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Logging history (1820–2000) of a heavily exploited southern boreal forest landscape: Insights from sunken logs and forestry maps

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ABSTRACT

Over the last two centuries, logging has caused major, but unquantified, compositional and structural changes in the southern portion of the North American boreal forest. In this study, we used a series of old forest inventory maps coupled with a new dendrochronological approach for analyzing timber floating histories in order to document the long-term transformation (1820–2000) of a southern boreal landscape (117 000 ha) in eastern Quebec, Canada, in response to logging practices. Landscape exploitation became increasingly severe throughout this time period. During the ninetieth century (1820–1900) of limited industrial capacity, selective logging targeted pine and spruce trees and excluded balsam fir, a much abundant species of the forest landscape. Logging intensity increased during the first half of the twentieth century, and targeted all conifer species including balsam fir. After 1975, dramatic changes occurred over the landscape in relation to clear-cutting practices, plantations, and salvage logging, which promoted the proliferation of regenerating areas and extensive plantations of the previously uncommon black spruce. Overall, logging disturbance resulted in an inversion in the forest matrix, from conifer to mixed and deciduous, and from old to regenerating stands, thus creating significant consequences on forest sustainability. If biodiversity conservation and sustainable forestry are to be management goals in such a heavily exploited forested landscape, then restoration strategies should be implemented in order to stop the divergence of the forests from their preindustrial conditions.

1. Introduction

Multi-century logging has considerably affected forest dynamics at the planetary scale (Östlund et al., 1997; Foster et al., 1998; Kouki et al., 2001; Frelich, 2002). The impacts of forestry practices have surpassed those of natural disturbances throughout most regions of the world's forests and can indeed be considered a major component of a new disturbance regime. Retrospective studies have demonstrated that forestry practices, including harvesting and large-scale plantations, have strongly reduced average forest ages, diminished the abundance of dead trees, and favored the proliferation of pioneer species, and homogenized landscape structure and composition (Foster, 1992; Whitney, 1994; Östlund et al., 1997; Kouki et al., 2001; Andersson and Östlund, 2004; Schulte et al., 2007). The effects of these changes within managed regions suggest major impacts on the biodiversity and productivity of forest ecosystems (Fischer and Lindenmayer, 2007).

Several authors have suggested that forest management should aim to emulate the structure and composition of preindustrial forests at site and landscape scales in order to preserve or restore their biodiversity (Attiwill, 1994; Harvey et al., 2002; Kuuluvainen, 2002; Lindenmayer et al., 2008). A major difficulty in developing such practices is the lack of sites that possess attributes of natural ecosystems, particularly in heavily logged regions (Axelsson and Östlund, 2002). In lieu of pristine reference ecosystems, historical ecology methods can be used to reconstruct past ecosystems and landscapes and document their transformation under human activities. In the United States, the enumeration of witness trees on land surveyed for colonization allows the composition of precolonial forests to be inferred (Bourdo, 1956; Lorimer, 1977; Friedman et al., 2001), along with how they have transformed in response to human activities (Siccama, 1971; Friedman and Reich, 2005; Schulte et al., 2007). In Canada, survey records have not been used extensively, presumably because they rarely contain witness tree observations (Clarke and Finnegan, 1984; Jackson et al., 2000; Aubé, 2008). In southern Québec, notary deeds were used as an alternate source of historical data to reconstruct vegetation that existed before the influence of logging and agriculture (Simard and

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Bouchard, 1996; Brisson and Bouchard, 2003). In addition, forest inventory maps made at the beginning of the 20th century in North America and Fennoscandia have also been used to document the structure and composition of forests and their transformation under the influence of forestry practices in a spatially explicit manner (Hessburg et al., 1999; Axelsson and Östlund, 2002; Etheridge et al., 2005; Boucher et al., 2009).

In this study we provide a retrospective analysis on long-term landscape change and logging disturbance in the Rimouski River watershed of eastern Canada. This region was selected because it represents one of the earliest logged areas in the North American boreal forest and because multi-date forestry maps were available. Changes in the structure and composition of the landscape in response to 20th century forestry practices were documented by comparing forestry maps of 1930, 1948, 1975, and 2000. As no map was available to reconstruct the logging practices prior to 1930, we compared logging history between the 19th and 20th centuries, from dendrochronological dating of logs that had sunk in the Rimouski River during the timber driving era (1820–1964). Throughout the 19th and 20th centuries, log drives were an important means of transporting wood in several regions of the world (Whitney, 1994; Barros and Uhl, 1995; Törnlund and Östlund, 2002; Nilsson et al., 2005). The technique consisted of gathering logs on frozen lakes and watercourse banks so that at the moment of the spring thaw they would be transported by the water to sawmills, which were typically located at the mouths of the rivers (Judd, 1989; Törnlund and Östlund, 2002). A fraction of these logs would sink to the bottom of the watercourse during the voyage (Cayford and Scott, 1973). Information obtained from the sunken logs (species identification and tree ring dating) offers a portrait of the trees that were logged since the beginning of the 19th century in the Rimouski River watershed. Specifically, our objectives were (1) to reconstruct landscape change since 1930 using the series of forest inventory maps; (2) document the logging history since 1820 from sunken logs; (3) compare results from objective 1 and 2 to infer logging-induced landscape changes that may have occurred prior to 1930; (4) evaluate the consequences of these changes for sustainable forest management.

