Emulating boreal forest disturbance dynamics: Can we maintain timber supply, aboriginal land use, and woodland caribou habitat?

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ABSTRACT

The effects on timber supply incurred by implementing an ecosystem-based management strategy were evaluated in an eastern Canadian boreal forest management unit. Standard linear programming was used to test the effects of four key policy issues: (1) aim for a targeted forest age structure inspired by natural fire regime and forest dynamics (multi-cohort approach), (2) agglomerate harvest blocks in operating areas to reproduce natural disturbance patterns at the landscape scale, (3) maintain cumulated clearcutting and natural disturbance rates inside the historical range of variability, and (4) exclude from harvest areas of potential interest to aboriginal people. The targeted forest age structure was achieved with a minimum reduction of periodic timber supply, but only after 50 years. Compared to a "business-as-usual" scenario, inclusion of the first three policy issues resulted in a 3% to 11% reduction in planned timber supply and a restoration period requiring that 43% to 67% of the productive area be excluded from clearcutting activities for the next 50 years. Such results require that partial cutting not be confined to operating areas eligible for clearcutting. Further exclusion of forest areas of potential interest to aboriginal people resulted in an additional 4% to 10% decrease in planned timber supply. Validation of the coarse filters used in this study (first three policy issues) was done using habitat requirements of woodland caribou (*Rangifer tarandus caribou*). Almost all scenarios induced a disturbance rate likely to allow a self-sustaining woodland caribou population within 25 years.

Keywords: ecosystem-based management, EBM, multi-cohort management, timber supply, boreal forest, aboriginal people, forest management scenarios, linear programming, woodland caribou

FRÉSUMÉ

Les effets sur l'approvisionnement en matière ligneuse découlant de l'implantation d'une stratégie d'aménagement écosystémique ont été analysés dans le cas d'une unité de la forêt boréale sous aménagement forestier dans l'est du Canada. Une programmation linéaire standard a été utilisée pour évaluer les effets de quatre principales politiques : (1) chercher à établir une structure d'âge cible de la forêt découlant du cycle naturel des feux de forêts et de la dynamique forestière (approche avec plusieurs cohortes), (2) rapprocher les blocs de coupe dans les zones exploitées afin de reproduire les patrons de perturbation naturelle à l'échelle du paysage, (3) maintenir les niveaux cumulatifs de coupe à blanc et de perturbations naturelles à l'intérieur de l'intervalle habituel de variabilité et (4) exclure les coupes d'exploitation dans les zones d'intérêt potentiel pour les peuples autochtones. La structure d'âge cible de la forêt a été atteinte suite à une réduction minime de l'approvisionnement périodique en matière ligneuse, mais seulement après 50 ans. Comparativement au scénario « usuel », l'inclusion des trois premières politiques a entraîné une réduction de 3% à 11% de l'approvisionnement planifié en matière ligneuse et une période de restauration nécessitant que 43% à 67% du territoire productif soit exclu des activités de coupe pour les 50 prochaines années. De tels résultats impliquent que les coupes partielles ne soient pas confinées dans les zones d'opération retenues pour la coupe à blanc. L'exclusion additionnelle du territoire forestier ayant un intérêt potentiel pour les peuples autochtones a provoqué une réduction supplémentaire de 4% à 10% de l'approvisionnement planifié en matière ligneuse. La validation des trois critères de base utilisés dans cette étude (les trois premières politiques) a été effectuée au moyen des exigences en matière d'habitat du caribou des bois (*Rangifer tarandus caribou*). Presque tous les scénarios ont engendré un niveau de perturbation permettant vraisemblablement le maintien des populations de caribou des bois en moins de 25 ans.

Mots clés : aménagement écosystémique, aménagement avec plusieurs cohortes, approvisionnement en matière ligneuse, forêt boréale, peuple autochtone, scénarios d'aménagement forestier, programmation linéaire, caribou des bois

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Introduction

Forest ecosystems are shaped by environmental conditions and natural disturbances such as fire, insect epidemics, and diseases (Seymour and Hunter 1999, Stocks *et al*. 2002, Flannigan *et al*. 2005). The fire regime of the North American boreal forest is characterized by a predominance of frequent and severe fires that reset the successional clock over large areas (Payette 1992, Flannigan *et al*. 2005). While the widespread occurrence of catastrophic wildfire has long been used to justify even-aged management of boreal forests (Bergeron *et al.* 2002), the natural disturbance regime over much of this forest is not driven solely by stand-replacing fires. Secondary disturbances also play an important role by altering internal stand structure and the spatiotemporal distribution of stands across the boreal landscape. Hence, secondary disturbances should also be taken into account when designing management strategies that are aimed at emulating natural disturbances (Bergeron *et al.* 2001).

Until recently, timber supply was determined by following the concept of sustained yield. The forest was "regulated", meaning that an equal volume of wood could be harvested each year in perpetuity, eventually leading to all age classes occupying equal areas (Davis *et al.* 2001, Buongiorno and Gilless 2003). This unrealistic assumption has led to simplified forest ecosystems and reduced biodiversity (Seymour and Hunter 1999). Consequently, even-aged management fails to emulate many aspects of natural disturbance processes (Kimmins 2004). Moreover, a fully regulated forest landscape has a truncated age-class distribution with no over-mature or old-growth stands. Such a structure is outside the range of natural variability (Bergeron *et al.* 2002, Bergeron 2004, Cyr *et al.* 2009). Reducing the differences between the spatiotemporal patterns that are created by management activities and natural disturbances can therefore help maintain the integrity of forest ecosystems (Haeussler and Kneeshaw 2003, Gauthier *et al.* 2009).

Ecosystem-based management (EBM), which is based on natural disturbance dynamics, offers an alternative to even-aged management for preserving forest diversity and function (Harvey *et al.* 2002, Gauthier *et al.* 2009). EBM implies the use of silvicultural strategies that seek to reproduce the frequency, severity, and spatial distribution of natural disturbances (Haeussler and Kneeshaw 2003, Gauthier *et al.* 2009). The theoretical framework of EBM has been described extensively (Landres *et al.* 1999, Seymour and Hunter 1999, Bergeron *et al.* 2002, Harvey *et al.* 2002) and proposals have been made for its application in the field. One example is the multi-cohort management approach designed for implementation in eastern Canadian boreal forests (Bergeron *et al.* 2002).

The aforementioned approach is based on a compromise between rotation age and the expected longevity of black spruce trees (*Picea mariana* [Mill.] BSP), and is implemented in several steps. First, the forest age-class distribution is divided into three cohorts, which reproduce natural stand development stages (Franklin *et al.* 2002). Second, different silvicultural strategies are proposed, either to maintain the stands in the same cohort or to shift them to another cohort. Third, proportions of each cohort in the boreal landscape, together with cohort transition rates, are based on a modelled disturbance regime (Bergeron *et al.* 2002) and forest successional dynamics (Harvey *et al.* 2002). However, the applicability of the cohort approach in terms of its ecological suitability, economic viability, and social acceptability has yet to be evaluated in an operational context.

One of the main challenges that is associated with the social acceptability of forestry practices is the recognition and inclusion of traditional ecological knowledge (Cheveau *et al.* 2008, Wyatt 2008, Beaudoin 2012, Jacqmain *et al.* 2012). With the intensification of industrial forestry that followed the colonization of rural regions of boreal Canada, aboriginal people have felt that their land had been unfairly expropriated, which led to conflicts with forest product companies and governments (Treseder and Krogman 1999, Wyatt 2008). For example, the Kitcisakik Anicinapek (Algonquin) community of Quebec maintains the claim that timber extraction over the last century has resulted in the loss of biodiversity and has failed to protect their relationship with the forest environment (Saint-Arnaud *et al.* 2009). Yet, it is widely recognized that the success of public forest management depends mainly upon the active participation of local communities, including indigenous peoples (Brunson 1996, FSC 2004, Saint-Arnaud *et al.* 2009). Forest management is more acceptable to local communities if they feel that their concerns have been addressed and that they have been treated fairly during the planning process (Brunson 1996, Wyatt *et al.* 2011).

