

ARTICLE

Vegetation Ecology

Keeping logs on the past: Log driving tells the story of fire regimes in pine forests of eastern Canada

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Abstract

In North America, forest ecosystems have changed drastically since European settlement due to logging, land-use changes, and altered disturbance regimes. For example, red and white pine stands declined significantly in the last three centuries, and this decline was attributed to their extensive harvesting during settlement. Human-induced changes in fire regime is another probable cause of pine forests' decline that has gained attention in the last decades. However, the study of red and white pine forests can be challenging, because few pre-settlement pine forests remain today, as they were extensively harvested during the 19th century. During this extensive exploitation of pine forests, logs were transported via log driving, and many of them sunk to the bottom of lakes. These sinker logs represent an opportunity to study pre-settlement pine forests and their natural disturbance regimes. The aim of this research was to reconstruct fire regimes from the pre-settlement period to late 20th century (1700–1970) in eastern Canadian pine forests. To achieve this goal, 1151 submerged logs were extracted from lakes in the Témiscamingue region (Québec), 60 of which exhibited fire scars. We built a reference chronology using 140 living pines to cross-date 81 scars and were able to reconstruct fire activity since 1717. We then modeled the relative probability of fire occurrence across settlement periods using a Bayesian approach. Our results showed that the probability of fire occurrence almost doubled following the beginning of settlement (1840), highlighting the impact of intensified logging and land conversion on fire frequency. Our study is among the first to use sinker logs and a Bayesian approach to reconstruct and model preindustrial fire regimes in pine forests. This new knowledge is crucial to develop sustainable forest management practices and conservation strategies in red and white pine forests in North America.

KEYWORDS

dendrochronology, disturbance ecology, ecosystem-based management, paleoecology, red pine, white pine

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INTRODUCTION

Red pine (*Pinus resinosa*) and white pine (*Pinus strobus*) are among the most ecologically and economically valuable tree species in North America. Their tall and complex structure provides essential habitats and feeding sources for many animals such as porcupines (*Erethizon dorsatus*), black bears (*Ursus americanus*), and moose (*Alces alces*) and for plants such as wild ginger (*Asarum canadense*), bryophytes, and lichen (Carleton, 2003; Uprety et al., 2013). Their derived wood products (furniture, doors, and molding) are among the most commercially valuable for the forest industry and were essential for the development of early settlements (Abrams, 2001; Latremouille et al., 2008). Their presence has also been essential for Indigenous communities, as many pine parts were used for medicine, fishing, and arts and crafts (Abrams, 2001; Uprety et al., 2013). In the last three centuries, the abundance of red and white pine (hereafter pine) declined over most of their distribution both in the United States and in Canada (Abrams, 2001; Thompson et al., 2006). In Témiscamingue (eastern Canada), the abundance of white pine in land surveys has decreased from 57% to 7% since the end of the 19th century (Danneyrolles et al., 2016b). The causes of this abrupt decline are unclear, although it is generally attributed to intensive harvesting during the last 200 years (Latremouille et al., 2008). The decline in pines could also be the result of major changes in fire regimes preventing successful regeneration (Engelmark et al., 2000; Marschall et al., 2022).

Intensive harvesting of pine in eastern North America began early in the 19th century, along with European settlement (Abrams, 2001; Riopel, 2002). During this period, pines were specifically targeted by the forest industry because their long and straight shape was ideal for ship building (Latremouille et al., 2008). This extensive harvesting was facilitated by log driving, during which logs were floated along waterways (Aird, 2016; Sedell et al., 1991). Although many logs were lost to the bottom of the lakes (Marchand & Filion, 2014), log driving remained the cheapest and most efficient way of moving the logs from the cutting area to the sawmill until the end of the 1970s (Sedell et al., 1991). This targeted cutting could have caused a significant decline in pine abundance as well as a transition from conifer-dominated to deciduous-dominated forests (Danneyrolles et al., 2019; Egande, 2021).

The indirect effect of increasing anthropogenic activities on disturbance regimes could also have had an impact on the natural regeneration of pines during settlement (Weyenberg et al., 2004). Red and white pine can only regenerate by seed, and the regeneration is highly

sensitive to competition (Uprety et al., 2014). Ideal conditions for germination and the survival of seedlings include exposed mineral soil and low understory cover (Pitt et al., 2011, 2016). Therefore, pine forests are closely associated with relatively frequent, low-severity surface fires that eliminate competition and expose the mineral soil (Gonzalez-Perez et al., 2004; Hart & Chen, 2006), although seedling establishment is a result of competing outcomes between seedling mortality and conditions facilitating establishment. Human activities during and after settlement, such as land clearing and fire suppression, have undoubtedly modified fire regimes (Terrail et al., 2020). For example, in Témiscamingue, sustained settlement activities between 1840 and 1915 are believed to have increased the fire frequency, while subsequent fire exclusion significantly diminished fire frequency (Drever et al., 2006). This pattern has been observed in many regions throughout North America (Engstrom & Mann, 1991; Meunier et al., 2019). However, precisely quantifying these changes in fire frequency in eastern temperate regions like Témiscamingue remains challenging, because of deteriorating fire scar evidence over time (Margolis et al., 2022).

In recent years, the First Nation of Kitcisakik (southern Abitibi) has urged forestry companies to restore and maintain pine populations on their territory (Uprety et al., 2013). To achieve this goal, it is essential to deepen our understanding of the factors contributing to the decline of pine forests. In particular, knowledge of preindustrial fire regimes, which created conditions for pine regeneration, is crucial (Bergeron & Brisson, 1990; Nyamai et al., 2014). This objective is challenging because most pine forests have undergone major anthropogenic modifications, and only few are left in a landscape now dominated by hardwood species (Danneyrolles et al., 2016b). The pine logs that sank to the bottom of the lakes during log driving in the 19th and 20th centuries (hereinafter referred to as sinker logs) were well preserved because of the anoxic and cold conditions found at the bottom of the lakes. These sinker logs have the potential to provide insights into historical fire regimes in the now-sparse pine forests and to guide future sustainable forest management practices (Labrecque-Foy & Montoro Girona, 2023).

This study aimed (1) to reconstruct past fire regimes in red and white pine forests of Témiscamingue from the pre-settlement period until the second half of the 20th century, (2) to evaluate the impacts of settlement phases on fire regimes in pine forests in the 19th and 20th centuries, and (3) to develop a new Bayesian statistical method for analyzing fire frequency using fire scars on trees. Settlement was divided into three periods: pre-settlement (<1840), settlement (1840–1915), and post-settlement

(>1915), according to the historical literature on land-use patterns in Témiscamingue (Lienert, 1966; Riopel, 2002). Based on the effects of settlement on fire regimes presented in other regions of North America (Boucher et al., 2014; Marschall et al., 2022; Terrail et al., 2020), we expect fire frequency to have increased during the period of settlement, between approximately 1840 and 1915.

