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Projections of future forest age class structure under the influence of fire and harvesting: implications for forest management in the boreal forest of eastern Canada

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In northeastern Canadian boreal forests, a coarse-filter approach was adopted to provide sustainable ecosystem services in order to maintain a balance between biodiversity, ecosystem function and timber production. An old forest (>100 years) maintenance target was established considering the range of historical variability in the proportion of this forest stage. However, the estimation of the harvesting rate that maintains the target level in old forests did not consider explicitly the impact of current and future, i.e. possibly higher, fire frequency. In this context, we compared historical, current, and future age structures according to recorded or projected fire activity and the current level of harvesting in western Quebec's boreal forest. Results show that under the current rates of harvesting and fire, the proportion of old forests could reach a minimum level rarely seen in the natural landscape in the past. The situation could become even more critical with the projected increase in fire activity under climate change. Numerous forest and fire management solutions exist, such as increasing rotation length, implementing a diversified silviculture, using a fire-smart approach or reaching a better balance between intensive management and conservation. We advocate their rapid implementation to reverse the projected decrease in the proportion of old forests.

Introduction

The United Nations Conference on Environment and Development in 1992 (Earth Summit, Rio de Janeiro, Brazil) issued a statement of principles that led to the first global agreement on the management of forest ecosystems. The main emphasis was to include an ecologically sustainable approach in the management of forest ecosystems worldwide. Under this approach, at the ecosystem level, forest management should ensure the maintenance of forest ecosystem resilience and biodiversity, while also meeting society's needs (Lindenmayer *et al.*, 2000). Ecosystem resilience is a fundamental component of ecosystem service assessment and could be defined as the ability of the forest ecosystem to withstand and recover from disturbances to provide ecosystem services and goods (Kandziora *et al.*, 2013).

Starting in the 1990s, the goals of forest management set by governments, institutions and the forest industry have greatly diversified to include various aspects of ecological, social and cultural sustainability. These trends have paralleled our improved understanding of the ecological dynamics and biodiversity of unmanaged boreal forests (Angelstam and Kuuluvainen, 2004; Bergeron *et al.*, 2004; Gauthier *et al.*, 2009; Shorohova *et al.*, 2009; Kuuluvainen and Aakala, 2011). In the accumulated body of research, two conclusions are particularly important for forest restoration and management . First, it has become evident that the unmanaged boreal forest displays high variability in structure and dynamics, which is important for biodiversity and ecosystem functioning (Kuuluvainen *et al.*, 2015). Second, unmanaged boreal forest typically contains a high component of forest older than the industrial forest rotation (typically 70–100 years for Canadian boreal forests; Cyr *et al.*, 2009; Kuuluvainen, 2009). These ecological findings are of fundamental importance because such intrinsic ecosystem properties define ecological constraints on how the forest should be managed or restored without losing its defining properties or diminishing the ecological services it provides.

According to recent global forest resources assessment, 35 per cent of the global forest area is classified as primary forest (FAO, 2015). The UN Convention on Biological Diversity encourages the conservation of old forests to create habitats of high value for the protection of biological diversity. The majority of old forests are located in the boreal and temperate regions of the Northern Hemisphere (Mackey *et al*., 2015). Indeed, most Canadian boreal forest regions have retained their structural and biological diversity due to the existence of a high proportion of inaccessible forests (Mackey *et al*., 2015), but the increase in the demand for wood products has led to the expansion of commercial logging activities towards northern boreal regions. Expansion of harvesting activities to the north implies operational constraints due to the increase in distance to processing mills and poor road infrastructure (Jobidon *et al*., 2015) that make forest management less profitable for the forest industry. In addition to harvest, these are fire-prone, low productivity regions, and this could possibly speed up the loss of biodiversity and habitats at a global scale (Powers *et al*., 2013).

Currently, despite recognition of the importance of preserving old forest, forest management still predominantly employs clear-cut harvesting with short rotations relative to the mean interval between natural disturbances. Such even-aged silvicultural systems tend to reduce the proportion of older forest stands while homogenizing the forest structure (Bergeron *et al*., 2006; Bouchard and Garet, 2014; Dhital *et al*., 2015; Kuuluvainen *et al*., 2015). This management regime may result in the loss of biological and structural diversity (Venier *et al*., 2014), thereby reducing ecosystem resilience (Kuuluvainen, 2009), particularly in a climate change context (Gauthier *et al*., 2015b).

In its new Forest Act, the Gouvernement du Québec (2015) includes ecosystem management, so forest managers are required, among other things, to target an age class structure within the regional natural range of variability that was historically created by fire (Landres *et al*., 1999). However, the expected global change in future climate (Hansen *et al*., 2006) will likely have a negative impact on boreal forests with a potential decrease in forest productivity due to summer droughts (Girardin *et al*., 2016), and changes in forest age structure and tree species composition (Gauthier *et al*., 2014, 2015b) due to an increase in burn rates (Bergeron *et al*., 2006). These changes could result in decreases in future timber supplies (Dhital *et al*., 2015; Gauthier *et al*., 2015a). Consequently, climate change will probably reduce the trade-off space existing between the supply targets required for a profitable forest industry, biodiversity conservation and climate change mitigation (Lemprière *et al*., 2013).