In EBM, the natural forest age structure is reproduced in a non-spatial, coarse-filter approach to maintain the habitat requirements of most species present (Haufler *et al.* 1996, Seymour and Hunter 1999). Agglomeration of harvesting activities allows for the adjustment of frequency distributions of forest patch sizes and disturbance rates (two other coarse filters), which minimize fragmentation and maximize connectivity between habitat patches at the landscape scale (Bergeron *et al*. 1999, Belleau *et al.* 2007). Fine filters are complementary to coarse filters and focus on the conservation of specific elements that are not captured by the latter (Haufler *et al.* 1996). For example, agglomerating harvesting activities can limit the extent of anthropogenic disturbances and could thus potentially protect key habitat attributes of endangered species such as the woodland caribou (*Rangifer tarandus caribou* [Gmelin, 1788]) (Faille *et al.* 2010, Moreau *et al.* 2012). However, timber harvesting has a greater negative impact than fire on the probability of conserving a sustainable caribou population (Vors *et al.* 2007, Wittmer *et al.* 2007, Environment Canada 2011). Therefore, the management of this endangered species is likely to require a fine-filter approach.

Our objective was to quantify the sensitivity of timber supply to EBM implementation within an eastern Canadian boreal forest management unit. Results were compared with a business-as-usual (BAU) scenario. We hypothesized that 1) timber supply would not decrease as a result of implementing EBM, and that 2) it is possible to take into account aboriginal considerations through the coarse-filter approach offered by EBM without drastically reducing timber supply. We further hypothesized that coarse-filter measures would increase the likelihood of maintaining viable woodland caribou populations by providing larger forest tracts.

Methodology

Study area

The study area was Forest Management Unit 085-51 in western Quebec, which covers an area of 1.08 million ha (Fig. 1). About half of the territory (542 000 ha) was considered productive, i.e., having the capacity to produce more than 50 m^3

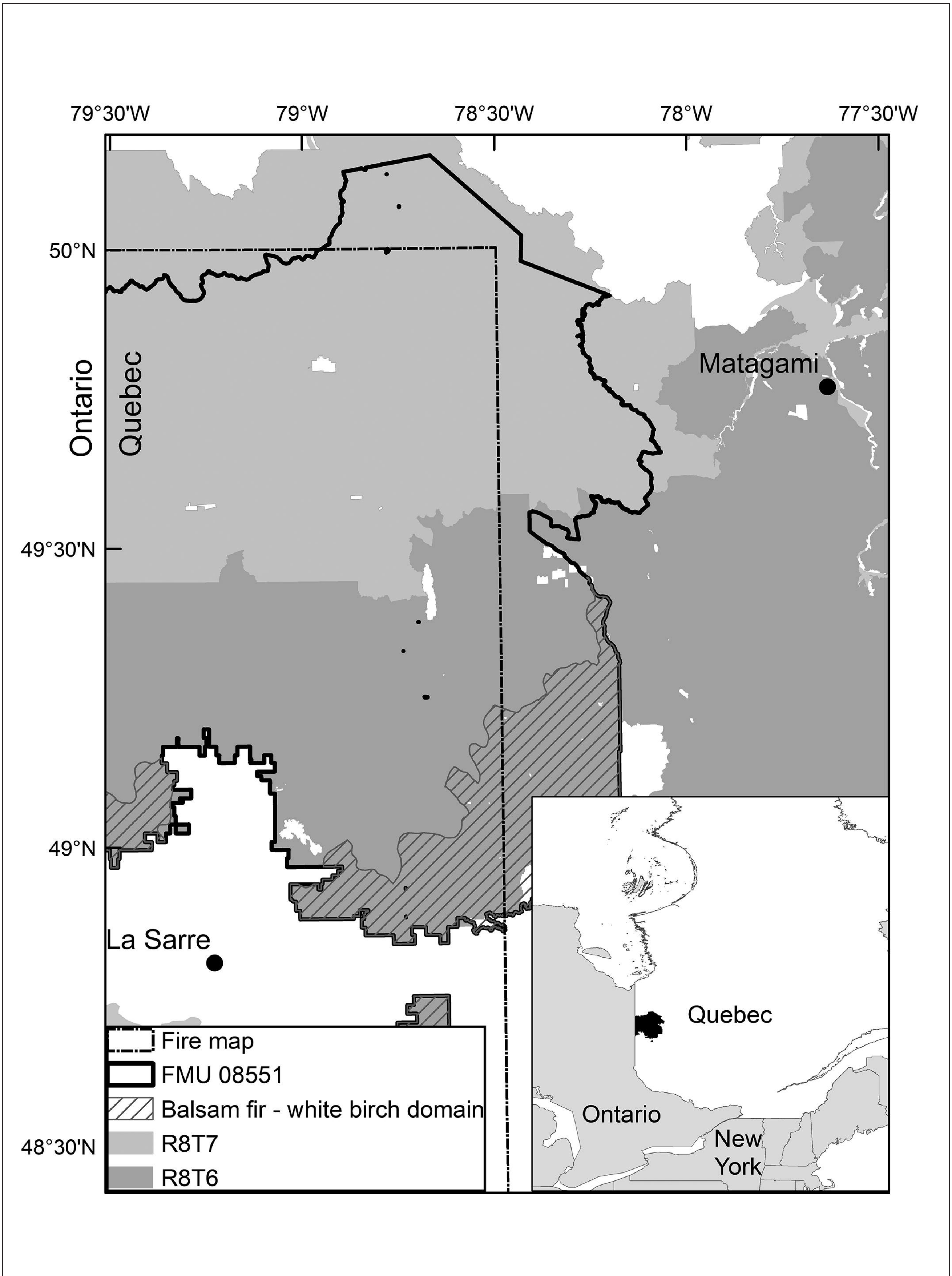

Fig. 1. Study area (Forest Management Unit 085-51). R8T7 and R8T6 are two distinct forest inventory units.

ha^{-1} of wood in one rotation (Tembec 2007). The company responsible for the forest management unit wished to apply EBM to meet certification standards (FSC 2004).

A substantial portion of the ancestral territory of the Pikogan Anicinapek (Algonquin) community (ca. 800 members) is located within the study area. People from Pikogan extensively use the territory for several cultural activities such as hunting, trapping and collecting various forest products (Germain 2012).

The study area is located entirely in the boreal bioclimatic zone, and mostly within the black spruce–feather moss bioclimatic sub-domain (Robitaille and Saucier 1998). Plains dominate the topography with an elevation averaging 280 m a.s.l. Soils of the northern half of the study area are characterized by poorly drained clay, whereas better-drained tills are more frequent in the southern half, even though clay deposits remain abundant. Mean annual temperature varies from -2.5°C to 0°C, the length of the growing season is 150 to 160 days, and total precipitation is 700 mm to 800 mm (Robitaille and Saucier 1998). Forest landscapes are fairly uniform, dominated by extensive pure black spruce stands. Black spruce is sometimes accompanied by other species such as balsam fir (*Abies balsamea* [L.] Mill.), paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.), and, to a lesser extent, balsam poplar (*Populus balsamifera* L.). Bryophytes and dwarf ericaceous shrubs form the understory. Herbaceous species are sparse (MRN 2003, Fenton and Bergeron 2006).

The natural disturbance regime of the study area is dominated by large crown fires (Bergeron *et al.* 2004), but gap-phase dynamics and windthrow are also important, as the present fire cycle (ca. 400 years, Bergeron *et al.* 2004) is longer than the mean longevity of black spruce (100 to 150 years, Robichaud and Methven 1993). The burn rate in the study area has declined sharply from 0.68% per year between 1850 and 1920 to 0.25% per year since 1920 (Bergeron *et al.* 2004). In the prolonged absence of fire, the productivity of black spruce stands gradually declines due to paludification. Jack pine (*Pinus banksiana* Lamb.) and aspen colonize post-fire stands in well-drained areas (Belleau and Légaré 2009).

The forest dynamics in the region can be simplified to three main successional pathways, which are dominated by black spruce, jack pine, or trembling aspen (Bergeron *et al.* 2002, Nguyen-Xuan 2002, Gauthier *et al.* 2004). These pathways can be further subdivided into two to three developmental stages or cohorts. The first developmental stage (cohort 1) corresponds to stands that were recently initiated by a stand-replacing fire. Stands in cohort 1 are dense and closed, with a simple vertical structure. In the absence of stand-reinitiating disturbances, cohort 1 evolves into cohort 2, which is characterized by a semi-open and irregular canopy. At this developmental stage, shade-intolerant species are gradually replaced by black spruce. In the absence of a stand-reinitiating disturbance, stands continue to evolve into a third cohort, with complete replacement of the individuals established during the first and second cohorts (Belleau and Légaré 2009). Third cohort stands are relatively open and uneven-aged, with a well-developed vertical structure.