MATERIALS AND METHODS

Study area

Our study took place in Témiscamingue, Western Québec, Canada (46.73° N; 79.09° W; Figure 1). The study region is in the sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*) bioclimatic domain (MRNF, 2021). Mean annual temperature and annual precipitation (2001–2020) are 5.1°C and 892 mm, respectively (Barrage Témiscamingue; Environnement Canada, 2024). Surface deposits consist primarily of glacial and fluvio-glacial tills and moraines, and rocky outcrops are found at higher

elevations (Gouvernement du Québec, 2024). The estimated time required to burn the 179,000 ha of forest covering Témiscamingue based on fire occurrence during the last century is 5081 years (Drever et al., 2006).

History of settlement and agroforestry in Témiscamingue

More than 5000 years ago, Témiscamingue was occupied by nomadic Indigenous people that had limited influence on fire regimes (Riopel, 2002). Around 1840, commercial forest exploitation began that targeted red and white pines for ship and house building (Lienert, 1966). In 1851, Indigenous people were relocated, and forest exploitation intensified (Riopel, 2002). Soon after, in 1879, agricultural settlement began to provide hay, oats, and potatoes to the forest workers and their horses (Paquin, 1979). At that time, settlers were expected to clear at least 1 ha of land every year, and fire was frequently used as a fast way to clear the land (Province of Quebec, 1920). In 1905, forest exploitation started to shift eastward, because pine

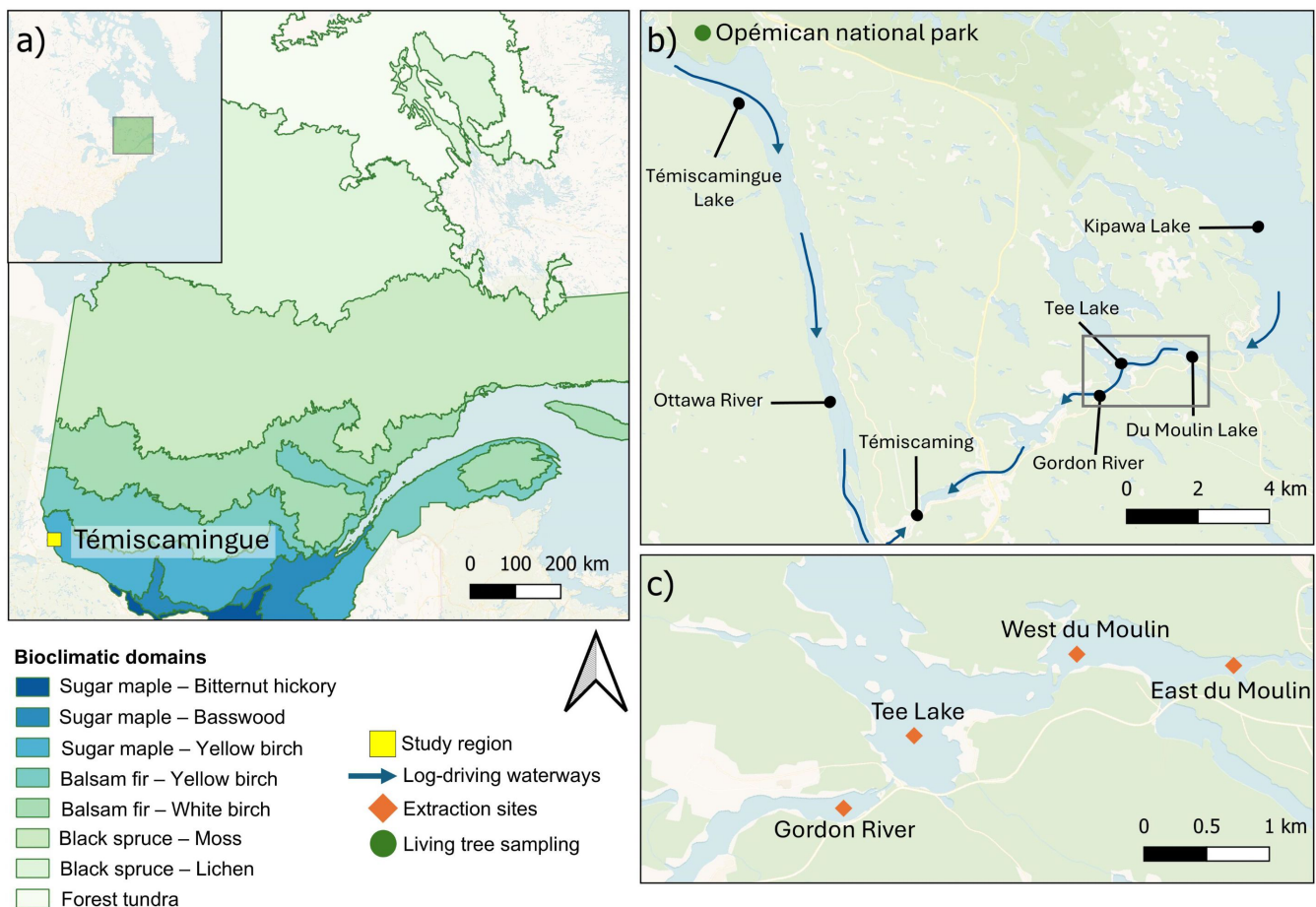


FIGURE 1 (a) Study region, (b) log driving waterways, and (c) log extraction sites near the city of Témiscamingue (46.73° N; 79.09° W), Western Québec, Canada.

abundance had decreased due to extensive exploitation (Paquin, 1979). The settlement period ended between 1914 and 1917 in Témiscamingue (Drever et al., 2006; Lienert, 1966; Riopel, 2002). Lienert (1966) claims that this drastic settlement halt in Témiscamingue happened because newcomers chose to settle in Abitibi (~150 km north-east) where a newly constructed transcontinental railway facilitated their arrival. In 1917, the establishment of a pulp and paper mill in Témiscamingue (Riordon Pulp & Paper company, 1917–1950) oriented forest harvesting toward black spruce, and thus, anthropogenic activities were concentrated near spruce forests (Riopel, 2002). Fire suppression efforts began around 1930, but they were not effective until the installation of radio stations and fire towers at the end of the 1940s (Lienert, 1966).

