Forest Ecology and Management 259 (2010) 418–427

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Comparing different forest zoning options for landscape-scale management of the boreal forest: Possible benefits of the TRIAD

Pascal Côté [a,1], Rebecca Tittler [a,*], Christian Messier [a], Daniel D. Kneeshaw [a], Andrew Fall [b], Marie-Josée Fortin [c]

[a] Centre d'étude de la forêt, Université du Québec à Montréal, C.P. 8888, Succ. Centre-Ville Montréal, QC, H3C 3P8, Canada
[b] School of Resource and Environmental Management, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada
[c] Department of Ecology and Evolutionary Biology, University of Toronto, Toronto, ON, M5S 3G5, Canada

ARTICLE INFO

Article history:
Received 16 July 2009
Received in revised form 23 September 2009
Accepted 28 October 2009

Keywords:
Fragmentation
Sustainable forest management
Spatially explicit landscape event simulator (SELES)
TRIAD
Conservation areas
Forest zoning

ABSTRACT

Forest management has been criticised in the last 20 years for its negative impact on the native species, structures and functions of the forest. Of many possible alternatives proposed to minimize these effects, the functional zoning (or TRIAD) approach is gaining popularity in North America. The goal of this approach is to minimize the negative environmental impacts of forestry while maintain timber supply by dividing the forest into three broad land-use zones: (1) conservation, (2) ecosystem management, and (3) wood production. In this study, we used a spatially explicit landscape model to simulate the effects of fire and six different forest management scenarios on a boreal mixedwood forest management unit in central Quebec. The management scenarios examined included the current practices scenario, a scenario proposed by the provincial government, and four TRIAD scenarios varying in the amount of forest allocated to each of the three zones. For each scenario, we examined the harvest volume, percentage old-growth forest or old forest managed to favour old-growth attributes, and effective mesh size of forest patches by 20-year age classes. With more area set aside for conservation and high-retention partial cut harvesting techniques designed to maintain the attributes of old-growth stands, all TRIAD scenarios resulted in higher percentages of stands with old-growth attributes than the current practices scenario and the government proposed scenario, and two of the four TRIAD scenarios also resulted in higher harvest volume over the long term. All forest management scenarios resulted in significantly lower effective mesh size than the fire-only scenario, but this difference was not as pronounced for the four TRIAD scenarios as for the current practice and government proposed scenarios. We conclude that the TRIAD approach has the potential to minimize some of the negative impacts of forestry on the landscape, while maintaining timber supply over the long term.

1. Introduction

Many important ecosystem services provided by forests are altered by human activities (Gonzalez et al., 2005). While deforestation is the main human activity affecting tropical forests nowadays (Sodhi et al., 2004), forest management is the main activity affecting temperate and boreal landscapes (Östlund et al., 1997; Lindenmayer and Franklin, 2002; Burton et al., 2003). In Canada, as elsewhere, inappropriate forest management is thought to be responsible for the widespread simplification of the forest at both the stand and landscape levels and for marked declines in old-growth stands and stands with old-growth attributes, as well as their associated diversity of ecological structures, functions, and species. For this and other reasons, there has been increasing public pressure to develop new and truly sustainable forest management practices that integrate the concerns of all stakeholders while conserving the diversity of native structures, functions, and species, especially those associated with old-growth (Hamersley Chambers and Beckley, 2003). Furthermore, there is social and economic pressure to maintain a viable forest industry.

Two very different broad forest management options have been proposed to address these social, environmental, and economic concerns. The first option aims at satisfying all needs throughout the forest through multiple-use or integrated forest management (McArdle, 1953; Franklin, 1989). A contrasting option suggests dividing the forest into a number of zones for different, but

* Corresponding author. Tel.: +1 514 987 3000x4866; fax: +1 514 987 4647.
E-mail address: rtittler@gmail.com (R. Tittler).
[1] Present address: Observatoire d'oiseaux de Tadoussac, Corporation Explos-Nature 302, rue de la Rivière, Les Bergeronnes, QC, G0T 1G0, Canada.

0378-1127/$ – see front matter
doi:10.1016/j.foreco.2009.10.038

complementary uses (Seymour and Hunter, 1999; MacLean et al., 2008). Although the debate is still ongoing regarding the advantages and disadvantages of the two options, and the appropriateness of the choice may be somewhat case-specific, the zoning option has been gaining in general popularity (Zhang, 2005). According to some researchers, zoning of the landscape is advantageous because it provides clear, specific, and effective management directions (Haas et al., 1987) and reduces conflicts between stakeholders by establishing a hierarchical order of uses within each zone (Walther, 1986; Andison, 2003; Zhang, 2005). Moreover, zoning can help to concentrate harvesting activities in the landscape, thus minimizing anthropogenic fragmentation and the extent of the road system and optimizing economic benefits (Swallow et al., 1990; Binkley, 1997; Beese et al., 2003).

One of the most cited zoning strategies proposed in North America is the TRIAD (or three zone) approach proposed by Seymour and Hunter (1992), in which three different zones are established with three different sets of objectives and priorities. To maintain the ecological integrity of the forest, one zone is usually dedicated to conservation, as a network of reserves. To counterbalance the decline in wood available for harvest in the conservation zone, a wood production zone has been proposed (Seymour and Hunter, 1992; Hunter and Calhoun, 1996; Messier et al., 2003; MacLean et al., 2008). The third zone is devoted to ecosystem management (sensu Grumbine, 1994). In this zone, management strategies are designed to emulate natural disturbance (Landres et al., 1999) such as fire (Hunter, 1993). Such a ''coarse-filter'' approach, termed ''natural disturbance—based management'' is assumed to benefit native species by providing conditions similar to those to which they are adapted (Hauffler et al., 1996; Landres et al., 1999), and also to maximize the conservation of the natural structural and functional diversity of the forest. In the ecosystem management zone, various harvesting techniques may also be applied to emulate old-growth attributes or ''old-growthness'' (sensu Bauhus et al., 2009), i.e., to create stands with the structural and functional diversity of old-growth stands by maintaining trees of different ages (including those over 100 or 200 years old), different types of deadwood, and more late-successional species. Potential loss of available harvest resulting from application of these techniques in the ecosystem management zone may also be counterbalanced by gains in the wood production zone. Higher costs associated with the application of these techniques in the ecosystem management zone may also be counterbalanced by reduced transportation costs in the wood production zone, which should be located in close proximity to the mills.

There are several examples of real-world applications of TRIAD forest management. In 1994, the TRIAD approach was applied in Maine by Champion International Corporation, a large industrial landowner (Redelsheimer, 1996). By the end of the 1990s, the project had been abandoned due to a lack of interest from the company, but it left a legacy of large protected areas that are still in place today. In the early 2000s, Riverside Forest Products planned to apply the TRIAD zoning concept to a 145,000 ha Tree Farm License (TFL 49) near Kelowna, British Columbia (D'Eon et al., 2004), but the zoning plan was abandoned in 2004, when the company was bought out by Tolko Industries. Currently, the TRIAD approach is being applied on an 890,000 ha forest management unit in central Quebec (Messier et al., in press). After a five-year planning phase, the approach was implemented beginning in 2008.

Unfortunately, these real-world applications of the TRIAD approach were either abandoned too soon or have not been in place long enough to allow for a rigorous evaluation of the long-term economic and ecological impacts of the various zoning strategies. Several modelling studies have attempted to fill this gap (Krcmar et al., 2003; Montigny and MacLean, 2006), but results differ greatly depending on the productivity of the system studied. Furthermore, although these studies may help to define the trade-off between forest values, neither one examines any spatial results such as landscape configuration. This may be problematic within the paradigm of natural disturbance—based management; to emulate a natural disturbance regime or to judge how well proposed management strategies emulate a natural disturbance regime, we must examine not only landscape composition (amounts of different stand types of interest), but also landscape configuration (the size and spatial arrangement of stands).