Forest stratification and timber yield

Analyses were based on the data gathered for the last timber supply analysis that was performed by the Ministère des Ressources naturelles (MRN) for the 2008–2013 planning period. From the forest maps used for the timber supply analysis, we grouped forest polygons into inventory strata based on cover type, stand density and height, age class, and ecological type. Inventory strata with a canopy height >7 m (467 strata) were characterized using 400-m^2 circular temporary sample plots (2696 plots). Within sample plots, species and diameter at breast height (DBH, 1.3 m; 2 cm diameter classes) were recorded for every tree with a DBH >9 cm. Height and age were also noted for four to nine randomly selected canopy-dominant or co-dominant trees per plot. About 40% of these plots were sampled in 1996 or 1997 within two forest inventory units covering the study area (Fig. 1). Plots that had been sampled earlier (between 1986 and 1996) but were located in forest polygons that had remained undisturbed between their initial measurement and 1996 were aged to 1996 with an empirical growth model created by the MRN. To complement this dataset, the MRN added a further 1050 plots outside of these two inventory units, based on similarity in their cartographic attributes (Bernier *et al.* 2010). To simplify timber supply analyses, inventory strata were grouped into 328 management strata with the following method:

1. Inventory strata with stand age <30 years (canopy height <7 m) were considered under regeneration, irrespective of their origin (729 inventory strata). Considering their ecological types and age classes, these regeneration strata were grouped into 124 separate management strata based on their regeneration mode (including secondary anthropogenic disturbances such as commercial and precommercial thinning).
2. Cluster analysis grouped 467 inventory strata into 180 management strata for which sample plot data were available. The precision in merchantable volume estimation for an inventory stratum was calculated as the ratio of half the 95% confidence interval of the mean on the mean volume. The Mahalanobis distance (Mahalanobis 1936) was calculated with vectors of merchantable volume per species groups and DBH classes (5 cm classes) between the stratum with the lowest precision and the remaining strata with similar potential vegetation (Robitaille and Saucier 1998). Species groups were based on softwood/hardwood distinction and shade-tolerance/intolerance. An *F*-test determined if there was a significant difference with the closest stratum; strata were grouped when the *F*-test was not significant. The procedure was iteratively repeated until strata could no longer be grouped. The CANDISC procedure (SAS Institute, Cary, NC) was used to perform the cluster analysis.
3. To group inventory strata that were neither regenerating nor had sample plot data available, a key was developed that was based on cartographic information using age, species group, ecological type, canopy height, and density class available from the last forest inventory. The 209 inventory strata having attributes similar to those of management strata, which had been obtained with the cluster analysis, were included in these management strata. The remaining 104 inventory strata (15 051 ha; <3% of the total productive area) were grouped into 24 new management strata.

The yield trajectory of each management stratum was based on area-based weighted averages of the yield tables that were compiled by the MRN during their last timber supply analysis. These yield curves were calculated using the model developed by Pothier and Savard (1998). Species volumes were also aggregated on the basis of softwood/hardwood distinction and shade tolerance/intolerance information.

Forest developmental stages

Forest age-class structure is the main coarse-filter indicator used in the multi-cohort management approach. A target age structure is expressed in terms of areal proportions of developmental stages or cohorts and is derived from a theoretical age-class distribution. Assuming a random probability of fire, Van Wagner (1978) showed that these estimates follow a negative exponential distribution. The calculation of areal proportions by cohort requires a mean time since the last stand-initiating fire and estimates of ages at which transitions are expected to occur from one cohort to another. For this purpose, the fire history of the study area was extracted from the fire history map produced by Bergeron *et al.* (2004) to compute a mean time since the last fire (147 years, with lower and upper 95% confidence limits of 125 and 170 years, respectively). Gauthier *et al.* (2004) estimated transition ages of roughly 150 years between first and second cohorts, and 275 years between second and third cohorts. Consequently, cohort proportions were estimated using eq. 3 of Van Wagner (1978), as 63%, 21%, and 16% of the forest area for cohorts 1, 2, and 3, respectively.

To monitor cohort proportions during timber supply analyses, cohort characterization had to be linked to yield curves. Stand age normally corresponds to the mean age of canopy trees, and differs from time since the last fire when mean tree longevity is exceeded. Gauthier *et al.* (2004) linked cohort transitions with changes in stand structural and compositional attributes. For the successional pathways that were dominated by jack pine (intolerant softwood) and trembling aspen (intolerant hardwood), cohort transition is linked to changes in species composition, while it is a function of stand structural changes for the pathway dominated by black spruce (tolerant softwood). Consequently, successional pathways first had to be identified, and then, two different strategies had to be followed to identify cohort number with yield curves (i.e., one for the pathways dominated by jack pine or trembling aspen, and one for the black spruce pathway). An identification key was constructed with the yield curves of each management stratum specifying the volume proportions of each species and, using the method of Nguyen-Xuan (2002), identifying the successional pathway for each sample plot of the corresponding stratum. Minimum confusion between the assignments of successional pathways to strata with plots or yield curves was attained with the pathway assigned to black spruce when the volume proportion of tolerant softwoods was >70%, to trembling aspen when the volume proportion of intolerant hardwoods was >30%, and to jack pine otherwise. When this key was applied, the concordance level between the two assignment methods was 84%.

For jack pine and trembling aspen successional pathways, two identification keys (one for each successional pathway) were developed to determine cohort number, based on the volume proportion of each species and age class. With these keys, confusion matrices of cohort number prediction between sample plots and yield curves showed concordances of 56% (jack pine) and 62% (trembling aspen). For the black spruce pathway, a different analysis was carried out, with the cohort number derived directly from yield tables rather than from sample plots. Nguyen-Xuan (2002) distinguished cohorts, based on stem densities of the middle- and upper-canopy layers. Pothier and Savard (1998) provided yield tables for different minimum merchantable DBHs (i.e., 9 cm to 17 cm), which allowed stem density estimation for both layers (i.e., 9 cm to 15 cm, and >15 cm). For each age step of a set of black spruce yield curves that covered the observed range of site index and stand density in the study area, the number of stems per hectare was thus estimated for two DBH classes, which were respectively assigned to the middle and upper layers, consistent with the Nguyen-Xuan (2002) method. A general logistic model (PROC LOGISTIC, SAS Institute, Cary, NC) was then used to estimate the probability of a stratum being in a specific cohort as a function of standing volume and age. The Nagelkerke pseudo-R^2 of the logistic regression was 0.86.

Silvicultural strategies

In the BAU scenario, careful logging around advanced regeneration (CLAAG) (Groot *et al.* 2005) was the only available silvicultural option for timber harvesting. No hypotheses were made regarding forest succession. Hence, the species composition of any regenerated stand was assumed to be equivalent to that of the pre-harvest stand. In the EBM scenario, more diverse silvicultural strategies were followed to reproduce natural succession. CLAAG was used to initiate regeneration of black spruce stands, while clearcutting followed by planting was used to renew jack pine stands, and clearcutting followed by natural regeneration was used to regenerate trembling aspen stands. Partial cuts were used to emulate the transition of even-aged stands to irregular stands, and to convert irregular stands to uneven-aged forests. Cut with protection of small merchantable stems (in Quebec, CPPTM: *coupe avec protection des petites tiges marchandes*) was used as a partial cut option. CPPTM is a diameter-limit cut where merchantable stems <15 cm DBH are left standing (Thorpe and Thomas 2007, Simard *et al.* 2009), although it is not necessarily considered a regeneration cut as it frees the undergrowth (Bouchard 2009). Irregular shelterwood cuts (50% removal of merchantable volume; Raymond *et al.* 2009) were used as a potential alternative to CPPTM.

Harvest agglomeration

To agglomerate harvest blocks, the territory was divided into different spatially organized compartments (operating areas) as a function of canopy closure, species composition and landscape patterns (Annie Belleau, Biologist, MRN, personal communication, 2009). Operating areas varied in size between 30 km^2 and 150 km^2 (Belleau and Légaré 2009) to emulate the observed range of fire sizes (Bergeron *et al.* 2004, their Fig. 8). Each operating area was required to have more than a given percentage of its productive area (e.g., 30%, 50% or 70%) eligible for harvest (i.e., older than the minimum harvesting age) before any harvesting could occur. Once an operating area was open for harvest, it remained so for the rest of the planning horizon. The planning horizon was 150 years (30 periods of five years).

