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RESEARCH ARTICLE

Cumulative patterns of logging and fire (1940–2009): consequences on the structure of the eastern Canadian boreal forest

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Abstract
Context Although logging has affected circumboreal forest dynamics for nearly a century, very few studies have reconstructed its influence on landscape structure at the subcontinental scale.
Objectives This study aims to document spatiotemporal patterns of logging and fire since the introduction of logging in the early twentieth-century, and to evaluate the effects of these disturbances on landscape structure.
Methods We used historical (1940–2009) logging and fire maps to document disturbance patterns across a 195,000-km^2 boreal forest landscape of eastern Canada. We produced multitemporal (1970s–2010s) mosaics providing land cover status using Landsat imagery.
Results Logging significantly increased the rate of disturbance (+74 %) in the study area. The area affected by logging increased linearly with time resulting in a significant rejuvenation of the landscape along the harvesting pattern (south–north progression). From 1940 to 2009, fire was the dominant disturbance and showed a more random spatial distribution than logging. The recent increase of fire influence and the expansion of the proportion of area classified as unproductive terrestrial land suggest that regeneration failures occurred.
Conclusions This study reveals how logging has modified the disturbances dynamics, following the progression of the logging frontier. Future management practices should aim for a dispersed spatial distribution of harvests to generate landscape structures that are closer to natural conditions, in line with ecosystem-based management. The challenges of defining sustainable practices will remain complex with the predicted increase in fire frequency, since this factor, in combination with logging, can alter both the structure and potentially the resilience of boreal forest.

Keywords Disturbance pattern · Land use · Landsat · Forestry practices · Global change · Clear-cutting

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Introduction

Land use and natural disturbances are the main factors shaping the structure, composition and spatial organization of landscapes (Foley et al. 2005; Nowacki and

Abrams 2015; Turner and Gardner 2015). In the circumboreal forest, fire was the main stand-replacing disturbance prior to human influence. Throughout the Holocene, regional fluctuations of fire return intervals controlled the landscape structure and forest patch distribution (Zackrisson 1977; Payette 1992; Niklasson and Granström 2000). During the Anthropocene, increasing human-induced disturbances related to the introduction of large-scale industrial logging have modified natural disturbance regimes (Crutzen and Steffen 2003; Gauthier et al. 2015). Forest management activities increase the frequency of stand-replacing disturbances and can alter age structure and spatial organization of patches across the forest landscape (Spies et al. 1994; Löfman and Kouki 2003; Cyr et al. 2009; Boucher et al. 2015). Furthermore, the combined influence of fires and logging, in a context of global change with predicted increases in fire frequency (Bergeron et al. 2010; Gauthier et al. 2015), could promote more frequent compound disturbances and have cumulative effects on the structure of forest landscapes. These, in turn, could reduce productivity and erode resilience by affecting boreal tree species regeneration (Paine et al. 1998; Girard et al. 2008; Côté et al. 2013).

To our knowledge, despite the economic and ecological importance of forestry for northern countries, very few studies (if any) have analyzed the relative influence of logging versus fire history on boreal forest disturbance dynamics and its effect on landscape structure at the subcontinental scale (10^5 km^2). The main problem when monitoring very large, remote forest areas such as the boreal forest is the lack of detailed maps of historical forest conditions and disturbances. Historical ecology techniques are key tools for revealing past forest conditions and their transformation under the influence of disturbances and global change. In North America and Scandinavia, studies have quantified natural and human-induced disturbances at different scales, using historical records such as early land surveys or old forestry maps (Axelsson et al. 2002; Boucher et al. 2014). However, field measurements and photointerpretation are not only challenging and time consuming, but they may not be adapted for the study of global vegetation cover of large areas. In contrast, remote sensing with satellite-based sensors is probably the most effective way to map and monitor forest cover for large areas (e.g. Wulder and Nelson 2003). The Landsat series of satellites, activated in the early 1970s, has allowed consistent and continuous monitoring of forest cover structure over time. The exploitation of satellite images from freely accessible archives allow us to investigate the temporal evolution of the forest landscape; it has opened new avenues for understanding ecological and land cover dynamics (Cohen and Goward 2004; Hansen and Loveland 2012).

The aim of this study was to quantify, by combining historical disturbance maps and multitemporal (1970s–1990s–2000s–2010s) mosaics of Landsat images: (1) the spatiotemporal patterns of logging and fire since the introduction of industrial clear-cut logging ($\sim$1940), in order to evaluate (2) the relative influence of logging on disturbance regime and (3) their impact on the contemporary landscape structure of a large area (1.95×10^5 km^2) of the eastern North American boreal forest.

Methods

Study area

The study area covers a total of 195,450 km^2 of the boreal zone (Rowe 1972). It extends in central Quebec from lat. 49°00′N–52°00′N and from long. 75°00′W–66°00′W (Fig. 1) in the Canadian Shield's Greenville Province. The climate is subpolar, subhumid, with a short growing season and average temperatures ranging from −4.9 to +1.6 °C following altitudinal and latitudinal gradients. Annual precipitation varies from 700 to 1250 mm and gradually increases following a west–east gradient (Robitaille and Saucier 1998). The study area was divided into western and eastern sectors, which roughly coincide with Quebec's Saguenay–Lac-Saint-Jean and Côte-Nord administrative regions, respectively. The Côte-Nord region is characterized by a more rugged terrain composed of higher hills than the Saguenay–Lac-Saint-Jean region, where the landscape is dominated by rolling hills. The most abundant tree species in the study area, by far, is black spruce (*Picea mariana*). Balsam fir (*Abies balsamea*), white birch (*Betula papyrifera*) and trembling aspen (*Populus tremuloïdes*) are also present, mostly in the south of the study area. Early successional species (*Betula* and *Populus*) are more abundant in the southern part of the study area, due to a more favorable climate and anthropic disturbances such as