1.1. Study area

The study area is located in the Lower St. Lawrence region of eastern Canada. The boundaries of the studied landscape correspond with the limits of the Price Brother's Company forestry map made in 1930 within the Rimouski River watershed. The study area, which covers 72% of the total Rimouski River watershed, is dominated by forests and drains an area of 117 000 ha (Fig. 1). The Rimouski River begins at the border between Québec and New Brunswick and flows 110 km north to the St. Lawrence River estuary at the city of Rimouski. This region is part of the

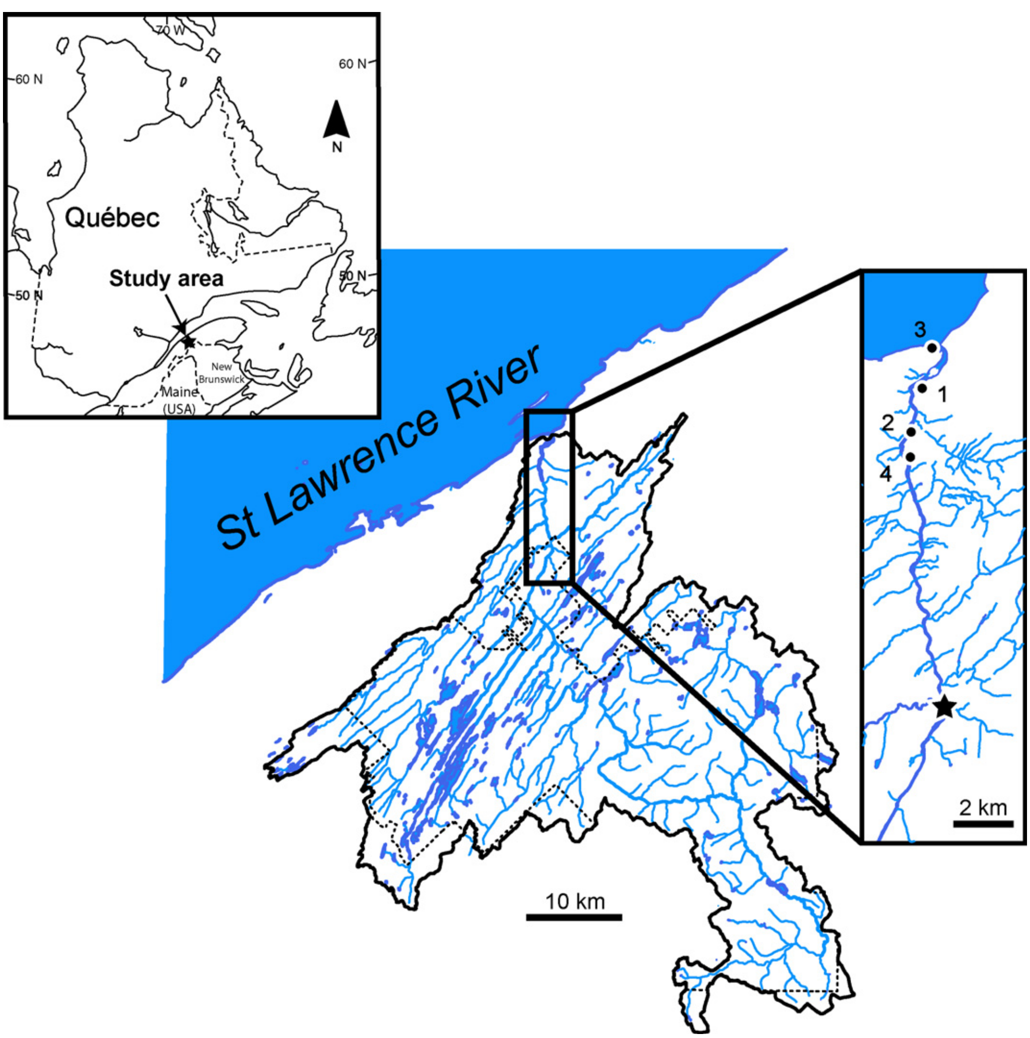

Fig. 1. Location of the Rimouski River study area in Quebec, Canada. The solid line indicates the Rimouski River watershed limits and the dashed line delineates the area covered by the 1930 forest cartography. The boxed area shows the unique site where logs were collected (star) and the locations of the mills described in Table 1 (circled numbers).

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Table 1
Description of the most important mills that are known to have existed along the Rimouski River. Corresponding locations are shown in Fig. 1.

No.	Period	Owner	Comments	Source[a]
1	From about 1825 to 1931	Several owners, but mostly the Price Family	Sawmill before 1889; white cedar shingle mill thereafter	1, 2, 3
2	Prior to 1857 up to 1912	Several owners	Known as the Hall sawmill after 1867; see Fig. 2a	1, 2, 3
3	1901–1964	Price Brother's	Reported to be one of the largest sawmill in eastern North America during the 1930's; destroyed by a fire in 1950 and rebuilt smaller in 1951; see Fig. 2b	2, 3, 4, 5
4	1903–1927	Price Brother's	Pulpmill	2, 3, 4

[a] 1: Lebel (1875); 2: Leclerc (1927); 3: Bérubé (1956); 4: Larocque (2006); 5: Fortin et al. (1993).

Appalachian geological formation composed of sedimentary rocks (Lajoie, 1972; Robitaille and Saucier, 1998). The deposits in the western section of the study area are composed primarily of weathered materials while those in the east are glacial till. Likewise, the topography in the western section is relatively smooth (altitude varying between 100 and 300 m above sea level), with the eastern section being more mountainous (altitude varying between 250 and 650 m) (Lajoie, 1972; Robitaille and Saucier, 1998). The mean annual temperature is 2.5 °C. Approximately 929 mm of precipitation falls annually with 37% of it falling in the form of snow. The growth season varies between 150 and 170 days with 1381 growing degree days >5 °C (Environment Canada, 2009).

Following the ecological classification system of Québec, the region belongs to the balsam fir-yellow birch bioclimatic domain, which forms the southern section of the boreal zone (Grondin et al., 1998). The present-day regional vegetation includes a mix of balsam fir (*Abies balsamea* L. (Mill.)) and yellow birch (*Betula alleghaniensis* Britt.) on mesic sites, sugar maple and yellow birch on the summits and upper slopes, and balsam fir, eastern white cedar (*Thuja occidentalis* L.), and black spruce (*Picea mariana* Mill.) on the lower slopes and hydric sites (Robitaille and Saucier, 1998). Young spruce plantations (*P. mariana*, *P. glauca*, and *P. abies* L.) cover 22% of the area, compared to 23% for balsam fir dominated stands, 10% for maple forests, 9% for intolerant deciduous species (birches and poplars), and 7% for cedar forests. Stands dominated by pine (*P. strobus*, *P. banksiana* Lamb., and *P. resinosa*) are rare. Since 1930, no large-scale natural disturbances have affected the area except for the last spruce budworm (*Choristoneura fumiferana* Clemens) outbreak between 1975 and 1990 (Boulanger and Arseneault, 2004).