Timber supply calculation (baseline scenarios)

The baseline scenarios were first constructed for both BAU and EBM. Standard versions of an optimal timber supply problem (e.g., Bettinger *et al.* 2009) were elaborated in Woodstock (Remsoft Inc., Fredericton, NB) and solved by linear programming with Mosek 5.0 (Mosek ApS, Copenhagen, Denmark) for the BAU and EBM baseline scenarios. In either case, the general objective was to maximize the volume planned for harvest, subject to an even-flow of harvest volume. Woodstock adds default constraints of non-negative harvested areas and resource availability.

For the EBM scenario, jack pine plantations were limited to less than the actual plantation level (7500 ha per period, Tembec 2007) to constrain their potential effect on the allowable cut. Furthermore, the maximization problem was solved iteratively to reach targeted area proportions under cohorts 1, 2 and 3 (63%, 21%, and 16%, respectively) in a minimum amount of time. Since the present areas under cohorts 1, 2, and 3 were 79%, 19%, and 2%, respectively, the starting period for applying these constraints had to be delayed to find a feasible solution for the baseline EBM scenario.

A first type of sensitivity analysis was conducted with shadow prices. Shadow prices are provided with the resolution of an optimization problem and correspond to the change in the value of the objective function should a particular constraint be changed by one unit (Davis *et al.* 2001). Shadow prices help identify binding constraints and the intensity of the binding. In this study, maximum values of shadow prices for clearcutting and partial-cutting harvests by period were used to identify the most constraining periods.

Sensitivity analyses

The volume planned for harvest was used to assess the economic aspect of the scenarios and to rate the sensitivity of the analyses with respect to four key policy issues: (1) aim for a forest age structure targeted with the multi-cohort approach, (2) agglomerate harvest blocks in operating areas to reproduce natural disturbance patterns at the landscape scale, (3) maintain cumulated clearcutting and natural disturbance rates below the historical range of disturbance rates, and (4) exclude forest areas of potential interest to aboriginal people.

Different target forest age structures were considered for the EBM scenarios, by assuming that the mean time since last fire was equal to either its lower (125 years) or upper (170 years) confidence limit to represent shorter and longer fire cycles, respectively. These changes led to corresponding target age structures of 70% : 19% : 11% and 58% : 22% : 20% in cohorts 1, 2, and 3, respectively.

Three different intensities of harvest agglomeration were tested. As previously stated, the percentage of productive area that was eligible for harvesting was used as a criterion to open an operating area to harvest activities. The minimum percentage varied between 30% and 70%. This constraint was specified in the timber supply problems with the help of time-dependent opening curves having either 0 (closed) or 1 (open) values. The values were specified for each operating area by first simulating the baseline timber supply problem without harvest. Operating areas were kept closed until the minimum percentage of stands eligible to harvest was reached and were then left open for the rest of the planning horizon. Harvest agglomeration should have an important effect on the timber supply level and, therefore, two alternative scenarios were considered. The first scenario consisted of agglomerating all harvesting activities, as inspired by natural disturbance sizes as an integral part of our EBM approach. The second type of scenario assumed that partial cutting, which is considered a small-scale secondary disturbance (e.g., Harvey *et al.* 2002), could be less detrimental to species that were associated with late-successional forest stages (Vanderwell *et al*. 2007). In this latter scenario, only clearcutting activities were spatially concentrated.

Clearcutting rates should not exceed the difference between historical and present burn rates (Gauthier *et al.* 2009). The present (1920 and later) burn rate is 0.251% per year (= 1/398 years) (Bergeron *et al.* 2004). Considering an historical rate of 0.680% per year (= 1/147 years), the clearcutting rate should therefore not exceed 0.429% per year. To express the area that was harvested by clearcutting as a rate, harvested areas were divided by the area corresponding to the terrestrial portion of the forest management unit (1.08 million ha). Harvest agglomeration tends to control the clearcutting rate and, as a result, acceptable agglomeration intensities (expressed by the percentage of stands eligible for harvest) had to be higher than the level where the clearcutting rate equaled the aforementioned maximum rate.

Lastly, Germain and Asselin (2010) showed that forest areas adjacent to roads (<100 m) and water bodies (<60 m) were used by the Pikogan aboriginal community for cultural activities such as hunting, trapping, and the collection of various forest products. Zones of aboriginal interest in the study area were thus excluded from the timber production area in the sensitivity analysis by delimiting them as buffer zones. Two types of scenarios were constructed, one that excluded all of these buffer zones from the timber production area, and one that excluded only buffers on all-season roads and water bodies having an area >0.5 ha. The first 20 m that surrounded water bodies (riparian buffer zones) was excluded from harvest in all scenarios, as required by provincial forest regulations.

Risk assessment for woodland caribou persistence

Environment Canada (2011) has shown that the proportion of forest that is younger than 40 years old is strongly related to the mean recruitment of caribou calves throughout the species range. Recruitment is related to the probability of observing stable or increasing caribou populations over a 20-year period. Compared to burned areas, however, harvested areas apparently exert a detrimental influence on habitat suitability for woodland caribou up to a distance of 500 m from their borders. The 500-m border represents a minimum distance and may be challenged (e.g., Vors *et al.* 2007, Moreau *et al.* 2012). Nevertheless, Environment Canada (2011) showed that increasing the buffer size up to 2000 m did not significantly improve the correlation between the proportion of cumulated disturbed area (fire and harvest) and recruitment of caribou calves.

Since the timber supply models that were used in the present study are non-spatial and since agglomeration of harvesting blocks has an impact on the disturbed area for woodland caribou because of overlapping buffers, we evaluated the strength of the relationship between the proportions of disturbed area with and without a buffer at the level of operating areas. We created 500-m buffers from the margin of forest polygons harvested over the last 40 years in Arc GIS 9.3 (ESRI, Redlands, CA). Overlap of disturbed areas was removed before estimating the total disturbed area, as required by Environment Canada (2011). A Gompertz function was selected on the basis of its minimum root mean square error (RMSE) and lack of bias. Parameters were estimated by nonlinear least squares (PROC NLIN, SAS Institute, Cary, NC):

$$[1] \quad p_{bd} = \beta_1\left(1 - e^{-\beta_2 p_d}\right)^{\beta_3}$$

where p_{bd} and p_d are the proportions of disturbed area in an operating area, with (*bd*) or without (*d*) buffers, and β_1, β_2 β_3 are parameters to be estimated.

For each period of the timber planning scenarios that were considered in this study, the total proportion of area disturbed by harvest was estimated by summing the proportions calculated with eq. 1 and weighted by the operating area's terrestrial coverage. Two levels of disturbance were then considered to provide a disturbance range. The minimum level only considered the area disturbed by harvest. The maximum level added the expected proportion of area burned in 40 years

$$(1 - e^{-40 \times 0.00251} = 0.096).$$

Results

In 2007, the Chief Forester's Office of Quebec (CFOQ) recommended a timber supply of 3.45 Mm^3 for the period 2008–2013 in the study area (Tembec 2007). The periodic timber supply level for the BAU baseline scenario was 9% higher than the CFOQ's recommendation, mostly because different planning techniques were used (optimization *vs.* simulation). Under the EBM scenario, the periodic supply level of the baseline scenario was 14% higher than the CFOQ's recommendation. The difference between BAU and EBM scenarios is mostly due to the possibility of partial cutting in EBM. The possibility, in EBM, of converting black spruce to jack pine through planting (Table 1) had only a slight effect (1%) on timber supply. Diversification of harvesting strategies in the EBM scenario led to diversification of harvesting ages. For the successional pathway that was dominated by black spruce, the mean harvest age scheduled by optimization of the timber planning problem was 121 years for CPRS, 164 years for CPPTM, and 100 years for the irregular shelterwood cut. Conversion of black spruce stands to either jack pine or trembling aspen was planned to occur, on average, between 155 and 170 years from now. Contrary to this result, mean harvest age varied only between 96 and 123 years in the alternative BAU baseline scenario.

For both baseline scenarios (BAU and EBM), the critical period (when available volume for harvest equals the harvested volume) lay between 45 and 50 years from now. A shadow price analysis confirmed that the first 50 years provide the greatest constraint for both scenarios in terms of area available for harvest (Fig. 2), but constraints were more restrictive during the first seven 5-year periods for the EBM baseline scenario. This was due to the cohort proportion constraints that indirectly affected the area available for harvest. Periodic timber supply was only reduced by 1% when a targeted forest structure was required, but a solution could only be obtained when the cohort proportion constraints were applied from the 11^{th} period onward, and not before.