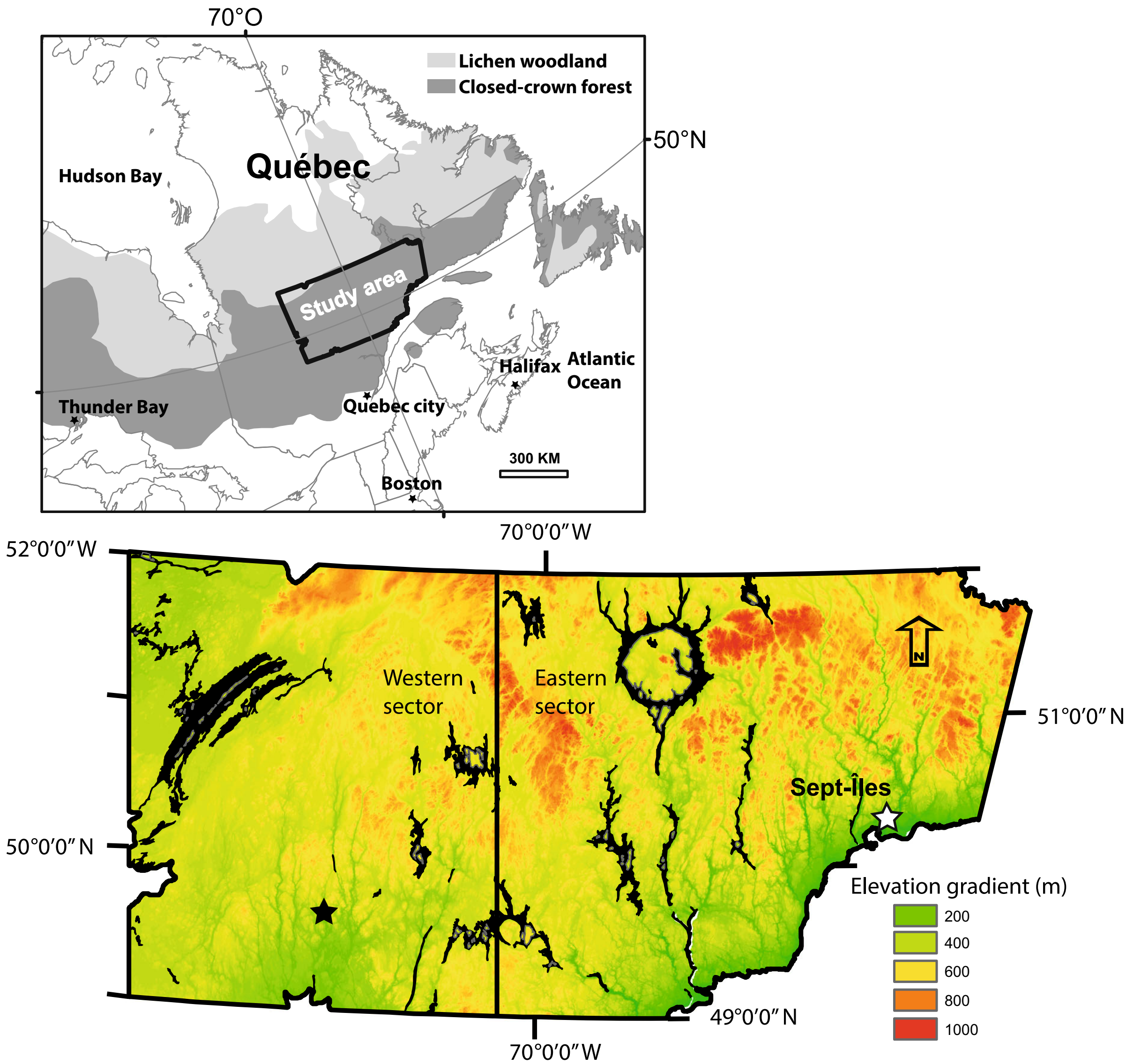

Fig. 1 Study area in the boreal forest of central Quebec, eastern Canada

escaped settlement fires and logging (Boucher et al. 2014). Since the early twentieth century, the forest industry has built large complexes of saw and pulp and paper mills which were among the most important in the world.

Dendroecological reconstructions have determined that over the last 200 years, the natural stand-replacing (>75 % mortality of forest cover) disturbance regime has been dominated by large fires with rotations (or cycles) varying from 100 to >500 years along a west–east gradient (Bouchard et al. 2008; Mansuy et al. 2010). Although the Cree and the Innu First Nations occupied the area well before the arrival of the first Europeans, nothing in the ethnographic literature indicates their use of fire, unlike what has been documented in other parts of northeastern North America (Munoz et al. 2014). Stand-replacing windthrows and insect outbreaks are also common disturbances, but have relatively minor effects on landscape structure at these latitudes (Boucher et al. 2011).

Mapping the relative influence of logging and fires during the twentieth century

We used Government of Quebec archives to document the history of fires and logging from 1940 to 2009 for the whole study area. The influence of fire was estimated using the province's fire database. Fire perimeters were delineated with the help of aerial photographs and/or Landsat images for the vast majority of fires (for details, see Mansuy et al. 2010). In contrast, areas affected by clear-cutting since the 1940s were compiled using the last 4 decennial surveys (from the 1960s to the 2010s), ecological forest mapping surveys conducted by the Government of Quebec using aerial photographs (scale 1:15,000). For each polygon delineated on the ecological forest map, the type of stand-replacing disturbance (fire, logged area, etc.) and the moment of the event (year of occurrence or time elapsed since the survey) are available. In addition, developmental stage (age class), tree cover type composition, and land occupancy (forest, water bodies, wetlands, unproductive terrestrial land) were also photo-interpreted in each survey. All ecological forest maps were validated in the field using a dense network of 0.04-ha terrestrial forest plots (50,137 plots established since the first survey) located using a stratified sampling design that aimed to characterize the study region's different stand and cover types (Bouchard et al. 2008; MFFP 2016). Landscape areas affected by fires or logging were calculated by decade and latitudinal zone over the entire study area and for each sector. Linear and quadratic relationships of the area affected by stand-replacing disturbances (fires or logging) over time (decades) were tested for each latitudinal zone, with the lm function in R (R Development Core Team 2015). To estimate the relative influence of logging and fires in our study area over the 1940–2009 period, we calculated the rotation (or cycle) of each disturbance, which is the time needed to disturb an area equivalent to the study area. The disturbance rotation was evaluated along the study area's latitudinal gradient using the technique proposed by Johnson and Gutsell (1994). First, the disturbance rotation (*DR*) was estimated with the following formula: $DR = 1/TA/PA/100$, where *TA* is the total area (%) affected by the disturbance and *PA* is the period of analysis (70 years: 1940–2009). The reciprocal value of DR then provides the % of landscape affected by each disturbance annually.

