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# Multi-proxy analysis of early Holocene vegetation dynamics on the islands of proglacial Lake Ojibway (northeastern America)

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**ABSTRACT:** Following deglaciation, lowland sites in eastern Canada that were covered by proglacial Lake Ojibway recorded direct afforestation with boreal mixedwood taxa, without an initial tundra phase, contrary to sites that were never covered by this lake. Because former islands of proglacial Lake Ojibway were colonized by vegetation before lake drainage around 8200 cal a BP, we hypothesized that these paleo-islands went through a non-arboreal phase which eventually transitioned to boreal mixedwoods, hence providing a source of propagules for rapid and later colonization of the lowlands. We carried out a multi-proxy analysis combining pollen, macro-remains, sedimentary ancient DNA and charcoal to document vegetation composition and dynamics on two paleo-islands. Both study sites recorded progressive vegetation establishment starting with a tundra-like phase with only herbs and shrubs, followed by open forests dominated by either larch or pine, culminating with the establishment of the boreal mixedwoods about 300 years before the final drainage of proglacial Lake Ojibway. Fire regimes seem to have partially driven vegetation dynamics and diversity on the paleo-islands. Paleo-islands were sources of propagules, which helps explain how the former Lake Ojibway lowlands were directly colonized by boreal mixedwoods, without an initial tundra phase. © 2024 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

**KEYWORDS:** fire dynamics; island biogeography; macro-remains; pollen; sedaDNA

## Introduction

At the transition between the Pleistocene and Holocene, North American ice sheets started retreating northwards as climate was warming, progressively freeing landscapes for colonization by vegetation. Southeastern Canada was liberated from the Laurentide Ice Sheet ca 14 000 calibrated years before present (hereafter cal a BP), whereas northeastern Canada became open for colonization much later, around 6000 cal a BP (Dalton et al., 2020). During deglaciation, melt water accumulated in front of the glacier and created proglacial lakes (Carrivick and Tweed, 2013). In eastern Canada, several proglacial lakes successively covered the newly liberated landscapes, and one of the largest was Lake Ojibway (ca 115 000 km<sup>3</sup>). It covered the current provinces of Quebec and Ontario between ca 10 750 and 8200 cal a BP and progressively drained into Hudson Bay between 9400 and 8200 cal a BP through an opening in the Laurentide Ice Sheet (Roy et al., 2015; Godbout et al., 2020; Brouard et al., 2021).

Proglacial lakes acted as geographical barriers preventing rapid vegetation colonization of the newly liberated landscapes. Yet, the postglacial migration rate observed in

North America was much faster than the estimated migration rate based on plant dispersal capacity if colonization had progressed as a united front from south to north (Clark et al., 1998; Ordonez and Williams, 2013; Payette et al., 2022). Explanations for the rapid postglacial migration rates are long-distance dispersal events and presence of glacial refugia (Powell and Zimmermann, 2004; Harnik et al., 2018). However, no glacial refugia have been identified in the area covered by proglacial Lake Ojibway. Maximum elevations in western Quebec and eastern Ontario, less than 600 and less than 700 m a.s.l. (above sea level) respectively, are not high enough to have acted as nunataks as the glacier was at least 2 km thick (Pfeffer et al., 1997; Marshall et al., 2000). Hence, long-distance dispersal events have remained the most likely mechanism explaining rapid afforestation of deglaciated landscapes in northeastern North America.

Vogel et al. (2023) showed that islands of proglacial Lake Ojibway were colonized by tree species (*Larix laricina*, *Picea mariana*, *Pinus* spp., *Betula* spp.) at least 200–450 years before lake level started to decrease (i.e. between 9950 and 9660 cal a BP). Vogel et al. (2024) suggested that these 'paleo-islands' could have acted as migratory outposts providing northern sources of seeds. This hypothesis would explain the almost immediate presence of vegetation typical of the boreal mixedwood forests in the Abitibi lowlands following the final drainage of Lake Ojibway ca 8200 cal a BP, without an initial

