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Using forestry archives to assess long-term changes in forest landscape age structure and tree composition (1950–2020) in eastern Canada

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A R T I C L E I N F O

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A B S T R A C T

Global forest landscapes are undergoing profound changes driven by the influence of multiple interacting factors, including forestry, natural disturbances, and climate change. Monitoring and understanding these complex dynamics is challenging due to the lack of data at the spatiotemporal scale at which changes occur (i.e., millions of ha over decades). In this study, we analyzed forest management plans from the 1950s alongside contemporary forest inventories to track changes in age structure and tree species composition across 18 large landscapes covering 3.8 million hectares of eastern Canada's forests. Using cluster analysis, we grouped the 18 studied landscapes into four broad ecological regions (i.e., northern and southern boreal and western and eastern temperate mixed forests) characterized by similar forest composition in the 1950s and subsequent disturbance regimes from 1950 to 2020. The boreal regions transitioned from old-growth-dominated landscapes to those dominated by young stands, mainly due to clearcutting. This transformation was associated with declines in spruces and paper birch and increases in poplars, balsam fir, and jack pine. In contrast, the temperate regions—already logged before the 1950s—experienced subtler age structure changes. Birches and black spruce declined in those forests, while maples, balsam fir, and white pine became more prevalent. We discuss the potential interactive effects of forestry practices, natural disturbances, and climate change on these changes. We conclude that forestry archives are valuable long-term ecological data that should be systematically analyzed to assess global long-term forest change.

1. Introduction

Global forest landscapes are undergoing profound changes driven by the influence of multiple interacting factors, including forestry practices, natural disturbances, and climate change (McDowell et al., 2020; Seidl and Turner, 2022). More than half of the world's forests are actively managed (Lesiv et al., 2022), making forestry-related disturbances, such as logging, the most prevalent disturbance type globally (Curtis et al., 2018). Forestry-related disturbances compound with natural disturbance (e.g., fire, insect outbreaks; Paine et al., 1998; McDowell et al., 2020), which can be profoundly altered by climate and land-use changes (Seidl et al., 2020, 2017; Wang et al., 2025). In addition, increasing atmospheric CO_2 and changing temperatures and precipitation can trigger physiological disruptions in trees (e.g., Reich et al., 2015; Montgomery et al., 2020), which can alter population dynamics (e.g., Stanke et al., 2021; Sharma et al., 2022). All these potential drivers interact to produce complex changes in forest structure and composition at the stand level (Seidl and Turner, 2022). When combined, these changes contribute to the emergence of large-scale dynamics across landscapes or broader subcontinental regions. Understanding such large-scale dynamics is crucial for assessing the impacts of global changes and setting forest management targets that ensure the resilience of forests and the critical ecosystem services they provide to human communities (e.g., carbon sequestration, wood production, biodiversity habitats).

Monitoring and understanding these complex forest dynamics is

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often challenging due to the lack of data on the spatiotemporal scale at which changes occur. Since trees have long lifespans, the processes driving forest dynamics—such as recruitment, growth and mortality—typically function slowly, leading to significant forest changes over decades to centuries (McDowell et al., 2020). As a result, datasets that enable the reconstruction of forest dynamics over large areas (e.g., millions of hectares) and with sufficient temporal depth are scarce. For example, in most North American and European countries, systematic and standardized national forest inventories allowing reliable large-extent forest monitoring over time started in the 1980s-1990s (Breidenbach et al., 2021; Lawrence et al., 2010). Remote sensing data have been widely used to reconstruct global- or continental-scale forest dynamics, but they remain limited in temporal coverage (e.g., ~1985-present for Landsat; Wulder et al., 2022) and lack accuracy in estimating essential forest characteristics such as stand age or composition (e.g., Maltman et al., 2023; Guindon et al., 2024). Historical ecological data sources that are unconventional—that is, non-traditional or infrequently used types of ecological data—have great value in reconstructing long-term forest changes (Vellend et al., 2013), often being the only means to track dynamics over extended periods (e.g., >50 years), but they also present several challenges. For example, early land survey data can cover vast territories (e.g., Rhemtulla et al., 2007; Thompson et al., 2013; Danneyrolles et al., 2021), but their ecological precision is limited to a list of tree species or bearing trees present at specific locations (Larsen et al., 2015; Terrail et al., 2014). Resurvey of legacy studies (i.e., early scientific surveys of forest vegetation) may contain very ecologically precise data but don't span over large territories (e.g., Beckage et al., 2008; Savage and Vellend, 2015; Brzeziecki et al., 2020). Historical forest management plan archives have been used in Europe and the United States to reconstruct long-term forest dynamics and changes in management practices (e.g., Audinot et al., 2020; Fridman et al., 2014; Kulla et al., 2017; Müllerová et al., 2014, 2013; Stephens et al., 2018), demonstrating their strong potential for retrospective analysis. However, these archives also present methodological challenges, particularly when comparing data collected under evolving inventory protocols, spatial resolutions, and classification systems over time.

In this study, we analyzed forest management plans from the 1950s alongside modern forest inventories to track forest changes across 18 extensive landscapes covering 3.76 million hectares of eastern Canada's boreal and mixed temperate forests. Those 18 landscapes correspond to former timber harvest concessions on public lands managed by Consolidated Bathurst Limited from the early 20th century until the late 1980s. During the 20th century, forestry companies operating in Quebec's public lands had to produce these management plans to meet the Quebec government's requirements (Boulet, 2015). They had to inventory the forests in their concession limits, including stand ages and wood volume of the most frequent tree species, and build their management plans to prove their responsible exploitation of public resources. The forest inventory effort (i.e., the number of field plots) up to the 1970s was highly intensive and surpassed today's inventory standards (Boucher et al., 2021). In this region, conifer tree species were exploited since the 19th century, but the large-scale exploitation of deciduous species only began in the mid-20th century (i.e., 1950s; Boulet, 2015). The first objective of this study was to evaluate the potential of such historical archives to reconstruct change in age structure and forest composition across a large spatial extent. We collected data compiled in the 1950s management plans and compared them with estimates from the Quebec government's national forest inventories conducted in recent decades. Our second objective was to analyze such changes in the light of the disturbance regime between the two periods. We reconstructed the area of the 18 landscapes affected by human and natural disturbance between the 1950s and 2010s (i.e., clearcutting, partial logging, fire and spruce budworm outbreak). We finally discuss the role of distinct disturbance regimes in shaping long-term changes in age structure and forest composition.