From 1840 until 1978, log driving was used as the main way to transport timber in the region (Riopel, 2002). Log driving remained broadly used even when railways (1948) and wood trucks (1952) became available (Lienert, 1966). Logs were floated along two main waterways to reach the city of Témiscamingue (Figure 1b). Logs cut in the Témiscamingue Lake watershed were floated down the Ottawa River, while logs cut in the Kipawa Lake

watershed were floated along the Gordon River (Riopel, 2002). During that process, numerous logs sank to the bottom of rivers and lakes (Figure 2a; Marchand & Filion, 2014). Sinker logs represent an invaluable source of information about the state and dynamics of preindustrial pine forests because they were among the first trees to be cut at the beginning of the forest exploitation (Labrecque-Foy & Montoro Girona, 2023). Moreover, given that the logs' source locations within these watersheds are unknown, the results of our study paint a broad brush of fire regimes in the area and may reflect a mixture of fire regimes among specific locations on the landscape.

Field sampling

Sampling of sinker logs and identification of fire scars

Professional divers of the Bois de Drave company extracted a total of 1151 logs from four locations along the Kipawa–Témiscamingue waterway from 2019 to 2023 (Figure 1c). In 2019–2022, logs were extracted from two



FIGURE 2 (a) Sinker logs that sank to the bottom of Tee Lake, Témiscamingue, (b) 5-cm sections of sinker logs that were extracted from Tee Lake and that are drying in the greenhouse, and (c–e) three examples of the fire scars that were used in the study. Notice the smooth edges of the scars followed by growth releases. Photo credits: (a) Nathalie Lasselin, Aquanaut, and Aquasubterra; (b–e) Julie-Pascale Labrecque-Foy.

locations in Lake du Moulin and one location in Tee Lake. In 2023, logs were extracted from the Gordon River. The company provided 5-cm-thick sections of the widest extremity of each log, which were used for this study (Figure 2b). The widest extremity of the logs is most likely to have been near the ground and thus affected by fire, although there is no way to know exactly how many logs were cut per tree. We dried the samples in a greenhouse for approximately 3 months and sanded them with gradually finer grit up to 400 grit.

For this study, we only used pine samples bearing fire scars. To identify red and white pines, we used macroscopic species identification criteria: creamy wood color, gradual (white pine) or abrupt (red pine) transition between early and late wood, and numerous evenly distributed resin ducts. We identified fire scars based on two criteria. Samples had to display a visible scar with smooth edges followed by an evident growth release (Figure 2c–e). We only counted scars whose origin could be attributed to fire with high certainty. In total, we selected 60 pine fire-scarred samples, adding up to 81 fire scars.

Living samples

We sampled living trees in order to establish a chronology dating back to the sinker logs to assign scars to calendar years. In August 2023, we collected two cores from each of 140 white pines at breast height in the protected forest of Opémican national park to facilitate the dating of the sinker logs (Figure 1b). We chose to only sample white pines because they are known to be the oldest trees in the park, and we chose trees that were expected to be old enough to overlap with rings of the sinker logs (at least 150 years). We used white pines to date red and white pines due to their very similar ecology and response to environmental stressors (Rudolf, 1990). We glued the cores on wooden supports and sanded them according to the same protocol as the sinker logs.

Dendrochronological approach

We measured ring width in CooRecorder (v.9.8.0; Maxwell & Larsson, 2021) along one (live tree cores; two cores per tree) or two (fire-scarred sinker logs) radii. We performed cross-dating and dating to calendar year in Past5 (v.5.0.620; Hammer et al., 2001, Austria) and validated the results with COFECHA (Holmes, 1983). We compiled chronology statistics (expressed population signal [EPS] and mean correlation) with the dplR package in R to validate dating accuracy (v.4.3.3; Bunn, 2008; R Core Team, 2021). We combined fire scars dated at ± 2 -year

intervals on different trees to account for dating uncertainties of the scars (Engstrom & Mann, 1991; McBride, 1983).

Data analysis

Division of the settlement periods

We divided settlement periods based on historical documentation for the Témiscamingue region (see *History of settlement and agroforestry in Témiscamingue*):

1. Pre-settlement (before 1840): The region is mainly occupied by nomadic Indigenous people that have limited impact on fire regimes.
2. Settlement (1840–1915): Settlement follows the limit of forest exploitation. Fire is the main land conversion method used by settlers, increasing the risk of forest fires.
3. Post-settlement (after 1915): Intensive settlement ends around 1915 in Témiscamingue. Forest exploitation is reoriented toward the pulp and paper industry. Anthropogenic activities are relocated near spruce forests (north-east).

Bayesian modeling

We modeled the effect of the settlement period on the occurrence of fire using the 81 fire scar dates obtained from the sinker logs, in order to test if the relative frequency of scars was different between periods. We also took sample depth into consideration because the number of samples for a given year can influence the probability of observing a fire scar.

The model used a Bayesian framework with Markov chain Monte Carlo sampling implemented in JAGS (v.4.3.2; Plummer, 2003). We chose Bayesian modeling to explicitly account for uncertainty in the data and incorporate prior knowledge regarding the relationships between variables, including the effect of sample depth and settlement periods.

In practical terms, our Bayesian model aims to relate the data that we observed (the number of scars counted for each calendar year) to the unobserved variables that we are interested in (the relative probability of fire occurrence during each settlement period). To do this, our framework needs to consider both the probability of a fire occurring and the probability of observing a scar if a fire did occur. This distinction is necessary to account for the difference in sample depth throughout the study period in a probabilistic manner. It also allows us to consider the possibility that fires may have

occurred without scarring any sampled trees, especially in years where sample size is low. The probability of a fire occurring is ultimately related to the settlement period when the trees were scarred through a generalized linear model with a logit link, thus allowing distinct fire probability parameters to be computed for each of the three periods.

More precisely, we modeled the number of observed fire scars using a binomial distribution as follows:

$$k \sim \text{Binomial}(p, n) \quad (1)$$

where k is the number of fire scars observed in a specific year, p is the probability to observe a fire scar, and n is the number of sinker log samples of that year. We determined the probability p as follows:

$$p = p1 \times p2 \quad (2)$$

where $p1$ is the occurrence of a fire at a specific year somewhere over the stands of provenance of our logs (i.e., a binary variable coded as 1 if a fire occurred and 0 otherwise) and $p2$ is the probability to observe a scar in our logs if there is a fire somewhere over their stands of provenance. Based on this equation, if there is no fire ($p1 = 0$), the probability to observe a fire scar (p) is zero. In this model, we estimated the probability to observe a fire scar if there is a fire ($p2$) to be constant for any fire, although its value is not known a priori. While this simplification is necessary, it has some limitations: it does not account for variations according to the location of the logged stands or to the intensity and extent of the fires. We modeled the occurrence of a fire in any period ($p1$) by a Bernoulli distribution as follows:

$$p1 \sim \text{Bernoulli}(b, 1) \quad (3)$$

where b is the probability of the occurrence of a fire over the stands of provenance of our logs for a specific period. Finally, we accounted for the effect of each period on the probability b with the following generalized linear regression with a logit link function:

$$\text{logit}(b) = \beta1 + \beta2 \times \text{period2} + \beta3 \times \text{period3} \quad (4)$$

where $\beta1$ is the intercept (b over the pre-settlement period), $\beta2$ is the effect of the second period (settlement), and $\beta3$ is the effect of the third period (post-settlement). The factors “period2” and “period3” are equal to 1 if we are in the corresponding period, and equal to 0 otherwise. We sampled each of the parameters included in the model and derived the difference between $\beta2$ and $\beta3$ ($\beta2 - \beta3$) to also test the difference between the probabilities of fire during periods 2 and 3.