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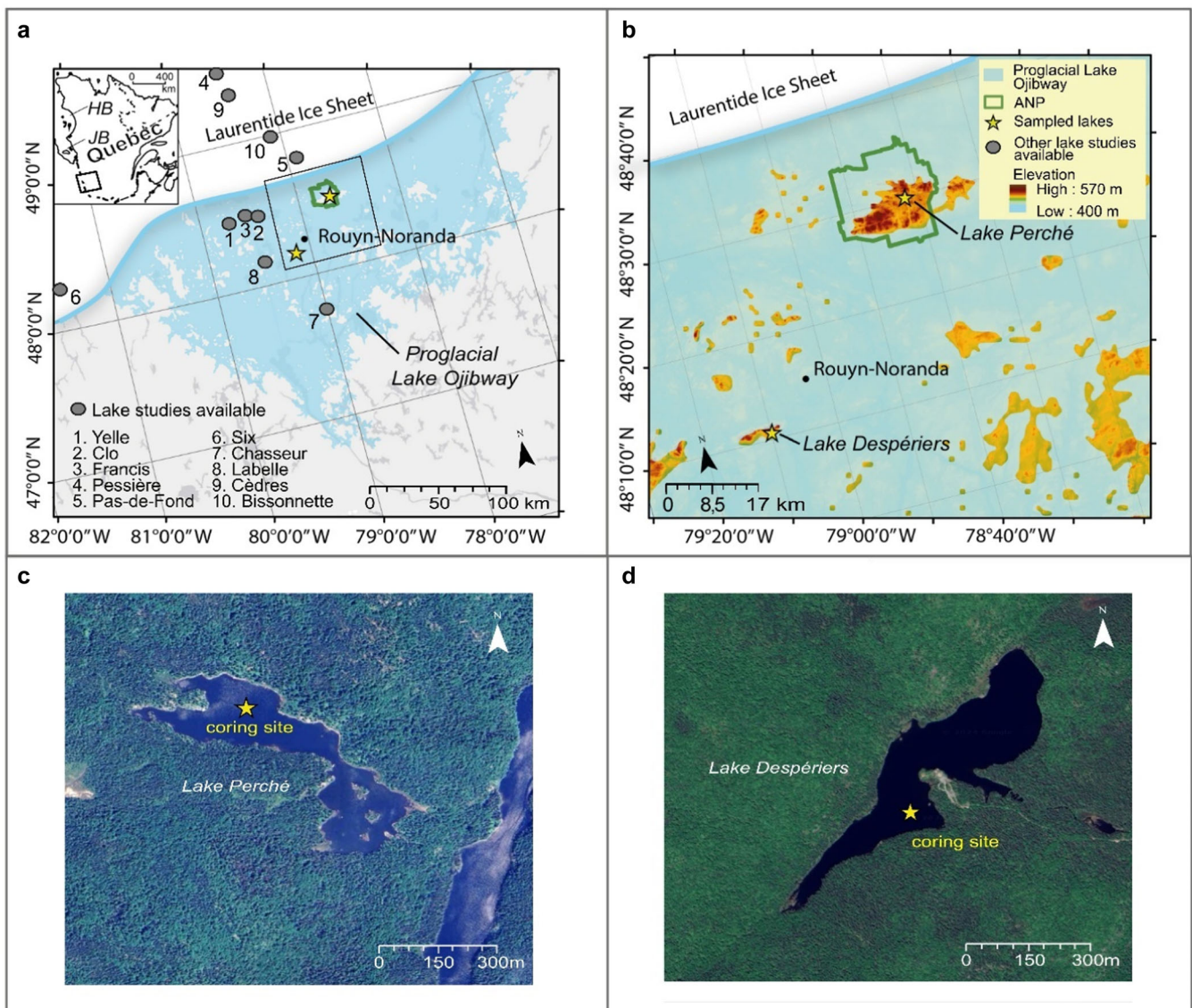
tundra phase preceding afforestation (Richard, 1980; Carcaillet et al., 2001; Ali et al., 2008). However, while Vogel et al. (2023) demonstrated early colonization of paleo-islands by some tree species, a more complete suite of paleoecological proxies is needed to describe plant communities and better understand successional patterns.

We used a multidisciplinary approach based on three complementary vegetation proxies—pollen, sedimentary ancient DNA (sedaDNA) and plant macro-remains—to provide a comprehensive overview of the early vegetation on paleo-islands of Lake Ojibway (Jørgensen et al., 2012; Pedersen et al., 2013; Garcés-Pastor et al., 2019; Parducci et al., 2019; Fracasso et al., 2022). We also analyzed charcoal particles to reconstruct fire activity on the paleo-islands. We hypothesized (i) that the paleo-islands recorded progressive vegetation establishment, including an initial tundra-like non-forested phase; and (ii) that boreal mixed-woods developed on the paleo-islands earlier than in the adjacent lowlands.