2. Material and methods

2.1. Study area

The study area covers 3.76 Mha of northern temperate and boreal forests in Quebec, eastern Canada (Fig. 1; Robitaille and Saucier, 1998; Olson et al., 2001), defined by 18 former timber harvest concessions (Table 1). Mean annual temperatures range from approximately −1 °C to + 5 °C, and mean total annual precipitation from 900 mm to 1200 mm, with 30–40 % falling as snow (Robitaille and Saucier, 1998). The natural disturbance regime is mainly characterized by stand-replacing fires (fire return interval ~200–700 years; Couillard et al., 2022) and cyclic spruce budworm outbreaks of various severity (return ~40 years; Blais, 1985; Boulanger and Arseneault, 2004; Bouchard et al., 2007; Navarro et al., 2018).

Although the Algonquin, Atikamekw, and Innu First Nations occupied the area long before the arrival of Europeans, ethnographic literature provides no evidence of significant landscape transformation due to their land use. In the southern section of the study area, widespread European settlement in the study area began in the early 19th century. The first industrial forestry activities around the mid-19th century involved the selective logging of large-diameter conifers (*Pinus* spp. and *Picea* spp.) along major watercourses for sawn timber (Riopel, 2002; Boulet, 2015). Logging of smaller conifer trees and across larger territories started at the turn of the 20th century with the rise of the pulp and paper industry (Bogdanski, 2014). The harvesting of hardwood species then strongly developed in the second half of the 20th century, with widespread harvesting mechanization and improved road transport (Boulet, 2015). The vast majority (> 95 %) of the study area has remained forested and was never devoted to agriculture.

2.2. Historical data

Our historical data were extracted from the forest management plan archive documents, which include data compilation of age structure and forest tree species composition (hereafter forest composition) in the 1950s for 18 extensive landscapes (i.e., former forest concession boundaries). Forest management plans, maps, and tally sheets of the inventories are preserved in the Archives of Patrimoine Shawinigan, located in Shawinigan, Quebec. The archive library was visited in 2018 to collect historical data.

The Consolidated Bathurst Limited forestry maps documented the age structures in the 1950s (Royer and Grondin, 1958). The maps were produced using vertical aerial photographs (scale ~1:15 850) taken between 1928 and 1961. The historical forest maps include six age classes (0–20, 20–40, 40–60, 70–80, 80–100, and > 100 years), which were summarised as a proportion of the total forested area of each of the 18 landscapes in their forest management plans.

The forest composition in the 1950s was also compiled in the 18 forest management plans of Consolidated Bathurst Limited. Volume table estimates by tree species or taxa in each forest management plan were used to reconstruct forest composition at the scale of the timber harvest unit. The methodology used by the company is described in detail in its management plans (Royer and Grondin, 1958). Survey maps produced using vertical aerial photographs (scale ~1:15 850) taken between 1928 and 1961 were prepared before the field survey to plan the location of the cruise. The field surveys were done along non-parallel and discontinuous strips stratified to represent the main stand types. Sample plots ranging from 1/5-acre plots (6 chains [1 chain: 20.1 m] by 1/3 chain) to 1/4-acre (1/4 chain x 10 chains) plots were taken at irregular intervals along survey strips located on the base map. The species and diameter at breast height (DBH; in 2-inch or ~5 cm classes) of all tree species with a DBH > 3.5 in. (~9 cm) in each plot were recorded during surveys. Tree species or taxa inventoried included the most abundant tree species of the region (see Figure S5).

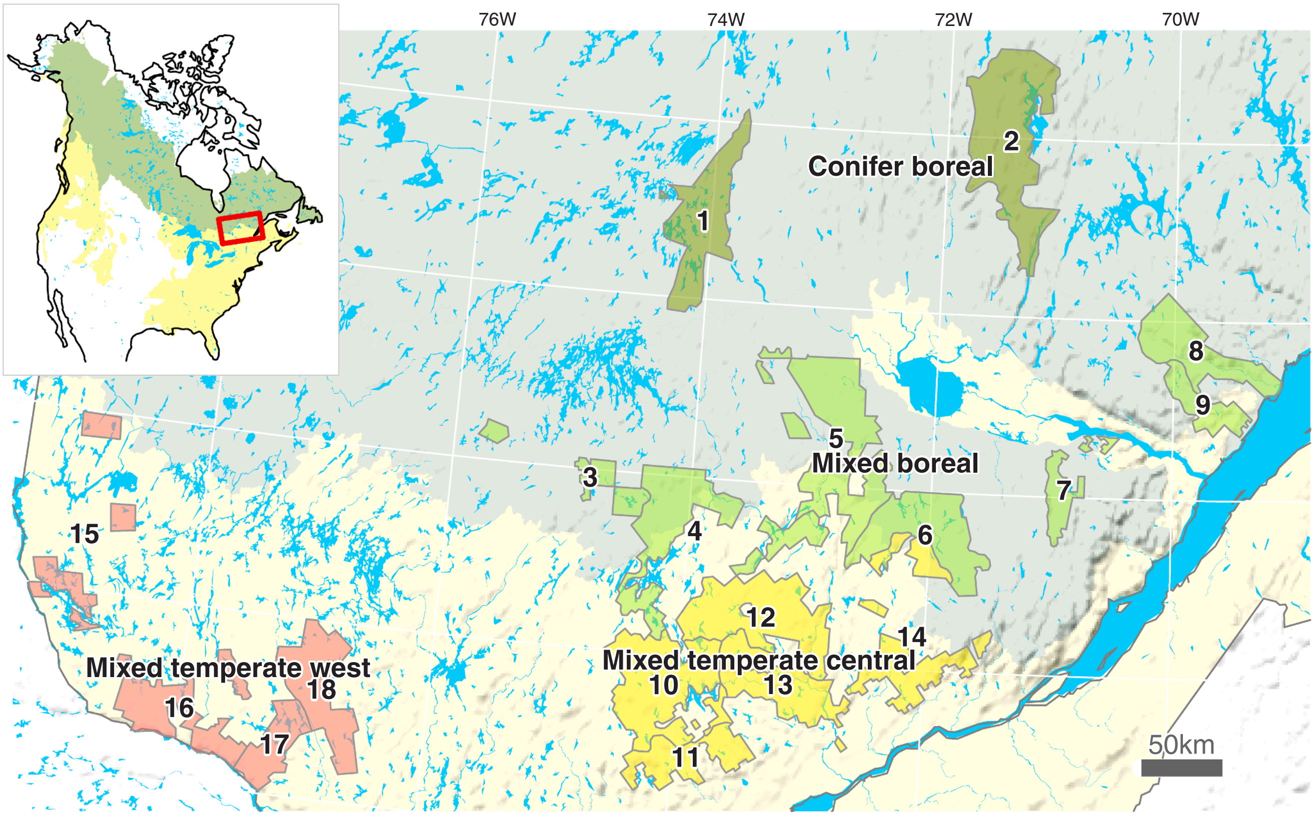

Fig. 1. Localization of the study area and the 18 landscapes analyzed in this study. The numbers indicated on the map refer to the landscapes index in Table 1. The colours indicate the ecological regions identified by the geographically constrained clustering based on the initial tree composition and disturbance rates since 1950 (i.e. homogeneous zones of tree composition and disturbance regime). The colored regions in the background distinguish the temperate (yellow) and boreal (green) forest biomes (North America: Olson et al., 2001; Québec: Robitaille and Saucier, 1998), while dark grey lines indicate the southern border of the province of Québec, Canada.