Based on studies conducted in our region (Boucher et al., 2006, 2009; Sorel, 2004; Boulanger and Arseneault, 2004) and in peripheral areas (Wein and Moore, 1977; Lorimer, 1977; Etheridge et al., 2006; Fraver et al., 2007; de Römer et al., 2007), the natural disturbance regimes was dominated by small gaps, windthrows, insect outbreaks, and rare fires. The local Native American communities did not seem to have significantly influenced the fire regime, as has been suggested for other regions in North America (Day, 1953; Whitney, 1994). However, at the end of the 19th and during the first half the 20th centuries, land clearing for agriculture involved slash burning that resulted in significant fires at the margins of inhabited areas (Guay, 1942; Fortin et al., 1993).

1.2. Logging history of the study area

Since the early 19th century, logging activities have profoundly transformed the forests of eastern Canada (Brisson and Bouchard, 2003; Mosseler et al., 2003; Boucher et al., 2006, 2009). The Rimouski region was colonized towards the end of the 17th century and began with the clearing of the littoral terraces for agriculture, but the population remained very low until the early 19th century (Fortin et al., 1993). The establishment of an important timber trade between Québec and England at the start of the 19th century contributed to the arrival of timber merchants, which accelerated the development of the region (Lower, 1973; Fortin et al., 1993). The Rimouski River was used by the forest industry continuously throughout the 19th and 20th centuries. An analysis of land survey archives related to the mapping of the river (Lebel, 1875; Leclerc, 1927), along with historical synthesis (Bérubé, 1956; Larocque, 2006), reveals that several mills were in operation along the river between the 1820's and 1964 (Table 1 and Figs. 1 and 2). The most important mills were constructed in the downstream reaches within 5 km of the river mouth, with the first two being installed ~4 km from the mouth around 1820 (#1, #2 in Fig. 1, Fig. 2a, Table 1). The two largest mills were constructed

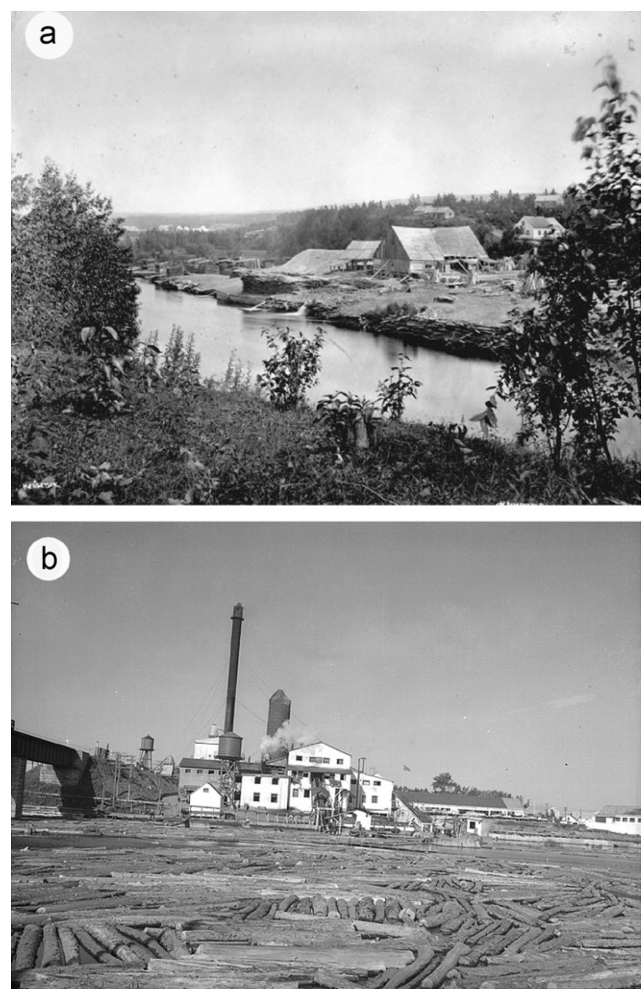

Fig. 2. Photographs of two mills erected along the Rimouski River during the last two centuries. (a) The Hall sawmill in 1875. This mill was built at an unknown date, several years prior to 1853, and remained active until 1912. Credit: Henderson, A./ Library and Archives Canada/PA-022075. (b) The Price Brother's sawmills (1901–1964) at its apogee in 1944. Credit: Michaud, J.W. Bibliothèque et Archives nationales du Québec E6, S7, SS1, P21273.

in relatively quick succession by the Price Brother's Company. The Price Brother's sawmill (1901–1964; #3 in Fig. 1, Fig. 2b) was positioned at the river's mouth and the Price Brother's pulpmill (1903–1927; #4 in Fig. 1) being constructed about 5 km upstream 2 years later. A previous comparison of the 1930 and 2000 forest maps for this watershed has shown that prior to 1930 logging has been concentrated in the lowlands adjacent to the main watercourses, a trend not longer detectable in 2000 (Boucher et al., 2009).