## Material and methods

### Study area

The study area is located in the Abitibi-Témiscamingue region of western Quebec and is part of the clay belt of Quebec and Ontario created by deposits of proglacial Lake Ojibway (Fig. 1a; Vogel et al., 2023). Among the hills that punctuate the landscape, we selected the Abijévis Hills in Aiguebelle National Park, and the Kekeko Hills which are 50 km south of the park. Both hills originated from marine volcanism and are composed of mafic rocks, i.e. mostly non-carbonate rocks such as gabbro and andesite. Surface deposits are glacial till (Nutz et al., 2020; MERN—Système d'information géominère, 2022). The ice sheet retreated around 10 650 cal a BP (Veillette, 1994; Dyke, 2004) and its action rounded the summits of the hills. Today, with maximum elevations of 570 and 488 m a.s.l., respectively, the Abijévis and Kekeko Hills are among the highest reliefs in Abitibi-Témiscamingue (Fig. 1b), surrounded by a generally plain area (between 180 and 350 m a.s.l.).



**Figure 1.** (a) Extent of proglacial Lake Ojibway in western Quebec around 9600 cal a BP (Brooks, 2020), showing the locations of the two studied paleo-islands (yellow stars) and lowland sites from previous studies (colors indicate different studies): 1, Lake Clo (Richard, 1980); 2, Lake Pas-De-Fond (Carcaillet et al., 2001); 3, Lake Bissonnette (Terasmae & Anderson, 1970); 4, Lake aux Cèdres (Ali et al., 2008); 5, Lake à la Pessière (Carcaillet et al., 2001); 6, Lake Six (Liu, 1990); and 7, Lake Chasseur (Paillard et al., 2023). The inset shows the location of the study area relative to Hudson Bay (HB) and James Bay (JB), into which proglacial Lake Ojibway drained between 9400 and 8200 cal a BP. (b) Close-up of the study area showing paleo-islands (in light to dark orange), including the Abijévis and Kekeko Hills, where Lakes Perché and Despériers were sampled, respectively. Green lines indicate the limit of Aiguebelle National Park (ANP). Panels (a) and (b) modified from Vogel et al. (2023). Satellite view and location of coring sites at Lake Perché (c) and Lake Despériers (d). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/jqs.3682)]

The lake-level history of proglacial Lake Ojibway was reconstructed based on the locations of ancient shorelines (Godbout et al., 2020). Paleo-islands are currently hills with elevations higher than the maximum elevation reached by Lake Ojibway. The highest shorelines of Lake Ojibway (ca 9400 cal a BP) differ for the Abijévis and Kekeko Hills despite their relative proximity: they were estimated at slightly less than 400 and 380 m a.s.l., respectively (more details in Godbout et al., 2017).

### Site selection and lake sediment sampling

We selected two small lakes—Lake Perché in Aiguebelle National Park (Abijévis Hills) and Lake Despériers in the Kekeko Hills—located at 380 and 407 m a.s.l., respectively, i.e. near or above the Lake Ojibway washing limits (Table 1; Fig. 1) and thus corresponding to lakes located within paleo-islands. We chose headwater lakes surrounded by steep shores to maximize sediment collection and avoid sediment disturbance. The current forest vegetation surrounding both lakes is dominated by black spruce (*Picea mariana*), white spruce (*Picea glauca*), jack pine (*Pinus banksiana*) and balsam fir (*Abies balsamea*) (Table 1). No wetland was identified around Lake Despériers, whereas the northern part of Lake Perché has shallower water and a more humid vegetation border (Fig. 1c, d). Cores were extracted from Lake Perché in 2018 and from Lake Despériers in 2021. We used a 60-mm-diameter Livingstone corer to extract 1-m-long cores to obtain the complete organic sediment (gyttja) sequences and the transition with the underlying mineralogic sediment (silt) at the center of each lake (Fig. 1c, d). We stored sediments in plastic wrap and foil paper into plastic tubes and kept them in cold conditions (4°C) until laboratory analyses. We focused on the early Holocene history, and therefore we only worked on the basal 1-m-long core at each lake, containing the transition to mineralogic sediments.

### Age–depth models

We obtained three  $^{14}\text{C}$  dates from bulk sediment for each lake and two and one  $^{14}\text{C}$  dates from macro-remains for Lake Perché and Lake Despériers, respectively (Table S1). We calibrated the  $^{14}\text{C}$  dates with the IntCal20 calibration curves (Reimer et al., 2020). We built age–depth models with the ‘rbacon’ package in R (Blaauw et al., 2022; R Core Team, 2022) for the basal part of the sediment sequences at each lake, corresponding to the beginning of organic sediment accumulation, and thus the early Holocene vegetation history.