2.3. Modern data

We extracted each landscape's modern age structure (~2020) from Quebec government's modern forest maps (MFFP, 2018), which contain age classes identical to those in the 1950s inventories. We then combined six age classes from 1950 and 2020 to form a coarser classification representative of forest developmental stages: 0–40 years (young), 40–80 years (intermediate), and > 80 years (old forest).

The forest composition of the modern period was estimated with 30,418 field plots surveyed from 1995 to 2023 through Quebec's government forest inventory (MFFP, 2016). From here on, we will refer to this period as 2020 or the "modern period". These 400 m^2 circular plots were distributed along 500 m to 1500 m transects stratified to represent the main stand types. Tree species and DBH for merchantable trees (> 9 cm) in 2 cm classes were recorded in each plot (MFFP, 2016). Raw data include an estimation of the merchantable volume of each species inventoried in each plot. We aggregated the data to compute the proportion of the volume represented by each species in each of the 18 landscapes to match the method used in the 1950s Consolidated Bathurst Limited management plans. We also grouped some species at the taxa level to match those of the 1950s management plans (maples, *Acer* spp. and poplars, *Populus* spp.).

We used the Quebec government's Tesselle Forest Information System (SIFORT; MRNF, 2021) to characterize each landscape's disturbance regimes from 1950 to 2020. In brief, these data simplify the government's forest maps produced each decade since the 1970s by transforming 1:25,000 polygons into a grid of ~14 ha pixels. This transformation simplifies temporal analyses while effectively capturing broad-scale landscape changes, making it valuable for studying long-term disturbance regimes across large areas like those in our dataset. This dataset allowed for quantifying the percentage of landscapes affected by six natural disturbances and forestry practices. Natural disturbances included two stand-replacing events—fire and severe spruce budworm outbreaks (>75 % basal area [BA] removal)—and one partial disturbance, light spruce budworm outbreaks (25–50 % BA removal). Forestry practices encompassed clearcutting (>75 % BA removal), partial logging (25–50 % BA removal), and plantations, where coniferous trees (*Picea* and *Pinus* species only) are replanted after stand-replacing disturbance if natural regeneration is lacking.

2.4. Data analyses

We classified the 18 landscapes into four large zones of homogeneous tree composition in 1950 and post-1950 disturbance regimes. We used the *hclustgeo* function from the *ClustGeo 2.0* package (Chavent et al., 2018), which is available in R. The function performs geographically constrained Ward-like hierarchical clustering using two dissimilarity matrices as input. A mixing parameter, alpha (ranging from 0 to 1), controls the relative weight given to the geographic constraint matrix in the clustering process. We first constructed a Bray-Curtis dissimilarity matrix using the landscape's 1950 forest composition and the proportion of the landscape affected by each disturbance since 1950. We first ran an unconstrained hierarchical clustering on the Bray-Curtis dissimilarity matrix alone to determine the optimal number of cluster groups, which minimizes the number of groups and intra-group variation in terms of composition. We then repeated the clustering, this time incorporating geographical distance constraints (i.e., a geographical distance matrix between landscapes) and using a mixing alpha parameter of 0.4, which value was retained to maximize geographical contiguity of groups while minimizing loss in intra-group variation in composition and

Table 1
Index of the 18 landscapes analyzed in this study, with their former timber harvest concession names, year of the management plan, membership to geographically constrained clusters (i.e. homogeneous zones of tree composition and disturbance regime) and total forested areas. The numbers in the first column refer to those in the map in Fig. 1.

#	Name	Management plan date	Cluster	Area (Kha)
1	Normandin	1955	Conifer boreal	224.2
2	Peribonca	1956	Conifer boreal	396.2
3	Bazin-Monet	1957	Mixed boreal	80.9
4	Manouan	1957	Mixed boreal	311.6
5	Trenche	1959	Mixed boreal	367.2
6	Metabetchouan	1956	Mixed boreal	238.2
7	Mars-HaHa	1960	Mixed boreal	76.0
8	Portneuf	1957	Mixed boreal	197.6
9	Escoumins	1954	Mixed boreal	86.9
10	Upper-Mattawin	1956	Mixed temperate central	319.7
11	Assomption-Mastigouche	1960	Mixed temperate central	140.1
12	Vermillon	1958	Mixed temperate central	301.9
13	Lower-Mattawin	1959	Mixed temperate central	199.3
14	Batiscan-St.Anne	1957	Mixed temperate central	210.3
15	Upper-Ottawa	1959	Mixed temperate west	107.3
16	Lower-Ottawa	1958	Mixed temperate west	194.8
17	Schyan-Black	1958	Mixed temperate west	101.7
18	Coulonge	1951	Mixed temperate west	204.5

disturbance regimes.

We separately calculated age structure and forest composition changes for the study area and the four groups. Age classes and forest composition were calculated as the means of the landscapes, with the values weighted by the forested area of each landscape to account for landscape size differences.

Finally, we extracted climate variables for each cluster group from the ERA5 global climate reanalysis dataset (https://cds.climate.copernicus.eu; Hersbach et al., 2020). Climate normals for the 1991–2020 period were derived, including the mean annual temperature, total annual precipitation, and the percentage of precipitation that occurred as snow. We also examined annual trends in mean temperature and total precipitation over the period 1940–2024. Long-term climate trends were analyzed using piecewise linear regression with a single breakpoint per time series, implemented via the *segmented* R package (Muggeo, 2008).

3. Results

Geographically constrained clustering analysis identified four groups of landscapes based on their forest composition in 1950 and subsequent disturbance regimes between 1950 and 2020. These groups were named according to their location within broader ecological regions: conifer boreal, mixed boreal, mixed temperate central, and mixed temperate west (Fig. 1).