2. Methods

2.1. Cartographic analysis

A series of forest inventory maps (1930, 1948, 1975, and 2000) were used to reconstruct the transformation of the landscape in the 20th century. Each map was produced from aerial photographs during past forest inventories (Table 2). The maps, that depicted age and cover type classes, were digitized in vector format and georeferenced using ARCGIS 8.3 (ESRI, 2003). Main cover types (conifer, mixed, deciduous) were based on the same classification criteria for the four maps, thus allowing direct comparison. The composition of forest cover on each of the original maps were reclassified into four types: 1—"regenerating" (i.e. stands too young to be classified), 2—"conifer" (>75% of the cover dominated by conifers), 3—"mixed" (>25% of the cover dominated by conifers and >25% by deciduous species), 4—"deciduous" (>75% of the cover dominated by deciduous species). In contrast to cover type, criteria used to classify cover age in the four maps were unknown. To allow valid comparison of age classes between dates, we reclassified age classes into "young-aged" (0–40 years old) and "mature" (40 years old and over) (Table 2). We assumed that such wide classes could be easily mapped in each of the four inventories. More detailed comparisons of the ages classes transitions between dates are possible when considering only the 1930 and 2000 maps, as recently done (Boucher et al., 2009). For each map, stand origin disturbances (fire, logging, and plantation) of young-aged forest were also considered as indicated on the maps. The four maps were incorporated into a raster-based geographic information system using IDRISI I32.11 (Eastman, 1999). Taking into consideration the minimal size of the cartographic units for each map, the landscape was divided into a grid with each pixel representing an area of 1 ha. Transitions of pixels between age classes were determined using cross tabulation for each pair of successive maps.

2.2. Analysis of sunken logs in the Rimouski River

In order to reconstruct the long-term trends of logging activities at the landscape scale, we gathered information on the composition and cut period of logs that sunk into the Rimouski River during the log driving era, which began around 1825 and ended with the closure of the last mill in 1964. All sites containing sunken logs were researched while canoeing on the Rimouski River, considering two criteria. First, they had to be situated within the lower section of the watershed, upstream of the principal mills (i.e. nos. 1–4 in Table 1 and Fig. 1) in order to provide a representative sample of the whole watershed. Second, they had to be located in a fluvial context that was likely to accumulate a large number of logs during the entire log driving period in order to reduce the possibility of the logs being biased towards particular events, such as a large log jam. Although wood floatability varies among species (Hoadley, 1990), logs collected in such a context would provide useful information on the temporal trends in the exploitation of each of the most logged species. A single site was found possessing these criteria and corresponded to a section of the river with an area of 3.9 ha within a shallow (<2 m depth) concave zone of a large meander (star in Fig. 1). The entire area was exhaustively inspected using a steel probe in order to find sunken, often buried logs. Logs showing indications of having been cut (saw or axe marks) were recovered using a cant hook.

The recovered logs ($n = 614$) were brought to the riverbank where transverse disks were sampled at the points of maximum log diameter for anatomical and dendrochronological analysis. The disks were identified to species or genus in the laboratory by observing their anatomical structure (Hoadley, 1990). Bearing in mind the regional species pool, the anatomical analysis allowed the identification of balsam fir, red pine, white pine, eastern white cedar, and tamarack (*Larix laricina* (Du Roi) K. Koch). Spruce (*Picea* spp.), birch (*Betula* spp.), poplar (*Populus* spp.), and ash (*Fraxinus* spp.) could not be identified to the species level and were thus grouped to their genus (Hoadley, 1990). The disks were dried and mechanically sanded to count the number of annual growth rings. Ring widths were measured on screen with the aid of the computer program OSM (SCIEM, 2005) along two opposite radii digitized at a resolution of 4800 dpi. The dating of logs to the calendar year was accomplished using the software PAST 4 (SCIEM, 2004) along with the regional chronologies previously developed by Sorel (2004) and Boulanger and Arseneault (2004) and supplemented with our own data. Standard validation procedures were conducted using COFECHA (Holmes, 1983). The presence of the last growth ring corresponding to year the tree was logged (precision of ±1 year) was present on 61% of the cross-dated specimens as deduced from the smooth and non-eroded external surface of the samples. Based on the low variability of their maximum number of tree rings, at least on the portion of their circumference in contact with sediment, the remaining samples were only slightly eroded. Logging dates were binned into 10 years intervals to account for such stem erosion.

3. Results

3.1. Landscape change between 1930 and 2000

In 1930, the study area was dominated (65%) by mature forest (40 years and over). Considering forest composition, coniferous and mixed forests accounted respectively for 64 and 27% of the total landscape area (Figs. 3a and 4). However, a significant portion (33%) of the landscape had been logged prior to 1930 (Figs. 3a and 4). These logged areas were mostly adjacent to the Rimouski River and its principal tributaries (Figs. 1 and 3a). Burned areas

Table 2
Scale and type of aerial photographs used to create the forest inventory maps. BW: black and white; IR: infra-red (false colours).

Map	Photo scale and type	Original map scale	Minimum unit area	Source
1930	1:32,000; BW	1:32,000	1 ha	Archives nationales du Québec à Chicoutimi, Price Fund, Maps and plans
1948	1:35,000; BW	1:50,000	4 ha	Université du Québec à Rimouski archives
1975	1:15,000; BW	1:20,000	4 ha	Ministère des Terres et Forêts, Gouvernement du Québec. First provincial forest survey (1975)
2000	1:15,000; IR	1:20,000	4 ha	Ministère des Ressources Naturelles du Québec (MRNQ, 2000). Third provincial forest survey, produced in 1993, updated in 2000