We used non-informative priors for $p2$ (uniform between 0 and 1), $\beta1$, $\beta2$, and $\beta3$ (normal distribution with a mean of 0 and a SD of 100). We ran five chains of 10,000 iterations, with a thinning rate of 20 and a burn-in of 1000 using the JAGS program (v.4.3.2; Plummer, 2003) in R. A graph summarizing the model construction and figures of the chain convergence and autocorrelation between successive sampling is available in Appendix S1: Figures S1–S3. Full model code is available online (Labrecque-Foy et al., 2025).

This innovative Bayesian approach enabled us to consider the probabilistic effect of sample depth in our analysis and limit its impact on our results, therefore improving the reliability of our results. Moreover, the posterior distributions provide detailed information on the uncertainties of important parameters influencing fire frequency. The flexibility of our Bayesian modeling framework would also make it easy to test further variables that could have an impact on either fire frequency or the proportion of samples bearing scars in a given fire year. Despite this, we can realistically only estimate the relative probability of fire occurrence between periods, and not the absolute probability of fire, because of the many unknowns involved (tree origin, part of the tree that was scarred, probability of fire causing a scar, etc.).

RESULTS

Ring width chronology and dates of fire events

The tree-ring chronology built with the 60 samples bearing fire scars covers the 1717–1967 period (Figure 3). Sample depth remains relatively stable (around $n = 53$)

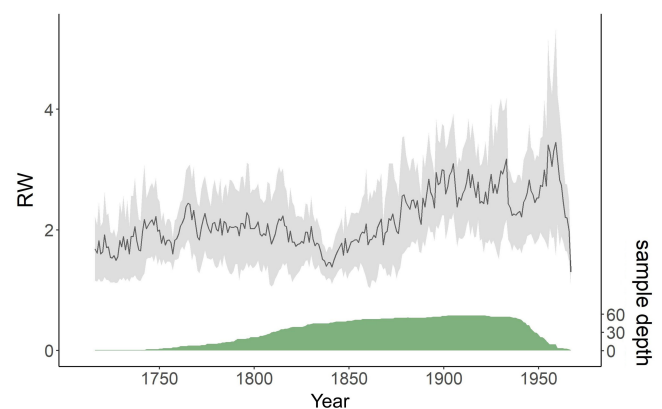


FIGURE 3 Mean raw ring width (RW; in millimeters) chronology of the log-driven samples with fire scars. Gray-shaded area represents SE of the mean, and green-shaded area represents sample depth.

between 1825 and 1930. EPS and mean correlation between all pairs of samples are 0.933 and 0.302, respectively, thus validating the dating of the chronology and the fire scars.

In total, we dated 81 fire scars, representing 21 fire years (Figure 4a). The first fire scar was dated to 1763 and the last fire scar to 1954, covering almost 200 years of

the fire history in the study area. The estimated fire return interval for period 1, starting from the first recorded fire (1763), was 25.7 years. The estimated fire return intervals for periods 2 and 3 were 6.3 and 8.7 years, respectively. Fifteen trees present multiple fire scars, confirming a relatively short time between repeated fires. Based on the number of trees bearing a fire scar per fire