Evolution of the forest landscape structure (1970s–1990s–2000s–2010s)

Landscape structure at different periods (1970s, 1990s, 2000s and 2010s) was quantified by constructing 4 mosaics using mid-resolution Landsat satellite images. The images were acquired with different Landsat sensors depending on the period. For the ~1975 mosaic, Landsat 1, 2 and 3's Multispectral Scanner (MSS) was used, while Landsat 4 and 5's Thematic Mapper (TM) and Landsat 7's Enhanced Thematic Mapper (ETM+) were used for the most recent mosaics (~1990, ~2000 and ~2010). We adopted a 30-m spatial resolution for the mosaics for all Landsat sensors except the MSS instruments, for which it was 79 m. All imagery was geometrically resampled to a 60-m cell size to facilitate multitemporal analysis. For each mosaic, we selected a single-year image, taken on a day with very little cloud cover (<10 %) during the growing season (mid-June to late August). Clouds or hazy areas were masked. An alternative image (subsequent or preceding year) was chosen when the cloud cover threshold was not respected. Preprocessing operations involved 3 steps: (1) transformation from the original digital numbers into radiance values at sensor level, (2) correction of the luminance according to the relief using the C-correcting method (Li et al. 2012) and (3) normalization of all images used to create each mosaic (Yang and Lo 2000). The eastern and western sectors of the study area were divided into 2 independent sectors to overcome large radiometric differences observed during our preliminary tests. In all, 8 mosaics (2 per decade) were created, each containing from 8 to 13 separate images. Finally, we normalized the multidate mosaics of ~1990, ~2000 and ~2010 to obtain a uniform radiometric distribution for each mosaic and to allow informal visual comparisons. Unfortunately, the radiometric differences between the MSS sensor and the TM and ETM sensors were too important for us to normalize the ~1975 mosaic with the 3 others. Fortunately, each mosaic was classified independently. All mosaics composing the multitemporal land cover were preprocessed using Geomatica® OrthoEngine® 10.1 software (PCI Geomatics Inc. 2007).

We developed our own land classification system for this project. Other systems commonly used in Canada, such as the "Earth Observation for Sustainable Development of Forests" (EOSD from Wulder and Nelson 2003), do not clearly discriminate between the development stages of the boreal forest (i.e., young forests <40 years and closed-canopy forests ≥40 years, see below). However, like EOSD, we applied an unsupervised image classification to each mosaic using the clustering algorithm Iterative Self-Organizing Data Analysis Technique (ISODATA). This algorithm was modified from the k-means clustering algorithm to identify groups of pixels forming homogenous classes in terms of spectral signature (Jensen 2005). The 4 Landsat MSS bands were used for the analysis of the ~1975 mosaic. Bands 3, 4, 5 and 7 of Landsat 4, 5 and 7 were used for the 3 more recent mosaics because they were the most decorrelated and therefore allowed better vegetation discrimination among available bands (Jensen 2005). Our classification allowed us to identify, for each mosaic, the 4 following classes: (1) young forests (<40 years) with >25 % tree cover; (2) closed-canopy forests (≥40 years) with >25 % tree cover; (3) unproductive terrestrial land (areas occupied by rock outcrop or low-density forests [<25 % tree cover] where lichens, ericaceous shrubs or alder occupy most of the area); and (4) water bodies (lakes, rivers, and wetlands) (MFFP 2016). Our classification distinguishes only 2 wide age classes (less than 40 years, or 40 years and more). In the end, although we carried out many iterations in an attempt to discriminate older forest classes, we limited the older class to the biologically significant closed-canopy forests class, to ensure a robust classification using Landsat imagery. In contrast, young forests are known as a very important land cover class, since they limit habitat quality for many late-successional boreal forest species affected by human land use (Spies et al. 1994; Drapeau et al. 2009).

We used the forest maps of the 4 decennial forest inventories to regroup and label the clusters produced by the unsupervised ISODATA classification of each mosaic (~1975, ~1990, ~2000 and ~2010). The ISODATA algorithm was originally set to create a set of 30 spectral clusters which were individually inspected for labelling to a class. This manual inspection was made by looking at the histogram tied to each spectral cluster and using the class identified at points on the forest maps following a systematic grid. A large number of points were used for each mosaic: 188,143 (~1975), 245,873 (~1990), 262,460 (~2000) and 328,089 (~2010) for the western sector mosaics, and 114,594 (~1975), 148,374 (~1990), 127,784 (~2000) and 192,695 (~2010) for the eastern sector mosaics. Points were separated by a distance of 15 s in latitude and longitude. We inspected the histogram of all classes for each spectral cluster to label the cluster to the dominant class. We selected survey points on the forest maps to minimize the time gap between the acquisition date of the inventory photo and the remote sensing data. After completing the first pass for spectral labelling, we added water bodies to match pixels and the corresponding classes. Finally, to fine-tune our classification, we performed a second pass of the ISODATA algorithm to subdivide the clusters each of the 4 classes into 30 spectral clusters. This new subdivision allowed the redirection of small clusters that had been wrongly labelled during the first iteration. This two-pass classification procedure generated land maps of the 4 selected classes over the study area for 4 dates. In comparison to decennial forest inventories, remote sensing data provides a quick (same year) "snapshot" of the landscape features that is less expensive than a conventional photointerpretation method procedure, for which photos of the area must be acquired and interpreted during a 10-year cycle.

We assessed the accuracy of our classification for each mosaic using a cross-tabulation table (error matrix) to compare it with the ecological forest maps available from the 4 decennial forest surveys (1970s, 1990s, 2000s, 2010s). The forest maps used for validation were the same as those used for the training, but with randomly generated validation points instead of those from the systematic grid. The values from the random locations on the forest maps were extracted and compared with the class labelled from the application of our classification method. We followed the recommendations of Congalton and Green (1999) to define the number of samples needed to assess map accuracy when class proportions in the land cover map are unknown. We adopted the "worst-case" multinomial distribution algorithm: $N = B/4b^2$, where B is the upper $(\alpha/k) \times 100$th percentile of the Chi square (X^2) distribution with 1 degree of freedom, and k is the number of classes (in our case, 4). With 600 points, the validation provided a level of confidence of (α) of

95 % and a precision of 5 % for all k classes. These 600 validation points were generated randomly, for each mosaic within the study area where forest maps were available. Overall accuracy, users' and producers' accuracies, and the Kappa statistic were then derived from the error matrices. The Kappa statistic incorporates the off-diagonal elements of the error matrices (i.e., classification errors) and represents agreement obtained after removing the proportion of agreementt that could be expected to occur by chance.

Long-term monitoring is an important challenge that inevitably requires using diverse sources of information. In our study, we combined aerial photographs (ecological forest mapping surveys) and Landsat satellite images, two sources of data with distinct limitations. We used the 1960–2010 photographs of the decennial ecological forest surveys to document the 1940–2009 stand-replacing disturbance history. Based on our knowledge of the dynamics of the study area's forests and field validation in a similar region (Boucher and Grondin 2012), we determined that most stand-replacing disturbances were easily detectable on the air photographs and Landsat images for at least 20 years after they occurred. Therefore, we are confident that the documented disturbance chronology extends back to 20 years before the 1960s photographs used by the first decennial survey. However, small fires or cutovers that occurred before the 1960s are probably much harder to delineate. Despite this possible slight underestimation, recent disturbances (<20 years) contrast strongly in the landscape matrix. This makes us confident that our estimates over the 1940–2009 period are accurate, systematic, and unbiased.