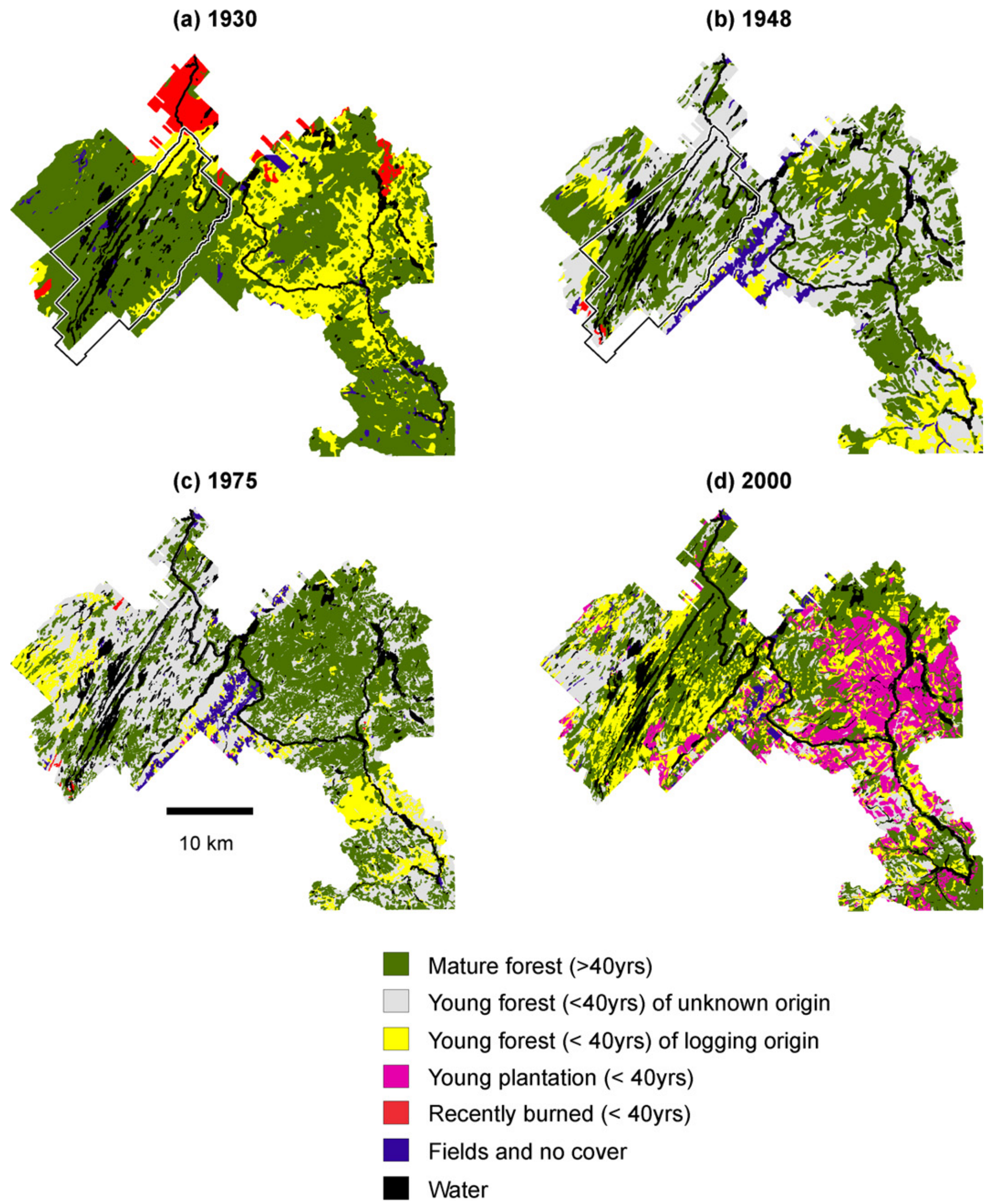

Fig. 3. Age and stand origin disturbances of forests within the Rimouski River watershed in 1930 (a), 1948 (b), 1975 (c), and 2000 (d).

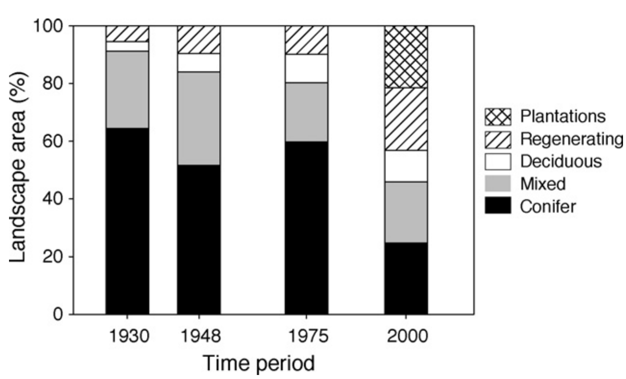

Fig. 4. Relative abundances of cover types in 1930, 1948, 1975, and 2000 in the forest landscape of the Rimouski River watershed.

comprised 5% of the study area and mostly originated from an escaped settlement fire in 1923 (Fig. 3a, Table 3).

Major changes occurred between 1930 and 1948 and were characterized by a significant reduction in the area of mature forest, along with a corresponding increase in young-aged class. While forest of more than 40 years still formed the landscape matrix in 1930, they occupied only 42% of the area in 1948 (Fig. 3 and Table 4). Conversely, the area of young-aged forest (<40 years) increased from 35 to 58% to become the dominant age class. At the same time, the abundance of conifer-dominated areas decreased from 64% in 1930 to 52% in 1948 (Fig. 4).

Although age classes and cover types areas remained relatively stable between 1948 and 1975 (Table 4 and Fig. 4), the landscape was highly dynamic spatially. Mature forest stands tended to replace younger stands in the eastern section of the watershed, while the reverse trend occurred in the western section (Fig. 3c).

Table 3
Correspondence between age classes (years) used in this study and the classifications used in the 1930, 1948, 1975, and 2000 forest inventory maps.

Age class in the present study (years)	Age class for the 1930 map	Age class for the 1948 map	Age class for the 1975 map	Age class for the 2000 map
0–40 years	Recently burned	10 recently burned, cutover	Recently burned, clear-cut	10, severe insect outbreak
0–40 years	20–40	30, partial-cut	Young immature	30, 30–50[a], 30–70[a], young uneven aged
>40 years	40–60	50	Mature regular	50, 50–90[a]
>40 years	60–80, 80–100, >100	70, old irregular	Mature irregular, mature uneven aged	70, 70–30[a], 70–50[a], 90, 90–30[a], 90–50[a], 120, old uneven aged

[a] Two-storied stand.

