regarding possible forest management scenarios is critical. This feedback can then be used in an iterating loop between the public and management professionals to refine the preferred set of forest management scenarios to further meet the needs and desires of both groups. For this reason we have used these visualizations in a number of public forums within the context of this project, with the intent of increasing the transparency of the forest management process, simplifying the means by which we communicate complex spatio-temporal concepts and most importantly, sparking an ongoing dialogue aimed at further elucidating our collective valuations of forests and their subsequent management.

6. Conclusions

The multi-resource nature of modern forest management requires the capability to evaluate complex spatio-temporal relationships associated with competing forest values. In developing strategic and tactical management plans, decision makers require DSSs that allow them to assess the potential implications of management alternatives for a range of ecological, economic and social indicators of sustainable forest management. Hierarchical modelling frameworks, in which a series of complementary models are linked either dynamically or through shared databases, represent an effective method for meeting such challenges. While DSSs, invariably based on our limited knowledge of forest ecosystems, do not provide any 'new' information (e.g. Bunnell and Boyland, 2002), they do provide a framework to assess the consequences of management decisions within a system that conforms to our assumptions about ecosystems and are thus useful in a decision-support role. Where possible, natural disturbance regimes should be incorporated into DSSs to facilitate the development of management plans that are robust in the face increasing uncertainty in climate and associated natural disturbance events.

Acknowledgements

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