In that context, our objective was to assess the impact of current and future fire activity on the ability to reach and maintain an age structure target. More specifically, we aimed to assess the current (2010) and projected (2050) distribution of forest age classes at the scale of forest management units (FMUs) in relation to fire and harvesting rates. We conducted the study over a large region (area: 126 000 km^2) of the boreal forest in the northern zone of Quebec's managed forest in eastern Canada. In this region, there are specific targets of old forest maintenance that need to be included in all management plans (Jetté *et al*., 2013; Bouchard *et al*., 2015). Moreover, this area provided us with a large range of historical disturbance rates, including an east–west gradient of burn rate and a north–south gradient of harvesting rate (Grondin *et al*., 2014). To reach our objectives, we reconstructed and projected the age class structure using a variety of databases. We projected the future proportion of old forest up to 2050, based on the current harvesting rate and the current or future projected burn rate under climate change. We then compared our results with the targets fixed by the provincial government to maintain a natural range of variability and examined the impact of forest management strategies on the maintenance of old forests.

Methods

Study area

The region selected for this study is located in the western black spruce feathermoss bioclimatic subdomain of Quebec (Robitaille and Saucier, 1998, area of 126 000 km^2, Figure 1). Fire is a dominant disturbance agent in this region. Fire cycle (as estimated with the fires that occurred between 1972 and 2009) varies from 67 to >1000 years (Gauthier *et al*., 2015c). Harvesting activities began ca. 1900 and have intensified in the later part of the twentieth century (Figure 1). The topography is generally flat in the western part of the region and dominated by thick glaciolacustrine clay deposits originating from the proglacial Lake Ojibway (Robitaille and Saucier, 1998). Topography is more broken in the central region with till-rich plateaus and, to the east, more accentuated, with rocky or till-covered hilltops (Messaoud *et al*., 2007). Mean annual temperature is 0.65°C with an average growing season of 165 days. Mean annual precipitation is 700 mm. This forest is dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) and, to a lesser extent, by jack pine (*Pinus banksiana* Lamb.). The other species are aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.) and white spruce (*Picea glauca* (Moench) Voss). The understory vegetation is composed of *Sphagnum* spp., feathermosses (mainly *Pleurozium schreberi* [Brid.] Mitt.), and ericaceous species (*Rhododendron groenlandicum* (bog Labrador tea), *Kalmia angustifolia* (dwarf-laurel), *Vaccinium angustifolium* (low sweet blueberry) and *Vaccinium myrtilloides* (velvetleaf blueberry)).

We obtained a map of FMUs from the ministère des Forêts, de la Faune et des Parcs du Québec (MFFP; Quebec's department responsible for forest management) and used by the Chief Forester's Office for their last timber supply calculations (2013–2018), from which we extracted delimitations of FMUs and the share of timber production and protected areas. Only FMUs that had more than 75 per cent of their area included in our study area were selected (19 units in total, with FMU areas varying between 700 and 22 200 km^2).

In the current management plan of the study area, there is a requirement to maintain a minimum amount of old forest over the planning period. The historical proportion of old forest was derived from simulations based on disturbance regime data from previous studies covering fire history and spruce budworm outbreaks for the last 200 years at the scale of FMUs (Bouchard *et al*., 2015; Table 1). This provided the historical median abundance of old forest (hereafter, historical amount of old forest), which was then used by the MFFP to set an old forest maintenance target aimed at maintaining a minimum of 30 per cent of the historical old forest proportion over 80 per cent of the area of each FMU (Jetté *et al*., 2013; Table 1). This threshold was based on a meta-analysis by Andrén (1994) concerning the fragmentation effect on bird and mammal species. When setting this target, no provision was made for the impact of current fire frequency as well as the possible increase in fire activity due to climate change on the proportion of old forest.

Determination of forest age class structures for the year 2010

An estimation of the proportion of old forest in 2010 without harvesting was carried out to be used as the baseline to evaluate the pressure already exerted by harvesting on the proportion of old forest. We derived two forest age class structures for the year 2010 (Table 1): one with