The ability of the TRIAD forest management approach to emulate landscape patterns created by the natural disturbance regime and maintain old-growth attributes and a viable forestry industry may vary depending on the proportion of forest allocated to each of the three zones. Seymour and Hunter (1999) specified only that an equal three-way division may not be optimal. Although the optimal proportion of the forest allocated to each of the three zones will likely vary somewhat from case to case, if the TRIAD approach is to be applied, we must at least gain some understanding of the effects of varying these proportions.

Here we use a spatially explicit landscape model (Fall et al., 2004) to examine how various proportions of conservation, ecosystem management, and wood production zones affect the landscape patterns and age-class structures of the forest. Specifically, we compare the current management scenario, a scenario proposed by the provincial government, and four TRIAD forest management scenarios to a natural disturbance-only scenario to address the following questions: (1) How do the different management scenarios compare to each other and to a natural disturbance-only scenario in terms of the proportion of old-growth forest maintained in the landscape? (2) How do they compare in terms of landscape configuration? (3) How do the different management scenarios compare in terms of harvest volume? We use amount of forest with old-growth attributes and landscape configuration (spatially explicit) for comparison between the different scenarios because these are generally negatively affected by management and may play an important role in the conservation of native ecological structures, functions, and species [e.g., Drapeau et al., 2003 and Boudreault et al., 2002 on the importance of old-growth, and Schmidt and Roland, 2006 on the effects of landscape structure (but also see Fahrig, 2003)]. We use harvest volume as a way to compare the economic viability of the various scenarios. We use fire as the natural disturbance to emulate because it is the dominant natural disturbance in our study area.

2. Methods

2.1. Study area

The study area is a forested landscape of approximately 390,000 ha in the upper Mauricie region in south-central Quebec (Fig. 1). It contains two boreal forest ecotypes: balsam fir-yellow birch and balsam fir-white birch. The landscape is dominated by white birch (*Betula papyrifera* Marsh), black spruce (*Picea mariana* Mill.), jack pine (*Pinus banksiana* Lamb.), and trembling aspen (*Populus tremuloides* Michx.).

Fire is the dominant natural disturbance agent in this area. Most fires are small (less than 150 ha), but large infrequent fires (10,000 ha or more) are responsible for more than 60% of the area burned. Although spruce budworm (*Choristoneura fumiferana*) outbreaks and wind throw also affect the forest, fire was the only natural disturbance simulated in the scenarios described below.

As elsewhere, old-growth stands in the area are characterized by gap dynamics, with a diversity of species and age-classes

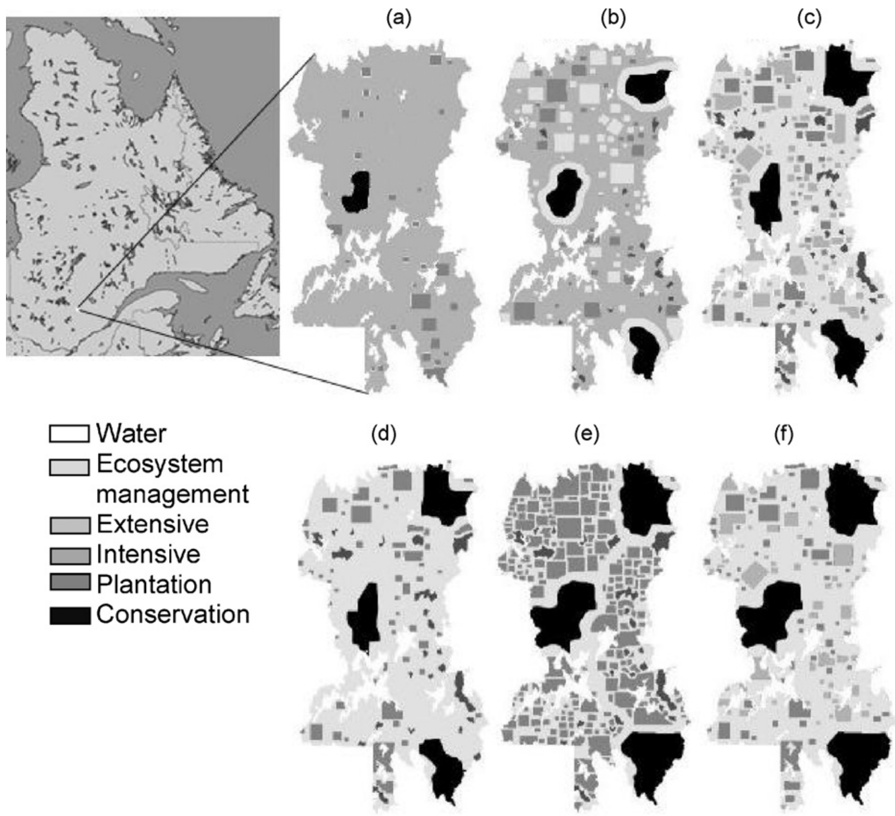

Fig. 1. Location of the study area in Quebec, with the spatial allocation of the zones for each management scenarios: (a) Status Quo, (b) Government Proposed, (c) TRIAD 12% Extensive, (d) TRIAD 12%, (e) TRIAD 20%, (f) TRIAD 20% Extensive.

represented (Wirth et al., 2009). In these stands, pioneer species like aspen are no longer dominants, and late-successional or shade tolerant species like white spruce (*Picea glauca*) and balsam fir (*Abies balsamea*) reach their maximum longevity (100–200 years or more). These stands are also rich in herbaceous plants, fungi, and lichens, and provide habitat for a diversity of insect, mammalian, and avian species, including large standing deadwood and logs. Most of all, these stands are characterized by heterogeneity in terms of species composition and distribution, spatial structure, and function.

Since the mid-19th century, the main disturbance in the region has been commercial forestry (Fall et al., 2004). The current forestry regime involves clearcuts of up to 150 ha in size on a rotation of 100 years or less. Regeneration is mainly natural, although some planting is done when natural regeneration is deemed insufficient. Manual brushing and pre-commercial thinning are the two most important silvicultural treatments.

Although the current forestry regime does not maintain old-growth attributes in managed stands, there has been some research into techniques that could maintain these attributes (e.g., Bauhus et al., 2009). These techniques include high-retention partial cutting (>50–75% retention) that leaves a diversity of age-classes and structure in old stands, including various types of deadwood.

The initial raster data layers were based on data from SIFORT, the third decadal forest inventory database of Quebec (Pelletier et al., 2007). With a resolution of 50 × 50 m, these raster layers represented the main biotic and abiotic characteristics of the forest environment (age of dominant and secondary tree species, drainage type, site type, slope, soil type, site index and dominant tree species, and location of plantations, roads, and railways).

2.2. Spatially explicit landscape disturbance model

We used the Vermillon Landscape Model (VLM) (James et al., 2007) developed in SELES (Spatially Explicit Landscape Event Simulator) (Fall and Fall, 2001). The SELES language is used to specify key processes or sub-models, which are then executed in a discrete-event simulation. We built three dynamic sub-models representing aging, fire, and management processes. In keeping with the resolution of the SIFORT data used as the basis for the model, the spatial resolution (grain) of the model was 50 × 50 m. The spatial extent was the entire study area (390,000 ha), and the time-step was one year.

2.2.1. Aging sub-model

The aging sub-model was directly influenced by the disturbance regimes. Thus, disturbance (fire or harvesting) reset stand age to zero and aging increased stand age. Stand age did not increase past 300 years because the individual trees of the area do not generally live longer than this, and we assumed stands older than 300 years were in a gap-phase dynamic condition (here referred as "300+ years"). For a more detailed description of the aging sub-model, including sensitivity analysis and verification, see James et al. (2007), Didion et al. (2007), and Fall et al. (2004).

