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The global potential of log-driven trees for reconstructing forest ecosystems dynamics

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The composition and structure of modern forest ecosystems result from past and present climate as well as centuries of anthropic and natural disturbances. Concerns related to the integrity and resilience of forests in the context of climate change have led to novel ecosystem-based management methods that require extensive knowledge about the preindustrial state of forests and past disturbance regimes. At the beginning of industrial forest exploitation, waterways were used as the main conduits to transport wood, but the timing and impacts of this log driving remain understudied. Given that an estimated 15% to 50% of log-driven logs sank during their transport, this accumulation of subfossil wood can serve as a proxy tool for reconstructing the dynamics and structure of preindustrial forests and inform modern forest management practices. This review provides a global overview of log driving and highlights the significant value of these submerged logs for disturbance ecology. We demonstrate that log driving was used on most continents, implying that proxy records from subfossil logs may be available from numerous boreal and mountainous regions. Our review is one of the first to illustrate the paleoecological value of log-driving remnants and explain how such a resource provides a valuable tool for understanding past forest ecosystems. Such knowledge is crucial for informing forest management in the face of climate change.

KEYWORDS
dendroecology, disturbance ecology, ecosystem-based forest management, log floating, log driving, paleoecology, preindustrial forests, subfossil logs

1 Introduction

Over the past several centuries, lumber industries have been a crucial element in the economic development of many countries. In numerous regions, early timber felling lacked access to the few existing roads and railways for transporting logs (Barros and Uhl, 1995). Without this infrastructure, timber transport commonly relied on waterways (Agnoletti, 1995; Haba and Deusa, 2001; Törnlund and Östlund, 2002). This *log drive* served—for more than 200 years in some regions—as the primary means of moving timber from the forest to sawmills. Despite the importance of this historical disturbance, no study has reviewed where and when log driving was used.

Because of earlier intensive logging, many modern forest landscapes exist beyond their natural range of variability (Kuuluvainen et al., 2021). The current simplification and homogenization of forests make them highly vulnerable to climate change and its expected impacts on natural disturbance regimes (Montoro Girona et al., 2023a). Recently, forest management approaches have promoted harvesting techniques that emulate natural disturbance effects to restore and maintain forest structure and function (Stockdale et al., 2016). This *ecosystem-based management* requires knowledge of regional past disturbance regimes and preindustrial forest conditions (Gauthier et al., 2023; Montoro Girona et al., 2023a). However, despite current efforts to understand past forest states (Montoro Girona et al., 2018; Navarro et al., 2018; Aakala et al., 2023), there remains a significant knowledge gap in regards to past climate variations, disturbance regimes, and the state of preindustrial forests (Montoro Girona et al., 2023b). This missing information is critical for establishing more sustainable harvesting practices (Hof et al., 2021; Achim et al., 2022; Montoro Girona et al., 2023c).

During log driving, approximately 15% (eastern Canada) to 50% (central Siberia) of logs entering the waterways sank, resulting in often massive accumulations of wood on lake and river bottoms (Figure 1A; Marchand and Filion, 2014; Hellmann et al., 2016). Over the last decades, restoration efforts have aimed to return rivers and lakes to their natural state and function (Helfield et al., 2007; Pilotto et al., 2018). This restoration includes the removal of lost logs that, in some cases like in eastern Canada, have spent more than 200 years on the lake bottom (Tremblay, 1991; Houde, 2007). These sunken logs often remain in excellent condition (Figure 1B), enabling their recovery and commercial use (Lemay, 2016). These well-preserved subfossil logs are also of high interest for use in disturbance ecology as well as for reconstructing preindustrial forest ecosystems and the spatiotemporal patterns of forest exploitation.

This review provides a global overview of log-driving history and highlights the significant value of submerged log-driven wood for disturbance ecology and the reconstruction of climate and preindustrial forest structure. We reviewed scientific (22) and historical (14) papers that mentioned the use of log driving and summarized where, when, and how log driving was used in multiple regions around the world (Table 1). We discuss how well-preserved submerged wood can help reconstruct the structure and dynamics of preindustrial forest ecosystems and provide relevant information for new management strategies to help protect and restore global forests.