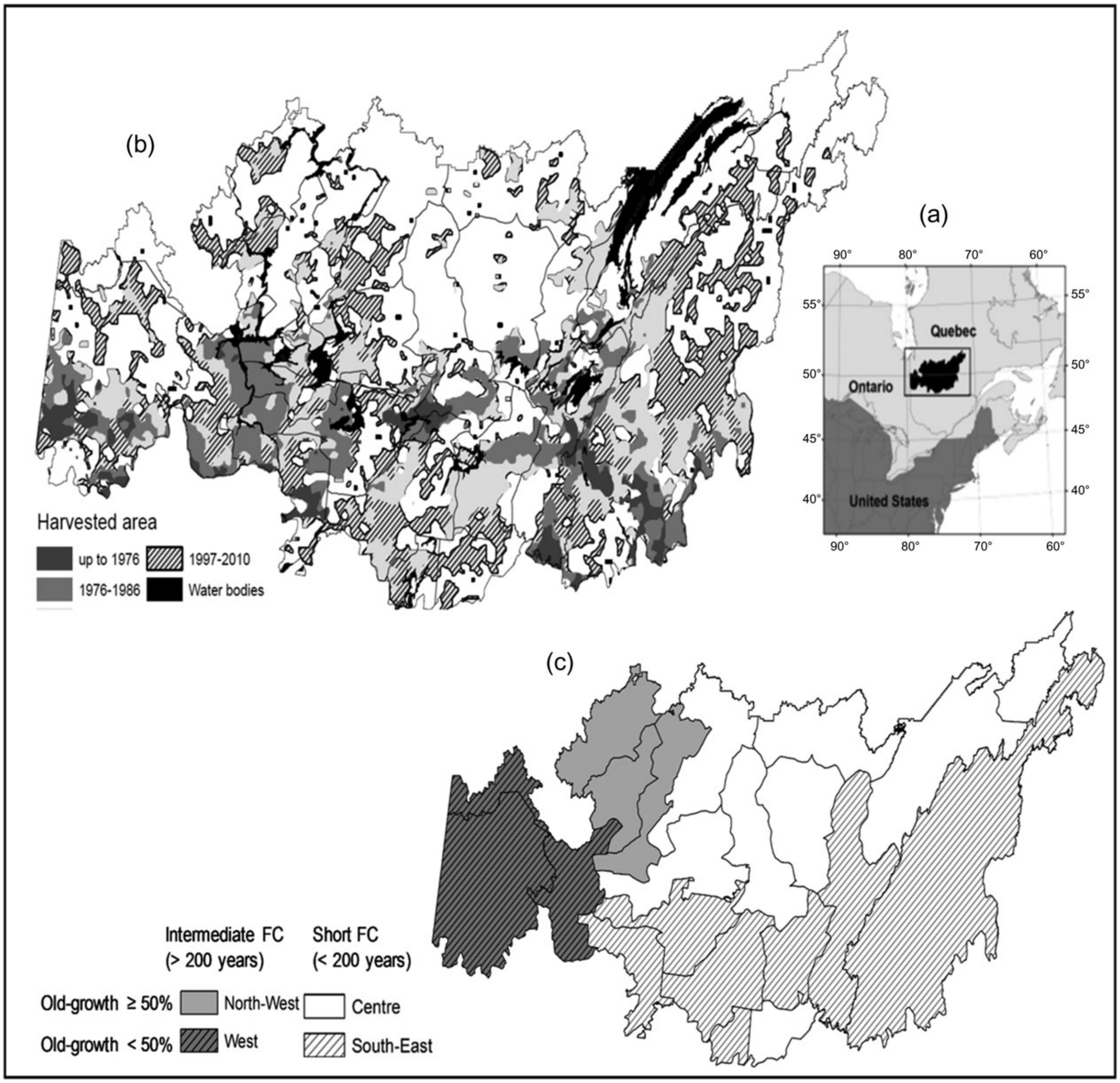

Figure 1 Map showing the location of the study area (a) and the area covered by clear-cut harvesting over time on the landscape within the study area (b). Harvesting data were derived from the SIFORT geodatabase updated to 2010. Map of forest management units (FMUs) (c). The study area was divided into four regions on the basis of historical fire cycle (FC) data (short: white; intermediate: dark grey; Bouchard *et al*., 2015) and the proportion of old forest that should have been observed if no harvesting had occurred (hatched: less than 50 per cent; no hatching: more than 50 per cent). See Supplementary data for specific FMU information on harvesting rate and proportion of old forest.

both fire and harvesting (managed) and one with fire only (natural). We used the following age classes: 0–20 (10), 21–40 (30), 41–60 (50), 61–80 (70), 81–100 (90), and >100 years old (100+). First, when considering both fire and harvesting, the age class structures were directly derived from SIFORT (an information system on forest composition based on a raster geodatabase (Pelletier *et al*., 2007) established by MFFP). This database is derived from the photointerpretation of aerial photographs (scale: 1:15 000) taken between 1990 and 2000 (corresponding to the third inventory programme). Each SIFORT unit matches a rectangular tile of 15° of latitude and 15° of longitude, covering ~14 ha (hereafter pixels), and provides information on forest stand composition, age, cover density, height, soil characteristics and past disturbances. We further updated this database to 2010 using the forest maps updated yearly by the MFFP to account for harvesting operations. As forest age classes in this database are determined by photointerpretation and have some uncertainty, we used inventory forest sample plots provided by the MFFP to take this into account. This inventory covers the whole study region at a relatively high density (8 plots/100 km^2). For each age class mapped, we computed the standard deviation of the difference between the age on the map and the age of the plots. We then derived a normal distribution centred on 0 using this standard deviation; from which negative and positive values can be applied to the age class mapped in order to reflect the uncertainty (see below for more details on how it was used).

Second, to obtain the age structure with fire only (natural) in 2010, we needed to evaluate the age class structure in harvested pixels. To do

Table 1 Description of comparison values, current age structure definition and description of the different simulation scenarios.

Information	Explanation	Information provenance
Historical values	Median of historical proportion of old forest (>100 years) based on simulation of disturbance regime over the last 200 years for each FMU.	Bouchard *et al.* (2015)
Target values	Maintain at least 30% of the historical values over 80% of the FMU.	Jetté *et al.* (2013)
Current age classes		
Current age class with fire and harvesting (2010)	The age class observed in the forest in 2010.	Based on MFFP forest inventory data
Current age class with fire only (2010)	It represents an estimation of the age structure in 2010 if harvesting had not occurred.	Based on MFFP forest inventory data and age reconstruction of the harvested stands from Irulappa Pillai Vijayakumar *et al.* (2015)
Future age classes		
Without harvest, with current fire	An estimate of the amount of old forest present in the future with current future fire activity.	Simulation from 2010 to 2050 using recent burn rate and its variability.
Without harvest, with future fire	An estimate of the amount of old forest present in the future with projected future fire activity.	Simulation from 2010 to 2050 using projected burn rates from Boulanger *et al.* (2014) with no variability.
With harvest, without fire	The estimate at which the ability to maintain the target until 2050 is currently set.	Simulation from 2010 to 2050 using harvesting rates derived from Bureau du Forestier en chef (2015)
With harvest, with current fire	An estimate of the amount of old forest present in the future under current fire activity and current harvesting rates.	Simulation from 2010 to 2050 using recent burn rate and its variability and harvesting rates derived from Bureau du Forestier en chef (2015)
With harvest, with future fire	An estimate of the amount of old forest present in the future under projected future fire activity and current harvesting rates.	Simulation from 2010 to 2050 using projected burn rates from Boulanger *et al.* (2014) with no variability and harvesting rates derived from Bureau du Forestier en chef (2015)