2.2.2. Natural disturbance (fire) sub-model

The empirical landscape fire model (Van Wagner, 1978) was based on historical information in the region and driven by fire cycle and mean fire size parameters (James et al., 2007). Each year, the number of fires ignited was selected from a negative exponential distribution. For each fire, the ignition cell was chosen randomly, and the target size was also selected from a negative exponential distribution. Fires spread randomly in all directions until the target size was reached or until no further forest was available. Fire ignition and spread were thus independent of weather, terrain, stand age, etc (as justified by James et al., 2007). With this random-spread model, the patches produced by the fires were irregular in shape, similar to the landscape patterns generally created by real fires (e.g., Johnson et al., 1998). For a more detailed description of the fire sub-model, including sensitivity analysis and verification, see James et al. (2007), Didion et al. (2007), and Fall et al. (2004). To simplify the comparison between scenarios, this sub-model was only applied in the Fire scenario (where no logging was simulated) and in the conservation zones of the management scenarios; see Section 2.2.3 for details.

2.2.3. Zoning and forest management sub-model

Forest management was modelled based on the spatial allocation of three zones: (1) the conservation zone, with no logging; (2) the ecosystem management zone, where high-retention (>50%) partial cutting and clearcuts with 5% retention were modelled; and (3) the wood production zone, which was subdivided into three forest management sub-zones (3i) the extensive silviculture sub-zone, where the current forestry practice of small clearcuts distributed over the landscape was modelled; (3ii) the intensive silviculture sub-zone, where planting and various silvicultural treatments were modelled; and (3iii) the plantation sub-zone, with fast-growing hybrid larch and poplar.

The main difference between these zones was the annual harvest level. For the conservation zone, the level was set to 0%. For the ecosystem management zone, it was set to an effective rate of 0.8% of the productive forest area per year, out of which 0.4% was attributed to clearcutting and a volume equivalent to a rate of 0.4% for partial cutting. For the extensive silviculture sub-zone, it was set to 1%. For the intensive silviculture sub-zone, it was set to 1.2%, and for the plantation sub-zone, to a conservative 2%, assuming that increasing silvicultural intensity leads to higher yields and shorter rotations (see Paquette and Messier, 2009 for examples of typical gains in yield attributable to various silvicultural practices).

Since the goal of this study was not to do a detailed timber supply analysis, we used fixed harvest rates (fixed in time) based on averages for these management systems in this type of forest. We applied an area-based target because we were interested in comparing yield outputs among different scenarios; such a target provided a common currency for comparison [fire, harvest, and conservation areas were all modelled using area, as in Didion et al. (2007), James et al. (2007), and Fall et al. (2004)].

For the ecosystem management zone, half of the volume harvested came from clearcuts and the other half from high-retention partial cuts. Clearcuts were 5–60 ha in size with 5% retention of live trees, similarly modelled in the extensive management zone. Partial cuts were applied over a larger area at lower volume recovery. We assumed that these high-retention partial cuts emulated the natural gap dynamics of old-growth stands and so caused no change in stand age or landscape structure. We also assumed that they could be accessed from the existing road network, so roads were not constructed just to access a partial cut block (note that traffic volume was not modelled). Hence partial cutting was not modelled explicitly, but the longer rotation of the ecosystem management zone ensured adequate availability of stands for partial cut treatment and minimum re-entry intervals. The average volume harvested from the clearcuts in the ecosystem management zone was used as an estimate of the contribution from partial cutting. The extent to which these assumptions are justified is discussed in Section 4.1 below.

The annual yield rate modelled in the wood production zone was double that elsewhere because of the assumed benefits of the various silviculture treatments (see Paquette and Messier, 2009 for a review). In the plantation sub-zone, fast-growing species were assumed to be planted after the completion of the first rotation. The minimum harvest age in the plantations was divided into three groups (20, 30, or 40 years) based on the site index (height in metres at 50 years). Yield curves typical for fast-growing species were also specified following these harvest age groups (Pothier and Savard, 1998).

Although we applied the fire model with no harvesting to the conservation zone in all scenarios, we only modelled harvesting in the management zones. We did not model fire outside the conservation zone (other than in the fire-only scenario) because we were interested in comparing the different management strategies. As such, we could be criticized for assuming complete fire suppression in the management zones, which would not be realistic or even advisable. Natural processes such as natural disturbance are particularly integral to effective ecosystem management, as defined by Grumbine (1994). The strength of the modelling approach is that it allows for some simplifications so that specific factor(s) of interest can be examined. In this case, the effect of fire in the management zones is not the issue of interest; rather, we hope to be able to compare the structure, composition, and harvest volumes of the various management scenarios. Introducing a stochastic factor such as fires, and fire suppression, could mask differences between these strategies (Fall et al., 2004).

2.3. Zone location

We established the TRIAD zoning system as proposed by Seymour and Hunter (1999), setting conservation areas aside first, followed by wood production areas. Everything not designated as conservation or wood production was put in the ecosystem management zone. Within the wood production zone, we first set aside areas for fast-growing plantations, then for intensive management, then extensive management.

2.3.1. Selection of the conservation zone

Conservation location was based on the heterogeneity method developed by Montigny and MacLean (2005), but adapted to the geographic information available from the forest inventory. The degree of heterogeneity per cell was derived from the soil, drainage, and site type (vegetation community) layer data and classified in 10 classes. Each variable had an equivalent weight in determining the level of heterogeneity. The raster layers created were overlaid and a neighbourhood analysis was used to produce raster grids of 2500 × 2500 m. With the new raster layer, we identified the areas with the highest heterogeneity as those most suited for conservation, assuming a correlation between this heterogeneity and species richness and diversity (e.g., Nichols et al., 1998).

Representation of ecological types (Austin and Margules, 1986) was the final criterion to establish the conservation areas. The number of conservation areas was limited to obtain larger areas and thus increase the conservation potential of each area. Three conservation areas of similar size were designed along a south–north gradient for five of the six scenarios. Due to the low percentage of area assigned to conservation in the Status Quo scenario (see below), only one conservation area was identified (Fig. 1).

Based on the biosphere reserve model (Gregg et al., 1989), reserves were surrounded by buffers of ecosystem management zoning and, in some cases, connected by corridors. If the majority of the landscape was under ecosystem management, a buffer area of at least 500 m in width was applied. Otherwise, buffers and corridors between conservation areas were 2500 m wide.

2.3.2. Selection of the plantation sub-zone

We used site index values (height in metres at age 50 years) to decide which areas were best suited to the plantation of

Table 1
Percentage of land allocated to each management scenario (see text for scenario descriptions).

Management scenario	Conservation zone	Ecosystem management zone	Wood production zone		
			Extensive	Intensive	Plantation
Status Quo	2	0	93	5	0
Government Proposed	8	20	64	7	1
TRIAD 12% Extensive	12	60	14	10	4
TRIAD 12%	12	74	0	10	4
TRIAD 20% Extensive	20	60	10	10	0
TRIAD 20%	20	40	0	36	4

fast-growing tree species (Norfolk and Erdle, 2005). We selected cells with a site index of over 18 m first, followed by those with a site value of over 15 m. We almost never selected cells with a site index of less than 15 m. One quarter of the plantations was 100–500 ha in size, while the rest were 500–5000 ha.

2.3.3. Selection of the intensive and extensive silviculture sub-zones

To locate the intensive and extensive silviculture sub-zones, we randomly selected 150 of the polygons from the soil layer, then added soil polygons to these at random until we reached the desired percentage of the total area for each sub-zone. We used the soil layer simply because the soil polygons were the largest so using them allowed us to reach our desired percentages more rapidly.

2.3.4. Selection of the ecosystem management zone

Any land not designated for conservation or wood production was assigned to the ecosystem management zone.