A second major transformation occurred between 1975 and 2000, as demonstrated by extensive logging and replacement of conifer by spruce plantations. In 2000, 22% of the study area consisted of spruce (*Picea* spp.) plantations (Figs. 3 and 4). As for the 1948 and 1975 landscapes, young-aged forest still dominated and accounted for more than 57% of the landscape in 2000 and was distributed throughout the entire study area (Fig. 3d and Table 4). Similarly to the 1930–1948 and 1948–1975 transitions, the landscape was dynamic spatially between 1975 and 2000, reflecting the high rate of logging disturbance.

3.2. Analysis of the sunken logs

The 614 sunken logs collected from the bottom of the Rimouski River were distributed among balsam fir (63.7%), spruce (17.4%), red pine (14.7%), white pine (2.6%), tamarack (0.7%), and eastern white cedar (0.5%). Deciduous trees, including *Betula*, *Populus*, and *Fraxinus*, made less than 1% of the recovered logs. In total, 201 of the 614 logs (32.7%) could be cross-dated using dendrochronology, thus allowing an estimation of their cutting year (Fig. 5). Cross-dating was highly successful with red pine (76%) and white pine (80%), intermediate with fir (28%) and very low with spruce (7%) specimens. The relatively low rate of success of cross-dating among fir and spruce logs were mostly related to their insufficient

Table 4
Spatially explicit transition (percent of total landscape area) of age classes between the forest maps of 1930 and 1948 (a), 1948 and 1975 (b), and 1975 and 2000 (c).

	1930		
	0–40 years	>40 years	Total
(a) 1930 vs. 1948			
1948			
0–40 years	22.12	35.65	57.76
>40 years	13.14	29.10	42.24
Total	35.26	64.74	100.00
	1948		
	0–40 years	>40 years	Total
(b) 1948 vs. 1975			
1975			
0–40 years	38.29	22.37	60.65
>40 years	19.16	20.19	39.35
Total	57.45	42.55	100.00
	1975		
	0–40 years	>40 years	Total
(c) 1975 vs. 2000			
2000			
0–40 years	34.69	22.43	57.12
>40 years	26.16	16.72	42.88
Total	60.85	39.15	100.00

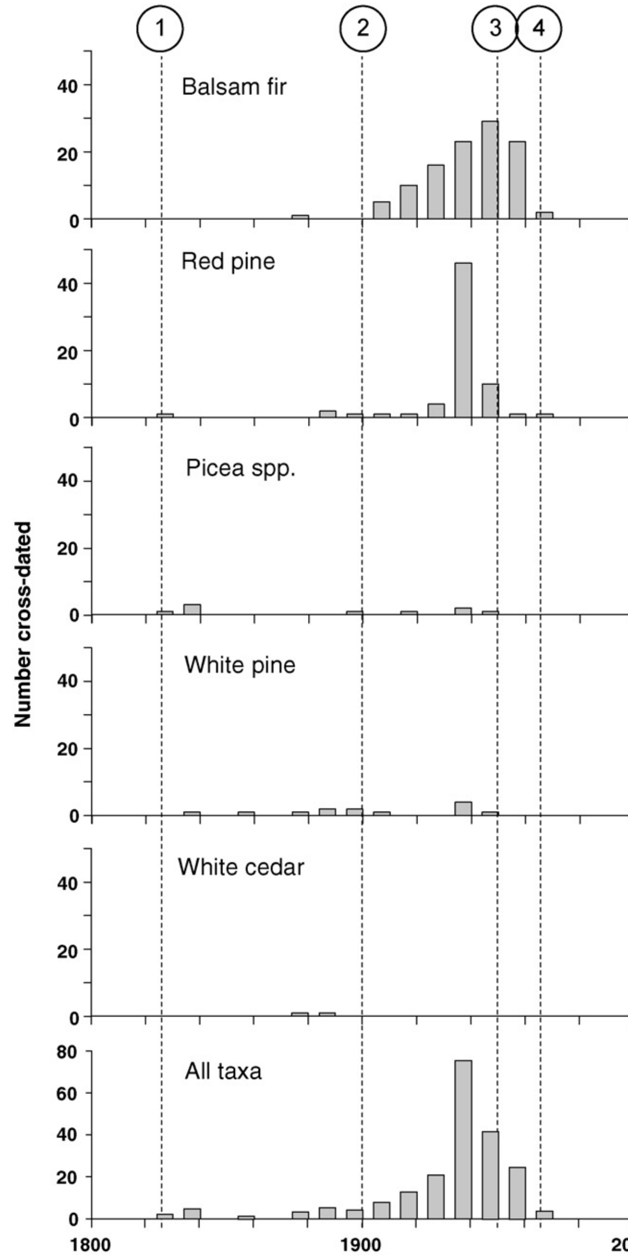

Fig. 5. Year of mortality according to taxa for sunken logs collected from the bottom of the Rimouski River. Note that pine abundance is overestimated relative to spruce and fir because of a much higher cross-dating rate. Circled numbers refers to the following events: (1) construction of the first mill around 1825; (2) construction of the Rimouski sawmill (1901) and pulpmill (1903); (3) burning of the Rimouski sawmill in 1950 and reconstruction of a smaller mill in 1951; (4) closure of the last mill (1964).

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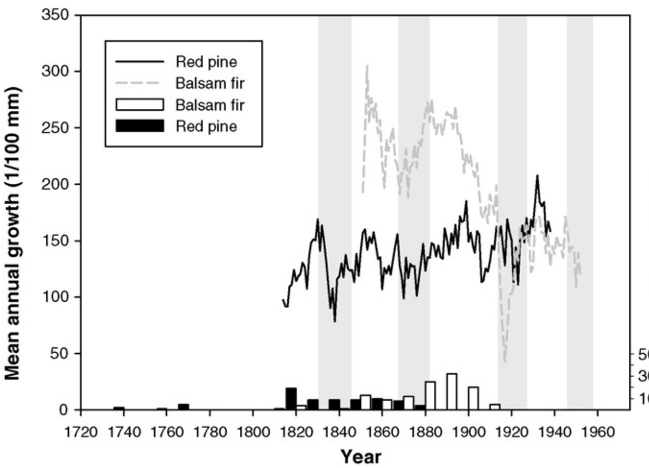

Fig. 6. Frequency distribution of the innermost tree ring (a) and mean annual increment curve (b) for balsam fir and red pine cross-dated logs. Other less common species are not shown. Gray bars refer to spruce budworm outbreaks reconstructed from a tree rings analysis in our study area (Boulanger and Arseneault, 2004). Tree recruitments and associated growth pattern of balsam fir were closely associated with spruce budworm outbreaks. Noteworthy are the recruitment pulses around 1740–1770 and 1820 for red pine.

amount of contained tree rings. All dated specimens were logged between 1827 and 1967.