The conifer boreal region underwent the most significant changes in age structure (Fig. 2), with old-growth stands (>80 years) decreasing from 73 % to 36 % (−37 %), and young stands (0–40 years) increasing by 40 % (all changes are expressed in absolute terms). In 1950, forest composition was dominated by black spruce (67 %), followed by balsam fir (14 %) and paper birch (13 %) (Fig. 3). Between 1950 and 2020, the composition shifted, with declines in paper birch (−8 %) and black

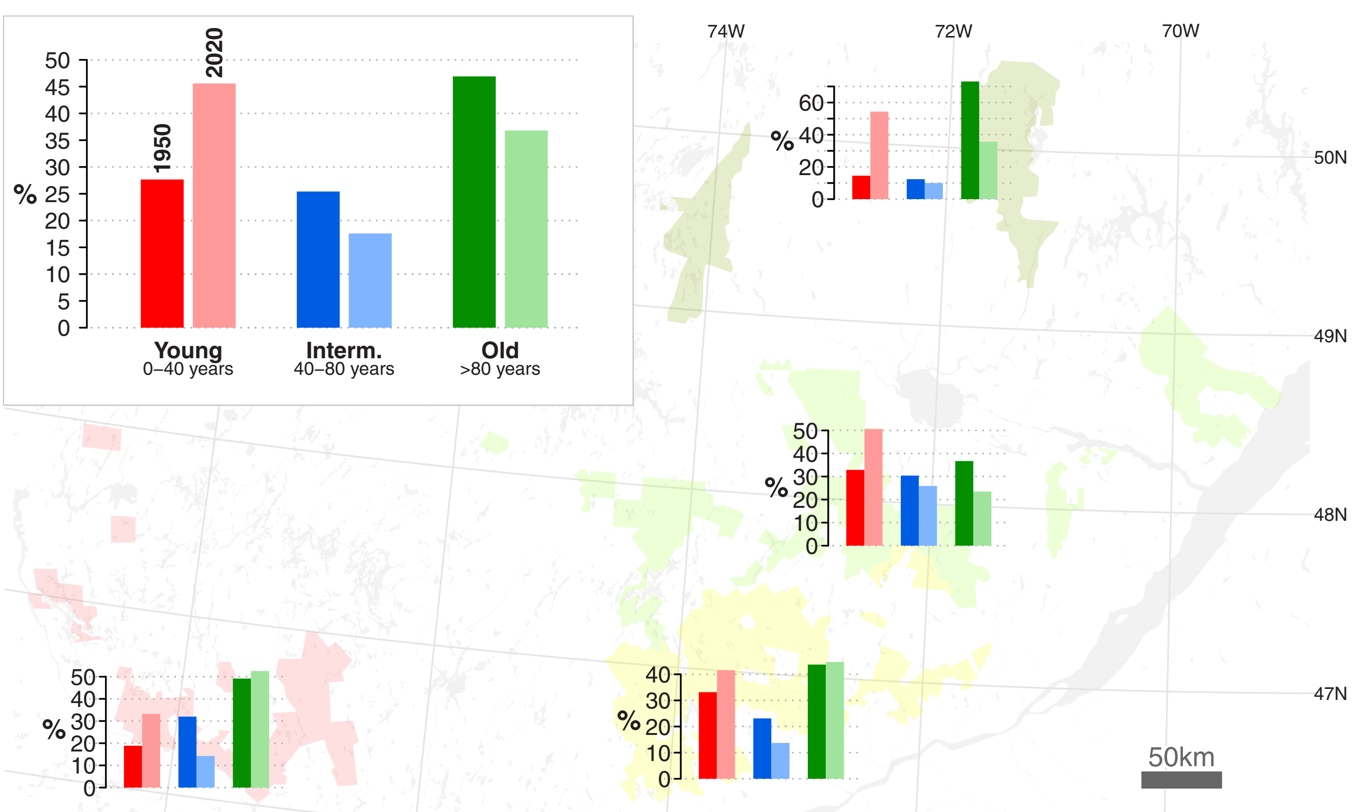

Fig. 2. Changes in landscape age structure between 1950 and 2020 for the whole study area (large graph in the top left corner) and the four homogeneous zones of tree composition and disturbance regime (ecological regions). Each of the three regrouped age classes (young: [0–40 years], intermediate: [40–80 years] and old [>80 years]) in the two surveys is shown in plain (1950) and transparent (2020) colours.