2 What is log driving?

Log driving is the transport of wood logs using river flow (Sedell et al., 1991). Cut logs are floated from the forest to main water bodies for direct export (Hardy, 2001) or, more frequently, to sawmills for processing (Sedell et al., 1991; Grabner et al., 2004). In most locations, log driving consisted traditionally of numerous steps, including marking, dumping, booming, raft building, transport, sorting, and storage. First, logs were marked on land at their cutting site by carving or stamping the wood with the company name or logo (Figures 1C, D) before being dumped into a nearby river (Schulman, 1974; Agnoletti, 1995). Dumping is the action of moving a log from the land to the water, either by rolling

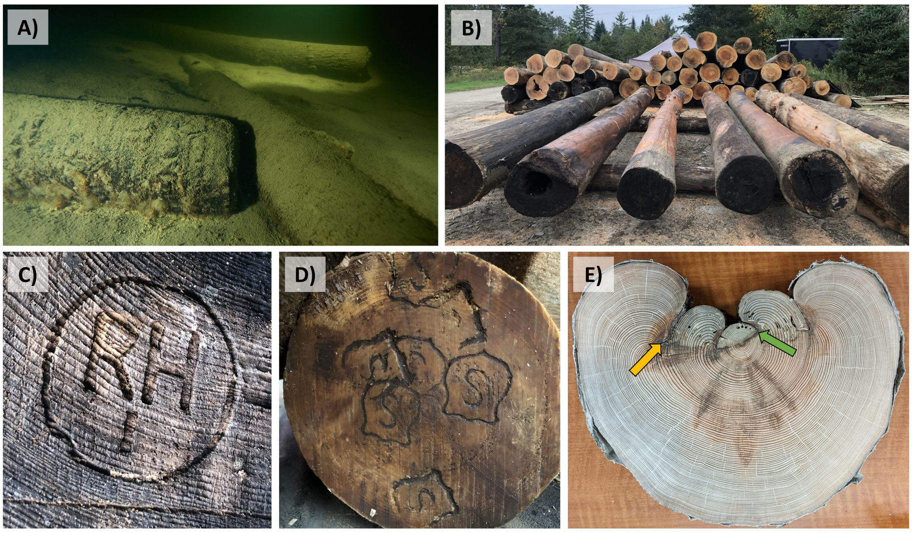

FIGURE 1
(A) Subfossil logs on a lake bottom; the logs sank during log driving in the Mauricie region of Québec (Canada); **(B)** well-preserved logs extracted from Tee Lake (Témiscamingue, Canada); **(C)** stamp of the R.A. Hurdman Company on a recovered log (Ottawa, Ontario, ca. 1892); **(D)** stamp of the Grès Falls Company on a recovered log (Trois-Rivières, Québec, ca. 1908); **(E)** cross-section of a log recovered from a lake bottom, showing two fire scars. The green arrow indicates the first (oldest) fire, and the yellow arrow indicates the second (more recent) fire. Photo credits: **(A)** Nathalie Lasselin Aquanat, **(B–D)** Julie-Pascale Labrecque-Foy, and **(E)** Amélie Bergeron.

TABLE 1 References stating the beginning and ending years of log driving in the different regions and countries around the world.