### Extraction of plant macro-remains

We took half of each 0.5-cm sediment slice from 557.5 to 485.5 cm depth for Lake Perché and from 294.5 to 233 cm depth for Lake Despériers and bathed it in a hexametaphosphate ( $\text{NaPO}_3$ )<sub>6</sub> solution for at least 12 h on a stirrer to deflocculate the organic matter. We sieved each sample

through a 250- $\mu\text{m}$  mesh and hand-picked plant macro-remains under a dissecting microscope. We used a guide book to identify plant macro-remains (Lévesque et al., 1988). We recorded presence and absence at each level for all taxa, and macro-remain assemblage zones for Lake Perché (PMAZ) and Lake Despériers (DMAZ) were calculated based on the constrained incremental sum of squares (CONISS) method (Grimm, 1987).

### SedaDNA analyses

#### DNA extraction and sequencing

We took ca 1-cm-thick samples every 5 cm from the silt–gyttja transition up—three samples at Lake Perché (from 554.5 to 544.5 cm depth) and five at Lake Despériers (from 294.5 to 274.5 cm depth)—representing the period between the start of organic matter accumulation and the drainage of Lake Ojibway at both sites. We sampled the sediment in a draught-free room cleaned with bleach and ethanol. We equipped ourselves with full body suits, hair nets, facial masks, clean clothes, shoes with sterile plastic protections and double gloves. We changed our gloves between each step and manipulation of the sampling process. We used sterile equipment. We removed the sediment in contact with the plastic wrap with sterile knives and discarded it to allow us to take uncontaminated sediments from the middle of the cores with a sterile syringe and stored them in sterile 15-mL falcon tubes. We worked from bottom to top on each core and froze the samples until further analyses.

To perform DNA extraction, we decontaminated hood and equipment with UV lights and ‘DNA away’ solution (Thermo Scientific) in a different clean room than the sampling room and autoclaved it when possible to avoid DNA contamination. We used the DNeasy PowerSoil Pro DNA isolation kit (Qiagen) and followed the manufacturer’s protocol. For each sample, we performed three replicates and then pooled them before amplification to homogenize sediments and reduce sequencing costs (Ray et al., 2019). We collected ca 0.25 g for each sample. We also performed three negative controls, one every 10 samples.

We performed polymerase chain reaction (PCR) using the *g* and *h* plant primers of the P6 loop region of the chloroplast *trnL* (Taberlet et al., 2007) and the ITS5 and 5.8S\_fungi (Epp et al., 2012) for fungi (Table S2). We carried out DNA amplification for each sample in 20  $\mu\text{L}$  final volumes containing 3  $\mu\text{L}$  of the pooled DNA, 0.5 $\times$  Gold buffer, 0.8 U of AmpliTaq Gold, 1.25 mM  $\text{MgCl}_2$ , 0.1 mM dNTPs, 0.1  $\mu\text{M}$  of the forward primer, 0.1  $\mu\text{M}$  of the reverse primer, 80 ng  $\mu\text{L}^{-1}$  bovine serum albumin and nuclease-free water to complete 20  $\mu\text{L}$ . We followed different steps (temperature and duration) (Table S2) for each pair of primers (Taberlet et al., 2007; Epp et al., 2012; Bellemain et al., 2013; Voldstad et al., 2020). We amplified the eight pooled samples with the three pairs of primers, for a total of 24 samples and three negative controls.

**Table 1.** Main characteristics of Lake Perché and Lake Despériers and sediment cores retrieved from each lake (Vogel et al., 2023).

Name	Latitude of sampling location	Longitude of sampling location	Elevation (m a.s.l.)	Area (ha)	Organic sediment core length (cm)	Water column depth at sampling location (cm)	Current local vegetation by order of dominance
Lake Perché	48°30′8.10″N	78°41′56.90″W	380	9.70	554	370	<i>Picea mariana</i> , <i>Pinus banksiana</i>
Lake Despériers	48°11′4.22″N	79°9′38.80″W	407	8.89	292	750	<i>Picea mariana</i> , <i>Picea glauca</i> , <i>Abies balsamea</i>

We then conducted the sequencing on an Illumina MiSeq P300 platform at the Genome Quebec laboratories.

### Bioinformatics analysis

Paired-end (PE) Illumina raw sequences were processed in R using the DADA2 package (Callahan et al., 2016). We filtered, denoised and merged the sequences and removed chimeras to generate amplicon sequence variants (ASVs; Pauvert et al., 2019). Taxonomic assignment of ASVs was conducted using the 'assignTaxonomy' and 'addSpecies' functions, which allowed us to compare sequences to reference databases and associate the corresponding taxonomic name when the bootstrap confidence level was reached. Taxa were identified using the arctic and boreal plants libraries (Willerslev et al., 2014) for vascular plants and the UNITE 9.4 reference database (Köljalg et al., 2013) for fungi.