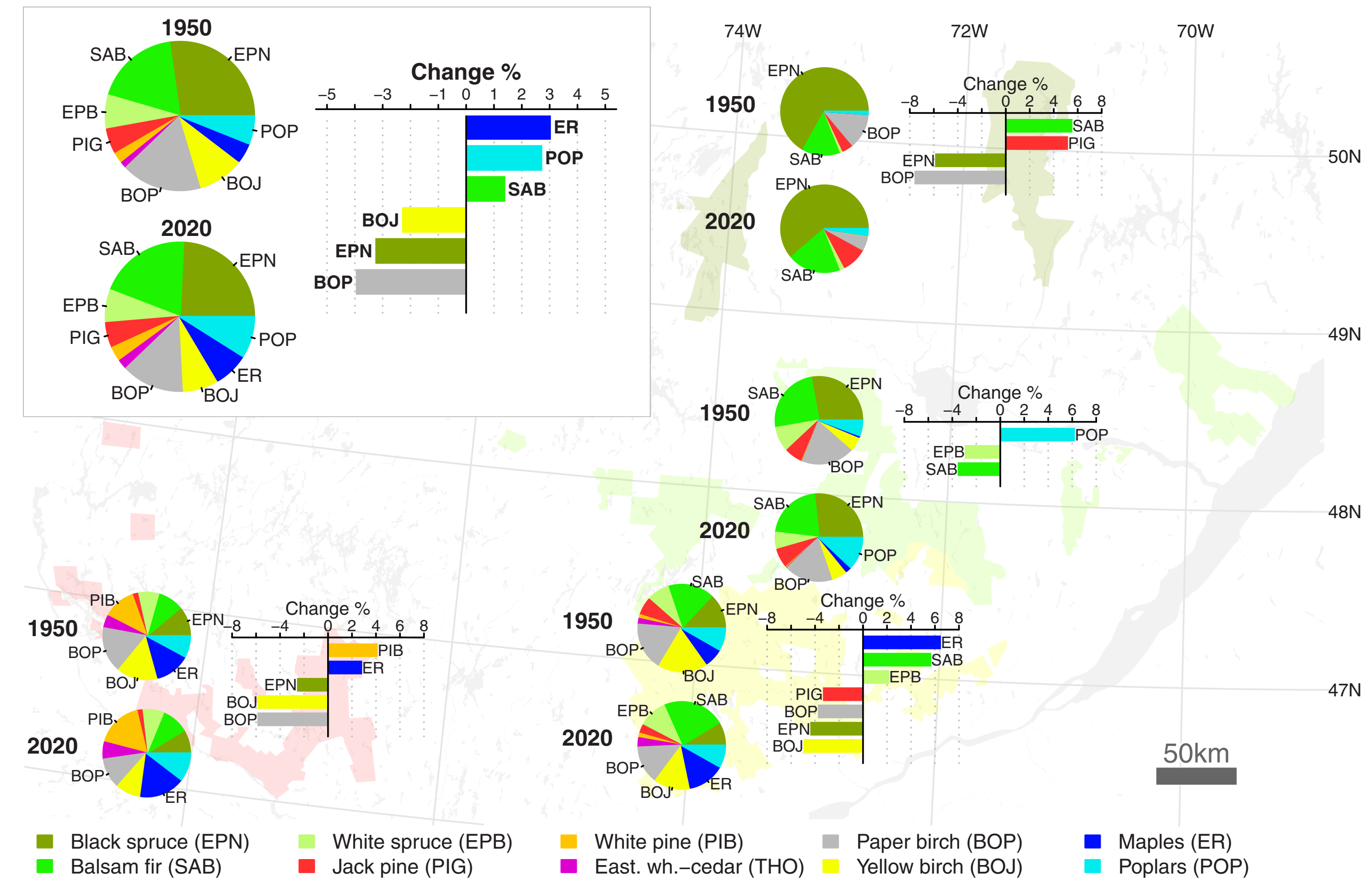

Fig. 3. Changes in tree composition between 1950 and 2020 for the whole study area (large graph in the top left corner) and the four homogeneous zones of tree composition and disturbance regime (ecological regions). The pie charts illustrate the estimated proportion of total volume occupied by each tree species during the two periods (only species representing more >5 % of the total volume in each period are shown). The bar charts show the changes in tree species composition, with only species with absolute changes > 2 % shown.

spruce (−6 %), and increases in balsam fir (+6 %) and jack pine (+5 %). Between 1950 and 2020, clearcutting affected 38 % of the area (0.58 %.year^{-1}), while other disturbances remained limited (Fig. 4).

The mixed boreal region's age structure (Fig. 2) shifted from a balanced distribution in 1950 (old: 37 %, intermediate: 30 %, young: 33 %) to a more young stand-dominated landscape in 2020 (51 %). In 1950, forest composition (Fig. 3) was dominated by a mix of black spruce (28 %), balsam fir (25 %), and paper birch (20 %), with smaller proportions of white spruce, jack pine, poplars, and yellow birch. Forest composition changes (Fig. 3) included an increase in poplars (+6 %), primarily at the expense of balsam fir and white spruce (−4 % and −3 %, respectively). Between 1950 and 2020, this region experienced a diverse disturbance regime (Fig. 4) with 33 % of the area affected by clearcutting (0.50 %.year^{-1}), 18 % by fire (0.27 %.year^{-1}), 21 % by light spruce budworm outbreaks (0.32 %.year^{-1}), 12 % by partial cutting (0.18 %.year^{-1}), and 9 % by severe spruce budworm outbreak (0.14 %.year^{-1}).

In the mixed temperate central region, landscape age structure (Fig. 2) in 1950 consisted of 44 % old stands, 33 % young stands, and 23 % intermediate stands. By 2020, the age structure shifted with slight increases in young (+8 %) stands, offset by a decline in intermediate-aged stands (−9 %). The forest composition (Fig. 3) was dominated in 1950 by yellow (18 %) and paper birch (17 %), along with balsam fir (17 %) and black and white spruces (13 % and 8 %, respectively). Changes in forest composition over the 70 year period showed declines in yellow birch (-5 %), black spruce (−4 %), paper birch (−4 %), and jack pine (−3 %), parallel to increases in maples (+7 %) and balsam fir (+6 %). Between 1950 and 2020, clearcutting and partial logging have each affected 31 % of the area (0.47 %.year^{-1}), while natural disturbances had a more negligible impact, with 12 % of the area affected by light spruce budworm outbreaks, 6 % affected by fire and < 2 % by severe spruce budworm outbreaks.

In the mixed temperate west region, the proportion of old stands remained stable between 1950 and 2020 (around 50 % in both periods; Fig. 2) while young stands increased from 19 % to 33 % (+14 %) and intermediate stands declined from 32 % to 14 % (–17 %). Forest composition in 1950 comprised 53 % broadleaf species (mainly white birch, 17 %, yellow birch, 14 % and maples, 12 %) along with 47 % conifers (mostly white pine, 11 %, black spruce, 10 % and balsam fir, 10 %). By 2020, forest composition shifted with an increase in white pine (+4 %), maples (+3 %), and poplars (+2 %), with a parallel decline in yellow birch (−6 %), white birch (−6 %) and black spruce (−3 %). From 1950–2020, disturbances were mainly partial, with 36 % of the area affected by partial cutting (0.55 %.year^{-1}) and 26 % by a light spruce budworm outbreak (0.39 %.year^{-1}), while clearcutting was the most critical severe disturbance (18 % of the area; 0.27 %.year^{-1}).

Analysis of changes in mean annual temperature and total precipitation from 1940 to 2024 (Fig. 5) revealed similar trends across all ecological regions, despite differing long-term averages (Table 2). Piecewise regression identified the onset of rising temperatures and precipitation between the 1960s and early 2000s. Across all ecological regions, data indicated an increase of approximately + 1.5–2°C in mean annual temperature and + 150–200 mm in total annual precipitation since 1980.