The transformation of forest landscape structure can be evaluated effectively using Landsat archives (Spies et al. 1994; Healey et al. 2008). However, few studies (but see Healey et al. 2008) have tried to reconstruct forest structure using the first Landsat sensor (MSS) in combination with more recent and precise sensors (TM and ETM). The use of the MSS Landsat sensor is challenging for two reasons. First, the MSS sensor used older technology than the TM and ETM sensors, which translates into a poorer spatial and radiometric resolution, larger spectral bands, and fewer detectors per band. Second, the MSS sensor has no near-infrared sensor, an important element for studying vegetation structure. By their nature, therefore, measurements taken in the 1970s with the MSS sensor are less precise than those taken later using the TM and ETM sensors (Cohen and Goward 2004; Healey et al. 2008). This difference must be taken into consideration when interpreting the results.

Results

Temporal patterns of stand-replacing disturbances

Overall, from 1940 to 2009, the proportion of cutovers per decade increased linearly in the study area ($p = 0.0031$, $R^2 = 0.91$). First, it rose sharply from 0.24 % for 1940–1949, to a maximum of 4.0 % in 1990–1999. It then decreased to slightly over 3.6 % for 2000–2009 (Fig. 2). As for fires, they affected 1.41 to 3.67 % of the study area from 1940 to 1990, with no linear trend during these decades ($p = 0.4492$, $R^2 = 0.15$). In 1990–1999, fires increased sharply to 5.1 %, and finally peaked at over 5.9 % in 2000–2009 (Fig. 2). For each decade, a greater proportion of area was affected by cuts in the western sector compared to the eastern sector. In addition, a larger proportion of area was burned in the western sector compared to the eastern sector. The proportion of burned area peaked at 6.6–10.6 % during the last two decades, compared to a maximum of 2.7 % for previous decades (Fig. 2). From 1940 to 2009, cutovers displayed a contagious (clumpy) distribution (Fig. 3a) and extended progressively from south to north (up to around 50°30′N) (Figs. 3a, 4). By contrast, burned areas were more randomly dispersed over time at the scale of the study area (Figs. 3b, 4).

Spatial patterns of stand-replacing disturbances

The latitudinal distribution of logging areas contrasts strongly with that of fires (Table 1; Figs. 4, 5). In fact, when considering the total area affected since 1940 for each latitudinal zone, we observe that logging occupies progressively less area from south to north ($p = 0.0021$, $R^2 = 0.93$; Fig. 5). Logging is the primary disturbance agent in the southern portion of the study area (from lat. 49°N–50°30′N), and uncommon above the 50°30′N line. Also, for all mosaics, logging affected a greater relative area in the west (320-year rotation) than in the east (515-year rotation). In contrast, the relative area burned displayed a

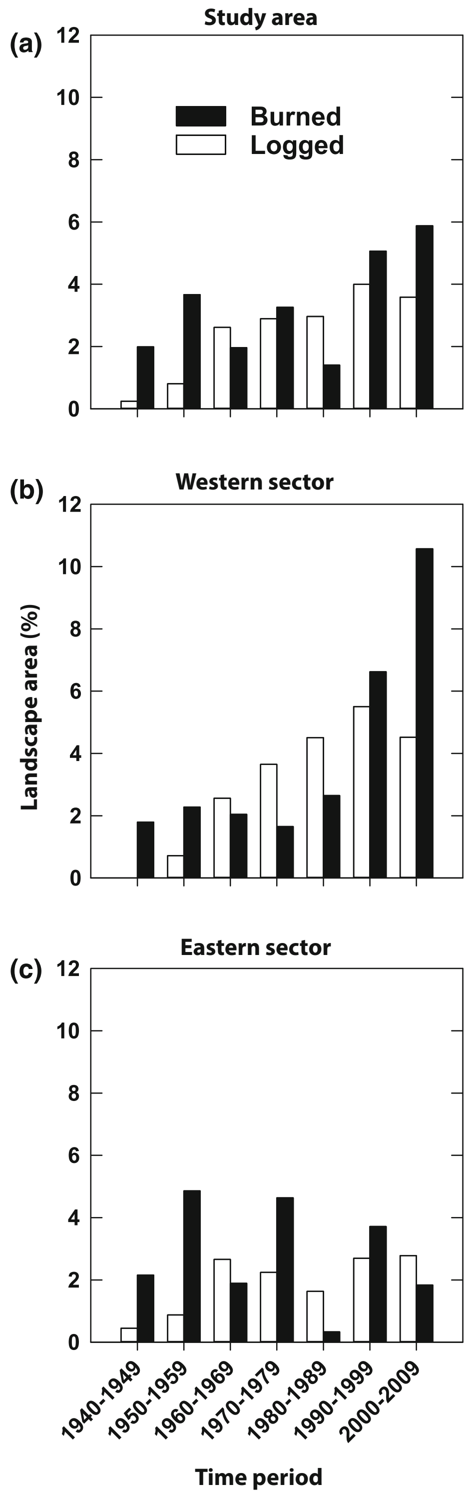

Fig. 2 Proportion of area logged or burned by decade between 1940 and 2009 for **a** the whole study area, **b** its western and **c** its eastern sector

quadratic relationship with the study area's latitudinal zones ($p = 0.0050$, $R^2 = 0.97$): it first decreased slightly from 22.4 to 12.3 % in the south (up to 51°N), then increased sharply up to 30.9 and 48.9 % in the northernmost section (Fig. 5).

When the impact of both logging and fires are combined, the western sector is most affected with a combined rotation period of 139 years, compared to 212 years for the eastern sector (Table 1). The overall cumulative impact of both disturbances for the entire study area has a rotation period of 170 years or an annual disturbance rate of 0.59 %/year. (i.e., 296 years for fire [0.34 %/year] and 402 years [0.25 %] for logging, Table 1). Consequently, logging causes a 74 % relative increase in the annual rate of disturbance, compared to a scenario where only fires are considered.