More than 90% of the dated specimens, i.e., 182 logs were cut in the 20th century (Fig. 5). The number of dated logs increased gradually from the decade of 1900–1909, where seven specimens were dated, to a peak in the decade of 1930–1939 with 75 dated specimens. After this peak the number of specimens diminished with the last one being logged in the decade 1960–1970. Balsam fir was by far the most frequent species cross-dated to this period, comprising 59.3% of all the logs. Red pine (35.2%), white pine (3.3%), and spruce (2.2%) comprised the remainder of logs dated during the 20th century. In terms of composition by decade, balsam fir made up more than 70% of the individuals dated between the decades of 1900–1909 and 1960–1969, with the exception of 1930–1939, where it decreased to a relative abundance of 30.7%, as compared to 61.3% for red pine (Fig. 5).

Only 19 of the dated specimens (9.5%) were cut in the 19th century; the majority of them (84.2%) were white pine (36.8%), spruce (26.3%), and red pine (21.1%). Eastern white cedar (10.5%) and balsam fir (5.3%) comprised the other species dated during this period. The number of dated individuals by decade in the 19th century (1820–1900) never exceeded five individuals per decade (Fig. 5). The most ancient specimen was logged in 1827.

The growth and recruitment pattern for balsam fir and red pine were very contrasted (Fig. 6). The mean annual growth of balsam fir appears closely related to the spruce budworm outbreaks documented in this area (Boulanger and Arseneault, 2004) and its recruitment pattern, as depicted by the temporal distribution of innermost tree ring (Fig. 6), resulted in an uneven aged structure. In contrast, the growth of red pine was less variable than that of fir over the comparable period whereas its recruitment pattern showed establishment pulses around 1740–1770 and 1820.

4. Discussion

In this study, sunken logs were used to reconstruct two centuries of timber harvesting in the Rimouski River watershed. Doing so, two important considerations preclude the comparison of logged stem abundance among taxa. Firstly, it is likely that varying wood density among species would have influenced the probability of log to sink and be preserved at the study site. For example, although white cedar was certainly logged, as indicated by the presence of a cedar shingle mill at the river mouth between 1889 and 1931 (Table 1 and Fig. 1), only five cedar trees were found (only two specimens were cross-dated), probably reflecting the fact that this species has the lightest wood of all species in our study area (Hoadley, 1990). Secondly, large trees float better than small trees, even within the same species. This depends on that large trees have more dead wood (and more air) than small trees. This phenomenon could then explain the low number of dated specimens in the 19th century compared to the 20th century, where smaller trees were floated (Fortin et al., 1993). Thirdly, the success of tree ring cross-dating varied importantly among species, implying that red and white pines abundances are overestimated among dated stems relative to fir and especially spruce trees.

In spite of these concerns, the temporal abundance of each taxa among the sunken logs allows a reconstruction of the trend of logging over the last two centuries in relation with a series of historical events that has marked the logging industry in the Rimouski River watershed (Fig. 5). During the 19th century, the most ancient dated log (1827) closely corresponds to the construction of the first mill around 1825. In addition, the low number of logs before 1900 reflects the limited industrial capacity as compared to that of the 20th century (Fig. 2). Our results thus agree with the forestry practices of the 19th century where pine (*P. resinosa* and *P. strobus*) and white spruce (*P. glauca*) were selectively harvested (Lower, 1973; Fortin et al., 1993; Whitney, 1994). For example, white pine, red pine, and *Picea* spp., comprised 84% of the dated logs for the period between 1827 and 1900. This is also consistent with notary deeds preserved at the archive department of the Université du Québec à Rimouski, showing that logs arranged to be delivered along the Rimouski River during the year of 1829 were mostly 17.5 feet long red pine timber. A similar situation was observed in northern Sweden where large-sized Scotch pine (*Pinus sylvestris*) was selectively harvested during the same period (Östlund, 1995).

During the 20th century, the progressive increases of dated logs after 1900 closely reflects the construction of the large sawmill (1901) and pulp mill (1903) at the river mouth. In addition to an increase in logging, the relative proportion of each harvested species changed radically. While white pine and spruces dominated the sunken logs in the 19th century, balsam fir became dominant in the 20th century (Fig. 5). The rise of the pulp and paper industry at the start of the 20th century favored the use of balsam fir, which was previously considered a secondary species due to its smaller size. The large abundance of red pine among the dated trees during the 1930–1950 is probably an artifact reflecting the highly successful pine cross-dating, along with the logging of the Duchénier sector between 1930 and 1948 (compare the abundance of mature forests in the boxed area between Fig. 3a and b), a unique area still comprising the most significant concentration of red pine within the Rimouski River watershed. The frequency of the dated logs peaked in the decade of 1940–1950 (excluding the peak of red pine), just before the burning of the Price sawmill in the spring of 1950. Subsequently, the decreasing trend of dated logs in the fifties and sixties paralleled the progressive increase of truck transport, the reconstruction of a smaller sawmill in 1951 until its closure in 1964 (Fortin et al., 1993), thus precipitating the end of the timber driving period and cessation of the sunken logs sequence (Fig. 5). Afterwards, the forests continued to be logged with the trees being exclusively transported by road to other mills.