so, we used the age class distribution of the time since the last fire map-(1880–2000, 120 years) of Irulappa Pillai Vijayakumar *et al.* (2015), which also allowed for an evaluation of the uncertainty around the age class. Irulappa Pillai Vijayakumar *et al.* (2015) did not provide a time since last fire value for cells when 50 per cent or more of their area had been disturbed by harvesting before 2000 (8.6 per cent of the pixels mapped). In this case, we used the natural disturbance interval estimated by Bouchard *et al.* (2015) to which we attributed an age class derived from a negative exponential model (Van Wagner, 1978). Finally, to take recent fires into consideration, we updated the two age structures to 2010 using the 2000–2010 fire maps produced by the MFFP.

Projection of forest age structures to the year 2050

We used both age structures (with and without harvesting) at year 2010 and projected the age class structures of the FMUs up to 2050 for several scenarios (Table 1; Figure 2): (1) without harvesting, (2) at the current harvesting rate constrained to maintain a minimum proportion of old forests, but with no consideration for future fire occurrence, (i.e. what is currently used to assess if the proportion of old forest can be maintained over the next 40 years); and (3) as in the second scenario, but including the random occurrence of fire events (see below for more details) in the future. The scenario without fire represents a particular case in which assumptions about potential losses to fire are excluded based on the idea that forest would be entirely protected against fire either due to an increase in firefighting efficiency or to a decrease in future burn rate in the older age class due to change in forest cover composition (Terrier *et al.*, 2013, but see Bernier *et al.*, 2016). The third scenario makes it possible to estimate the proportion of old forest by taking both fire activity and harvesting rate into account. This scenario considers two different variants of fire activity: one based on the current fire activity and the other using projections of future fire activity (Table 1, Figure 2).

Using a non-spatially explicit modelling approach similar to that developed by Reed and Errico (1986; their equation (9)), we projected the future forest age structure for time periods of 20 years using FMUs harvesting rates and, for the scenarios that include fire, using the burn rate (see Supplementary data) from 2010 to 2050. Harvesting was only allowed in the timber production area, as FMUs include both protected and timber production areas. At the start of a new period, the area in the first age class is equal to the total area that has been disturbed (harvested or burned) during the preceding period, while the other age classes (30–90) are updated for each period by transferring the area left at the end of the preceding period to the next age class. The last age class (100+) is not upper-bound and, as a consequence, it cumulates all older ages into the same class.

To set the harvesting rate, we used data from publicly available timber supply calculations reports issued by the Chief Forester's Office (Bureau du Forestier en chef du Québec, 2015) for each FMU (Supplementary Material). A minimum harvesting age was set to 80 years so that harvesting could only occur in the last two age classes (90 and 100+), reflecting the slow growth of forest in the study area (Gauthier *et al.*, 2015c). Harvesting was simulated to occur first in the oldest age class (oldest-first rule, e.g. Gustafson *et al.*, 2000, as is usually practiced in the study area). A constraint was added to the simulation model to maintain the target of oldest age class, so as to prevent harvesting in this age class when its abundance was below a target value fixed by MFFP.

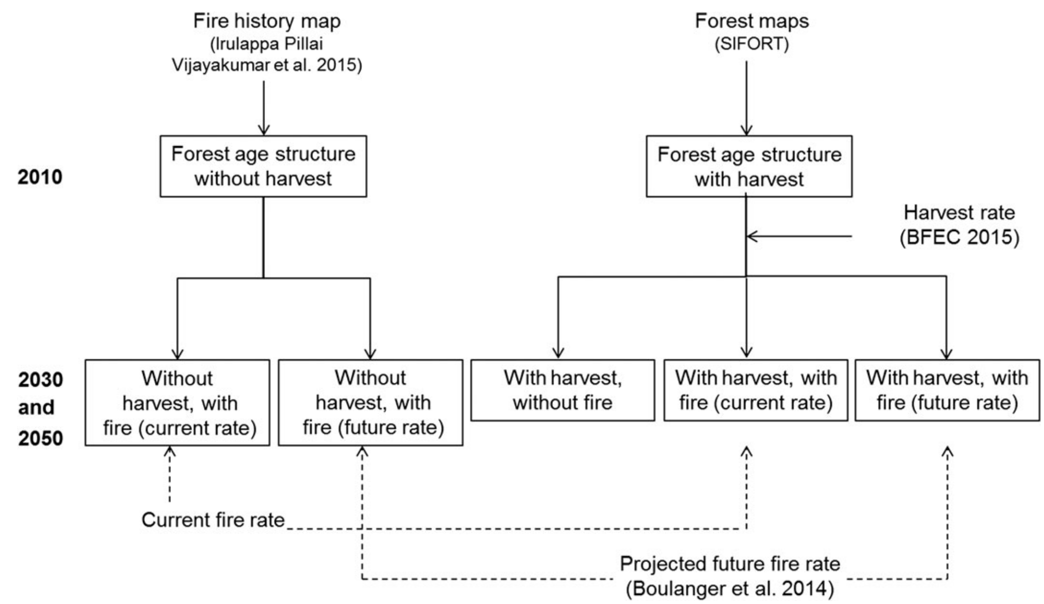

Figure 2 Age structure in 2010 and scenarios considered for the projection of old forest abundance for each forest FMU in 2030 and 2050.