2.4. Scenario parameters

The specific percentages of land allocated to the different zones varied among scenarios (Table 1); hereafter, we denote the different scenarios based on their various allocations (Status Quo, Government Proposed, TRIAD 12% Extensive, TRIAD 12%, TRIAD 20% Extensive and TRIAD 20%). In the Status Quo scenario (representing the current management regime), 2% of the area was zoned for conservation and none for ecosystem management. The Government Proposed scenario (that proposed by the provincial government) had three zones, with extensive, intensive, and fast-growing plantations in the wood production zone and 8% conservation. All the TRIAD scenarios had wood production, conservation, and ecosystem management zones. In these scenarios, the conservation zone either accounted for 12% or 20% of the forest: 12% because this is the target value recommended by many international commissions and non-governmental organizations (McNeely and Miller, 1984; WCED, 1987; WRI, 1994), and 20% because this is the proportion called for by some scientists and politicians (Senate subcommittee on the boreal forest, 1999). The four TRIAD scenarios also differed in whether or not they had intensive, extensive, and plantation management in the wood production zone. The TRIAD 12% Extensive scenario had all three types of management in the wood production zone, while the TRIAD 12% scenario had only intensive management and plantations (both had 12% conservation) (Messier and Kneeshaw, 1999). Social issues were of major concern in allocating fast-growing plantations. These plantations did not exceed 4% of the total area in any of the scenarios because higher percentages would likely not be socially acceptable on public land (BAPE, 1997). Similarly, the TRIAD 20% Extensive scenario had extensive and intensive management but no plantations in the wood production zone, while the TRIAD 20% scenario had intensive management and plantations but no extensive management (both had 20% conservation).

2.5. Scenario comparison

A coarse-filter approach (Hauffler et al., 1996; Landres et al., 1999) was used to determine the effect of the various management scenarios on the ecological integrity of the forest. We first compared the management scenarios to a fire-only (Fire) scenario to determine whether or not these scenarios maintained forest conditions and landscape patterns within the modelled range of natural variability (Kneeshaw et al., 2000; Wong and Iverson, 2004; Didion et al., 2007), at least when fire was not included in the managed zones of the management scenarios. We then compared management scenarios among themselves.

We selected three ecological indices to quantify the degree of variation: two measures of old-growth attributes (% forest area with stands over 100 and over 200 years old, either unmanaged or subjected to high-retention partial cutting designed to maintain old-growth attributes) and a landscape index related to spatial configuration (effective mesh size of forest patch by 20-year age-classes). Stands were said to have old-growth attributes if they had not been hit by a major disturbance (fire or clearcut) within the last 100 or 200 years. We assumed that minor disturbances, such as high-retention partial cutting designed to maintain old-growth attributes, did not affect the age of the stand itself; such stands would still be expected to show the characteristics of "old-growthness" (sensu Bauhus et al., 2009), with a diversity of age-classes represented, as well as many late-successional species and a diversity of deadwood). We examined both measures of old-growth attributes (stands >100 years and >200 years) because of varying definitions in the literature (Kneeshaw and Gauthier, 2003; Wirth et al., 2009).

Effective mesh size (Jaeger, 2000) is the expected number of cells within the same patch as a point selected at random on the landscape. It is calculated as the probability (P) that two points selected at random on a landscape will be in the same patch, multiplied by the size of the landscape. It therefore varies from 0 ($P = 0$, no other points in the same patch) to the size of the landscape ($P = 1$, all other points in the same patch), and is expressed in area units (here, in hectares). Smaller values therefore indicate more fragmentation. In contrast with mean patch size (McGarigal and Marks, 1995), it is area-proportionately additive, making it less sensitive to very small patches.

2.6. Economic indicator

We used harvest volume to assess the economic aspect of each scenario, as this is a key measure of productive capacity and the basis for timber supply assessments. We estimated harvest volumes from regression analysis of plot data, stratified by site productivity, bioclimatic region, species composition, and stand origin (S. Yamasaki, pers. comm.). Often used in studies dealing with multi-objective strategies or testing forest management alternatives (Maness and Farrell, 2004), harvest volume is included in the list of indicators developed in the Montreal Process and supported by the Canadian Council of Forest Ministers (CCFM, 1997).

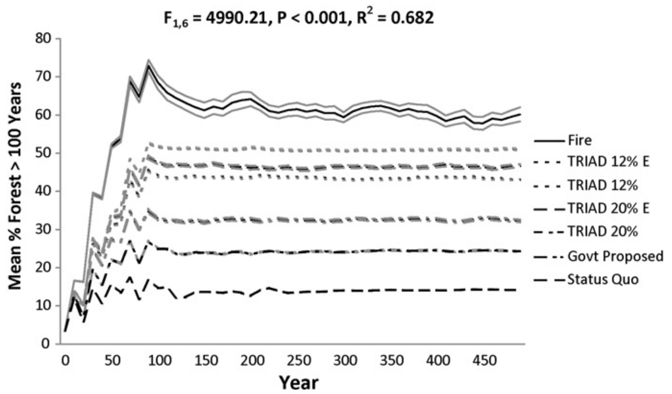

Fig. 2. Mean ± standard errors (grey lines) of percent forest with the attributes of stands over 100 years old over 490 years for the six different management scenarios and the fire-only scenario. n = 40 simulations per scenario. Where grey lines do not appear, standard errors are very small.

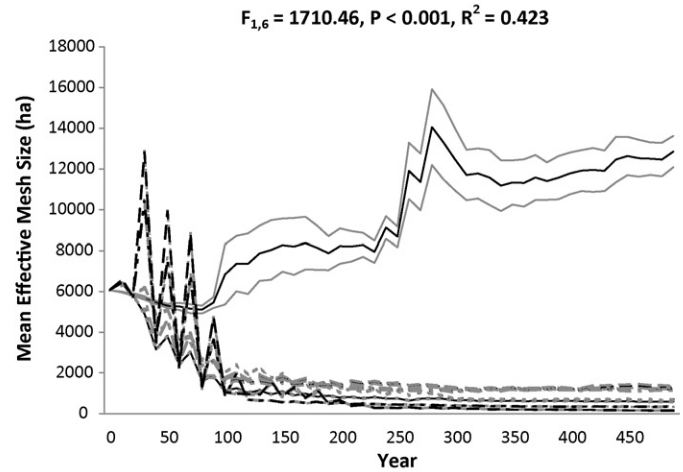

Fig. 4. Mean ± standard errors (grey lines) of effective mesh size of patches defined as 20-year age-classes over 490 years for the six different management scenarios and the fire-only scenario. n = 40 simulations per scenario. Where grey lines do not appear, standard errors are very small.

2.7. Scenarios

We ran each of the seven scenarios 40 times for 490 years and analysed the mean and standard errors of all metrics. Although we present model results for all 490 years, we also examine results after 150 years, since most management plans do not exceed this temporal scale. ANOVAs were performed using SPSS version 16.0.

3. Results

3.1. Ecological indices

As all scenarios were based on the same set of initial landscape conditions, it took some time for differences to become apparent (Figs. 2–4). The model reached equilibrium in all cases in terms of all the ecological indices considered, although this took longer in some cases than in others. In terms of percent forest with the attributes of stands over 100 years old, equilibrium was reached after 90 years of simulation (Fig. 2), but in terms of percent forest with the attributes of stands over 200 years, this took much longer (about 280 years; Fig. 3). Because of the initial age structure of the forest as represented in the inventory, it took 80 years for forests with the attributes of stands over 200 years to appear in any of the scenarios. In terms of effective mesh size, no equilibrium was attained in the fire scenario, and it took about 300 years for the model to reach equilibrium in the management scenarios (Fig. 4).