Such a correspondence between the sunken logs and historical records helps interpret and precise the sequence of landscape changes revealed by the forest maps of 1930, 1948, 1975 and 2000. Firstly, it is very likely that the areas indicated as cutover on the 1930 map (Fig. 3a) where logged after the construction of the two large mills in 1901 and 1903. This is suggested by the young age

(<40 years) of the regenerating stands, along with the increase of sunken logs after 1900. Thus, despite the fact that pine and spruce stems may have been selectively harvested along the main hydrographical network the selective logging of the 19th century had probably only a minor impact on the age and composition of the forest mosaic at the watershed scale. Most areas labeled as previously logged and less than 40 years old in 1930 likely consisted of mature stands only selectively logged prior to 1900.

Several data sources indicate that prior logging, the study area and its surroundings were largely occupied by old-growth coniferous forests. Indeed, a systematic forest inventory of southern Québec in 1938 provides valuable information concerning the species composition of these forests (Guay, 1939, 1942). This inventory indicates that extensive old forests (then classified as >100 years) were composed of balsam fir, white birch, white spruce, yellow birch, and eastern white cedar. The disturbance dynamics in these forests was periodically influenced by spruce budworm outbreaks of varying severities (Boulanger and Arseneault, 2004). Such dynamics resulted in the predominantly fine grained irregular, multi-cohort structures of the preindustrial forests (Guay, 1942). The predominance of mature stands away from the Rimouski River in 1930, along with the presence of shade tolerant late successional species (*A. balsamea*, *Picea*, and *T. occidentalis*) is an additional evidence that the natural dynamics were dominated by secondary disturbances (windthrows and insects outbreaks) that led to partial stand mortalities, unlike severe disturbances, which lead to forest regeneration spanning large areas. Indeed, our results suggest that such large, stand replacing disturbance were rare in the study area, and may be associated to recruitment pulses of red pine around 1740–1770 and 1820. In the adjacent forests of northern Maine and New Brunswick, several studies have repeatedly suggested a predominance of old-growth conifer-dominated forests along with secondary disturbances before the introduction of large-scale logging (Lorimer, 1977; Wein and Moore, 1977; Etheridge et al., 2005; Fraver et al., 2007, 2009).

Logging intensity probably increased markedly between 1900 and 1950. This is substantiated by the increasing abundance of dated sunken logs (Fig. 5) that correspond with the significant reduction in the abundance of old forests observed between 1930 and 1948 (Figs. 3 and 4), at a time when the Rimouski sawmill was reported to be one of the most important mills in Eastern North America (Fortin et al., 1993). In fact, the 1938 inventory reported that regional forests had been very heavily logged, with an annual logging rate more than 2.5 times in excess of the annual increment of accessible timbers. The inventory predicted that the regional forests would be exhausted 20 years later if logging was to continue at the same rate. In fact, the reconstruction of a smaller sawmill in 1951 and its closure in 1964 were probably the consequences of the progressive forest depletion that had occurred since 1900 (Fortin et al., 1993). Thus, progressive resource depletion along with a decreased industrial capacity probably explains the decreasing abundance of sunken logs after 1950, and the reduced rate of landscape change between 1948 and 1975. The beginning of log transportation by truck after about 1950 is an additional explanation for the decreasing number of sunken logs at that time.

Between 1975 and 2000, the cartographic analysis indicates a shift towards regeneration areas and extensive spruce plantations (Figs. 3d and 4). The important transformations of the forest throughout this period are explained by two main factors. Firstly, the area was affected by a severe spruce budworm outbreak between 1975 and 1992 (Boulanger and Arseneault, 2004) that triggered extensive salvage cuts that were regenerated in a large part with plantations comprised of black spruce, white spruce, and the exotic Norway spruce. Secondly, since the beginning of the 1960s mechanized clear-cutting began to be the main harvesting approach (Jackson et al., 2000; Etheridge et al., 2006). Compared to the selective winter logging at the start of the century, clear-cutting in the snow-free season favored the complete replacement of the original cover and created optimal conditions for the colonization of young successional stages by deciduous pioneer species (Archambault et al., 1998; Jackson et al., 2000; Archambault et al., 2006; Boucher et al., 2006).

5. Management implications

Throughout the last two centuries, logging practices have become progressively more severe, from selective winter cuts of pine and spruce trees along watercourses during the 19th century to widespread clear-cutting and planting during the second half of the 20th century. The intensive logging of old-growth conifer forests resulted in a shift in the forest matrix, from conifer to mixed and deciduous, and from old to regenerating stands and plantations. This progressive loss of old coniferous forests due to the impact of increasingly severe logging was indeed a generalized trend in North American and Fennoscandian landscapes during the 20th century (Wallin et al., 1996; Östlund et al., 1997; Jackson et al., 2000; Friedman and Reich, 2005; Schulte et al., 2007; Boucher et al., 2009) and reflects a global trend of increasing anthropogenic environmental impacts (Crutzen and Steffen, 2003).

In the context of ecosystem-based management, which endeavors to emulate natural forest dynamics in order to promote resilience, and ecosystem services (Swanson and Franklin, 1992; Attiwill, 1994; Kuuluvainen, 2002; Harvey et al., 2002), forest managers should develop silvicultural practices compatible with sustainable forest management. As old-growth forest dynamics was dominated by small gaps created by secondary disturbances, the present-day clear-cut approach over a 50–70 years rotation is unsustainable. The adoption of more diversified practices, including partial cuts such as shelterwood logging of various severities, could help restore the multi-cohort structure of old-growth forests that are typically generated by insect outbreaks, tree fall gaps, and windthrows (Wallin et al., 1996; Fortin et al., 2003; Ruel et al., 2007; Raymond et al., in press). Furthermore, compositional targets for the regional forests should be inspired by the species pool that existed in the preindustrial communities and should therefore avoid the creation of even aged forests dominated by black spruce plantations and early successional species. With this in mind, restoration programs involving irregular and uneven aged silviculture should be implemented in order to stop the divergence of the forests from their preindustrial conditions and bring the ecosystems back within their natural variability limits (Landres et al., 1999). This major goal of ecosystem-based management should be pursued while further relevant knowledge will continuously prompt adaptive management of forests.

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