To set burn rate, as in Reed and Errico (1986), we assumed that all stands have an equal probability of burning, regardless of their age. In the cases where we assumed the future burn rate would be the same as the one observed between 1972 and 2009 we used the annual burn rates for fire zones estimated by Gauthier *et al.* (2015c) . We therefore assumed that the past fire activity would remain the same for the next 40 years (i.e. the fire activity for the 2010–2050 period would be equivalent to that observed between 1972 and 2009). In this scenario, we assumed a future fire activity that would be similar to that of the recent past (similar climatic conditions, similar fire suppression policy and efficiency). For each 20-year period, we randomly picked (with replacement) 20 annual burn rates estimated between 1972 and 2009 for each fire zone to derive a periodic burn rate. For this purpose, we assumed that annual burn rates were independently distributed over time and that annual fire probabilities were similar to annual burn rates (Van Wagner, 1978). The burn rate observed during a given period of time (e.g. 20 years) was then equivalent to the complementary value of the probability of observing no fire during that period:

$$b_{20} = 1-\prod_{i=1}^{20}(1-b_i) \quad (1)$$

where b_{20} is the periodic burn rate for 20 years, and b_i is the annual burn rate.

In the cases for which fire activity was projected according to future climate projection, we used the future burn rates (2011–2040) provided by Boulanger *et al.* (2014). They developed a non-parametric model at the national scale for Canada by relating the observed burned area (1959–1995) to climate variables and then projecting burned areas using climate conditions provided by the IPCC SRES A2 scenario (Nakicenovic *et al.*, 2000) from the Canadian Regional Climate Model. In this scenario, which represents extremely severe fire-conducive conditions, no variation in periodic burn rate is simulated.

Number of simulations

All scenarios (Table 1) were computed at the FMU level and were repeated 1000 times to account for the uncertainty in age classes and the random nature of fire activity. The uncertainty related to the assessment of either mapped forest age or the age of the harvested forest was taken into account to allow for variation in the age distribution previously described in each simulation. Uncertainty was defined by error bars representing the 5th and 95th percentile of the replicates. For the burn rate, it varied following simulated scenarios (with the variability in recent empirical burn rates), while the harvesting rate derived from the data of the Chief Forester's Office was constant. For all scenarios, we assumed that the vegetation composition would not change significantly over the next few decades (Boulanger *et al.*, 2013).

From the 1000 runs, we computed the median proportion of old forest for each scenario and each period (see Supplementary data). Finally, to simplify the presentation of the results, we grouped the FMUs into four regions using the following two criteria: first, we divided the FMUs into two groups according to the fire cycle information provided by Bouchard *et al.* (2015), i.e. a short fire cycle (less than 200 years) or an intermediate fire cycle (between 200 and 1000 years). We then further subdivided these two sets according to the relative importance of old forests in the current age structure, to reflect the fact that the harvesting rate is non-uniformly distributed over the study area (Figure 1a). FMUs in which current old forests had more than of the expected median proportion (>50 per cent) estimated by Bouchard *et al.* (2015) were therefore grouped together (Figure 1b; see Supplementary Material for descriptive data on each FMU). We used the area's weighted mean of median values and of their deviation for each scenario to illustrate changes in the proportion of old forest from 2010 to 2050.

Comparison with the historical amount of old forest and the Government of Quebec targets

We had two different values against which we compared current and future proportions of old forest under all our simulated scenarios. First, we compared it against the median historical (last 200 years) values of old forest proportion as determined by Bouchard *et al.* (2015) and, second, against the target proportion set by MFFP for each FMU. Finally, in the cases where target values were not met under the current harvesting rate, we used scenarios in which the harvesting rate was gradually reduced (by increments of 1 per cent) until the minimum amount of old forest was reached.

Results

The proportion of old forest present in 2010 varied little (from 21 to 28 per cent) among regions (Figure 3) and, harvesting had already reduced the abundance of old forest in all regions. As shown by the age structure without harvesting in 2010, all four regions would present a proportion of old forest that should vary between 40 per cent (Centre) and 58 per cent (West) of their forested areas (Figure 3). The western part of the study area (West region) appears to be the most affected by past harvesting practices, with only 40 per cent of the expected amount of old forest remaining; the southeastern part follows with 45 per cent. The northern parts of the study region (North-West and Centre regions) appear more pristine, maintaining 56–65 per cent of their expected amount of old forest.

The amount of old forest that we estimated for 2010 without harvesting is similar to historical values, except for the North-West region, where it is lower (Figure 4). Projections of future age structure without harvesting result in an increase in old forest as compared with both 2010 and historical values if fire frequency remains similar to the current one in all regions (Figure 4). However, it would decrease in three regions should burn areas increase as projected for the future, reaching levels similar to historical values in the North-West region, or slightly lower for the Centre and South-East regions (Figure 4).

Even under a complete control of fires, when applying the target of old forest maintenance (without fire), the abundance of old forest decreases in the near future (Figure 4). Considering the current harvesting rate, i.e. 0.80 (Centre), 0.87 (West), 0.88 (North-West) and 1.00% y^{-1} (South-East), combined with either the current or the projected future burn rate (Supplementary Material), the abundance of old forest would drop in the future in most parts of the study area (Figure 4). With less than 1 (future burn rate) to 4 per cent (current burn rate) of old forest in 2050, the South-East region would register the most important drop. The Centre region does slightly better, with 9–17 per cent of stands older than 100 years by 2050. Both western regions perform better, with old forest abundance varying between a minimum of 14 per cent (West region with future burn rate) to a maximum of 28 per cent (North-West region with current burn rate; Figure 4). However, both regions are close to the minimum cut-off value set by Jetté *et al.* (2013): in the West region, both with current or projected fire activity whereas in the North-West region only under future fire projection, Figure 4.