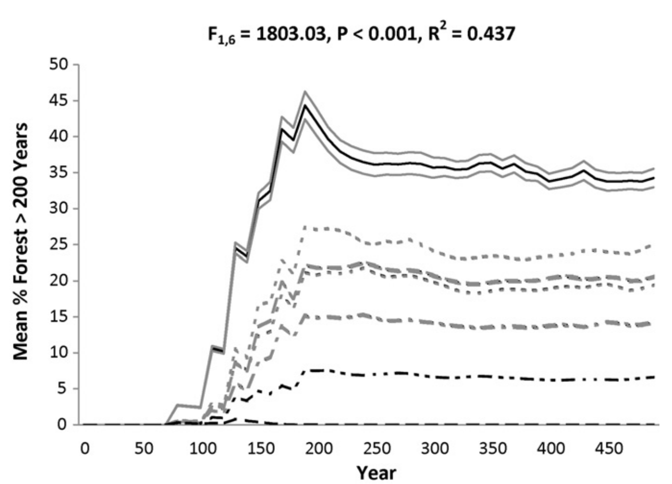

Fig. 3. Mean ± standard errors (grey lines) of percent forest with the attributes of stands over 200 years old over 490 years for the six different management scenarios and the fire-only scenario. n = 40 simulations per scenario. Where grey lines do not appear, standard errors are very small.

The percentage of forest with the attributes of stands over 100 years was higher at equilibrium than initially for all scenarios (Fig. 2), and the same was true in terms of forest with the attributes of stands over 200 years for all but the Status Quo scenario (Fig. 3). However, effective mesh size declined over time for the management scenarios, while they increased for the fire scenario (Fig. 4).

Overall, there was much more variation in the results from the fire scenario than from any of the management scenarios, and results differed significantly from those of the management scenarios in terms of all ecological indices examined (Figs. 2–4). The fire scenario resulted in significantly higher percentages of forest with the attributes of stands over 100 and 200 years and significantly higher effective mesh size than any of the management scenarios (Figs. 2–4). In the fire scenario, the drop in forest with the attributes of stands over 200 years old between years 150 and 200 is mostly related to rate of fire interacting with the initial age structure, and the time to reach quasi-equilibrium. That is, the area of forest less than 200 years old ages and becomes greater than 200 years old faster than fires burn it, but over a couple of fire cycles the forest reaches a quasi-steady state (Fig. 4).

For the most part, results of the four TRIAD scenarios were closer to those of the Fire scenario than were results of the Government Proposed and Status Quo scenarios (Figs. 2–4). Among management scenarios, the TRIAD 12% scenario resulted in the highest percentage of forest with the attributes of stands over 100 and 200 years, followed by the TRIAD 20% Extensive, TRIAD 12% Extensive, and TRIAD 20% scenarios (Figs. 2 and 3). The Government Proposed scenario came next, and the Status Quo scenario resulted in the lowest percentages, not much higher than the initial percentages (year 0 in the model) (Figs. 2 and 3). After 150 years of simulation, the TRIAD 12% scenario also resulted in the highest effective mesh size of all the management scenarios, closely followed by the TRIAD 20% Extensive and TRIAD 20% scenarios, then the TRIAD 12% Extensive scenario. The Status Quo scenario came next, and the Government Proposed scenario

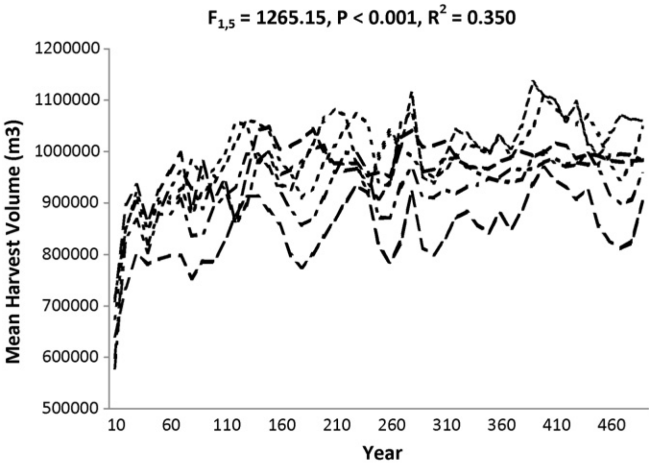

Fig. 5. Mean ± standard errors (grey lines) of harvest volume over 490 years for the six different management scenarios. $n = 40$ simulations. Where grey lines do not appear, standard errors are very small.

resulted in the lowest effective mesh size (Fig. 4). Although differences among management scenarios seem small compared to the differences between the Fire and the management scenarios (Figs. 2–4), ANOVAs are statistically significant, being characterized by little variability around the mean as a result of the models being run so many times (40 times for each scenario).

In general, the amount of forest with old-growth attributes resulting from the management scenarios increased with the amount of ecosystem management, while effective mesh size increased with the amount of conservation. After 490 years of simulation, the Spearman's rank correlation (r_s) between mean percentage of forest with the attributes of stands older than 100 years and percentage under ecosystem management was highly significant ($r_s = 0.986$, $p < 0.001$, $n = 6$), as it was between percentage of forest over with the attributes of stands over 200 years old and percentage under ecosystem management ($r_s = 0.986$, $p < 0.001$, $n = 6$). Effective mesh size was not significantly correlated with percentage of ecosystem management ($r_s = 0.638$, $p = 0.173$, $n = 6$). However, it was highly positively correlated with percentage conservation ($r_s = 0.971$, $p = 0.001$, $n = 6$).

3.2. Economic index

In terms of harvest volume, the model reached a quasi-equilibrium state after about 100 years of simulation (Fig. 5). It never reached a more stable equilibrium because we measured it in terms of area (i.e., we simulated harvesting a constant area per year). When harvesting a constant area per year, harvest volumes vary over time as stands of different productivity age through the system. If a volume-based target had been used (i.e., we had simulated harvesting the same volume per year), then the area harvested each step would have varied through time for the same reason. Therefore, there is no reason to believe that the harvest volume would have reached a more stable equilibrium had the model been run for longer.

Two TRIAD scenarios resulted in high mean harvest volumes over the long term. For the first 90 years of simulation, harvest volume was highest for the Status Quo scenario, but when we examined mean harvest volume per year over the whole first 150 years of simulation, the TRIAD 12% Extensive and TRIAD 12% scenarios resulted in harvest volumes comparable if not higher than those of the Status Quo (Fig. 6a). When we looked at the entire 490 years of simulation, these two scenarios resulted in significantly higher mean harvest volumes per year than the Status Quo scenario (Fig. 6b).

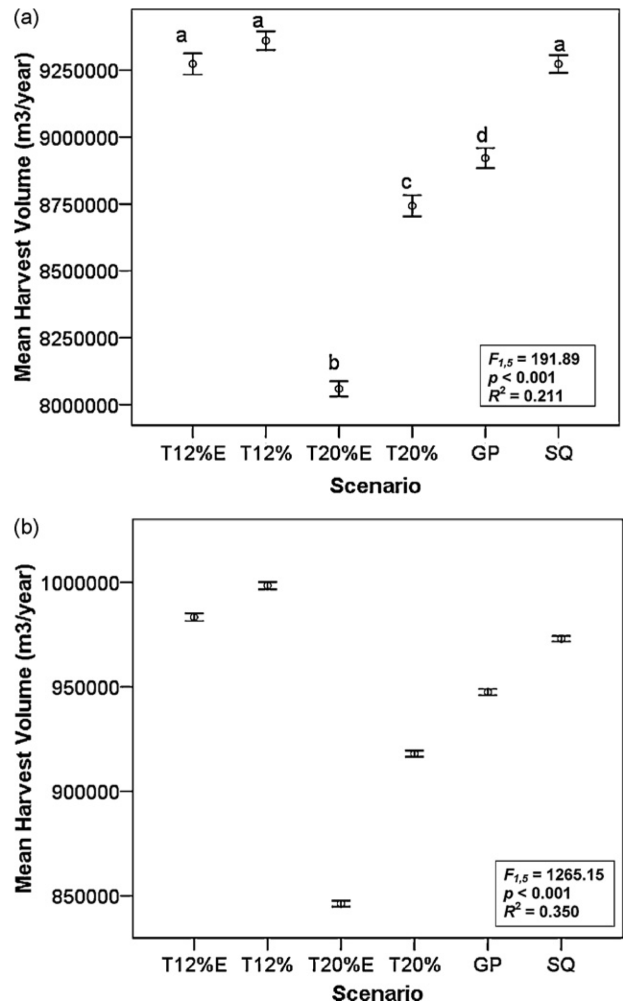

Fig. 6. Mean ± standard error of harvest volume per year over (a) the first 150 and (b) all 490 years of simulation for six different management scenarios. $n = 40$ for all scenarios. Homogenous subgroups are indicated for (a); for (b), all differences were significant at $\alpha = 0.05$. For the scenarios, T = TRIAD, E = Extensive, GP = Government Proposed, and SQ = Status Quo.