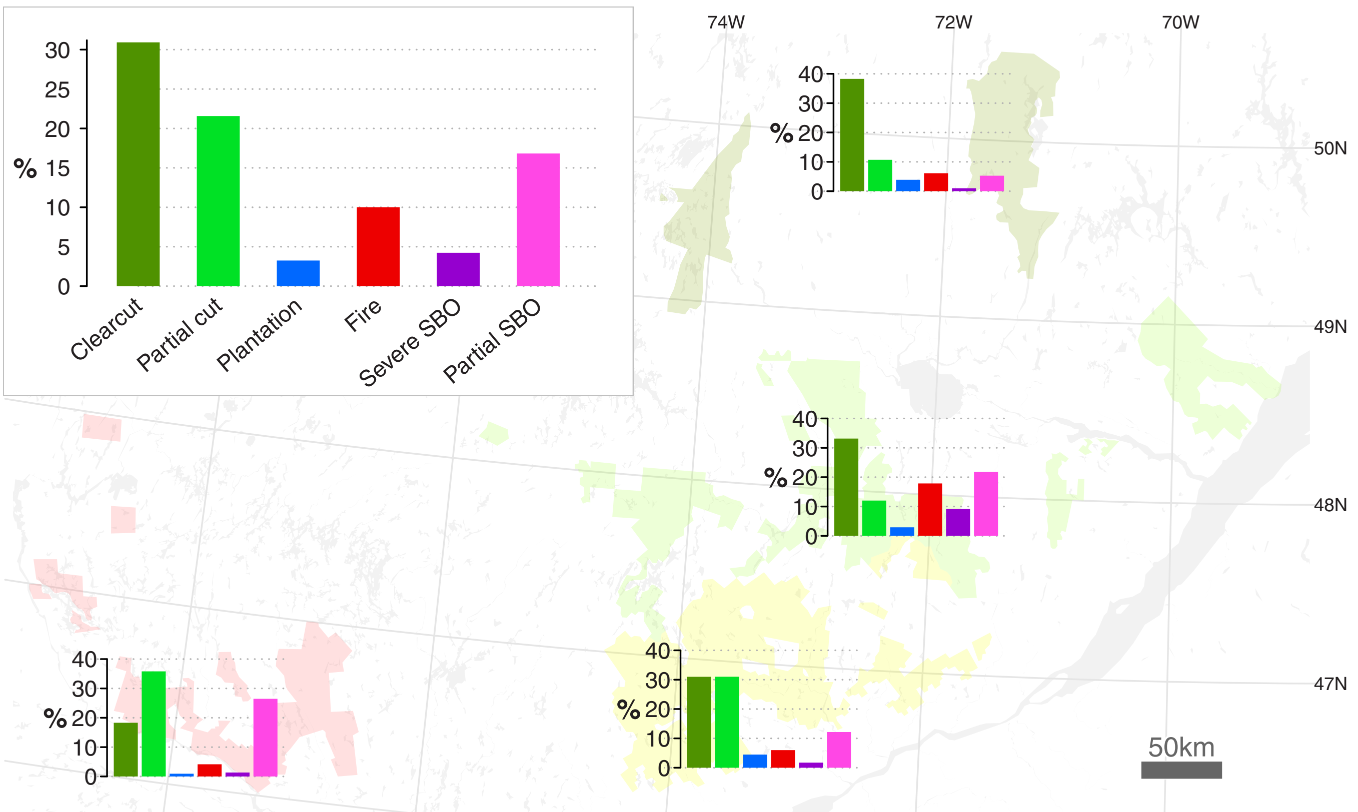

Fig. 4. Disturbance regimes between 1950 and 2020 for the whole study area (large chart in the top left corner) and the four homogeneous zones of tree composition and disturbance regime (ecological regions). Bar charts indicate the percentage of forested areas that were impacted by forestry interventions (clearcut, partial cutting and plantation) and by natural disturbances (fire, severe and partial spruce budworm outbreak; SBO).

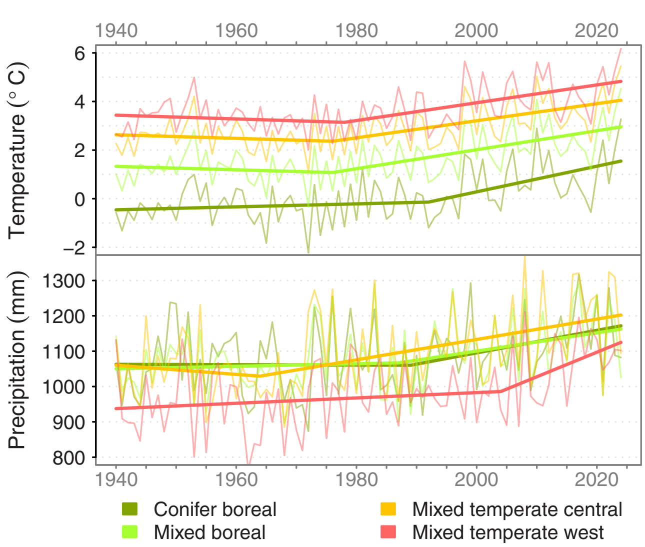

Fig. 5. Trends in mean annual temperature and total annual precipitation from 1940 to 2024 for each homogeneous zone of tree composition and disturbance regime (ecological regions). Thin lines indicate interannual variability, while thick lines indicate long-term trends revealed by piecewise linear regression analysis.

Table 2
Summary statistics of the 4 groups identified by the geographically constrained clustering (ecological regions). The column area indicates the total forested area covered by each group and climate normals (1991–2020; mean annual temperature, mean total precipitation and mean percentage of precipitation occurring as snow). The last column indicates the long-term fire cycles (1890–2020) estimated by Couillard et al. (2022).

Cluster groups	Area (Kha)	Temperature (°C)	Precipitation (mm)	As snow (%)	Long-term fire cycle (years)
Conifer boreal	620.3	0.3	1109	33	220–350
Mixed boreal	1358.3	1.9	1108	32	270–665
Mixed temperate central	1171.1	3.2	1126	28	270–840
Mixed temperate west	608.3	3.9	984	26	300

4. Discussion

To our knowledge, this is the first study to document changes in forest age structure and composition across a climatic gradient that spans from northern mixed temperate to conifer-dominated boreal forests (∼6° of latitude and longitude), and with such a large spatio-temporal extent (3.76 million hectares and 70 years). Historical data for tracking changes in these northern forests are generally limited, especially when compared to more southern temperate forests, which experienced intensive European settlement over the past centuries and for which reconstructions often cover much longer timescales (e.g., ∼1850-present; Rhemtulla et al., 2007; Dupuis et al., 2011; Thompson et al., 2013; Danneyrolles et al., 2019, 2021). As such, beyond its novel geographic scope, this study is also distinctive in its temporal focus, capturing forest changes in the second half of the 20th century—a period marked by widespread changes in forest management with the adoption of log skidders and the development of an extensive network of hauling roads (Boulet, 2015). This technological advancement led to the expansion of large-scale industrial logging into northern boreal forests (Boucher et al., 2017a) and the rise of hardwood species exploitation in mixed temperate forests (Boulet, 2015). This suggests that our data reflect the near pre-industrial conditions of deciduous forests, before significant human influence. Overall, our findings reveal changes in landscape age structure similar to those in other eastern Canadian regions, marked by a logging-driven shift from older, mature stands to younger ones (Etheridge et al., 2005; Barrette et al., 2010; Boucher et al., 2009, 2017b, 2021). Our results also reveal shifts in forest composition that differ slightly from those reported in neighboring regions, where studies have focused on longer timescales (e.g., ~1850-present; Pinto et al., 2008; Dupuis et al., 2011; Danneyrolles et al., 2020). Notably, our study documents a widespread decline of yellow and white birch, which contrasts with trends observed elsewhere. The following sections discuss regional trends in forest age structure and composition and the drivers that may have influenced these dynamics.