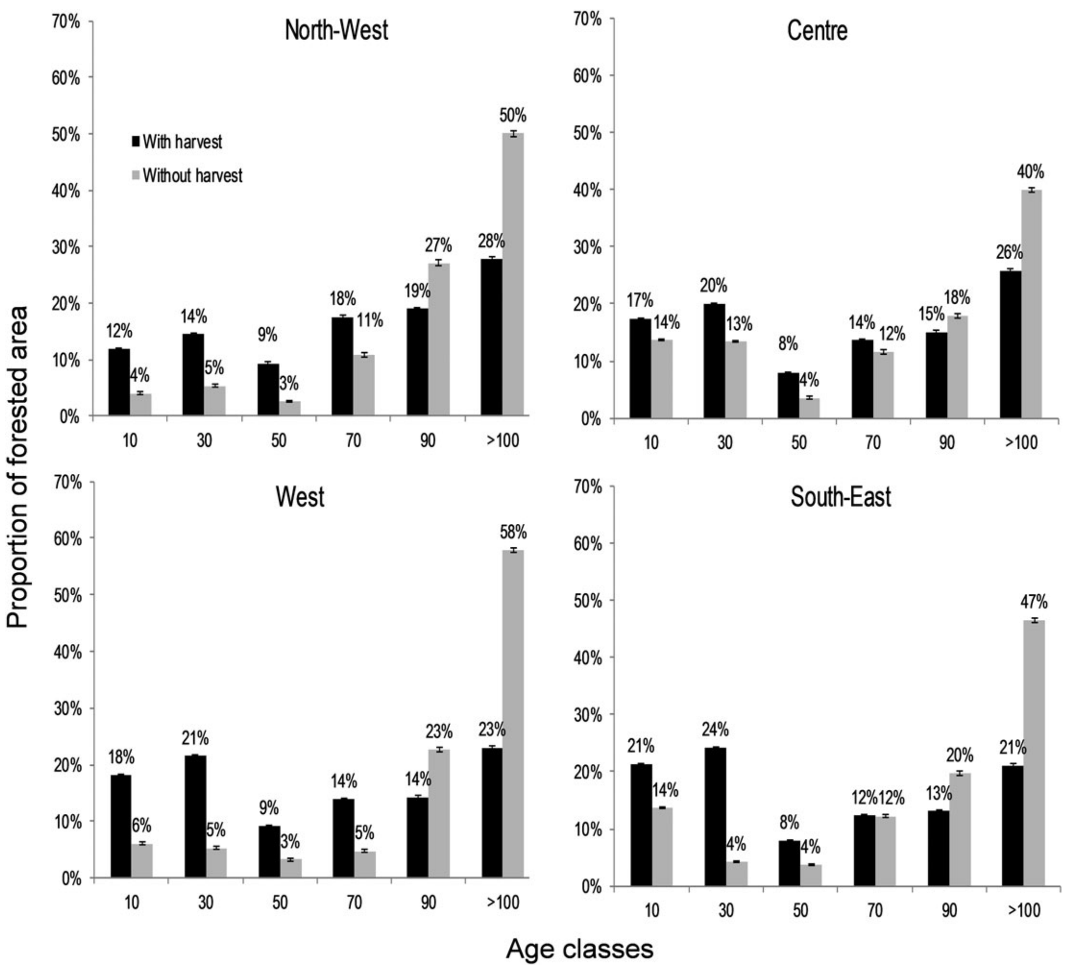

Figure 3 Forest age structures (aggregated by class of FMUs) for the year 2010 with fire only (light grey) or with fire and clear-cut harvesting (black) for the four regions of the study area (see Figure 1b). Error bars correspond to 95th percentile of 1000 simulation runs.