4. Discussion

4.1. Maintaining stands with old-growth attributes

Although none of the management scenarios even approached the levels of stands with old-growth attributes reached by the Fire scenario, the percentage of these stands increased over time in all but the Status Quo scenario. This is not surprising considering that a larger percentage of the forest was set aside for conservation in all other scenarios. Recall that the only disturbance modelled in the conservation zone was fire, and fire cycles were much longer than logging rotations, thus resulting in more old forest.

The TRIAD 12% scenario resulted in the highest percentages of stands with old-growth attributes, in part because of our assumption that high-retention partial cuts could maintain these attributes in the ecosystem management zone. There was a highly positive correlation between percentage stands with old-growth attributes and percentage ecosystem management because half the harvest volume from the ecosystem management zone came from high-retention partial cuts assumed to maintain old-growth attributes.

In reality, the extent to which partial cutting in old stands can maintain old-growth attributes is somewhat dependent on the levels of retention maintained in partial cuts. It is fairly clear that partial cuts with relatively low levels of retention are unlikely to emulate old-growth attributes (e.g., CCFM, 1997; Deal, 2001; Deal and Tappeiner, 2002). However, several studies indicate that partial cuts with relatively high levels of retention in mature or old stands can maintain old-growth attributes. For example, Stone et al. (2008) found that partial cuts with 65–75% retention retained much of the lichen biomass of old-growth balsam fir stands in Quebec's Gaspe Peninsula. Carey (2003) indicates that certain types of high-retention partial cuts may encourage the development of structural diversity characteristic of old-growth forests. Deal (2001) and Deal and Tappeiner (2002) found no difference in plant species richness and a high similarity in plant community structure between high-retention (>50%) partial cut and uncut stands of varying ages in coastal Alaska conifer stands. In the mixedwood forests of La Mauricie, Quebec, Archambault et al. (2009) found no difference in regeneration density and stocking between unharvested stands and diameter-limit cuts (approximately 65% retention) 50 years after harvesting. Thus, although research remains to be done in this area, high-retention partial cuts may emulate some old-growth attributes, particularly if large trees and snags are maintained (Archambault et al., 2009). Whether or not it is reasonable to assume that a harvest level of 0.4% per year can be supported by such high-retention partial cuts without building more roads is another issue that needs to be investigated. Further research should also investigate the ecological effect of the necessary increase in traffic volume and associated pollution required to access these partial cuts on the existing roads and the increased extraction costs associated with high-retention partial cutting.

4.2. Emulating the natural landscape structure

Contrary to the old-growth results, conditions worsened over time in all management scenarios in terms of all landscape indices examined. Patches became smaller and more numerous in all management scenarios, but larger and less numerous in the Fire scenario (data not shown). The Fire scenario results are not surprising considering that initial landscape conditions were based on a logged landscape; we would expect the landscape to return to a more natural state over time if logging was stopped, as effectively occurred in this scenario. However, the results from the management scenarios are not necessarily as expected. We would at least expect little change in the Status Quo scenario if this scenario effectively emulated the management regime that created the initial landscape conditions. In fact, the Status Quo scenario resulted in the greatest changes in landscape structure. This is likely due to changes in provincial policy in the late 1990s. Passed in 1996, the *Quebec Regulation respecting the standards of forest management for forests in the domain of the state* changed the size distribution of permitted cutblocks, putting much more of an emphasis on relatively small cutblocks (<=50 ha in this area) and limiting the maximum cutblock size to 150 ha. The current landscape, on which the initial conditions of the model are based, is still a reflection of the pre-1996 regulations, which allowed for much larger cutblocks. It is unclear exactly how long these "legacy effects" last, but they likely no longer have an effect once the model has reached equilibrium.

Not surprisingly, results strongly imply that effective mesh size was negatively affected by logging. This is supported not only by the fact that effective mesh size was much higher in the fire-only scenario than in any of the management scenarios, but also by the strong positive correlation between effective mesh size and percent of area set aside for conservation in the management scenarios. Since effective mesh size is highly positively correlated with mean patch size, this implies that management as modelled reduces patch size.

The Fire scenario was characterized by large variability in terms of all measures. This indicates a "natural" heterogeneity of landscape structure and composition at the landscape-scale. This heterogeneity is partly recreated in the conservation zone, but is largely excluded from the other zones, as indicated by the general lack of variability in the management scenarios. This is clearly due to the fact that fire was not modelled in the managed zones; inclusion of fire in these zones would have resulted in increases in variability (e.g., Didion et al., 2007).

Further research is also necessary to help formulate management recommendations as to cutblock size and spatial arrangement. As is, the results seem to suggest that cutblock sizes should be modified to maintain larger patches if we are to better emulate the landscape structure created under a fire regime. Larger cutblocks would result in larger patches, and would thus increase effective mesh size. In turn, since larger cutblocks lead to larger stands as cutblocks regenerate and age, maintenance of larger blocks could maintain species sensitive to habitat alteration and forest interior species with large home ranges, like marten (*Martes americana* Turton) (Potvin et al., 1999). However, in reality, although they were not modelled, fires, and especially large fires, will continue to occur in the managed landscape. This may negate the necessity to emulate large fires by implementing large cutblocks in an attempt to mimic the natural structure of the landscape.

4.3. Maintaining harvest volume

The third question addressed in this study was how the different management scenarios compared in terms of harvest volume. Both the TRIAD 12% Extensive and TRIAD 12% scenarios produced timber volumes equal to or higher than the Status Quo and Government Proposed scenarios over the long term. This was due to the increased proportion of land allocated to intensive management and fast-growing plantations.

A clear benefit of the TRIAD management strategy seems to be its ability to generate large harvest volumes on a small portion of the landscape. To reduce economic and ecological costs, this portion could be situated relatively close to the main roads and mills. In both the TRIAD 12% Extensive and TRIAD 12% scenarios, the 14% of the territory allocated to wood production and fast-growing plantations produced more than 20% of the harvest volumes (data not shown). Furthermore, as indicated by the relative performance of these two scenarios compared to the TRIAD 20% Extensive scenario (with only 10% wood production and no plantations), the intensive management and plantation sub-zones had only limited impacts on landscape patterns and amount of old-growth due to their small proportion over the landscape. These results do not correspond with those obtained by Montigny and MacLean (2005), who used a higher proportion of wood production and found a significant decrease in old-growth forest over 80 years of simulation.

It is difficult to assess the significance of the economic benefits related to the harvest volumes without a full cost-benefit analysis (Freeman and Portney, 1989; McKenney, 2000). However, our analyses should account for the short- and long-terms costs of the various scenarios tested and for some of the environmental benefits accrued to healthy ecosystems.