4.1. Changes in landscape age structure

Over the studied period, the decline in old-growth stands was primarily concentrated in boreal forests, where old-growth stands dominated in the 1950 s. Forestry activities in those northern regions were scarce before 1950 (Boucher et al., 2017b), so the 1950s landscape age structure was mainly shaped by stand-replacing fires, with long-term mean return intervals of approximately 200–400 years (Bélisle et al., 2011; Couillard et al., 2022; Cyr et al., 2007; Lesieur et al., 2002; Portier et al., 2016). Simulations of such fire return intervals show that they should result in age class distributions predominantly composed of old stands (Cyr et al., 2009). This applies to the northernmost boreal conifer region, where young stands were scarce in the 1950s and likely originated from fires in the 1910s (see Fig. S1). In comparison, the southern mixed boreal forests had a higher proportion of young stands in the 1950s. This likely resulted from a peak in burn rates between 1920 and 1950, when more than 20 % of the area was burned (Fig. S1), and early logging activities before 1950. Logging in northern and southern boreal forests intensified after 1950, progressively moving south to north (Boucher et al., 2017b). Clearcutting old-growth stands was the predominant harvesting mode in boreal forests, resulting in a substantial increase in young post-harvested stands. Fire in the 1990s and 2000s (Fig. S1) also played a secondary role in rejuvenating the landscapes of southern boreal mixed forests. Landscapes were also impacted by cyclic spruce budworm outbreaks before 1950 and thereafter (Boulanger and Arseneault, 2004; Navarro et al., 2018). However, at least after 1950, our results show that outbreaks were primarily non-stand-replacing and thus did not significantly impact the landscape age structure.

Temperate mixed forests experienced less change in landscape age structure than boreal forests, with a smaller increase in young stands, a decrease in intermediate stands, and a slight increase in old stands. This difference is partly due to the early onset of forestry activities in these southern regions compared to the boreal forests. During the end of the 19th and the first half of the 20th centuries, the pulp and paper industry underwent rapid and remarkable expansion, particularly in the central temperate mixed region, which provided pulpwood for what was then one of the world's largest paper production complexes (Bogdanski, 2014). This led to a swift increase in clear-cutting for pulpwood (Alvarez et al., 2011). Coupled with high burn rates in the early twentieth century (>17 % of the mixed temperate central region burned during the 1920s; Fig. S1), this had already significantly impacted the age structure by the 1950s. In the temperate mixed western region, forests in the 1950s had an older age structure, suggesting they were primarily managed through partial logging before the second half of the 20th century (Boucher et al., 2009; Danneyrolles et al., 2018, 2016). After 1950, our results show that central and western mixed forests were intensively harvested through clear-cutting and partial cutting. Clearcuts targeted mixed and pure conifer stands (Fig. S3), which were likely established by fires in the late 19th and early 20th centuries and matured by the end of the 20th century. This would explain why the increase in young stands occurred mainly at the expense of intermediate stands. In contrast, non-stand-replacing partial cuts primarily targeted hardwood or mixed stands (Fig. S3), likely in intermediate and old age classes. As a result, these stands were not rejuvenated, and intermediate stands could even mature into older stands over time. Similarly, although mixed temperate forests have been heavily affected by cyclic spruce budworm outbreaks before and after 1950 (particularly in the west; Bouchard et al., 2005; Navarro et al., 2018), our results indicate that these disturbances were non-stand-replacing and, therefore, did not alter significantly the landscape age structure.

4.2. Changes in forest composition

Varying trajectories of tree species composition across the four ecological regions underscore the strong influence of differing post-1950 disturbance regimes. Additionally, shifts in forest composition may have been influenced by rising temperatures and precipitation, which emerged during the 1970s and 1980s in the study area.

Birch species (comprising paper birch, *Betula papyrifera* and yellow birch, *Betula alleghaniensis*) have undergone the most substantial and widespread decreases in abundance. These two hardwood species differ in their functional traits; paper birch is a more early-successional and shade-intolerant species (Safford et al., 1991) than yellow birch, which is more intermediate in both successional status and shade tolerance (Barrette et al., 2024; Erdmann, 1991). Nevertheless, the decline of their populations may have resulted from common causes, which we discuss below. First, birch populations (mostly paper birch and, to a lesser extent, yellow birch) have undergone a large-scale, multifactorial mortality event known as the "birch dieback" in the 1940s-50s (Auclair et al., 1996; Balch and Prebble, 1940; Braathe, 1995). These events, which had already begun during the 1950s inventories (as noted in many management plans), likely have had repercussions that extended into the 1960s, contributing to the decline in birch volume observed in our study area. Secondly, while the industrial exploitation of birches and other hardwood species began in the 1920s in the temperate mixed forests, it reached a "golden age" between 1950 and 1970. This period was fueled by technological advancements, including improved harvesting methods such as the widespread use of log skidders, the incorporation of hardwoods into pulp production, the growth of the wood peeling industry, and the development of a denser hauling road network (Boulet, 2015). This period saw such intense exploitation that the Quebec government strengthened regulations to prevent resource depletion (Boulet, 2015). This history of intensive selective harvesting has undoubtedly contributed to the decline of high commercial value birches in temperate mixed forests, reducing their volume and population size. Alongside selective harvesting, the relatively high rate of clearcutting in temperate mixed forests has likely promoted the establishment and expansion of maple species, whose regeneration strategy—relying on abundant seedlings—is better adapted to take advantage of large canopy openings than that of yellow birch (Barrette et al., 2024). Concerning the decline of paper birch in the northernmost boreal region, another plausible explanation is that its abundance in the 1950s was a result of fires in the 19th and early 20th centuries, while the subsequent fire deficit period (~1950–2000; Drobyshev et al., 2017; Chavardès et al., 2022) disrupted its ability to maintain its populations.

Black spruce (*Picea mariana*) recorded a widespread decline throughout the study area (except in the mixed boreal region). The most likely cause of such decline is the extensive clear-cutting of black spruce stands, the most valuable species for Northeastern America's pulp and sawn timber industry (Natural Resources Canada, 2023). Its abundance has decreased since the 19th century in many other regions due to logging and other anthropogenic disturbances (Danneyrolles et al., 2020, 2016; Dupuis et al., 2020). Spruce budworm outbreaks may have partially contributed to the decline of black spruce populations, although they are known to cause more mortality in balsam fir populations (Blais, 1985; Bouchard et al., 2007, 2006, 2005). Finally, it is plausible that increased temperatures have contributed to black spruce's inability to regenerate effectively and maintain its dominance in disturbed stands at its southern range limit in temperate regions (Boulanger et al., 2022; D'Orangeville et al., 2018, 2016; Lesven et al., 2024).