The first element considered for sensitivity analyses was the proportion of territory under different cohorts. The first scenario considered a shorter fire cycle that required proportions of 70%, 19%, and 11% under cohorts 1, 2, and 3, respectively. Such a target could be met at the 11^{th} 5-year period of simulation, with only a slight loss in periodic timber supply (4%). The second scenario corresponded to a longer fire cycle, involving 58%, 22%, and 20% of the territory under cohorts 1, 2, and 3, respectively. Again, such a target was met at the 11^{th} period of simulation, but a more severe drop was incurred in periodic timber supply (28%). Periodic timber supply thus decreases when the target age structure departs from the present age class distribution, but an increase in fire cycle has a higher cost because it requires a higher proportion of cohort 3 stands.

Table 1. Silvicultural strategies used for ecosystem-based management scenarios

		Natural stand dynamics		Ecosystem-based management	
Dominant species	Initial cohort	Disturbance	Resulting cohort	Silvicultural strategy	Resulting cohort
Black spruce	1	Absence	2	No intervention	2
	2, 3	Gap dynamics	3	Partial cut	3
	1, 2, 3	Fire	1	CLAAG	1
				Clear cut + scarification	1 (Trembling aspen)
				Clear cut + scarification + plantation	1 (Jack pine)
Jack pine	1	Absence	2	No intervention	2
	1, 2	Fire	1	Clear cut + plantation	1
	2	Gap dynamics	3[a]	Partial cut	3[a]
Trembling aspen	1	Absence	2	No intervention	2
	1, 2	Fire	1	Clear cut	2
	2	Gap dynamics	3[a]	Partial cut	3[a]

[a]Cohort 3 is always dominated by black spruce.

The second element considered in the sensitivity analyses was harvest agglomeration. It was emulated by requiring that 30%, 50%, or 70% of the productive area was eligible for harvest before opening an operating area to clearcutting. This resulted in a sharp drop in periodic timber supply for both BAU and EBM scenarios (Table 2), but the drop remained consistently lower for the EBM scenario, by 40% to 70%. This difference was caused by the possibility, only in the EBM scenario, of partial cutting outside of the operating areas that had been opened for clearcutting. Indeed, both scenarios behaved similarly when partial cutting was constrained in the EBM scenarios to the operating areas that had been opened for clearcutting (Table 2). With these considerable drops in planned harvest, clearcutting rates tended to adjust to the difference between historical and current burn rates between 30% and 50% (Fig. 3). Applying a harvest agglomeration constraint implies that 43% to 67% of the productive area of the forest is closed to clearcutting for about 50 years (Fig. 4). This could be viewed as a restoration strategy, as the percentage of area eligible for clearcutting during the first planning period is well-correlated with recent harvest history in each operating area (Fig. 5; $r = -0.854$, $p < 0.05$).

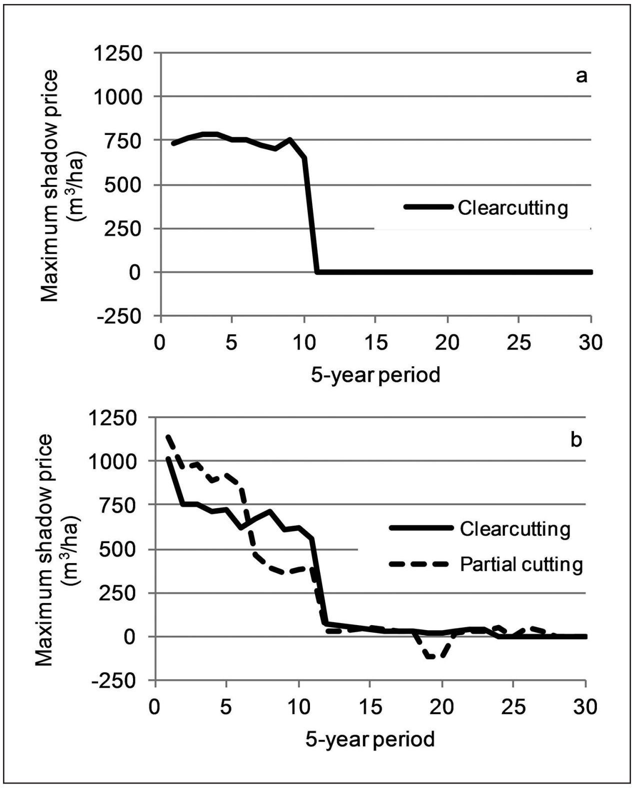

Fig. 2. Maximum value of shadow prices for clearcutting and partial cutting harvest by period under (a) business-as-usual (BAU) scenario and (b) ecosystem-based management (EBM) scenario.

Inclusion of a social criterion (excluding buffer zones around roads and water bodies from the productive landbase to protect areas of aboriginal interest) resulted in an 11% decrease in periodic timber supply in both the BAU and EBM baseline scenarios. When only buffers on all-season roads and water bodies >0.5 ha were excluded, the periodic timber supply level dropped by 3% to 4% relative to the BAU and EBM baseline scenarios.

In our sensitivity analyses, we assumed that a coarse-filter approach constraining the clearcutting rate to the difference between the historical and current burn rates could satisfy the habitat needs of woodland caribou. All scenarios in which harvests were agglomerated tended to lower the risk associated with a low probability of persistence of a woodland caribou population (Fig. 6). These scenarios had their peak area proportion under cumulated disturbances during the first five periods of the planning horizon. This proportion dropped below 45% after 25 years, a threshold below which the probability of woodland caribou persistence is higher than 40% (Environment Canada 2011). It even fell below 35% for the two most constrained scenarios (50% and 70%, Fig. 6), a level where woodland caribou populations are considered self-sustaining (Environment Canada 2011). However, this favorable level for caribou is not maintained throughout the planning horizon (Fig. 6).

Discussion

Gauthier *et al.* (2004) evaluated the possibility of achieving objectives of landscape-level cohort proportions based on the model of Bergeron *et al.* (2002) in the same forest manage-

Table 2. Change in timber supply level (%) relative to BAU or EBM baseline scenario under different spatial constraints and cutting types, and proportional volume harvested by clearcutting under the EBM scenario

Type of harvest spatially restricted	Proportion of eligible stands required before opening an operating area to harvest	Change relative to the BAU baseline scenario (%)	Change relative to the EBM baseline scenario (%)	% of harvest volume realized with clear cut in EBM scenarios
None	0% [a]	baseline scenario	baseline scenario	81%
Clearcutting	30%	-11%	-3%	82%
	50%	-36%	-11%	78%
	70%	-57%	-22%	71%
Clearcutting and partial cutting	30%	–	-8%	88%
	50%	–	-30%	83%
	70%	–	-58%	81%

[a]Baseline scenarios

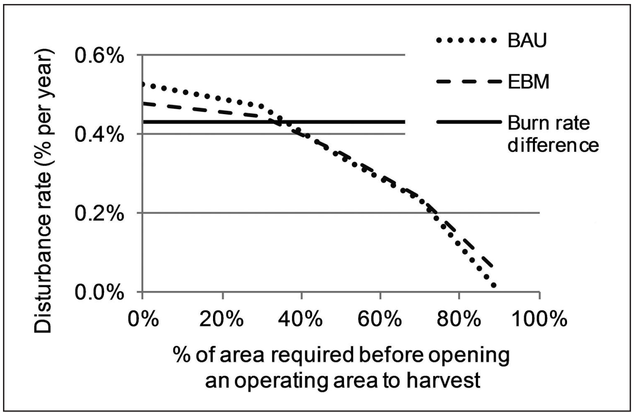

Fig. 3. Variation of the clearcutting rate of business-as-usual (BAU) and ecosystem-based management (EBM) scenarios as a function of the minimum percentage of productive area for an operating area that is required to be eligible for clearcutting before opening it. The horizontal black line shows the difference between present and historical fire disturbance rates in the study area.

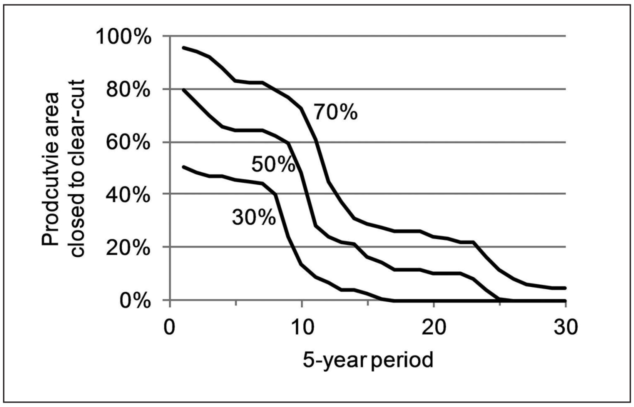

Fig. 4. Proportion of productive area closed to clearcutting as a function of three minimum percentages of the productive area for an operating area to be eligible for clearcutting before opening it.