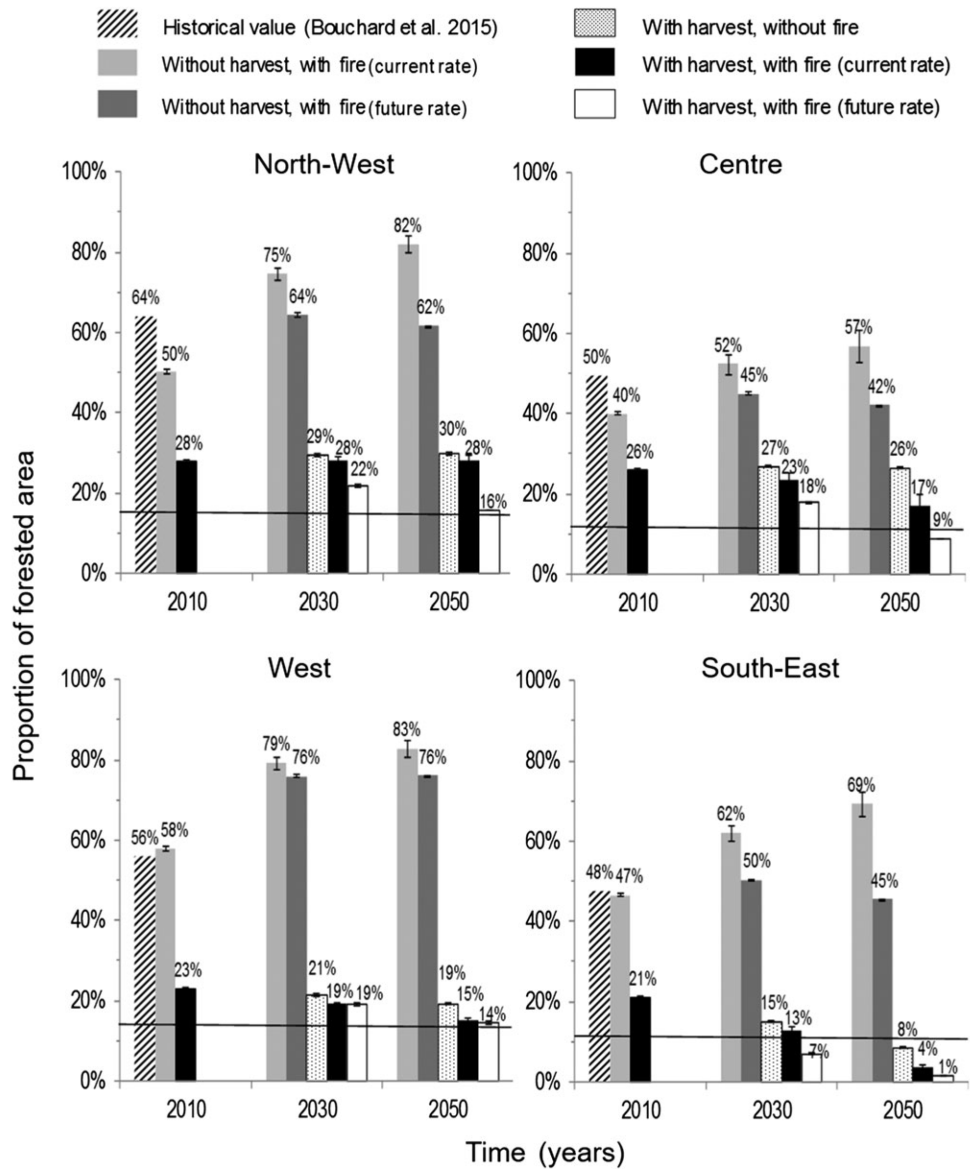

Figure 4 Abundance of old forests (>100 years) for the years 2010, 2030 and 2050, with or without harvesting, without fire or with current (1970–2010) or future (increasing – Boulanger *et al.*, 2014) burn rates. These proportions are compared with their historical values (Bouchard *et al.*, 2015). The black line corresponds to the targeted amount of old forest in management plans. For 2030 and 2050, values are the mean of the median values and of their deviation of old growth proportion obtained from 1000 simulations of each scenario.

In the South-East region, the clear-cut harvesting rate would need to be reduced by 36 per cent to maintain the proportion of old forest above its minimum value until 2050 under current burn rate conditions. If the burn rate increases due to climate change, clear-cut harvesting rates would have to be reduced by 26 and 61 per cent in the Centre and South-East regions, respectively.

Discussion

The fact that fire and harvesting regimes interact and exacerbate the loss of old forest is not a new observation. It has already been shown for many regions of Canada and Scandinavia (Cyr *et al.*, 2009; Bergeron and Fenton, 2012; Venier *et al.*, 2014; Kuuluvainen *et al.*, 2015). The main message in our assessment is that despite the recent efforts to maintain a minimum amount of old forest in the managed forest, the decreasing trend could continue (Figure 4) and soon reach critical levels that ecosystems have not experienced in the past.

The level at which the low abundance of old forests becomes critical is debatable. There is great variability in the response of individual species to habitat loss (Lindenmayer *et al.*, 2005). When marked changes in the pattern of species occurrence in remnants of suitable habitats do occur, a cut-off value between 10 and 30 per cent of that habitat is often identified (Swift and Hannon, 2010; Imbeau *et al.*, 2015). Cyr *et al.* (2009) looked at the complete Holocene period for western Quebec and estimated that during the Holocene, forests over 100 years old always accounted for more than 30 per cent in the landscape (with a mean of ca. 55 per cent). Cyr *et al.*'s (2009) results were obtained for a region with a relatively short fire cycle in western Quebec; therefore, in eastern Quebec, where current and, possibly Holocene burn rates were lower (Bouchard *et al.*, 2008; Remy *et al.*, 2017), the historical minimum amount of old forest might have been even higher. Using simulations, Bouchard *et al.* (2015) estimated that the lowest amount of old forest should be between 30 and 40 per cent in our study area. However, the current minimum cut-off value for the abundance of old forest in our study area for the year 2010, i.e. 30 per cent of the expected historical old forest amount over 80 per cent of the forested area (Table 1; Jetté *et al.*, 2013), corresponds to maintaining only 13–15 per cent of old forest (Figure 4). These values are below the historical minimum values observed in the above mentioned studies, and even those minimum values are difficult to sustain in all cases when future fire activity is included (Figure 4). In our simulations without harvesting (Figure 4), there is an increasing abundance of old forest. In fact, even when using an extreme scenario such as the future projection of burn rate that we are using, the amount of old forest would remain above 42 per cent by 2050. However, our results indicate that with the current rate of harvesting, the amount of old forest would decrease below the median value reported by Bouchard *et al.* (2015), indicating that the future decrease in old forest has more to do with the rate of clear-cutting than with the increase in future fire activity.

All simulation exercises involve an oversimplification of reality. In our case, we use a non-spatially explicit model that considers all productive stands to be available for harvesting. In reality, many stands can present a limited accessibility due to the surrounding topography. For instance, stands occupying steep slopes or located at the top of a hill may not be accessible for harvesting. When FMUs occur on rugged relief, the amount of residual forest that is unharvested due to limited access could represent a non-negligible proportion of landscape, thereby increasing the amount of old forest maintained. Our simulation takes into account conservation areas in the evaluation of the proportion of old forest but not inaccessible stands. However, it should be noted that, as these elements of the landscape are different in their physical set-up, they may not always have the same forest productivity as the harvested landbase. Therefore, their maintenance does not preclude the need to maintain part of the old productive forest.