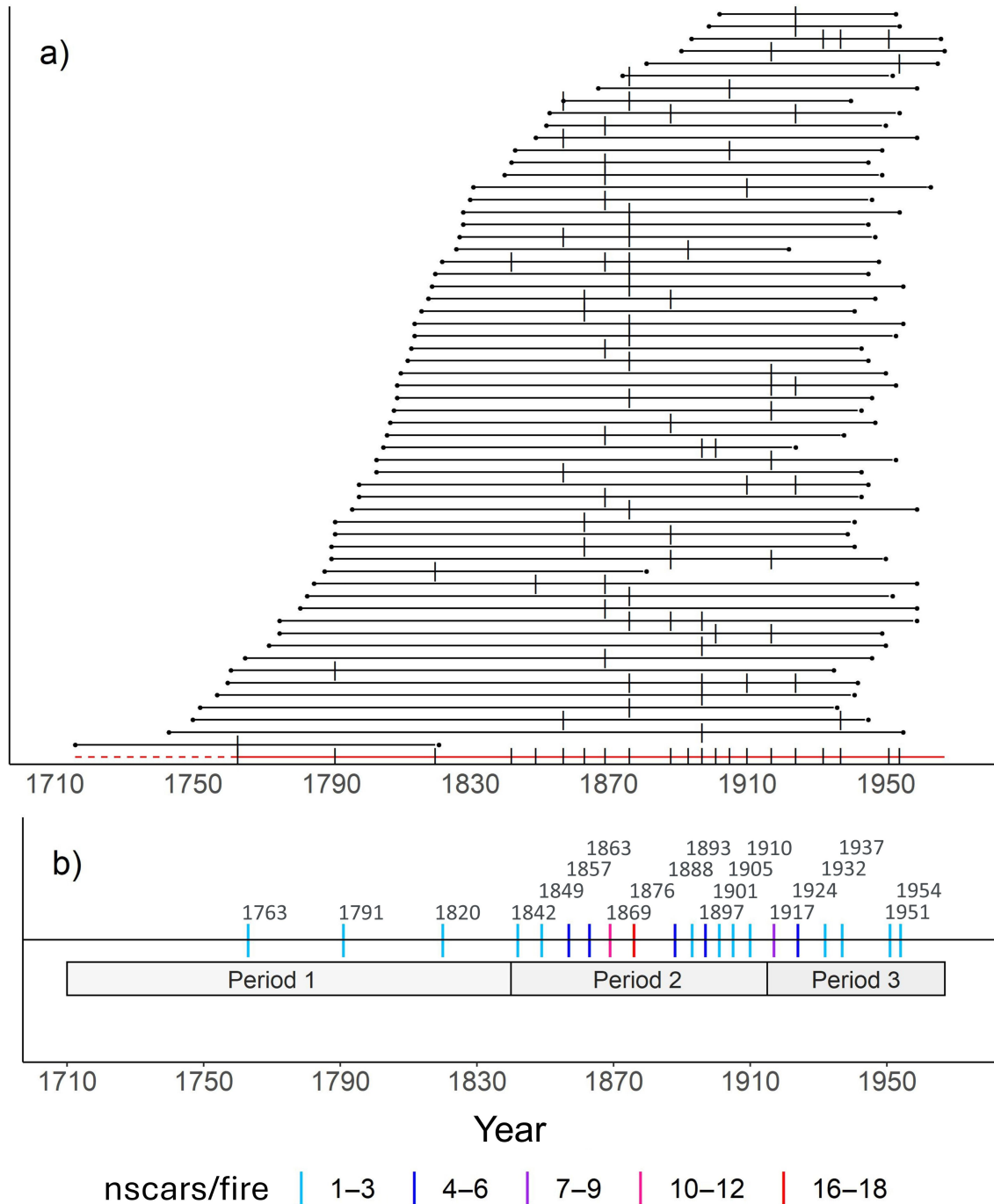


FIGURE 4 (a) Time span of the measured rings of each sinker log (horizontal lines) with the dating of their fire scars (vertical lines). At the bottom, in red, a composite chronology summarizing the dates of the 21 fire events identified in this study. (b) Number of scars (nscars) compiled for each of the 21 fire events dated in this study.

year (Figure 4b), there appear to have been several small, localized fires (scars occurring on <3 samples) and some widespread fires like in 1869 ($n = 11$), 1876 ($n = 17$), 1888 ($n = 6$), 1917 ($n = 7$), and 1924 ($n = 6$). However, although fire scar synchronicity can inform fire severity and size (Marschall et al., 2022), we can only hypothesize the severity and size of the fire because of the nature of our samples and their unknown exact provenance.

Fire probability among periods

Bayesian modeling suggests that the probability of fire is higher in the settlement and post-settlement periods (Figure 5; period 2 and period 3), even though only the effect of the second period (β_2) was different relative to that of period 1 according to 95% CIs of the posterior probabilities (Table 1). Thus, we found no difference between the effect of the second and the third periods ($\beta_2 - \beta_3$), and no significant difference between the first and third periods (β_3). We assessed the validity of the

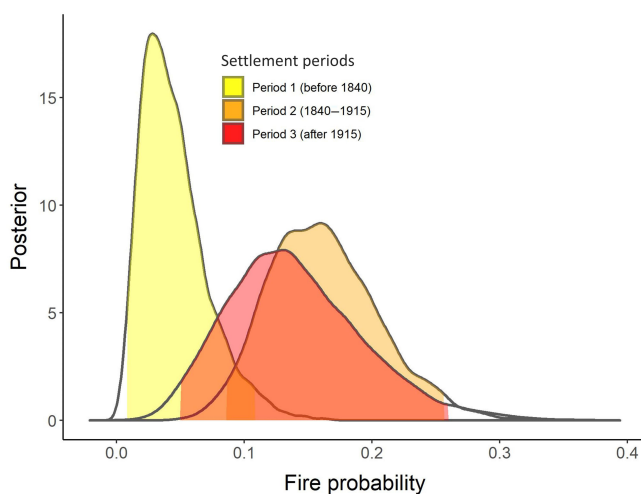


FIGURE 5 Posterior density of probability of a fire occurrence for each settlement period as modeled by the Bayesian modeling framework. Shaded areas represent the 95% CI.

TABLE 1 Mean value and 95% CI of the probabilities of a fire occurrence.

Parameter	Signification	Mean	95% CI
β_2	Difference between periods 2 and 1	1.56	0.3 to 3.1
β_3	Difference between periods 3 and 1	1.33	−0.1 to 3.0
$\beta_2 - \beta_3$	Difference between periods 2 and 3	0.22	−0.8 to 1.4

Bayesian model through standard convergence and sampling diagnostics (Appendix S1: Figures S2 and S3).

DISCUSSION

In regions that have been intensively exploited, reconstructing historical fire regimes using dendrochronology presents significant challenges because extensive human land use has contributed to the removal of old trees bearing fire scars (Margolis et al., 2022). Additionally, deterioration of existing fire scarred stumps, widespread logging, and fire exclusion has led to changes in forest composition, leaving fewer conifers that could record fires via fire scars (Danneyrolles et al., 2018; Margolis et al., 2022). In this study, we overcame these challenges by using log-driven trees to reconstruct fire histories with annual resolution. Our unique dataset enabled us to date fire scars spanning from the pre-settlement period to the second half of the 20th century (250 years) in forest stands that are now rare in the region. These log-driven vestiges of early forests exploitation serve as invaluable proxies for understanding past forest dynamics and hold significant potential for application across temperate and boreal regions (Labrecque-Foy & Montoro Girona, 2023).

Fire-settlement association from pre-settlement to the mid-20th century

Based on our dating of more than 80 fire scars on sinker logs, we estimate that fire frequency increased by a factor of 3–4 from the pre-settlement to settlement periods, with fire frequency increasing from one fire year every 26 years (before 1840) to approximately one fire year every 6–9 years after 1840. Our findings support our hypothesis that fire frequency increased during the settlement period, approximately between 1840 and 1915. These results reflect a common pattern in North American fire history, showing that European settlement typically results in more fire activity. In our study area, European settlement began around 1840 and was characterized by large-scale land clearing using fire (Riopel, 2002) and extensive exploitation of pine forests (Lienert, 1966). Around 1915, the pulp and paper industry began and reoriented harvest toward black spruce and balsam fir for the remainder of the 20th century (Riopel, 2002) and settlement activities slowed down (Lienert, 1966). These settlement activities and forest exploitation practices likely had very distinct effects on fire frequency.

This increase in fire frequency following settlement was also observed by other studies using historical land

surveys and air photos in eastern Canada (Danneyrolles et al., 2018; Drever et al., 2006). Settlement activities such as land clearing, deforestation using fire, and slash fires likely increased the probability of fire (Drever et al., 2006; Nyamai et al., 2014). Similar to our findings, Drever et al. (2006) identified a peak in fire activity between 1870 and 1890 in their study of southern Témiscamingue. In Saguenay, escaped settlement fires were found to be the main cause of fires in the 1875–1915 period (Boucher et al., 2014), and the settlement front was closely associated with fire activity in the Bas-Saint-Laurent region (Terrail et al., 2020). In north-central Pennsylvania, Marschall et al. (2022) also found that the highest fire frequency registered by fire scars was during the settlement period (1785–1914).

We cannot rule out the possibility that the increase in fire frequency during the settlement period was partially driven by the ending of the “Little Ice Age” and the concurrent climate warming (Danneyrolles et al., 2018; Gennaretti et al., 2017). However, previous studies in North America including climate in their models during our study period found such influences to be obscured by the apparently stronger influences of anthropogenic fire regimes (Danneyrolles et al., 2019; Marschall et al., 2022; Pechony & Shindell, 2010; Stambaugh et al., 2021). Unfortunately, our model and data could not enable us to disentangle the effects of climate from the effect of settlement activities, although they might not be mutually exclusive. However, two well-known continental-scale droughts occurred in 1818–1820 and 1929–1940 (Cook et al., 2007, 2010), which coincide with three fire events identified in this study.