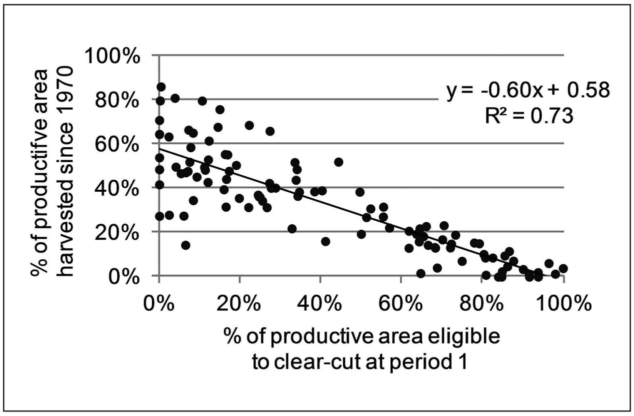

Fig. 5. Relationship between the proportion of productive area harvested since 1970 and the productive area eligible to be clearcut at period 1.

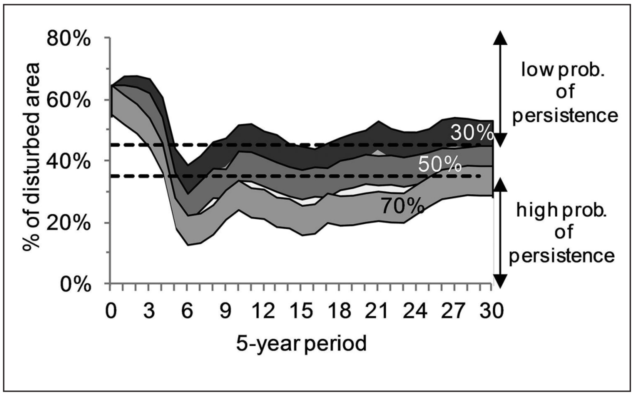

Fig. 6. Proportion of disturbed area (total area less than 40 years old, taking into account either harvest disturbance or cumulated harvest and fire disturbances). Three EBM scenarios are considered, constraining clearcutting in operating areas that had more than 30%, 50%, or 70% of their productive area that was eligible for harvest. Probability of persistence for woodland caribou follows Environment Canada estimates (2011, their Table 9).

ment unit. They found that such objectives could be achieved without significantly reducing the periodic timber supply. Our study confirms this result but also highlights the fact that the next 50 years will be critical for establishing a multi-cohort management strategy in this study area. The targeted forest age structure could be reached after 55 years (11^{th} simulation period), but not before. Consequently, harvesting activities that are realized in the near future will have a critical effect on the probability of success in establishing a multi-cohort management strategy (Fig. 2b). Yet, this can be achieved without reducing the timber supply level.

Harvest spatialization placed a severe constraint on timber supply in both BAU and EBM scenarios. The diverse silvicultural practices that were included in the EBM scenario gave it a comparative advantage over BAU. Although the use of partial cuts helped compensate for harvest spatialization in the EBM scenario, the consequences of their implementation on the growth and mortality of residual trees should be evaluated to determine the long-term effects of a multi-cohort management strategy. Commercially important boreal species respond positively to reduced competition through partial cutting (Thorpe and Thomas 2007). However, post-harvest mortality of residual trees remains a concern, since post-harvest mortality increases with the proportion of individuals harvested (Thorpe and Thomas 2007). For more than a decade, experimental partial cut designs have been implemented in Quebec (Ruel *et al.* 2007, Fenton *et al.* 2009) and elsewhere in the Canadian boreal forest (e.g., Thorpe and Thomas 2007). These will help better define the operability of such treatments, but they have only started to provide information regarding the mortality and growth of residual stands. We did not consider the economic impact of dispersing partial cutting, and this is probably not the best alternative. Cost-benefit analysis of such a partial cutting strategy was beyond the scope of this study but should point to other scenarios of spatial dispersion or aggregation of partial cuts.

Larger and more aggregated harvesting blocks should create landscape patterns that can accommodate edge-sensitive wildlife species (Rempel and Kaufmann 2003). Two key strategies were proposed by Belleau and Légaré (2009) to protect such habitats in this study area: (1) using partial cuts that favoured the maintenance of spruce–lichen woodlands, and (2) agglomerating harvesting activities to limit habitat fragmentation. Timber supply and habitat conservation objectives often conflict regarding the optimal size of harvesting blocks and the dispersed or aggregated distribution of these blocks (Rempel and Kaufman 2003, Tittler *et al.* 2012). Hence, we tested the effects of these two strategies. Our simulations showed that the proportion of the area under clearcutting could be reduced to attain a disturbance rate equivalent to the difference between historical and current burn rates, a situation probably more favourable to species such as woodland caribou (Hovington *et al.* 2010). In contrast to Rempel and Kaufman (2003), we did not consider spatial adjacency constraints in our planning models. Belleau *et al.* (2007), in a simulation study including our study area, observed that individual fires often agglomerate. They suggested that harvesting blocks could be agglomerated, as long as the proportion of first cohort stands was respected. Harvest agglomeration would lead to a 3% to 11% diminution of the planned harvest and necessitate a 50-year restoration period for 43% to 67% of the productive area. Partial cutting compensated for part of the loss of periodic timber supply caused by harvest agglomeration, but partial cuts had to be spread over the territory, thereby potentially increasing habitat fragmentation by roads. Functional habitat loss for woodland caribou has been shown to occur within 750 m to 1250 m from these linear features (Leblond *et al.* 2011), and their negative effect was not taken into account in the present study. Otherwise, limiting partial cutting to operating areas eligible for clearcutting aggravated the drop in periodic timber supply (Table 2). Given the importance of partial cutting in maintaining timber supply, different agglomeration strategies of partial cutting (e.g., Bergeron *et al.* 2004) should be considered in further analyses.

The habitat requirement of woodland caribou was used to evaluate whether or not the coarse-filter approach (maintaining forest age structure, agglomerating cut blocks, and limiting disturbance rate) could induce a disturbance rate capable of maintaining woodland caribou within the study area. The EBM strategies did seem to improve the likelihood of maintaining woodland caribou, especially when the percentage of stands eligible for harvest before opening an operating area to clearcutting was higher than 30% (Fig. 6, 50% or 70%). This effect was only temporary, however, but this was due to the limited adequacy of the approach used in the timber supply problem of agglomerating harvest with opening curves. This approach was used to avoid requiring optimization techniques other than linear programming that are much more difficult to solve (Weintraub and Murray 2006) or post-processing the results with spatial blocking (Rempel and Kaufmann 2003). In any case, this result points to the need for more sophisticated strategies of opening and closing operating areas for harvest, and an in-depth analysis of their impact on timber supply.

Taking aboriginal values into account has become a central issue in Canadian forest management (Saint-Arnaud *et al.* 2009, Germain and Asselin 2010). When management decisions are taken regarding state-controlled resources (e.g., forests), their effects on the general public should be considered (Brunson 1996). Aboriginal communities depend on forests for the goods and services that they provide and for cultural activities. Thus, management decisions have obvious impacts on their livelihoods. While it is recognized that the needs of local communities should receive the highest priority when making forest management decisions (Shindler *et al.* 1993, Brunson and Steel 1994), taking into account the needs of the Pikogan Anicinapek community resulted in a 4% to 11% decrease in planned timber supply level. Identical impacts of the social criterion in both BAU and EBM scenarios can be explained by the similar way in which this issue was taken into account in both models (i.e., reducing the timber production area). It should also be understood that each aboriginal community has its own relationship with the land (Germain and Asselin 2010) and, consequently, the effects incurred on timber supply by taking their needs into account will vary considerably. This effect on timber supply level could potentially be reduced by allowing partial cutting in buffer zones that are reserved for aboriginal activities, since aboriginal people often prefer selective or retention harvesting over clearcutting, as the former maintain ecological and cultural functions of the forests (Larouche 2008, Saint-Arnaud *et al.* 2009).