Region/Country	Year (beginning–ending)	References
EUROPE		
Spain	10^{th}–20^{th} century	Domínguez-Delmás et al., 2018
Italy	13^{th} century–1925	Agnoletti, 1995
Austria	1583–Second World War 1563–1924	Grabner et al., 2004 Grabner et al., 2021
France	17^{th}–20^{th} century	Jacod-Rousseau and Gob, 2020
	Second World War	Morris, 1920
Poland	19^{th} century	Daheur, 2019
SCANDINAVIA		
Sweden	1800–N.d. 1850–1991 1790–1991 1820–1976	Björklund, 1984 Nilsson et al., 2005 Östlund, 1995 Törnlund and Östlund, 2002
Finland	1860–N.d. 1800–1991 1850–1991	Björklund, 1984 Hänninen, 2009 Nilsson et al., 2005
RUSSIA		
Entire country	N.d.–Still used in 1967 1880–N.d.	Avakyan, 1967 Björklund, 1984
Central Siberia	Late 19^{th} century–present	Hellmann et al., 2016
Eastern Siberia	Mainly in the 19^{th} century	Hellmann et al., 2016
Western Russian	1840–present	Hellmann et al., 2016
	19^{th} century	Daheur, 2019
CANADA		
Québec	1806–1990	Lemay, 2016
Mauricie	1830–1990 Early 19^{th}–end of 20^{th} century 1829–1990 1832–1970	Chabot and Darveau, 2011 Hardy, 2001 Lemay, 2016 Marchand and Filion, 2014
Témiscamingue	1872–N.d.	Lienert, 1966
Beauce–Appalaches	1842–1956	Pomerleau, 1997
Rimouski	1820–1864	Boucher et al., 2009
Saguenay-Lac-Saint-Jean	1838–N.d. 1830–N.d.	Lemay, 2016 Tremblay, 1991
Portneuf	1920–1975	Chabot and Darveau, 2011
British Colombia	19^{th} century–Still used into 21^{st} century	White, 2001

(Continued)

TABLE 1 Continued

Region/Country	Year (beginning–ending)	References
UNITED STATES		
Maine	1830–1976	Moring et al., 1989
Pennsylvania	1850–N.d.	Cox, 1980
Kentucky and Tennessee	1900–1930 1870–1930	Montell, 1988 Schulman, 1974
West coast	1894–1941 1840–1978	Adams, 1971 Sedell et al., 1991
Alaska	N.d.–present	Pease, 1974
SOUTH AMERICA		
Brazil	15th–20th century	Barros and Uhl, 1995
ASIA		
Thailand	1870–1937	De 'Ath, 1992
AFRICA		
Nigeria	N.d.–present	Okon et al., 2021

N.d. stands for "No date", meaning that no dates were mentioned.

the log or by using slides, self-dumping barges, or even helicopters (White, 2001). Once in the water, and before their transport, the logs were kept in place by *log booms*—a barrier generally made of a chain of logs tied together by their ends (Schulman, 1974; White, 2001)—to immobilize the timber before being moved downstream. Transport of the logs was preferentially done during the high-water season (usually the spring freshet), when water levels and discharge are highest (Törnlund and Östlund, 2002). Logs could be floated individually or as bundles. When single logs were floated, they were guided by *log drivers*, i.e., workers standing on the logs or along the river bank, moving downstream with the logs and trying to prevent log jams (Pomerleau, 1997). Logs could also be tied together to build flat rafts (Grabner et al., 2021) to reduce the risk of logs sinking or drifting away (Hellmann et al., 2016). In certain rare cases, on larger rivers and when logs needed to be transported over a very long distance (sometimes up to 1500 km), rafts and wood bundles could be towed by boats (Adams, 1971; Barros and Uhl, 1995). Upon their arrival at the sawmill, the logs were sorted according to the company's stamp as well as by grade, species, and size (Agnoletti, 1995; White, 2001). Logs were then stored in shallow water near the shoreline until they could be processed (White, 2001).

3 History of log driving around the world

Although log driving began earlier in some regions, log driving has been used on all continents and simultaneously across all regions during the 19^{th} and 20^{th} centuries (Figure 2).