5. Conclusions

Our simulations show that both TRIAD scenarios with 12% conservation and 60–74% ecosystem management would generally result in landscapes more similar in structure to those produced by natural disturbance than the Status Quo or the Government Proposed scenarios, without incurring losses in harvest volumes. The Government Proposed scenario, which proposed to increase protected areas to from 2% to 8% without any significant increase in ecosystem management, did not help in the maintenance of old-growth attributes, nor did it result in a landscape structure comparable to that produced by fire over the long-term. Furthermore, it resulted in lower harvest volumes over the long-term than the Status Quo or the TRIAD 12% management scenarios.

With the assumptions used in our simulations, increased ecosystem management was more beneficial to the percentage of forest with old-growth attributes than increased conservation. However, note that (1) fire was modelled in the conservation zone, and (2) old-growth attributes were assumed to be maintained by high-retention partial cuts in the ecosystem management zone. Thus, these results might not hold if fire was added to the ecosystem management zone and if old-growth attributes cannot be maintained by high-retention partial cuts. Further research is needed in both cases.

In most cases, differences between management scenarios were not apparent until about 100 years of simulation, and much longer in terms of forests with the attributes of stands over 200 years. This clearly supports the idea that landscape patterns are highly resistant to change (Wallin et al., 1994; Wong and Iverson, 2004; Pelletier et al., 2007), even if the landscape is subjected to a zoning system with drastically different management scenarios. It also indicates the need for a long-term vision in management planning; although TRIAD management may be more beneficial ecologically and even economically than the status quo, it may be a long time before these benefits become apparent.

Although our simulations are necessarily a simplification of reality, our analysis illustrates the possible benefits and drawbacks of different TRIAD scenarios compared to the status quo for a large area of public land in Canada. It also constitutes the most in-depth and long-term analysis of TRIAD management scenarios to date both in terms of ecological and timber supply impacts.

Acknowledgements

This project was funded by grants to C.M. and his collaborators from the Sustainable Forest Management Network, Abitibi-Bowater Inc., and the National Science and Engineering Research Council of Canada (NSERC). We wish to thank Josiane Bonneau and Stephen H. Yamasaki for their technical help.

References

Andison, D.W., 2003. Tactical forest planning and landscape design. In: Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L. (Eds.), Towards Sustainable Management of the Boreal Forest. NRC Research Press, Ottawa, pp. 433–480.

Archambault, L., Delisle, C., Larocque, G.R., 2009. Forest regeneration 50 years following partial cutting in mixedwood ecosystems of southern Quebec, Canada. Forest Ecology and Management 257, 703–711.

Austin, M.P., Margules, C.R., 1986. Assessing representativeness. In: Usher, M.B. (Ed.), Wildlife Conservation Evaluation. Chapman and Hall, London, pp. 45–67.

Bauhus, J., Puettmann, K., Messier, C., 2009. Silviculture for old-growth attributes. Forest Ecology and Management 258, 525–537.

Beese, W.J., Dunsworth, B.J., Zielke, K., Bancroft, B., 2003. Maintaining attributes of old-growth forests in coastal B.C. through variable retention. Forestry Chronicle 79, 570–578.

Binkley, C., 1997. Preserving nature through intensive plantation forestry: the case for forest allocation with illustrations from Bristish Columbia. Forestry Chronicle 73, 553–559.

Boudreault, D., Bergeron, Y., Gauthier, S., Drapeau, P., 2002. Bryophyte and lichen communities in mature and old-growth stands in eastern boreal forests of Canada. Canadian Journal of Forest Research 32, 1080–1093.

Bureau d'Audience Publique sur l'Environnement (BAPE), 1997. Rapport d'enquête et d'audience publique, Programme de dégagement de la régénération forestière.

Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L. (Eds.), 2003. Towards Sustainable Management of the Boreal Forest. NRC Research Press, Ottawa.

Canadian Council of Forest Ministers (CCFM). 1997. Criteria and Indicators of Sustainable Forest Management in Canada. Technical Report. Natural Resources Canada, Canadian Forest Service, Ottawa.

Carey, A.B., 2003. Biocomplexity and restoration of biodiversity in temperate coniferous forest: inducing spatial heterogeneity with variable-density thinning. Forestry 76, 127–136.

Deal, R.L., 2001. The effects of partial cutting on forest plant communities of western hemlock – Sitka spruce stands in southeast Alaska. Canadian Journal of Forest Research 31, 2067–2079.

Deal, R.L., Tappeiner, J.C., 2002. The effects of partial cutting on stand structure and growth of western hemlock-Sitka spruce stands in southeast Alaska. Forest Ecology and Management 159, 173–186.

D'Eon, R.G., Hebert, D., Viszlai, S.L., 2004. An ecological rationale for sustainable forest management concepts at Riverside Forest Products, south central British Columbia. Forestry Chronicle 80, 341–348.

Didion, M., Fortin, M.-J., Fall, A., 2007. Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: a landscape level sensitivity analysis. Ecological Modelling 200, 45–58.

Drapeau, P., Leduc, A., Bergeron, Y., Gauthier, S., Savard, J.-P.L., 2003. Les communautés d'oiseaux des vieilles forêts de la pessière à mousses de la ceinture d'argile: problèmes et solution face à l'aménagement forestier. Forestry Chronicle 79, 531–540.

Fahrig, L., 2003. Effects of habitat fragmentation on biodiversity. Annual Review of Ecology, Evolution, and Systematics 34, 487–515.

Fall, A., Fall, J., 2001. A domain-specific language for models of landscape dynamics. Ecological Modelling 141, 1–18.

Fall, A., Fortin, M.-J., Kneeshaw, D.D., Yamasaki, S.H., Messier, C., Bouthillier, L., Smyth, C., 2004. Consequences of various landscape-scale ecosystem management strategies and fire cycles on age-class structure and harvest in boreal forests. Canadian Journal of Forest Research 34, 310–322.

Franklin, J., 1989. Towards a new forestry. American Forestry 95, 37–44.

Freeman, A.M., Portney, P.R., 1989. Economics clarifies choices–Benefit-cost analysis provides guidance. Journal of Forestry 87, 34–38.

Gonzalez, P., R. Hassan, Lakyda, I. McCallum, S. Nilsson, J. Pulhin, B. van Rosenburg, Scholes, B. 2005. Forest and woodland systems. In: Millenium Ecosystem Assessment (Ed.), Ecosystems and Human Well-being Current State and Trends. Findings of the Condition and Trends Working Group. Island Press, Washington D.C., pp. 585-621.

Gregg Jr., W.P., Krugman Jr., S.L., Wood Jr., J.D., 1989. In: Proceedings of the Symposium On Biosphere Reserves, Fourth World Wilderness Congress, (September 14–17, 1987-Estes Park, Colorado). U.S. Dept. Int., National Park Service, Atlanta.

Grumbine, R.E., 1994. What is ecosystem management? Conservation Biology 8, 27–38.

Haas, G.E., Driver, B.L., Brown, P.J., Lucas, R.C., 1987. Wilderness management zoning. Journal of Forestry 85, 17–21.

Hamersley Chambers, F., Beckley, T., 2003. Public involvement in sustainable boreal forest management. In: Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L. (Eds.), Towards Sustainable Management of the Boreal Forest. NRC Research Press, Ottawa, pp. 113–154.

Hauffler, J.B., Mehl, C.A., Roloff, G.J., 1996. Using a coarse-filter approach with species assessment for ecosystem management. Wildlife Society Bulletin 24, 200–208.

Hunter Jr., M.L., Calhoun, A., 1996. A triad approach to land-use allocation. In: Szaro, R.C., Johnstone, D.W. (Eds.), Biodiversity in Managed Landscapes. Oxford University Press, Oxford, pp. 477–491.

Hunter Jr., 1993. Natural fire regimes as spatial models for managing boreal forests. Biological Conservation 65, 115–120.