Taking into account all key policies simultaneously led to reductions of 7% (criterion of harvest agglomeration fixed at 30%, buffer zones on all-season roads and water bodies greater than 0.5 ha excluded from the productive area) to 21% (criterion of agglomeration fixed at 50%, all buffer zones excluded). In absolute terms, such reductions are equivalent to periodic timber supplies of 3.11 Mm^3 to 3.66 Mm^3 per period. The CFOQ (2011) expects a timber supply of 2.93 Mm^3 per period for 2013–2018, to account for the effects of new forest legislation (Government of Quebec 2010). For the purposes of comparison, this value has to be adjusted to remove the effect of creating 59 000 ha of protected areas within the forest management unit between 2007 and 2009 (3.10 Mm^3 per period). These values are lower than the volume harvested between 2000 and 2005 (3.52 Mm^3 per period), but are substantially higher than the volume harvested between 2005 and 2010 (1.98 Mm^3 per period, Louis Dumas, Tembec, personal communication, 2011).

Conclusion

Conventional management (BAU) and ecosystem-based management (EBM) are two forest management practices used in Canada. The main difference is that, under EBM, partial cutting is used in addition to clearcutting and harvesting activities are spatialized to reproduce natural forest dynamics more closely. Consideration of Aboriginal values and maintenance of coarse-filter indicators of biodiversity reduced the periodic timber supply. However, this decrease was lower with EBM thanks to the availability of several silvicultural strategies. An economic analysis of partial cuts and plantations should be undertaken, as they greatly influence timber supply solutions, affect operational costs, and have social impacts. The effects of harvest agglomeration, scattering of partial cuts and their associated road networks on habitat availability for woodland caribou should also be further investigated.

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References

Beaudoin, J.-M. 2012. Aboriginal economic development of forest resources: how can we think outside the wood box? The Forestry Chronicle 88: 571–577.

Belleau, A., Y. Bergeron, A. Leduc, S. Gauthier and A. Fall. 2007. Using spatially explicit simulations to explore size distribution and spacing of regenerating areas produced by wildfires: recommendations for designing harvest agglomerations for the Canadian boreal forest. The Forestry Chronicle 83: 72–83.

Belleau, A. and S. Légaré. 2009. Project Tembec: Towards the implementation of a forest management strategy based on the natural disturbance dynamics of the northern Abitibi region. *In* S. Gauthier, M.-A. Vaillancourt, A. Leduc, L. De Grandpré, D. Kneeshaw, H. Morin, P. Drapeau and Y. Bergeron (eds.). Ecosystem Management in the Boreal Forest. pp. 479–499. Presses de l'Université du Québec.

Bergeron, Y. 2004. Is regulated even-aged management the right strategy for the Canadian boreal forest? The Forestry Chronicle 80: 458–462.

Bergeron, Y., S. Gauthier, M. Flannigan and V. Kafka. 2004. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Québec. Ecology 85: 1916–1932.

Bergeron, Y., S. Gauthier, V. Kafka, P. Lefort and D. Lesieur. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Canadian Journal of Forest Research 31: 384–391.

Bergeron, Y., B. Harvey, A. Leduc and S. Gauthier. 1999. Forest management guidelines based on natural disturbance dynamics: Stand- and forest-level considerations. The Forestry Chronicle 75 : 49–54.

Bergeron, Y., A. Leduc, B. Harvey and S. Gauthier. 2002. Natural fire regime: A guide for sustainable forest management in the Canadian boreal forest. Silva Fennica 36: 81–95.

Bernier, P.Y., G. Daigle, L.-P. Rivest, C.-H. Ung, F. Labbé, C. Bergeron and A. Patry. 2010. From plots to landscape: a k-NN-based method for estimating stand-level merchantable volume in the province of Québec, Canada. The Forestry Chronicle 86: 461–468.

Bettinger, P., K. Boston, J.P. Siry and D.L. Grebner. 2009. Forest management and planning. Academic Press, New York. 331 p.

Bouchard, M. 2009. Silviculture in the context of forest ecosystem management in boreal and southern boreal forest. *In* S. Gauthier, M.-A. Vaillancourt, A. Leduc, L. De Grandpré, D. Kneeshaw, H. Morin, P. Drapeau and Y. Bergeron (eds.). Ecosystem Management in the Boreal Forest. pp. 319–342. Presses de l'Université du Québec.

Brunson, M.W. 1996. A definition of "social acceptability" in ecosystem management. *In* M.W. Brunson, L.E. Kruger, C.B. Tyler and S.A. Schroeder (eds.). Defining social acceptability in ecosystem management: a workshop proceedings, 23–25 June 1992, Kelso, WA. pp. 7–16. USDA Forest Service, Pacific Northwest Research Station, Gen. Tech. Rep. PNW-GTR-369. Portland, OR.

Brunson, M.W. and B.S. Steel. 1994. National public attitudes towards federal rangeland management. Rangelands 16: 77–81.

Buongiorno, J. and J.K. Gilless. 2003. Decision Methods for Forest Resource Management. Academic Press, Boston, MA. 439 p.

Cheveau, M., L. Imbeau, P. Drapeau and L. Bélanger. 2008. Current status and future directions of traditional ecological knowledge in forest management: a review. The Forestry Chronicle 84: 231–243.

[CFOQ] Chief Forester Office of Quebec. 2011. Mise à jour sommaire des possibilités forestières 2008–2013 dans le cadre de la planification des attributions de bois pour l'année 2013–2014. http://www.forestierenchef.gouv.qc.ca/actualites/mise-a-jour-sommaire-des-possibilites-forestieres-pour-2013-2014/ [Accessed on September 29, 2011].

Cyr D., S. Gauthier, Y. Bergeron and C. Carcaillet. 2009. Forest management is driving the eastern North American boreal forest outside its natural range of variability. Frontiers in Ecology and the Environment 7: 519–524.

Davis, L.S., K.N. Johnson, P.S. Bettinger and T.E. Howard. 2001. Forest Management to Sustain Ecological, Economic and Social Values. McGraw Hill, New York. 804 p.

Environment Canada. 2011. Scientific assessment to inform the identification of critical habitat for woodland caribou (*Rangifer tarandus caribou*), boreal population, in Canada: 2011 update. Ottawa. 102 p. plus appendices.

Faille, G., C. Dussault, J.-P. Ouellet, D. Fortin, R. Courtois, M.-H. St-Laurent and C. Dussault. 2010. Range fidelity: the missing link between caribou decline and habitat alteration? Biological Conservation 143: 2840–2850.

Fenton, N., B. Harvey, L. Imbeau, C. Boudreault, P. Drapeau and Y. Bergeron. 2009. Silvicultural and Ecological Evaluation of Partial Harvest in the Boreal Forest on the Clay Belt, Quebec. *In* S. Gauthier, M.-A. Vaillancourt, A. Leduc, L. De Grandpré, D. Kneeshaw, H. Morin, P. Drapeau and Y. Bergeron (eds.). Ecosystem Management in the Boreal Forest. pp. 373–393. Presses de l'Université du Québec.

Fenton, N.J. and Y. Bergeron, 2006. Facilitative succession in a boreal bryophyte community driven by changes in available moisture and light. Journal of Vegetation Science 17: 65–76.

Flannigan, M.D., K.A. Logan, B.D. Amiro, W.R. Skinner and B.J. Stocks. 2005. Future area burned in Canada. Climate Change 72: 1–16.

Franklin, J.F. *et al*. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management 155: 399–423.

[FSC] Forest Stewardship Council. 2004. Forest Stewardship Council Principles and Criteria for Forest Stewardship. http://www.fsccanada.org/docs/fsc-std-01-001.pdf [Accessed on November 07, 2012].

Gauthier, S., M.-A. Vaillancourt, D. Kneeshaw, P. Drapeau, L. De Grandpré, Y. Claveau and D. Paré. 2009. Forest Ecosystem Management: Origins and Foundations. *In* S. Gauthier, M.-A. Vaillancourt, A. Leduc, L. De Grandpré, D. Kneeshaw, H. Morin, P. Drapeau and Y. Bergeron (eds.). Ecosystem Management in the Boreal Forest. pp. 13–37. Presses de l'Université du Québec.

Gauthier, S., T. Nguyen, Y. Bergeron, A. Leduc, P. Drapeau and P. Grondin. 2004. Developing forest management strategies based on fire regimes in northwestern Quebec. *In*: A. Perera, L.J. Buse and M.G. Weber (eds.). Emulating Natural Forest Landscape Disturbances: Concepts and Applications. pp. 219–229. Columbia University Press, New York.