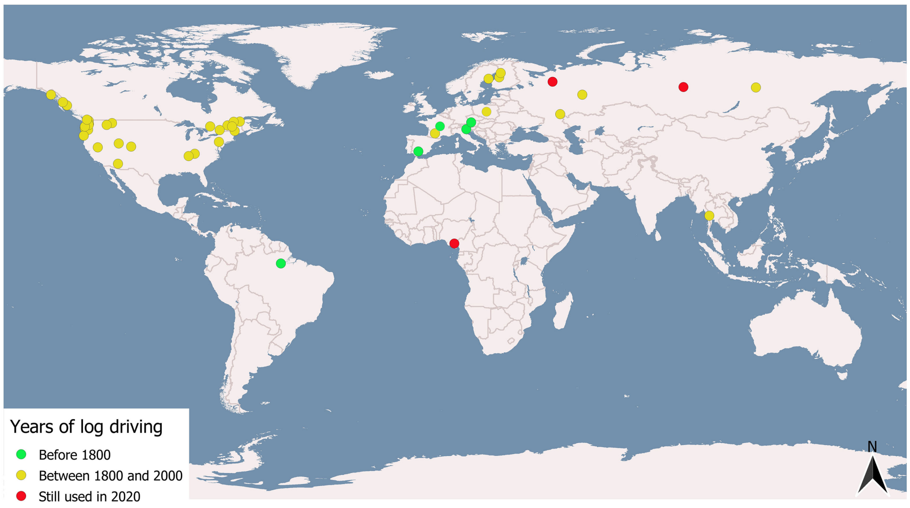

FIGURE 2
Spatiotemporal pattern of log driving around the world.

3.1 Europe

Log driving first began in southern Europe, already being used by the end of the 10th century on the Guadalquivir River in Andalusia (Spain). Timber companies floated mostly black pine (*Pinus nigra*) from the Cazorla and Segura forest for its use in the construction of palaces, religious buildings and ships (Haba and Deusa, 2001; Domínguez-Delmás et al., 2018). In Italy, log driving on the Piave River started in the 13th century to bring wood from the Alps to Venice and lasted until around the end of the First World War (Agnoletti, 1995). In Austria, log driving began in the mid-16th century and continued until the end of the Second World War (Grabner et al., 2004). The logs, mainly Norway spruce (*Picea abies*), were transported as rafts from the Limestone Alps to Vienna, and these rafts even served to transport passengers until 1860 (Grabner et al., 2021). In France, between the 16th and the 19th century, log driving was conducted on the Yonne river, from the Morvan mountainous massif to Paris (Jacod-Rousseau and Gob, 2020). Log driving was also used in France during the First World War, to supply wood to the British Army (Morris, 1920).

Log driving in Sweden developed at the beginning of the 19th century (Björklund, 1984) and was followed by the extensive clearing of rivers and the construction of a network of floatways affecting more than 30,000 km of rivers and lakes (Törnlund and Östlund, 2002; Nilsson et al., 2005). Intensive exploitation of the forests started around 1850 (Nilsson et al., 2005), and by the end of the 19th century, Sweden was a world leader in the exploitation of wood products (Björklund, 1984; Östlund, 1995). In Finland, the logging industry expanded quickly around 1860 (Björklund, 1984), and floatways available for log driving involved about 40,000 km of rivers (Nilsson et al., 2005). Over the second half of the 20th century, timber trucks gradually replaced log driving, leading to the end of log driving by the end of the 20th century in Scandinavia (Törnlund and Östlund, 2002; Hänninen, 2009).

3.2 Russia

The onset of log driving in Russian forests in the late 19th century occurred mostly in the Baltic Sea area, although it expanded rapidly to the White Sea region (Björklund, 1984; Hellmann et al., 2016). The Pechora River later became the main waterway used for log driving (Hellmann et al., 2016). Log drive was also done along the Vistule river, from Russia to Poland (Daheur, 2019). The primary purpose for wood exploitation in Russia was exportation and, by the onset of the 20th century, Russia was one of the largest wood exporters in Europe (Björklund, 1984). In 1965, about 125 million m^3 of wood was estimated to be delivered by waterways in Russia, 80% transported as rafts (Avakyan, 1967). Log driving continues today in some areas of central Siberia and western Russia, although wood bundles and rafts are guided by boats (Hellmann et al., 2016).