Maples recorded the most substantial increase across the study area, which comprised sugar maple *(Acer saccharum)* and red maple *(Acer rubrum*), but almost exclusively in the temperate mixed forests. Red maple is an opportunistic, pioneering, early-successional species that can quickly regenerate after both stand-replacing and less severe disturbances (Abrams, 1998; Fei and Steiner, 2009, 2007; Walter and Yawney, 1991). In contrast, sugar maple is considered a late-successional, highly shade-tolerant species (Godman et al., 1991). However, its ability to sustain a substantial seedling bank under the canopy offers a competitive advantage following partial disturbances, such as partial logging or insect outbreaks (Boucher et al., 2006; Danneyrolles et al., 2016). Sugar maple can also exhibit considerable ecological versatility, maintaining dominance even after stand-replacing disturbances, such as fires or clear-cutting (Nolet et al., 2008; Pilon et al., 2018; Pilon and Payette, 2015). It is thus not surprising that these two species have increased in the temperate mixed forests in response to clearcuts, partial logging and non-stand-replacing spruce budworm outbreaks. Rising temperatures may have benefited maples, especially following non-stand-replacing disturbances, which may accelerate the projected climate-driven shift from mixed to deciduous temperate stands (Brice et al., 2020).

Poplars (mostly trembling aspen; *Populus tremuloides*) increased within the mixed boreal region, which has been profoundly impacted by stand-replacing clearcuts, fires and spruce budworm outbreaks (totalling ~60 % of the area). Trembling aspen is a shade-intolerant deciduous pioneer species (Perala, 1991) and is well adapted to frequent or stand-replacing disturbances due to its capacity for clonal propagation through root suckering (Bergeron and Charron, 1994; Boucher et al., 2014; 2017a; Marchais et al., 2022). Although aspen has a good seed dispersal capacity, it can also easily colonize new landscapes via vegetative reproduction along recently built forest roads (Marchais et al., 2024). Therefore, trembling aspen has likely taken advantage of the stand-replacing disturbance rate increase to spread across the landscapes in this region.

Balsam fir (*Abies balsamea*) increased in temperate mixed and boreal conifer regions, while it decreased in the mixed-boreal region. Two factors driving balsam fir populations in opposite directions may explain these contrasting trends. On the one hand, spruce budworm outbreaks have caused widespread mortality in balsam fir populations, as this species serves as the primary food source for spruce budworm larvae (Blais, 1985). Even though a significant proportion of balsam fir stands impacted by spruce budworm outbreaks undergo cyclic succession (i.e., immediate return of balsam fir), some stands are replaced by other species (Bouchard et al., 2007, 2006; Morin, 1994). Thus, it is unsurprising that balsam fir decreased in the mixed boreal region that experienced the highest rates of stand-replacing and partial spruce budworm outbreaks. On the other hand, although balsam fir is a highly shade-tolerant species (Franck, 1990), its ability to maintain dense understory regeneration (Greene et al., 1999; Morin and Laprise, 1997) allows it to respond rapidly and dominate following canopy removal by logging. Therefore, it is likely that the high rates of partial and clear-cutting since the 1950s have allowed balsam fir to take over stands formerly dominated by black spruce or hardwood species.

Pine species have followed divergent trends depending on the regions. Jack pine (*Pinus banksiana*) has increased in the boreal conifer region, but despite this species being strongly fire-dependent (Gauthier et al., 1993; Greene et al., 2004; Rudolph and Laidly, 1990), this trend isn't likely related to fires that have been very scarce in those regions since 1950. One possible explanation is that, since clearcutting primarily targeted black spruce stands, it may have indirectly led to an increase in the relative abundance of jack pine in the region. Conversely, the slight decline in jack pine volume in the central temperate region may be attributed to the reduced fire activity after 1950 compared to earlier periods. White pine volumes have increased in the western temperate region. This is likely because intensive selective logging of large white pines in this region in the late 19th and early 20th centuries (Boulet, 2015; Danneyrolles et al., 2018) had significantly reduced the species' volume by the 1950s. Following this decline, white pine harvested volumes fell sharply in the second half of the twentieth century and have remained low today (Boulet, 2015). This likely allowed the smaller white pines, found in multi-storied old-growth stands (Abrams, 2001), spared in the period before 1950, to grow and gradually increase the species' volume to the present day.

5. Implications for management and conclusions

Our results document changes in landscape age structure and tree species composition over 70 years across 3.76 million hectares. Since the 1950s, our findings in the study area reveal a logging-driven shift in the landscape's age structure, characterized by a decline in old forest stands and an increase in recently harvested, younger stands. Concomitant changes in forest composition were complex and heterogeneous across the different regions. Still, the most striking change was the widespread decline of yellow and white birch and black spruce, accompanied by an increase of maples, balsam fir and poplars. Monitoring the long-term evolution of forest landscapes is essential for implementing sustainable management practices. In our study area, our results confirm the need to prioritize efforts aimed at increasing the proportion of old-growth forests and conserving key species such as yellow birch and black spruce to ensure long-term ecosystem resilience and biodiversity (MFFP, 2015). In the future, natural disturbances and climate change are expected to become more influential, potentially surpassing the impact of forest management. This reinforces the critical importance of continuous monitoring of large forest landscapes and the need to adapt management practices accordingly (Gauthier et al., 2023).

Beyond the management implications for our study area, this study also highlights the high value of historical forest management plans for tracking long-term forest changes. Forest management archives exist in many regions worldwide (e.g., Audinot et al., 2020; Fridman et al., 2014; Kulla et al., 2017; Müllerová et al., 2014, 2013; Stephens et al., 2018) and, while they can present methodological challenges due to changes in survey protocols over time, the data may also provide much greater detail and precision than the sources used in this study. For example, forestry archives may contain the raw data used to produce forest management plans, including high-resolution historical forest maps and thousands of field sheets from forest inventory plots (see, for example, Boucher et al., 2021). Digitizing and analyzing such raw data can uncover stand-level changes, providing valuable insights into the mechanisms driving forest dynamics at landscape or regional scales. However, these analyses are significantly more time- and cost-intensive than working with pre-aggregated data available in management plans, which are easier to compile and analyze. We recommend recognizing forestry archives as highly valuable long-term ecological datasets that merit systematic digitization and analysis.

CRediT authorship contribution statement

Victor Danneyrolles: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Yan Boucher:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Hugues Terreaux de Félice:** Writing – review & editing, Visualization, Project administration, Investigation, Data curation. **Martin Barrette:** Writing –

review & editing, Supervision, Methodology, Investigation, Conceptualization. **Jean Noël:** Writing – review & editing, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122990.

Data availability

Data will be made available on request.

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