Germain, R. 2012. Acceptabilité sociale de l'aménagement forestier écosystémique : le point de vue des Algonquins de Pikogan. M.Sc. thesis, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, QC. 195 p.

Germain, R. and H. Asselin. 2010. Zoning of potential for Aboriginal interest: a new decision-support tool in forestry. SFM Network Research Note Series No. 71. 4 p.

Groot, A., J.-M. Lussier, A.K. Mitchell and D.A. MacIsaac. 2005. A silvicultural systems perspective on changing Canadian forestry practices. The Forestry Chronicle 81: 50–55.

Government of Quebec. 2010. Loi sur l'aménagement durable du territoire forestier. http://www2.publicationsduquebec.gouv.qc.ca/dynamicSearch/telecharge.php?type=2&file=/A_18_1/A18_1.html [Accessed on November 07, 2012].

Haeussler, S. and D.D. Kneeshaw. 2003. Comparing forest management to natural processes. *In* P.J. Burton, C. Messier, D.W. Smith and W.L. Adamowicz (eds.). Towards Sustainable Management of the Boreal Forest. pp. 307–368. NRC Research Press, Ottawa, ON.

Harvey, B.D., A. Leduc, S. Gauthier and Y. Bergeron. 2002. Stand-landscape integration in natural disturbance-based management of the southern boreal forest. Forest Ecology & Management 155: 369–385.

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

Hovington, E., L. Imbeau and O. Valeria 2010. Woodland caribou habitat connectivity under different ecosystem-based management scenarios. SFM Network Research Note Series No. 67. 6 p.

Jacqmain, H., L. Bélanger, R. Courtois, C. Dussault, T.M. Beckley, M. Pelleter and S.W. Gull. 2012. Aboriginal forestry: development of a socioecologically relevant moose habitat management process using local Cree and scientific knowledge in Eeyou Istchee. Canadian Journal of Forest Research 42: 631–641.

Kimmins, J.P. 2004. Emulating natural forest disturbance: What does this mean? *In* A.H. Perera, L.J. Buse and M.G. Weber (eds.). Emulating natural forest landscape disturbances: concepts and applications. pp. 8–28. Columbia University Press, New York.

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

Larouche, M. 2008. La modélisation de scénarios d'aménagement forestier à l'échelle du paysage : un outil d'aide à la décision en foresterie autochtone. M.Sc. thesis, Université du Québec à Montréal, Montréal, QC. 80 p.

Leblond, M., J. Frair, D. Fortin, C. Dussault, J.-P. Ouellet and R. Courtois. 2011. Assessing the influence of resource covariates at multiple spatial scales: an application to forest-dwelling caribou faced with intensive human activity. Landscape Ecology 26: 1433–1446.

Mahalanobis, P.C. 1936. On the generalised distance in statistics. Proceedings of the National Institute of Sciences of India 2: 49–55.

Moreau, G., D. Fortin, S. Couturier and T. Duchesne. 2012. Multilevel functional responses for wildlife conservation: the case of threatened caribou in managed boreal forests. Journal of Applied Ecology 49: 611–620.

[MRN] Ministère des Ressources naturelles et de la Faune. 2003. Vegetation zones and bioclimatic domains in Quebec. Ministère des Ressources naturelles et de la Faune, Québec. 2 p.

Nguyen-Xuan, T. 2002. Développement d'une stratégie d'aménagement forestier s'inspirant de la dynamique des perturbations naturelles pour la région Nord de l'Abitibi. Rapport préliminaire de recherche effectuée dans le cadre du Volet I du programme de mise en valeur des ressources du milieu forestier présenté au Ministère des Ressources naturelles du Québec, Rouyn-Noranda. 36 p.

Payette, S. 1992. Fire as a controlling process in the North American boreal forest. *In* H.H. Shugart, R. Leemans and G.B. Bonan (eds.). A systems analysis of the global boreal forest. pp. 144–169. Cambridge University Press, Cambridge, UK.

Pothier, D. and F. Savard. 1998. Actualisation des tables de production pour les principales espèces forestières du Québec. Ministère des Ressources naturelles, Direction des inventaires forestiers. RN98-3054.

Raymond, P., S. Bédard, V. Roy, C. Larouche and S. Tremblay. 2009. The irregular shelterwood system: review, classification, and potential application to forests affected by partial disturbances. Journal of Forestry 107: 405–413.

Rempel, R.S. and C.K. Kaufmann. 2003. Spatial modeling of harvest constraints on wood supply versus wildlife habitat objectives. Environmental Management 32: 646–659.

Robichaud, E. and I.R. Methven. 1993. The effect of site quality on the timing of stand break-up, tree longevity, and the maximum attainable height of black spruce. Canadian Journal of Forest Research 23: 1514–1519.

Robitaille, A. and J.P. Saucier. 1998. Paysages régionaux du Québec méridional. Les publications du Québec, Ste-Foy, Québec. 213 p.

Ruel, J.-C., V. Roy, J.-M. Lussier, D. Pothier, P. Meek and D. Fortin. 2007. Mise au point d'une sylviculture adaptée à la forêt boréale irrégulière. The Forestry Chronicle 83: 367–374.

Saint-Arnaud, M., H. Asselin, C. Dubé, Y. Croteau and C. Papatie. 2009. Developing Criteria and Indicators for Aboriginal Forestry: Mutual Learning through Collaborative Research. *In* Stevenson M.G. and D.C. Natcher (eds.). Changing the Culture of Forestry in Canada. pp. 85–105. CCI Press and Sustainable Forest Management Network, Edmonton, AB.

Seymour, R.S. and M.L. Hunter Jr. 1999. Principles of ecological forestry. *In* M.L. Hunter Jr. (ed.). Maintaining Biodiversity in Forest Ecosystems. pp 22–61. Cambridge University Press, Cambridge, UK.

Shindler, B., P. List and B.S. Steel 1993. Managing federal forests: public attitude in Oregon and nationwide. Journal of Forestry 91(7): 36–42.

Simard, M., N. Lecomte, Y. Bergeron, P.Y. Bernier and D. Paré. 2009. Ecosystem Management of Quebec's Northern Clay Belt Spruce Forest and Especially the Soils. *In* S. Gauthier, M.-A. Vaillancourt, A. Leduc, L. De Grandpré, D. Kneeshaw, H. Morin, P. Drapeau and Y. Bergeron (eds.). Ecosystem Management in the Boreal Forest. pp. 257–286. Presses de l'Université du Québec.

Stocks, B.J. *et al*. 2002. Large forest fires in Canada, 1959–1997. Journal of Geophysical Research 108: 1–12.

Tembec Inc. 2007. General Forest Management Plan: FMU 085-51 Period: 2008–2013.

Thorpe, H.C. and S.C. Thomas. 2007. Partial harvesting in Canadian boreal: Success will depend on stand dynamic responses. The Forestry Chronicle 83: 319–325.

Tittler, R., C. Messier and A. Fall. 2012. Concentrating anthropogenic disturbance to balance ecological and economic values: applications to forest management. Ecological Applications 22: 1268–1277.

Treseder, L. and N.T. Krogman. 1999. Features of First Nation forest management institutions and implications for sustainability. The Forestry Chronicle 75: 793–798.

Vanderwel, M.C., J.R. Malcolm and S.C. Mills. 2007. A meta-analysis of bird responses to uniform partial harvesting across North America. Conservation Biology 21: 1230–1240.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8: 220–227.

Vors, L.S., J.A. Schaeffer, B.A. Pond, A.R. Rodgers and B.R. Patterson. 2007. Woodland caribou extirpation and anthropogenic landscape disturbance in Ontario. Journal of Wildlife Management 71: 1249–1256.

Weintraub, A. and A.T. Murray. 2006. Review of combinatorial problems induced by spatial forest harvest planning. Forest Ecology and Management 154: 867–879.

Wittmer, H.U., B.N. McLellan, R. Serrouya and C.D. Apps. 2007. Changes in landscape composition influence the decline of threatened woodland caribou population. Journal of Animal Ecology 76, 568–579.

Wyatt, S. 2008. First Nations, forest lands, and "aboriginal forestry" in Canada: from exclusion to comanagement and beyond. Canadian Journal of Forest Research 38: 171–180.

Wyatt, S., M.-H. Rousseau, S. Nadeau, N. Thiffault and L. Guay. 2011. Social concerns, risk and the acceptability of forest vegetation management alternatives: insights for managers. The Forestry Chronicle 87: 274–289.