3.3 North America

In the 19th century, North American colonies were Britain's most important wood suppliers (Aird, 2016). Commercial forestry and log driving in Québec (Canada) started in 1806 in the St. Lawrence River watershed and included the Québec City, Lac-Saint-Jean, Rimouski, Mauricie, and Outaouais regions (Pomerleau, 1997; Boucher et al., 2009; Gagnon et al., 2009; Chabot and Darveau, 2011; Marchand and Filion, 2014). In 1842, forest harvesting, accompanied by log driving, reached the Beauce–Appalachian region (Pomerleau, 1997) and then moved north to the Témiscamingue region by 1872 (Lienert, 1966). Timber harvesting also occurred in Ontario, from where the logs were floated on the Ottawa and St. Lawrence rivers before reaching Quebec City and being exported to Britain (Hardy, 2001). In most regions of eastern Canada, log driving ended around 1970 (Marchand and Filion, 2014).

In the United States, log driving began in multiple states between 1830 and 1870 (Sedell et al., 1991). In Maine, log driving occurred on many rivers between 1830 and 1976 (Moring et al., 1989). The first log drive in Pennsylvania took place in 1850 and was followed by intense logging (Cox, 1980), with large flat rafts of logs filling the western branch of the Susquehanna River in spring. In Kentucky and Tennessee, the Cumberland River was extensively used for log driving from 1870 to 1930 (Montell, 1988). Along this river, rafts containing up to 100,000 logs were floated down the river twice a year, once at the beginning of the winter and a second at the end of spring (Schulman, 1974). Log driving was also extensively used in the western United States. Rivers and streams in Nevada, Arizona, Montana, Utah, Colorado, Idaho, Oregon, Washington, and California all supported log drives at some point in the 19th and 20th centuries (Sedell et al., 1991).

Along the west coast of Alaska and British Columbia (Canada), log driving only began in the 20th century (Pease, 1974; Sedell et al., 1991). Log driving continued in areas of British Columbia into the 21st century (White, 2001).

3.4 South America, Asia, and Africa

Although less documented, log driving served as an important means of wood transport in South America, Asia, and Africa (De 'Ath, 1992; Barros and Uhl, 1995; Okon et al., 2021). In the Brazilian Amazon, commercial logging and log driving started around the beginning of the 17th century. By the end of the 20th century, log driving continued to be the main method of wood transport in remote areas (Barros and Uhl, 1995). In Thailand, between 1870 and 1937, teak logs were floated for 200 to 4000 km to reach Bangkok for export to Asia, Europe, and America (De 'Ath, 1992). Elephants were often used to move these logs from the cutting site to the river and to break log jams (De 'Ath, 1992). Finally, log driving continues to be practiced in Nigeria, as it remains the only option in regions with underdeveloped road networks (Okon et al., 2021).

4 The potential of sunken wood in forest ecology

4.1 Dendrochronology and forest ecology

Dendrochronology, i.e., the study of tree-ring records, has been widely used to reconstruct past climate (Pauly et al., 2021; Savard and Bégin, 2021) and disturbance regimes (Montoro Girona et al., 2016; Labrecque-Foy et al., 2020). Disturbances leave indicators such as scars, growth release, ring wedging, and growth suppression in trees' annual radial growth rings (Swetnam et al., 2009; Morin et al., 2010; Debaly et al., 2022). Therefore, tree rings from living trees constitute valuable high-resolution environmental archives for reconstructing frequency, intensity, and spatiotemporal patterns of past disturbance regimes over the trees' lifetimes (Pearson et al., 2014).

However, the temporal perspective of tree-ring analyses is limited by the life span of living trees (Stockdale et al., 2016). To increase the temporal perspective of tree-ring studies, researchers can also rely on wood collected from old buildings or dead trees (Krause, 1997; Payette et al., 2008; Boulanger et al., 2012). Dead wood found on land is often not well preserved, often preventing the development of long tree ring–based chronologies (Stockdale et al., 2016). However, accumulated wood preserved on lake bottoms can offer centennial- to millennial-scale records for boreal regions (Gennaretti et al., 2014). This preservation occurs in lakes having low lake-bottom oxygen levels and cold temperatures. These conditions limit decomposition (Pearson et al., 2014) and favor little to no modification of wood structure and anatomy (Beldean and Timar, 2021). Tree-ring chronologies from this well-preserved submerged wood, also called subfossil wood, can be dated when they overlap known and already-established chronologies (McCarroll and Loader, 2004). Therefore, subfossil wood enables researchers to study environmental conditions over a more extended period (Pearson et al., 2014). Given that 15% to 50% of log-driven logs sank during transport, the potential for such a paleoenvironmental resource is great for many boreal and mountainous regions.