In contrast to our expectation, fire frequency did not significantly decrease after 1915. However, a lengthening of the fire interval was observed around 1940, which could correspond to the rise of organized fire suppression (Lienert, 1966). This lengthening of the fire interval may also result from a shift in forest composition caused by selective harvesting that primarily removed conifers, thereby promoting the growth of early successional hardwood species, which are generally less flammable (Danneyrolles et al., 2016a). Many studies in the Témiscamingue region have found a decrease in fire frequency during the 20th century, which has generally been attributed to the development of efficient fire suppression methods and the slowing down of settlement (Bergeron & Brisson, 1990; Danneyrolles et al., 2019; Drever et al., 2006; Grenier et al., 2005). This decrease in fire frequency was also observed in red pine forests of northern Minnesota, where only one fire was observed after the beginning of fire exclusion in the region (1935) compared to 55 fires prior to fire exclusion (1535–1935; Stambaugh et al., 2021).

There are some limitations related to the use of sinker logs for the reconstruction of fire regimes. First, we are unable to confirm whether logs were cut at ground level, and logs we analyzed were all bottom logs. These factors strongly influence the probability of a fire being recorded; therefore, fire return intervals recorded by the sinker logs used in this study were likely a conservative estimate of fires. Also, while the logs all came from the same region, the exact provenance of logs is unknown. For this reason, some fires that were identified as widespread fires because of the number of trees that were scarred could also be localized fires scarring many trees in a small area. Finally, we were surprised that most of our sinker logs were cut during the third (post-settlement) period (after 1915), because pines were intensively exploited during the 1840–1915 period. The more recent sinker logs might have been the ones on the top of the lake sediments, therefore being easier to collect by the divers. Nonetheless, these trees were able to record several fires during the high-intensity harvesting period.

The role of fire in the decline and management of red and white pine forests

The changes in fire regimes observed in our study starting from the settlement period have likely played an important role in pine forest decline in the Témiscamingue region. Indeed, red and white pines need frequent low-severity fires to reduce competition and expose suitable seedbed for germination (Nyamai et al., 2014). However, very short fire intervals could compromise regeneration by killing seedlings and saplings, although there seems to be no consensus about what fire frequency would be optimal to ensure successful regeneration. For example, Bergeron and Brisson (1990) concluded that there need to be at least 36 years between fires for the regeneration to develop thick bark and survive the next fire, while Meunier et al. (2019) found that regeneration could survive fire intervals of less than 19 years. On the other hand, the results from Marschall et al. (2022) suggest shorter fire return intervals (between 2 and 8 years) during the periods when pine trees were still dominant. Nonetheless, the major increase in fire frequency that we observed starting in 1840 in our study could have compromised pine regeneration by decreasing seedlings' survival rates. Moreover, the most extensive fires (those leaving more than five scars per event) all occurred after the onset of European settlement. These more severe fires tend to create fewer canopy gaps, which are typically associated with regeneration patches near seed-bearing trees (Fredericksen & Agramont, 2011). Coupled with extensive exploitation, the increase in fire frequency and

severity may have contributed to the decline of red and white pines in the region during the 19th and 20th centuries, although these fire regimes may not have continued following logging.

While our study enabled us to reconstruct past fire history in pine forests and to determine fire intervals in these stands, our results differ from some of the previous studies on the same species. Therefore, we were not able to identify an optimal fire regime that should be set as a conservation target. Nonetheless, we recommend that fire management be included in pine conservation programs, as it plays a critical role in their regeneration success (Bernier et al., 2016; Drever et al., 2006; Nyamai et al., 2014).

CONCLUSION

In this study, we demonstrated the potential of sinker logs to reconstruct past disturbance regimes with yearly precision. To our knowledge, this study was the first to use sinker logs to reconstruct fire history in red and white pine forests. We were able to reconstruct more than 200 years of fire history and highlight the impact of anthropogenic activities on fire regimes in pine forests using log-drive samples. Using a novel Bayesian approach, we determined that the probability of fire almost doubled since the beginning of settlement (1840). While the increase in fire frequency observed during the settlement period (1840–1915) could have compromised regeneration and survival in pine forests, our results suggest that the absence of fire following that period could have also been detrimental to the perpetuation of pines. These results suggest that restoration strategies and conservation efforts should be oriented toward fire management in pine forests. Considering the potential impacts of global climate change on natural disturbances frequency and severity in the future (Drever et al., 2009; Girona et al., 2023; Seidl et al., 2017), more studies about pre-settlement disturbance regimes are essential to guide new management methods and conservation efforts.

AUTHOR CONTRIBUTIONS

Conceptualization: Julie-Pascale Labrecque-Foy and Miguel Montoro Girona. *Data curation:* Julie-Pascale Labrecque-Foy and Miguel Montoro Girona. *Formal analysis:* Julie-Pascale Labrecque-Foy, Marc-André Lemay, and Fabio Gennaretti. *Funding acquisition:* Julie-Pascale Labrecque-Foy and Miguel Montoro Girona. *Investigation:* Julie-Pascale Labrecque-Foy and Miguel Montoro Girona. *Methodology:* Julie-Pascale Labrecque-Foy, Marc-André Lemay, Fabio Gennaretti, Dominique Arseneault, and Miguel Montoro Girona. *Project administration:* Miguel

Montoro Girona. *Resources:* Fabio Gennaretti and Miguel Montoro Girona. *Software:* Marc-André Lemay, Fabio Gennaretti, and Miguel Montoro Girona. *Supervision:* Fabio Gennaretti, Dominique Arseneault, and Miguel Montoro Girona. *Validation:* Julie-Pascale Labrecque-Foy, Fabio Gennaretti, and Miguel Montoro Girona. *Visualization:* Julie-Pascale Labrecque-Foy and Marc-André Lemay. *Writing—original draft:* Julie-Pascale Labrecque-Foy. *Writing—review and editing:* Julie-Pascale Labrecque-Foy, Marc-André Lemay, Fabio Gennaretti, Dominique Arseneault, and Miguel Montoro Girona.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.


DATA AVAILABILITY STATEMENT

Data and code (Labrecque-Foy et al., 2025) are available from Figshare: <https://doi.org/10.6084/m9.figshare.28165319>.