Mapping the evolution of forest structure

The confusion matrix (Table 2) indicates an overall accuracy ≥81.0 % for all periods except the 1970s, which showed a lower overall accuracy of 76.8 %. The Kappa statistics are 57.0, 67.7, 67.6, and 71.3 % for the ~1975, ~1990, ~2000, and ~2010 mosaics, respectively. Users' and producers' accuracies of individual classes varied from 83.6 to 91.1 % for the closed-canopy forests (≥40 years), from 42.2 to 73.7 % for young forests (<40 years), and from 42.4 to 64.0 % for unproductive terrestrial land. The errors are well distributed among the classes for all 4 periods except the 1970s, which was associated to most of the lower values. The low level of accuracy (<50 %) for both young forests and unproductive terrestrial land cover types and the fact that the Kappa statistic is below the substantial agreement threshold (62.0 %) forced us to abandon the ~1975 mosaic. Consequently, the remainder of the results concern the ~1990, ~2000 and ~2010 mosaics only. By limiting our analysis to mosaics created using more similar sensors, we opted for more reliable comparisons between each mosaic but inevitably, to the detriment of the temporal perspective.

From the 1990s to the 2010s, closed-canopy forests decreased by 12.8 % over the study area, from 60.0 to 56.4 % and then to 47.2 % (Fig. 6). Landscape structure shows that stand-replacing disturbance rate was higher in the western sector: for all periods, closed-

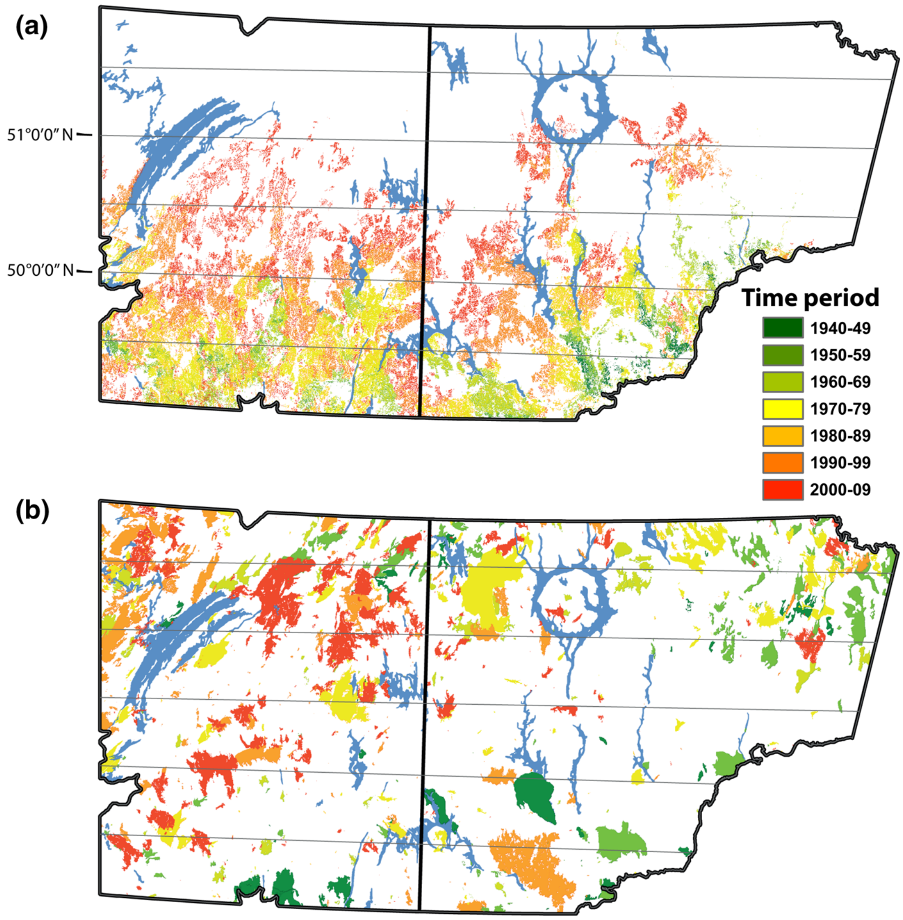

Fig. 3 Spatiotemporal distribution maps of **a** logged and **b** burned areas for the 1940–2009 period in the boreal forest of central Quebec, eastern Canada

canopy forests were less abundant in the western sector than in the eastern sector (Fig. 6). Over the latitudinal gradient, closed-canopy forests showed an inverted U-shaped distribution in the 1990s and the 2000s, and a more even distribution in the 2010s (Fig. 7a). For all latitudinal zone except the southernmost, closed-canopy forests decreased between 9.8 and 22.7 % from the 1990s to the 2010s. Forests located between latitudes 50°′N and 50°30′N decreased the most. Young forests increased gradually to represent 14.2, 17.0, and 21.5 % of the study area in the 1990s, 2000s, and 2010s, respectively. They increased by 1–16 % from the 1990s to 2010s in all latitudinal zones, and nowadays are more abundant at lower latitudes (<50°30′N) (Figs. 6, 7b). Finally, the proportion of unproductive terrestrial land also increased consistently over time: 15.1 % in the 1990s, 17.0 % in the 2000s and 19.9 % in the 2010s (Fig. 6). This proportion clearly increased along the latitudinal gradient (Fig. 7c). Considering the fact that the vast majority of lands classified as unproductive terrestrial land consists of rocky outcrops and low-density forests and that the abundance of rocky outcrops remains relatively constant through time, our results suggest that the relative abundance of low-density forests increased sharply (from 15.1 to 19.9 %, a difference of 4.8 %) from the 1990s to the 2010s (Fig. 6).

Discussion

To our knowledge, this study is the first to quantify the spatiotemporal patterns of industrial logging and fire at the subcontinental scale and to evaluate their cumulative impacts on the structure of the boreal forest. The use of diverse archival sources was