4.2 Reconstruction of disturbance regimes

Fire is one of the main disturbances in the boreal forest, and the study of past fire regimes and its relation to climate and anthropic activities is necessary to improve forest management, particularly in the context of climate change (Aakala et al., 2023; Montoro Girona et al., 2023b). Trees at a fire's edge or those growing within areas that experienced a moderate fire severity can develop fire scars (Erni et al., 2017). On a cross-section of a tree stem, fire scars can be identified (Figure 1E) and dated, even at a seasonal resolution (e.g., Swetnam et al., 2009), using the tree-ring record (Payette et al., 2008; Arseneault et al., 2021). Using fire scars from living and dead trees, Arseneault et al. (2021) reconstructed the fire dynamics over the last 200 years in northern Québec (Canada). However, using fires scars of subfossil wood extracted from six lakes in northern Québec, Gennaretti et al. (2014) were able to reconstruct a fire history covering about 1240 years.

Insect outbreaks can also be reconstructed with dendrochronology. For instance, during outbreaks of defoliating insects such as pine processionary moth (PPM; *Thaumetopoea pityocampa*) or spruce budworm (SBW; *Choristoneura fumiferana*), the defoliation of hosts trees leads to growth reductions that are noticeable in growth rings series (Morin et al., 2010; Sangüesa-Barreda et al., 2014). By dating radial growth reduction in living hosts species and comparing them to non-host species, researchers were able to reconstruct the past SBW outbreaks of the last two centuries in eastern Canada (Simard et al., 2011; Navarro et al., 2018). However, using subfossil wood, Pitre (2019) was able to reconstruct outbreaks episodes over the last 700 years, the longest chronology for SBW in North America.

4.3 Reconstruction of climate fluctuations

Climate reconstructions are essential for understanding how climate change affects forest ecosystems. Tree ring-based climate reconstructions rely on various properties, such as ring width, wood anatomy, and wood density (Bouriaud et al., 2005; Pritzkow et al., 2014; Büntgen et al., 2021). However, such records require detrending or standardization, which can sometimes modify or reduce the strength of the climatic signal (Labrecque-Foy et al., 2023). As an alternative, the isotopic analysis of the wood in the annual growth rings is receiving greater interest as a promising means of reconstructing past climate (Alvarez et al., 2018).

Oxygen and carbon stable isotope ratios ($\delta^{18}O$ and $\delta^{13}C$, respectively) are influenced by photosynthesis rates and evapotranspiration, both influenced by environmental and climatic conditions (McCarroll and Loader, 2004). Combining oxygen and carbon isotopes of tree-ring records in wood beams from ancient buildings in Rennes (France), Masson-Delmotte et al. (2005) reconstructed summer temperatures and water stress for the last 400 years. However, using ^{18}O isotopes of subfossil wood from one lake in northeastern Canada, Naulier et al. (2015) were able to reconstruct summer temperatures of the last 1000 years, and determined that the last three decades experienced the fastest warming over the last millennium.

4.4 Reconstruction of preindustrial forest composition and structure

Knowledge related to the composition and structure of preindustrial forest ecosystems is essential to set management goals and provide a reference state for future forest planning (Dupuis et al., 2011). The most direct means of assessing the natural state of preindustrial forests is to characterize old, never-harvested forests (Delisle-Boulianne et al., 2011). However, such forests are rare or non-existent in many regions because of earlier intense harvesting (Delisle-Boulianne et al., 2011). Therefore, researchers can rely on old land surveys to reconstruct past forest composition (Boucher et al., 2009; Terauds et al., 2011; Terrail et al., 2019). Although this technique has proven successful in specific contexts, the limited accessibility of such surveys, their inconsistent and low spatial coverage, and the relatively recent use of land surveys (often after the beginning of colonization) limit this approach (Boucher et al., 2014). Furthermore, old land surveys can be biased because they generally identify the dominant species, and rarely include the relative contribution of multiple subdominant species (Terauds et al., 2011).