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REFERENCES

- Abrams, M. D. 2001. "Eastern White Pine Versatility in the Presettlement Forest." *BioScience* 51: 967–979.
- Aird, P. L. 2016. "Logging and Rafting Square Timber in Ontario and Québec for Shipment to Great Britain Circa 1870 to 1908." *The Forestry Chronicle* 92: 394–400.
- Bergeron, Y., and J. Brisson. 1990. "Fire Regime in Red Pine Stands at the Northern Limit of the Species' Range." *Ecology* 71: 1352–64.
- Bernier, P. Y., S. Gauthier, P.-O. Jean, F. Manka, Y. Boulanger, A. Beaudoin, and L. Guindon. 2016. "Mapping Local Effects of Forest Properties on Fire Risk across Canada." *Forests* 7: 157.
- Boucher, Y., P. Grondin, and I. Auger. 2014. "Land Use History (1840–2005) and Physiography as Determinants of Southern Boreal Forests." *Landscape Ecology* 29: 437–450.
- Bunn, A. G. 2008. "A Dendrochronology Program Library in R (dplR)." *Dendrochronologia* 26: 115–124.
- Carleton, T. J. 2003. "Old Growth in the Great Lakes Forest." *Environmental Reviews* 11: 115–134.
- Cook, E. R., R. Seager, M. A. Cane, and D. W. Stahle. 2007. "North American Drought: Reconstructions, Causes, and Consequences." *Earth-Science Reviews* 81: 93–134.
- Cook, E. R., R. Seager, R. R. Heim, Jr., R. S. Vose, C. Herweijer, and C. Woodhouse. 2010. "Megadroughts in North America: Placing IPCC Projections of Hydroclimatic Change in a Long-Term Palaeoclimate Context." *Journal of Quaternary Science* 25: 48–61.
- Danneyyrolles, V., D. Arseneault, and Y. Bergeron. 2016a. "Pre-Industrial Landscape Composition Patterns and Post-Industrial Changes at the Temperate–Boreal Forest Interface in Western Quebec, Canada." *Journal of Vegetation Science* 27: 470–481.
- Danneyyrolles, V., D. Arseneault, and Y. Bergeron. 2016b. "Long-Term Compositional Changes Following Partial Disturbance Revealed by the Resurvey of Logging Concession Limits in the Northern Temperate Forest of Eastern Canada." *Canadian Journal of Forest Research* 46: 943–49.
- Danneyyrolles, V., D. Arseneault, and Y. Bergeron. 2018. "Anthropogenic Disturbances Strengthened Tree Community–Environment Relationships at the Temperate–Boreal Interface." *Landscape Ecology* 33: 213–224.
- Danneyyrolles, V., S. Dupuis, G. Fortin, M. Leroyer, A. De Römer, R. Terrail, M. Vellend, et al. 2019. "Stronger Influence of Anthropogenic Disturbance than Climate Change on Century-Scale Compositional Changes in Northern Forests." *Nature Communications* 10: 1265.
- Drever, C. R., Y. Bergeron, M. C. Drever, M. Flannigan, T. Logan, and C. Messier. 2009. "Effects of Climate on Occurrence and Size of Large Fires in a Northern Hardwood Landscape: Historical Trends, Forecasts, and Implications for Climate Change in Témiscamingue, Québec." *Applied Vegetation Science* 12: 261–272.
- Drever, C. R., C. Messier, Y. Bergeron, and F. Doyon. 2006. "Fire and Canopy Species Composition in the Great Lakes–St. Lawrence Forest of Témiscamingue, Québec." *Forest Ecology and Management* 231: 27–37.
- Egande, N. 2021. *Reconstitution historique de la composition des forêts preindustrielles boréales mixtes de l'ouest du Québec*. Rouyn-Noranda: Université du Québec en Abitibi-Témiscamingue. 48 p.
- Engelmark, O., Y. Bergeron, and M. D. Flannigan. 2000. "Age Structure of Eastern White Pine, *Pinus strobus* L., at its Northern Distribution Limit in Quebec." *The Canadian Field-Naturalist* 114: 601–4.
- Engstrom, F. B., and D. H. Mann. 1991. "Fire Ecology of Red Pine (*Pinus resinosa*) in Northern Vermont, U.S.A." *Canadian Journal of Forest Research* 21: 882–89.
- Environnement Canada. 2024. "Données historiques – Barrage Témiscamingue." https://climat.meteo.gc.ca/historical_data/search_historic_data_f.html.
- Fredericksen, T. S., and A. R. E. Agramont. 2011. "Regeneration Patterns of Eastern White Pine (*Pinus strobus* L.) in Hardwood-Dominated Forests in Virginia, USA." *New Forests* 44: 51–61.
- Gennaretti, F., D. Huard, M. Naulier, M. Savard, C. Bégin, D. Arseneault, and J. Guiot. 2017. "Bayesian Multiproxy Temperature Reconstruction with Black Spruce Ring Widths and Stable Isotopes from the Northern Quebec Taiga." *Climate Dynamics* 49: 4107–19.
- Girona, M. M., T. Aakala, N. Aquilué, A.-C. Bélisle, E. Chaste, V. Danneyrolles, O. Díaz-Yáñez, et al. 2023. "Challenges for the Sustainable Management of the Boreal Forest under Climate Change." In *Boreal Forests in the Face of Climate Change: Sustainable Management*, edited by M. M. Girona, H. Morin, S. Gauthier, and Y. Bergeron, 773–837. Cham: Springer International Publishing.
- Gonzalez-Perez, J. A., F. J. Gonzalez-Vila, G. Almendros, and H. Knicker. 2004. "The Effect of Fire on Soil Organic Matter – A Review." *Environment International* 30: 855–870.
- Gouvernement du Québec. 2024. "Forêt Ouverte." <https://www.foretouverte.gouv.qc.ca/>.
- Grenier, D. J., Y. Bergeron, D. Kneeshaw, and S. Gauthier. 2005. "Fire Frequency for the Transitional Mixedwood Forest of Timiskaming, Quebec, Canada." *Canadian Journal of Forest Research* 35: 656–666.
- Hammer, O., D. A. T. Harper, and P. D. Ryan. 2001. "PAST: Paleontological Statistics Software Package for Education and Data Analysis." *Palaeontologia Electronica* 4: 1–9.
- Hart, S. A., and H. Y. H. Chen. 2006. "Understory Vegetation Dynamics of North American Boreal Forests." *Critical Reviews in Plant Sciences* 25: 381–397.
- Holmes, R. L. 1983. "Computer-Assisted Quality Control in Tree-Ring Dating and Measurement." *Tree-Ring Bulletin* 43: 69–78.
- Labrecque-Foy, J.-P., M.-A. Lemay, F. Gennaretti, D. Arseneault, and M. M. Girona. 2025. "Data and Code for 'Keeping Logs on the Past: Log Driving Tells the Story of Fire Regimes in Pine Forests of Eastern Canada.'" Figshare. <https://doi.org/10.6084/M9.figshare.28165319>.
- Labrecque-Foy, J.-P., and M. Montoro Girona. 2023. "The Global Potential of Log-Driven Trees for Reconstructing Forest Ecosystems Dynamics." *Frontiers in Ecology and Evolution* 11: 1232543.
- Latremouille, C., W. C. Parker, F. Pinto, B. Fox, and L. McKinnon. 2008. *Ecology and Management of White Pine in the Lake Abitibi (3E) and Lake Temagami (4E) Ecoregions of Ontario*. Sault Ste. Marie, ON: Ontario Forest Research Institute. 70 p.
- Lienert, A. 1966. *The Story of the (Kipawa) Noranda Woods Division*. Rouyn-Noranda: Canadian Paper International. 98 p.