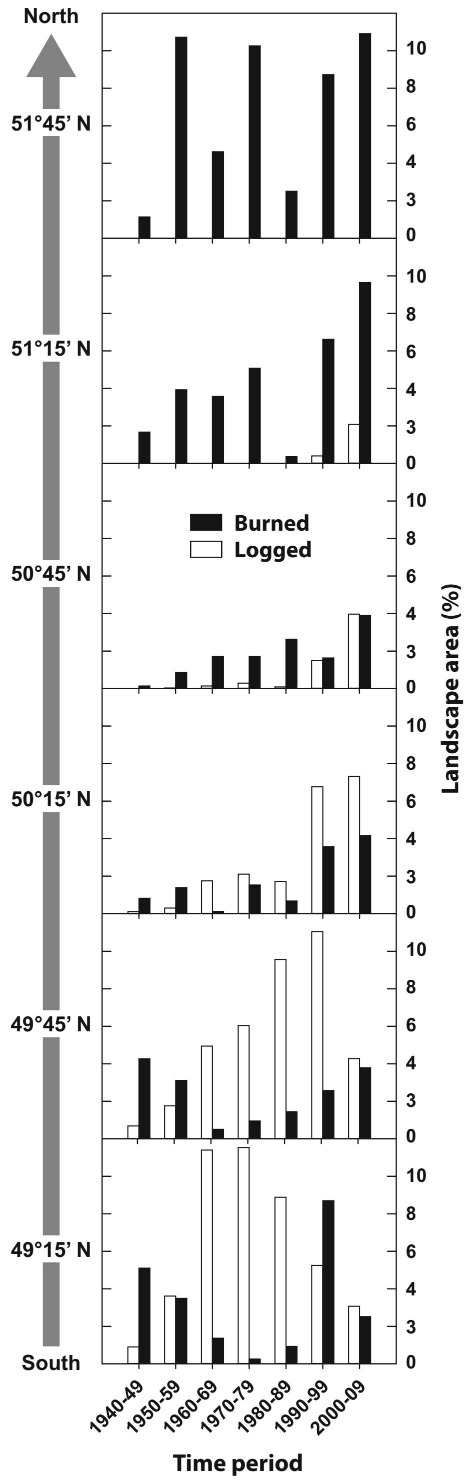

Fig. 4 Distribution of relative logged and burned areas for the 1940–2009 period according to latitudinal gradient in the boreal forest of central Quebec, eastern Canada

essential to reconstruct the stand-replacing disturbances that occurred over the last 70 years and to quantify the evolution of landscape structure. The vast extent of the study area allowed us to document disturbance dynamics and landscape structure patterns that are only revealed at large spatial and temporal scales. The spatio-temporal footprint of logging and fire display a strong contrasting distribution pattern according to latitude, which is reflected in the contemporary structure of the landscape.

Spatiotemporal patterns

Since the early twentieth century, the introduction of logging and the intensification of forest industry activities strongly increased the frequency of disturbances, following a contagious south-north distribution pattern. This pattern was triggered by the construction, in the first part of the twentieth century, of several saw and pulp and paper mills in the south of the study area, downstream of a dense river system allowing log floating (Côté 1999). Because log floating was the main way to transport timber to mills, forests were logged first in the south, along main rivers. In the 1960s, after many decades, log floating was gradually abandoned in favor of truck transport, which was then facilitated by the densified global road network (Judd 1989; Törnlund and Östlund 2002; Nilsson et al. 2005). Since then, the logging frontier has extended northward, and harvesting activities (ca 2016) are now concentrated around the 51st parallel. The smaller influence of logging in the eastern sector observed since 1940 can be related to the rough topography that imposes larger constraints to forest management and road network development than in the western sector. In Fennoscandinavia, the large-scale pattern of logging (from the coast to the inland) is also related to the explosion of pulp and paper activities at the turn of the twentieth century (Östlund 1993; Lundmark et al. 2013). However, this assumption is only supported by historical reviews, with little cartographical empirical evidence. Our study is the first to clearly document the distribution of clear-cut logging through time and to relate the progression of the logging frontier with the industrial development of northern countries.

The spatiotemporal pattern of fire in the study area is comparable to that described in studies

Table 1 Estimates of logging and fire rotation (cycle) periods for 1940–2009 according to latitude gradient and sectors

Latitudinal zone (median interval)	Rotation period, in years (% of land disturbed annually)								
	Whole study area			Western sector			Eastern sector		
	Logging	Fire	Logging + fire	Logging	Fire	Logging + fire	Logging	Fire	Logging + fire
49°15′N	157	313	104	133	366	97	202	263	114
	(0.637)	(0.319)	(0.962)	(0.752)	(0.273)	(1.031)	(0.495)	(0.380)	(0.877)
49°45′N	183	421	127	165	506	124	206	351	130
	(0.546)	(0.238)	(0.787)	(0.606)	(0.198)	(0.807)	(0.485)	(0.285)	(0.769)
50°15′N	349	571	217	283	351	156	417	1114	304
	(0.287)	(0.175)	(0.461)	(0.353)	(0.285)	(0.641)	(0.240)	(0.090)	(0.329)
50°45′N	1165	556	376	757	285	207	1495	1129	643
	(0.086)	(0.180)	(0.266)	(0.132)	(0.351)	(0.483)	(0.067)	(0.089)	(0.156)
51°15′N	2763	227	210	5993	161	156	1917	300	259
	(0.036)	(0.441)	(0.476)	(0.017)	(0.621)	(0.641)	(0.052)	(0.333)	(0.386)
51°45′N	∞	143	143	∞	135	135	∞	146	146
	(0.000)	(0.699)	(0.699)	(0.000)	(0.741)	(0.741)	(0.000)	(0.685)	(0.685)
Total	402	296	170	320	245	139	515	360	212
	(0.249)	(0.338)	(0.588)	(0.313)	(0.408)	(0.719)	(0.194)	(0.278)	(0.472)

Rotation periods and % of land disturbed annually are shown

∞ The logged area is very small and causes the rotation period to approach infinity (see rotation period formula in methods)

reconstructing the natural fire regime of the eastern Canadian boreal forest (Bouchard et al. 2008; Mansuy et al. 2010; Bélisle et al. 2012). These studies show that climate controls the fire rotation, which increases from west to east (from ≈100 years to >500 years) as humidity increases, due to the influence of the Gulf of St. Lawrence (Bouchard et al. 2008). The fire rotation also increases from north to south, due to 3 likely factors: (1) a drier climate conducive to fire in the north, (2) a larger proportion of deciduous species in the south that hinders fire propagation (Terrier et al. 2013), and (3) the proximity of inhabited zones in the south, which likely increases the effectiveness of fire suppression. Moreover, the recent increase in burned areas over the last two decades, despite the short evaluation period, supports recent works by Bergeron et al. (2010) who predicted that fire activity would significantly increase in the twenty-first century in response to climate change.

Forest landscape structure

South of the 51st parallel, the gradual increase in disturbance rates associated to twentieth-century clear-cut logging led to the present-day landscape in which the proportion of closed-canopy forests decreased to the advantage of young forests. Natural landscapes subjected to long fire rotations, like those in eastern Canada or in the Pacific Northwest, are characterized by a closed-canopy/old forest matrix (Spies et al. 1994; Kneeshaw and Gauthier 2003; Hessburg et al. 2015). By increasing the disturbance frequency, logging has progressively reduced the dominance of older forests in the southern part of the study area. Moreover, the recent increase in fire activity from 1990 to 2009, particularly north of the 51st parallel, further rejuvenated the landscape. However, unlike logging which only targets older stands, fire is stochastic and normally affects stands of all ages (Van Wagner 1978). Therefore, its impact on old forest reduction is less direct than logging. Our study concurs with several smaller-scale studies conducted in boreal forests of North America and Scandinavia (Östlund et al. 1997; Cyr et al. 2009; Bouchard and Pothier 2011; Boucher et al. 2014) that showed that the twentieth-century logging history contributed to the rarefaction of late-successional forests and to the proliferation of young forests.