Trees cut during the initial colonization phase represent preindustrial forests. Studying the log-driven subfossil wood of these preindustrial forests can help reconstruct the preindustrial forest composition and age. Boucher et al. (2009) combined old land surveys and subfossil wood to reconstruct past forest of the Rimouski region (Québec, Canada). Although selective logging could potentially bias a reconstitution, the authors found a good temporal representation of each study species. They reconstructed the state of the preindustrial forest (ca. 1820) and its gradual change in composition to the present.

The nature (size, species, age, etc.) of the wood found in the recovered logs can also inform about the practices of lumber industries over time (Boucher et al., 2009). They can help interpret how anthropic activities modified the composition and structure of forest ecosystem in the past (Jacod-Rousseau and Gob, 2020). For example, in the province of Québec (eastern Canada) selective logging occurred during the 19th and 20th century, which is reflected in the subfossil log-driven logs (Boucher et al., 2009). This is expected to be one of the main reasons why eastern white pines (*Pinus strobus* Linnaeus) and red pines (*Pinus resinosa* Ait) abundance significantly decreased in the forests during the 19th century (Marchand, 2013; Danneyrolles et al., 2016). Sarting in the 20th century, the transition from old conifer-dominated forests to young deciduous forests (Danneyrolles et al., 2019; Danneyrolles et al., 2021) is thought to be related to the end of selective logging and the extensive logging of numerous other conifer species such as spruce and fir (Barrette and Bélanger, 2007; Boucher et al., 2014).

4.5 Study of large wood dynamics in rivers

Forests and rivers are intimately connected, and the wood regime in rivers significantly influences river morphology (Wohl et al., 2019; Grosbois et al., 2023). Because log driving left persistent changes in river morphology (Jacod-Rousseau, 2022), efforts to restore rivers and their natural wood regimes gained interest in recent years (Wohl et al., 2019). Log-driven logs have great potential to inform about large wood debris dynamics in rivers. Indeed, the location of the logs can help identify sites more suitable for wood accumulation and their characteristics, and target the size (diameter and length) and species of logs that preferentially accumulate in rivers (Riuz-Villanueva et al., 2016). The level of decay of the logs and the dating of their last growth ring by dendrochronology can help inform about the residence time in the river (Riuz-Villanueva et al., 2016). Furthermore, the volume and biomass of log-driven logs that remain in the waterways of the boreal forests have not yet been determined. These information are crucial to restore the natural wood dynamics in rivers worldwide and to preserve aquatic and riparian habitats (Wohl et al., 2019).

5 Conclusion

Log driving played a major role in early forestry practices in many countries; however, the historical record of log driving remains poorly known. We note that log driving has been used on most continents at some point in history, and simultaneously in numerous countries during the 19th and 20th centuries. However, there exist a large bias favoring North America and Eurasia in the available literature. Also, historical documents were difficult to access, and their exploration can be limited by a language barrier and state of conservation, leaving a knowledge gap that can limit our understanding of this practice and its broader implications around the world.

Although intensive logging has had major negative impacts on forest landscapes, the logs that sank to lake bottoms during log driving also represent an invaluable resource for reconstructing past disturbances, climate, and the composition of preindustrial forest ecosystems. In the context of an ever-increasing demand for wood and global warming, this longer-term knowledge derived from log-driven wood is essential for improving forest management approaches in the face of climate change.

Author contributions

Conceptualization: J-PL-F and MMG. Writing—original draft: J-PL-F. Writing—review and editing: J-PL-F and MMG. Both authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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