The lack of variation in future projected burn rates can be seen as unrealistic. In fact, empirical data on fire occurrence show that burn rate varies from year-to-year and from decade-to-decade. The effect of climate change on variability in burn rate is largely unknown. In this regard, our simulations probably show an underestimated variability in the proportion of old forest in the future. The burn rate used in our simulations was also insensitive to vegetation composition. However, studies suggest that young forests especially if dominated by broadleaved trees may be more likely to be avoided by fire than old ones (Bernier *et al.*, 2016). This can contribute to reducing the regional burn rate, although it may decrease the amount of old forest even faster (Boulanger *et al.*, 2017).

Another simplification comes from the use of a constant harvesting rate over the 2010–2050 simulation horizon. In reality, harvesting rate is reviewed every 5 years by Chief Forester's Office in Quebec. Loss of mature and old forest areas to fire is therefore considered in each revision of the annual allowable cut. Managing fire loss *a posteriori* usually provides an opportunity to harvest more volume in the short term, but it may involve successive downward revisions of annual allowable cut (Savage *et al.*, 2011) and repeated hard negotiations opposing the forest industry to environmental group in the long run.

Potential solutions

Despite these limitations, our results also suggest that even the minimum proportion of old forest could be difficult to maintain with the projected harvesting rates under the current fire cycle in some regions, and in all regions until 2050 if the fire rate increases as expected due to climate change (Figure 4). Moreover, we have shown that meeting such minimum old forest targets for 2050 could imply a significant reduction in annual clear-cut harvesting rates (from 26 to 61 per cent) as shown for the two regions where the target could not be met especially if the change in future fire risk is included. As ecosystem management aims to somewhat reproduce the forest age structure resulting from historical fire frequency generally defined over a long period in the past, the low fire activity observed after the Little Ice Age, as compared with what happened before that period, offered the opportunity to replace fire with clear-cutting as a way to emulate natural disturbances (Bergeron *et al.*, 2002; Lauzon *et al.*, 2006; Gauthier *et al.*, 2009). In this context, harvesting was contributing to replacing fire in order to maintain a forest age structure that was more similar to the historical range of variability (Seymour and Hunter, 1999; Chaieb *et al.*, 2015). However, the decrease in old forest projected after 2010 clearly indicates that the possibility of replacing fire by clear-cutting will be decreasing in the future.

Many solutions in terms of forest or fire management are available to maintain old forests while minimizing the impact on allowable cuts and they have been proposed a long time ago (e.g. Seymour and Hunter, 1999; Bergeron *et al.*, 2002). In terms of forest management, the use of longer forest rotations to retain more old forest (Kneeshaw and Gauthier, 2003) is a possible strategy for minimizing the differences between a managed and a natural forest landscape (Burton *et al.*, 1999). Longer rotations negatively affect the level of periodic harvesting (e.g. Cissel *et al.*, 1999) and, therefore, the timber supply. Such a reduction needs to be compensated by a higher value for the harvested timber, which may come from larger log dimensions or from a different log processing that maximizes lumber recovery (Liu and Zhang, 2005). Reduction of the clear-cut harvesting rate can also be compensated by the use of partial cutting (Bergeron *et al.*, 2002; Garet *et al.*, 2012; Dhital *et al.*, 2015). However, partial cutting activities have been difficult to implement extensively because of their higher harvesting costs when compared with those of clear-cutting (e.g. Liu *et al.*, 2007). Again, higher costs can be compensated by the larger size of the harvested timber (Liu *et al.*, 2007; Moore *et al.*, 2012). Finally, increasing the proportion of protected forest can also increase the proportion of old forest and the loss of managed area could be compensated by a higher productivity in a portion of the FMU using intensive management. This approach, called Triad (Seymour and Hunter, 1992), is particularly interesting when the potential for increasing productivity is high (Tittler *et al.*, 2016).

Whatever the forest management solution(s) selected, current and future fires will have an impact on the remaining proportion of old forest. Maintaining old forest at their historical level is not only desirable for biodiversity, it could also be seen as a means of decreasing the risk of not being able to salvage the future burned forest (Leduc *et al.*, 2015). Such a trade-off may help compensate for some of the costs related to the implementation of old forest maintenance strategies. Manipulating forest composition in order to decrease fire susceptibility (fire smart strategy) could also be an alternative to decrease the loss of forest to fire (Terrier *et al.*, 2013; Girardin and Terrier, 2015). Improving fire suppression success could be done mainly in areas that are intensively managed since fire suppression is difficult to perform in remote areas that are more difficult to access (Gauthier *et al.*, 2005).

Conclusion

Trying to implement a minimum threshold of old forest without taking disturbance events into account could be seen as a hazardous practice in an environment that is at risk (Savage *et al.*, 2010). Our results clearly show that it will be difficult to meet and maintain the target fixed for the amount of old forest if the current rate of harvesting with clear-cutting remains the same, especially in the context of higher burn rates projected under climate change. Current management plans, however, include very few of the existing silvicultural alternatives to clear-cutting, fire smart strategies or intensive management solutions that could help maintain old forests. Fortunately, it is not too late to change forest management strategies as several solutions do exist. If these solutions are implemented rapidly, we still have a chance of maintaining the old forest stage that provides part of the ecosystem services we get from forested areas. Otherwise, we may have to face a situation where restoration will be the only remaining solution, the cost of which is known to be quite high.

Supplementary data

Supplementary data are available at *Forestry* online.

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Conflict of interest statement

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