The recent rise of stand-replacing disturbance rates has increased the probability of successive

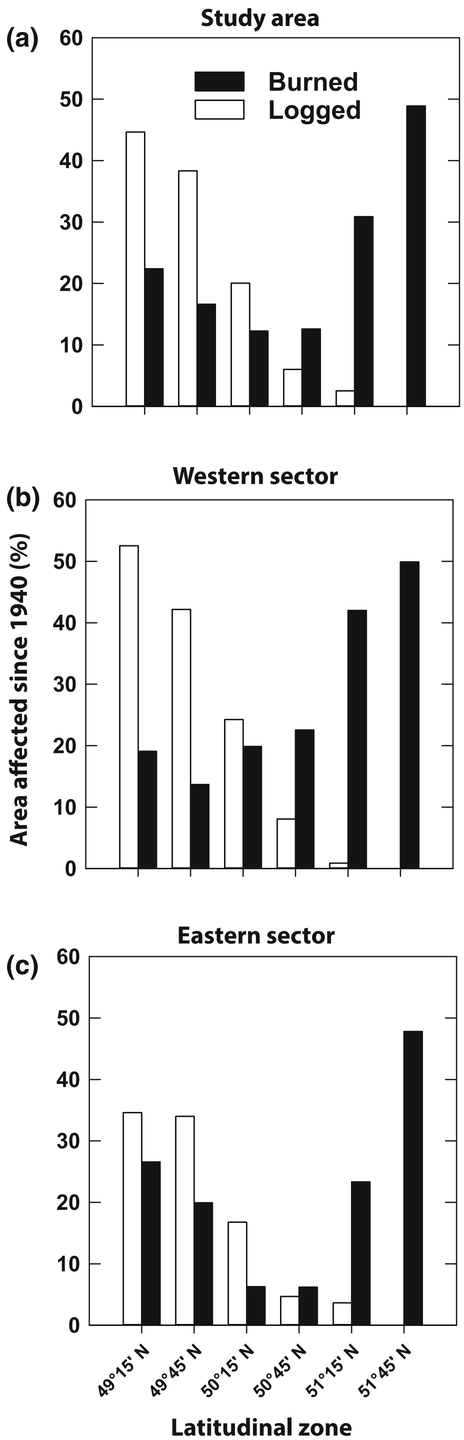

Fig. 5 Relative logged or burned areas along the latitudinal gradient from 1940 to 2009 for **a** the whole study area, **b** its western and **c** its eastern sector in central Quebec, eastern Canada

disturbances and likely triggered regeneration failure. In fact, when two successive stand-replacing disturbances occur within a period too short for black spruce to produce an adequate supply of seeds (<50 years), regeneration can be impaired and result in a low-density stand (Lavoie and Sirois 1998; Girard et al. 2008; Côté et al. 2013). Despite the fact that accuracy is moderate for unproductive terrestrial land, our remote sensing data show that the proportion of low-density forests increased consistently (+4.8 %) from the 1990s to the 2010s. These results strongly suggest that the recent increase in disturbance rate could have affected the boreal forest's regeneration potential and therefore, its resilience. Beyond the 51st parallel, successive fires are likely the cause of this increase (see Lavoie and Sirois 1998), whereas other disturbances beyond the scope of this study, such as low-severity fires or spruce budworm outbreaks followed by fires, may have generated low-density forests (Payette et al. 2000; Girard et al. 2009). In the southern part of our study area, in addition to successive fires, logging followed by fire triggered the creation of low-density forests. Indeed, the extensive area affected by clear-cut logging since 1940 has increased the statistical chance of successive disturbances. Logging history has had, and will continue to play a role in explaining regeneration failure across the managed boreal forest zone. Though they are based on indirect observations (remote sensing), our results are strongly supported by the works of Girard et al. (2008, 2009) conducted in the center of our study area. Using aerial photographs and thorough field validation, these authors found that 9 % of the area historically (1950) occupied by closed-canopy forests was now occupied (2002) by low-density forests following successive disturbances (mainly triggered by successive fires). They also observed that the transition followed a latitudinal gradient, in response to higher fire frequencies, a more rigorous climate, and lower functional diversity (regeneration mode) of tree species in the north.

Implications for management of the boreal forest

This study reveals how the introduction of logging greatly increased the rate of disturbance in the southern boreal forest, and significantly rejuvenated the landscape structure following a south to north harvesting pattern. As ecosystem-based management and biodiversity conservation have become major concerns worldwide (Lindenmayer et al. 2006; Gauthier et al. 2009), managers should reassess the rate and spatial organization of timber harvesting and strive towards a more natural forest landscape structure. In harvested areas, resilience and recovery mechanisms should be identified and favored at both landscape and stand scales (Fedrowitz et al. 2014). This can be achieved by preserving post-disturbance biological legacies and by mimicking the effects of fires for the organization of the residual closed-canopy forests at the landscape scale. For instance, if logging activities are more dispersed and distributed throughout management units, residual closed-canopy forest habitats would be better represented across the latitudinal gradient. This could help the maintenance of several boreal species such as the woodland caribou (*Rangifer Tarandus caribou*) (Drapeau et al. 2009). Moreover, since fire frequency is expected to increase sharply in the twenty-first century due to global change (Bergeron et al. 2010), forests at the logging frontier, now located at a higher latitude, are more

Table 2 Comparison of accuracy assessment results using the ISODATA classification method on the ~1975, ~1990, ~2000, and ~2010 Landsat mosaics

Class	Landsat mosaic							
	~1975		~1990		~2000		~2010	
	UA	PA	UA	PA	UA	PA	UA	PA
Closed-canopy forests (≥40 years)	88.1	85.9	91.1	90.5	83.6	89.5	83.6	89.5
Young forests (<40 years)	48.5	42.2	73.7	63.5	61.6	59.2	61.6	59.2
Unproductive terrestrial land	42.4	60.0	50.9	63.8	64.0	57.6	64.0	57.6
Water bodies	100.0	93.9	100.0	96.6	100.0	100.0	100.0	100.0
Overall accuracy	76.8		82.7		81.0		81.2	
Kappa statistic (%)*	57.0		67.7		67.6		71.3	

UA users' accuracy, *PA* producers' accuracy

* Agreement levels: 41–60 %: moderate agreement; 62–80 %: substantial agreement; 81–99 %: almost perfect agreement