Jaeger, J.A.G., 2000. Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landscape Ecology 15, 115–130.

James, P., Fortin, M.-J., Fall, A., Kneeshaw, D.D., Messier, C., 2007. The effects of spatial legacies following shifting management practices and fire on boreal forest age structure. Ecosystems 10, 1261–1277.

Johnson, E.A., Miyanishi, K., Weir, J.M.H., 1998. Fires in the western Canadian boreal forest: landscape patterns and ecosystem management. Journal of Vegetation Science 9, 603–610.

Kneeshaw, D.D., Leduc, A., Drapeau, P., Gauthier, S., Paré, D., Carignan, R., Doucet, R., Bouthillier, L., Messier, C., 2000. Development of integrated ecological standards of sustainable forest management at an operational scale. Forestry Chronicle 76, 481–493.

Krcmar, E., Vertinsky, I., van Kooten, G.C., 2003. Modelling alternative zoning strategies in forest management. International Transactions in Operational Research 10, 483–498.

Kneeshaw, D.D., Gauthier, S., 2003. Old growth in the boreal forest: a dynamic perspective at the stand and landscape level. Environmental Reviews 11 (1 (Suppl.)), S99–S114.

Landres, P.B., Morgan, Swanson, F.J., 1999. Overview of the natural variability concepts in managing ecological systems. Ecological Applications 9, 1179–1188.

Lindenmayer, D.B., Franklin, J.P., 2002. Conserving Forest Biodiversity. Island Press, London.

MacLean, D.A., Seymour, R.S., Montigny, M.K., Messier, C., 2008. Allocation of conservation efforts over the landscape: the TRIAD approach. In: Villard, M.-A., Jonsson, B.G. (Eds.), Setting Conservation Targets for Managed Forest Landscapes. Cambridge University Press, Cambridge.

Maness, T., Farrell, R., 2004. A multiple-objective scenario evaluation model for sustainable forest management using criteria and indicators. Canadian Journal of Forest Research 34, 2004–2017.

McArdle, R.F., 1953. Multiple use—multiple benefits. Journal of Forestry 51, 323–325.

McGarigal, K., Marks, B.J. 1995. FRAGSTATS–Spatial pattern analysis program for quantifying landscape structure. USDA Forest Service, General Technical Report PNW-GTR-351.
McKenney, D., 2000. What's the economics of intensive silviculture? Forestry Chronicle 76, 275–281.
McNeely, J.A., Miller, K.R., 1984. National Parks, Conservation, and Development: The Role of Protected Areas in Sustaining Society. Smithsonian Institute, Washington D.C..
Messier, C., Kneeshaw, D.D., 1999. Thinking and acting differently for sustainable management of the boreal forest. Forestry Chronicle 75, 929–938.
Messier, C., Bigué, B., Bernier, L., 2003. L'utilisation de plantes à croissance rapide pour promouvoir la protection des écosystèmes forestiers au Canada. Unasylva 54, 59–63.
Messier, C., Tittler, R., Kneeshaw, D., Gélinas, N., Paquette, A., Berninger, K., Rheault, H., Meek, P., Beaulieu, N. 2000. TRIAD zoning in Quebec: experiences and results after five years. Forestry Chronicle, in press.
Montigny, M.K., MacLean, D.A., 2005. Using heterogeneity and representation of ecosite criteria to select forest reserves in an intensively managed industrial forest. Biological Conservation 125, 237–248.
Montigny, M.K., MacLean, D.A., 2006. Triad forest management: scenario analysis of forest zoning effects on timber and non-timber values in New-Brunswick, Canada. Forestry Chronicle 82, 496–511.
Nichols, W.F., Killingbeck, K.T., August, P.V., 1998. The influence of geomorphological heterogeneity on biodiversity: II. A landscape perspective. Conservation Biology 12, 371–379.
Norfolk, C.J., Erdle, T.A., 2005. Selecting inten timber management zones as part of a forest land allocation strategy. Forestry Chronicle 81, 245–255.
Östlund, L., Zackrisonn, O., Axelsson, A.-L., 1997. The history and transformation of a Scandinavian boreal forest landscape since the 19th century. Canadian Journal of Forest Research 27, 1198–1206.
Paquette, A., Messier, C., 2009. The role of plantations in managing the world's forests in the Anthropocene. Frontiers in Ecology and the Environment, doi:10.1890/080116.
Pelletier, G., Dumont, Y., Bédard, M. 2007. Système d'information forestière par tesselle: Manuel de l'usager (préliminaire). Ministère des Ressources naturelles et de la faune, Gouvernement du Québec, Québec.
Pothier, D., Savard, F. 1998. Actualisation des tables de production pour les principales espèces forestières du Québec. Direction des inventaires forestiers Ministère des Ressources naturelles, Sainte-Foy.
Potvin, F., Courtois, R., Bélanger, L., 1999. Short-term response of wildlife to clearcutting in Quebec boreal forest: multiscale effects and management implications. Canadian Journal of Forest Research 29, 1120–1127.
Redelsheimer, C.L., 1996. Enhancing forest management through public involvement: an industrial landowner's experience. Journal of Forestry 94, 24–27.
Schmidt, N.B.C., Roland, J., 2006. Moth diversity in a fragmented habitat: importance of functional groups and landscape scale in the boreal forest. Annals of the Entomological Society of America 99, 1110–1120.
Senate subcommittee on the boreal forest. 1999. Competing realities: the boreal forest at risk. Senate of Canada, Ottawa.
Seymour, R.S., Hunter Jr., M.L., 1992. New forestry in eastern spruce-fir forests: principles and applications to Maine. Maine Agricultural Experiment Station, Orono. Maine Miscellaneous Publication 716.
Seymour, R.S., Hunter Jr., M.L., 1999. Principles of ecological forestry. In: Hunter, Jr., M.L. (Ed.), Maintaining Biodiversity in Forest Ecosystem. Cambridge University Press, Cambridge, pp. 22–61.
Sodhi, N.S., Koh, L.P., Brook, B.W., Ng, P.K.L., 2004. Southeast Asian biodiversity an impending disaster. Trends in Ecology and Evolution 19, 654–660.
Stone, I., Ouellet, J.P., Sirois, L., Arseneau, M.J., St-Laurent, M.H., 2008. Impacts of silvicultural treatments on arboreal lichen biomass in balsam fir stands on Québec's Gaspé Peninsula: implications for a relict caribou herd. Forest Ecology and Management 255, 2733–2742.
Swallow, S.K., Parks, P.J., Wear, D.N., 1990. Policy-relevant nonconvexities in production of multiple forest benefits? Journal of Environmental Economics and Management 19, 264–280.
Van Wagner, C.E., 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8, 220–227.
Wallin, D.O., Swanson, F.J., Marks, B., 1994. Landscape pattern response to changes in pattern generation rules: land-use legacies in forestry. Ecological Applications 4, 569–580.
Walther, P., 1986. The meaning of zoning on the management of natural resource lands. Journal of Environmental Management 22, 331–343.
Wirth, C., Messier, C., Bergeron, Y., Frank, D., Fankhanel, A., 2009. Old-growth forest definitions: a pragmatic view. In: Wirth, C., Gleixner, G., Heimann, M. (Eds.), Old-growth Forests. Ecological Studies 207. Springer-Verlag, Berlin Heidelberg, pp. 11–34.
Wong, C., Iverson, K., 2004. Range of natural variability: applying the concept to forest management in central British Columbia. BC Journal of Ecosystems and Management 4, 14.
World Commission on Environment and Development (WCED). 1987. Our Common Future. Oxford University Press, London.
World Resources Institute (WRI). 1994. World Resources. Oxford University Press, New York.
Zhang, Y., 2005. Multiple-use forestry vs. forestland-use specialization revisited. Forest Policy and Economics 7, 143–156.