- Marchand, N., and L. Filion. 2014. "A Dendroecological Analysis of Eastern Hemlock and White Pine in Relation to Logging in La Mauricie National Park (Québec, Canada)." *The Forestry Chronicle* 90: 351–360.
- Margolis, E. Q., C. H. Guiterman, R. D. Chavardès, J. D. Coop, K. Copes-Gerbitz, D. A. Dawe, D. A. Falk, et al. 2022. "The North American Tree-Ring Fire-Scar Network." *Ecosphere* 13: e4159.
- Marschall, J. M., M. C. Stambaugh, E. R. Abadir, D. C. Dey, P. H. Brose, S. L. Bearer, and B. C. Jones. 2022. "Pre-Columbian Red Pine (*Pinus resinosa* Ait.) Fire Regimes of North-Central Pennsylvania, USA." *Fire Ecology* 18: 11.
- Maxwell, R. S., and L.-A. Larsson. 2021. "Measuring Tree-Ring Widths Using the CooRecorder Software Application." *Dendrochronologia* 67: 125841.
- McBride, J. R. 1983. "Analysis of Tree Rings and Fire Scars to Establish Fire History." *Tree-Ring Bulletin* 43: 51–67.
- Meunier, J., N. S. Holoubek, and M. Sebasky. 2019. "Fire Regime Characteristics in Relation to Physiography at Local and Landscape Scales in Lake States Pine Forests." *Forest Ecology and Management* 454: 117651.
- MRNF. 2021. *Classification écologique du territoire québécois*. Québec: Direction des Inventaires Forestiers, Gouvernement du Québec. 11 p.
- Nyamai, P. A., P. C. Goebel, D. M. Hix, R. G. Corace, and I. Drobyshev. 2014. "Fire History, Fuels, and Overstory Effects on the Regeneration-Layer Dynamics of Mixed-Pine Forest Ecosystems of Eastern Upper Michigan, USA." *Forest Ecology and Management* 322: 37–47.
- Paquin, N. 1979. *Histoire de l'Abitibi-Témiscamingue*. Rouyn: Collège du Nord-Ouest. 202 p.
- Pechony, O., and D. T. Shindell. 2010. "Driving Forces of Global Wildfires over the Past Millennium and the Forthcoming Century." *Proceedings of the National Academy of Sciences of the United States of America* 107: 19167–70.
- Pitt, D., M. Hoepting, W. Parker, A. Morneault, L. Lanteigne, A. Stinson, and J. Farrell. 2016. "Optimum Vegetation Conditions for Successful Establishment of Planted Eastern White Pine (*Pinus strobus* L.)." *Forests* 7: 175.
- Pitt, D., A. Morneault, W. C. Parker, L. Lanteigne, M. K. Hoepting, and A. Stinson. 2011. "Influence of Herbaceous and Woody Competition on White Pine Regeneration in a Uniform Shelterwood." *The Forestry Chronicle* 87: 653–668.
- Plummer, M. 2003. "JAGS: A Program for Analysis of Bayesian Graphical Models Using Gibbs Sampling." In *Proceedings of the 3rd International Workshop on Distributed Statistical Computing*, Vienna. 10 p.
- Province of Quebec. 1920. *Guide du colon - Région du Témiscamingue et de l'Abitibi*. Québec: Ministère de la Colonisation des Mines et des Pêcheries Québec. 28 p.
- R Core Team. 2021. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.
- Riopel, M. 2002. *Le Témiscamingue: son histoire et ses habitants*. Saint-Laurent: Fides. 366 p.
- Rudolf, P. O. 1990. "*Pinus resinosa* Ait.: Red Pine." In *Sylvics of North America 1: Conifers*. Agriculture Handbook 654, Vol. 2, edited by R. M. Burns and B. H. Honkala 442–455. Washington, DC: U.S. Department of Agriculture, Forest Service.
- Sedell, J. R., F. N. Leone, and W. S. Duval. 1991. "Chapter 9: Water Transportation and Storage of Logs." In *Influences of Forest and Rangeland Management on Salmonid Fishes and their Habitats*, edited by W. R. Meehan, 325–368. Bethesda, MD: American Fisheries Society Special Publication.
- Seidl, R., D. Thom, M. Kautz, D. Martin-Benito, M. Peltoniemi, G. Vacchiano, J. Wild, et al. 2017. "Forest Disturbances under Climate Change." *Nature Climate Change* 7: 395–402.
- Stambaugh, M. C., E. R. Abadir, J. M. Marschall, R. P. Guyette, B. Palik, and D. C. Dey. 2021. "Red Pine (*Pinus resinosa* Ait.) Fire History and Management Implications in the Mississippi River Headwaters, Minnesota, USA." *Forest Ecology and Management* 494: 119313.
- Terrail, R., J. Morin-Rivat, G. De Lafontaine, M. Fortin, and D. Arseneault. 2020. "Effects of 20th-Century Settlement Fires on Landscape Structure and Forest Composition in Eastern Quebec, Canada." *Journal of Vegetation Science* 31: 40–52.
- Thompson, I. D., J. H. Simard, and R. D. Titman. 2006. "Historical Changes in White Pine (*Pinus strobus* L.) Density in Algonquin Park, Ontario, during the 19th Century." *Natural Areas Journal* 26: 61–71.
- Uprety, Y., H. Asselin, and Y. Bergeron. 2013. "Cultural Importance of White Pine (*Pinus strobus* L.) to the Kitcisakik Algonquin Community of Western Quebec, Canada." *Canadian Journal of Forest Research* 43: 544–551.
- Uprety, Y., H. Asselin, Y. Bergeron, and M. J. Mazerolle. 2014. "White Pine (*Pinus strobus* L.) Regeneration Dynamics at the Species' Northern Limit of Continuous Distribution." *New Forests* 45: 131–147.
- Weyenberg, S., L. Frelich, and P. Reich. 2004. "Logging Versus Fire: How Does Disturbance Type Influence the Abundance of *Pinus strobus* Regeneration?" *Silva Fennica* 38: 179–194.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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