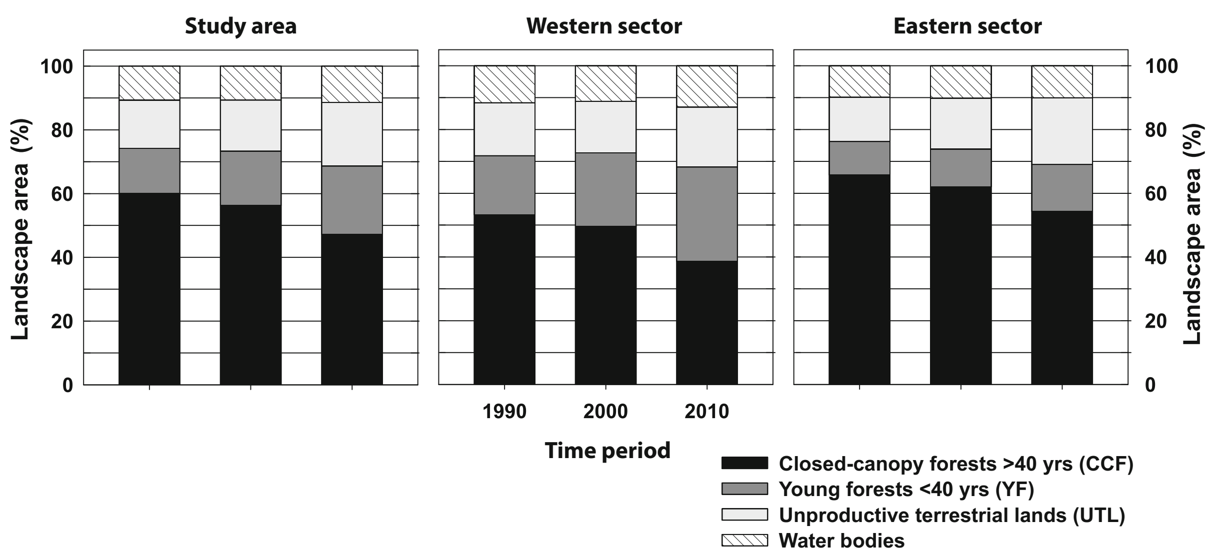

Fig. 6 Relative abundance of forest cover types depicting landscape structure in the 1990s, 2000s and 2010s for the whole study area, its western and its eastern sector in central Quebec, eastern Canada

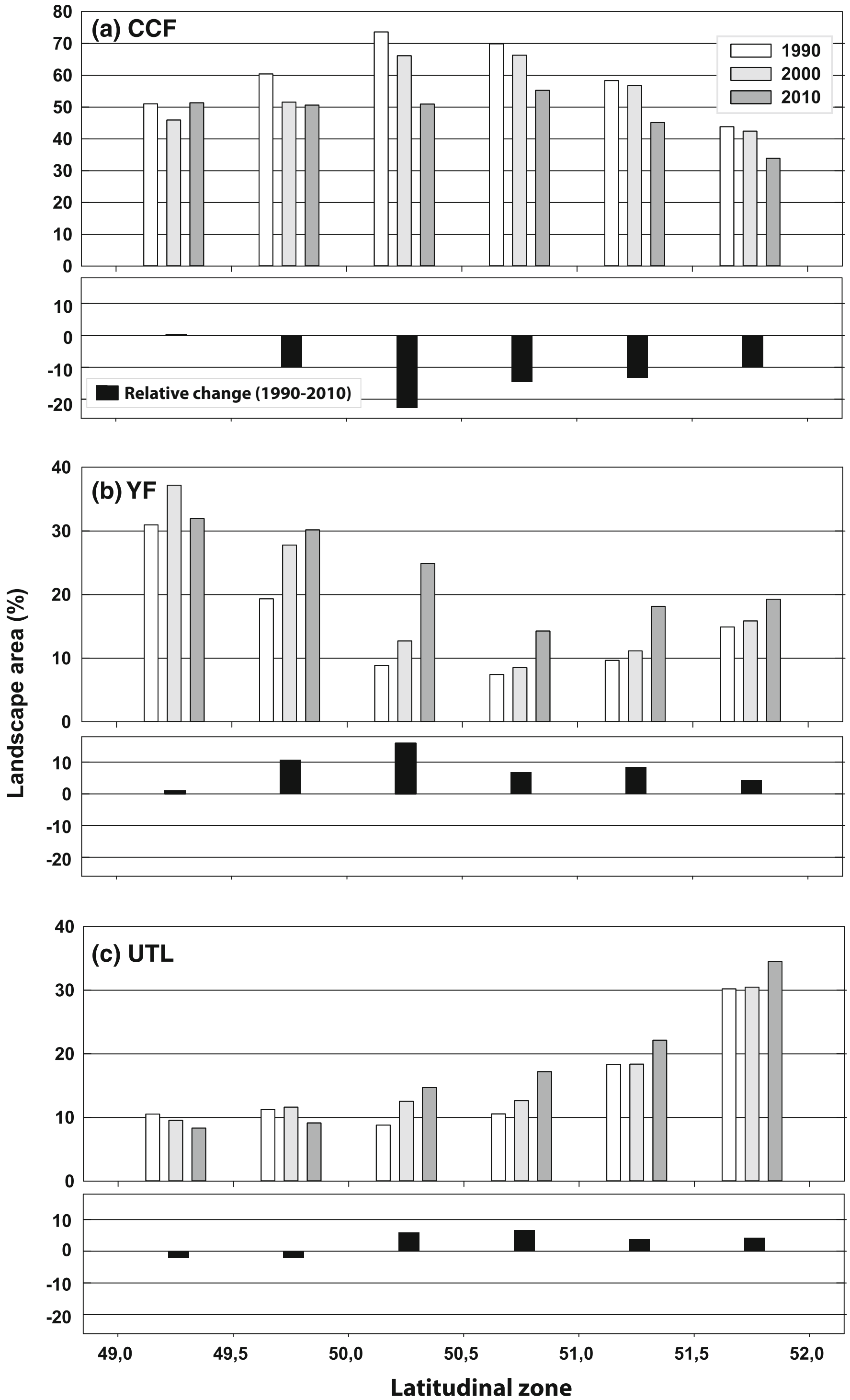

Fig. 7 Relative area occupied by **a** closed-canopy forests (≥40 years: CCF), **b** young forests (<40 years: YF) and **c** unproductive terrestrial land (UTL) in the 1990s, 2000s and 2010s following a latitudinal gradient in central Quebec, Canada. Net change for the 1990–2010 period is shown on the lower panel

likely to burn. Adaptation measures are thus needed to favor the productivity and resilience of the boreal forest in order to maintain ecosystem services. Considering the high cost of fire protection, risk assessments based on annual disturbance rates (fire, logging and others) should guide forest management at these latitudes, with a perspective of maintaining a sustainable timber supply.

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