### Pollen extraction and counting

A total of 54 samples were extracted from the Lake Perché sediment core every 1 cm from 564 to 511 cm depth for pollen analysis. We did not analyze Lake Despériers because pollen is a regional vegetation proxy. For each sample, 1 cm<sup>3</sup> of sediment was collected, to which we added three *Lycopodium* tablets to allow for estimation of pollen concentration. Samples were processed following standard procedures (Moore and Webb, 1978; Faegri et al., 1989), including HCl, KOH, acetolysis and HF. We counted pollen and non-pollen palynomorphs (NPPs) under a Leica BX50 LED microscope at a standard magnification of 500x. We used photo atlases to identify pollen and NPPs (Richard, 1970; McAndrews, 1973; Moore & Webb, 1978). For each sample, we counted a minimum of 300 pollen grains of terrestrial taxa (excluding spores) to obtain a representative count of pollen types based on rarefaction curves (Birks and Line, 1992; Djamali and Cilleros, 2020). We constructed pollen diagrams with the R package *Rioja* (Juggins and Juggins, 2019) and showed only the taxa with percentages higher than 0.1% for all subsamples along the studied sequence. Pollen assemblage zones (PAZs) were calculated based on the constrained incremental sum of squares (CONISS) method (Grimm, 1987).

### Biodiversity indices

To characterize vegetation evolution, we computed biodiversity indices on macro-remains and sedaDNA data from both lakes and on pollen data from Lake Perché. Each proxy was computed separately because they differ in their spatial source area, representation factors and taxonomic specificity. We used the 'hillR' R package (Li, 2018) to calculate Hill's N2 index (Hill, 1973) as follows:

$$N2 = \left( \sum_{i=1}^R p_i^2 \right)^{-1} \quad (1)$$

where  $R$  is the number of species and  $p_i$  is the relative abundance of the  $i$ th species.  $N2$  is recommended as an integrated measure of biodiversity for fossil assemblages from sediment sequences (Birks et al., 2016).  $N2$  corresponds to the effective number of dominant or highly abundant species present in an assemblage (here, a sample) (Chao et al., 2021), while rare species contribute almost nothing to the sum (Birks et al., 2016), so higher  $N2$  values correspond to higher biodiversity. We also assessed species evenness for each sample with the 'vegan' package (Oksanen et al., 2022).

We used the Shannon diversity index divided by its maximum value as an evenness indicator as follows:

$$E = \frac{-\sum_{i=1}^q p_i \log p_i}{\log q} \quad (2)$$

where  $p_i$  is the proportion of taxon  $i$  and  $q$  is the number of taxa in the sample (Mortensen et al., 2011). Low evenness values usually indicate the dominance of a single taxon or a few taxa in a plant assemblage.

### Fire history reconstruction

For each 0.5-cm sediment slice, we sampled 1 cm<sup>3</sup> from the center of the slice. We added hexametaphosphate (NaPO<sub>3</sub>)<sub>6</sub>, potassium hydroxide (KOH) and sodium hypochlorite (NaClO) before agitating the sample for at least 24 h to deflocculate the organic matter. We then sieved the solution through a 160-µm mesh and proceeded to charcoal sorting under a dissecting microscope.

We used the WinSEEDLE TM image analysis software (Regents Instruments Inc., <https://regent.qc.ca/>, August 2021) to measure particle area and number. Fire events were identified with the CharAnalysis software v1.1 (Higuera et al., 2008; <http://phiguera.github.io/CharAnalysis/>) that decomposes the charcoal accumulation rates (mm<sup>2</sup> cm<sup>-2</sup> a<sup>-1</sup>) into peaks and a low-frequency signal (variations in charcoal production and sedimentation processes) using a robust Lowess with a 200-year window width. Peaks were then identified as either fire or non-fire events based on a Gaussian mixture model (99th percentile threshold). Fire frequency (FF—number of fires per 1000 years) and peak magnitude were computed. For each fire event identified with CharAnalysis, we used the charcoal size distribution (CSD) method (Asselin and Payette, 2005; Oris et al., 2014; Remy et al., 2018) to determine whether the fire was local (within the paleo-island watershed) or regional. A high proportion of large charcoal particles is associated with a local fire event, whereas a smaller proportion of large charcoal particles corresponds to extra-local fire events (outside the paleo-island watershed). More details can be found in Vogel et al. (2023).

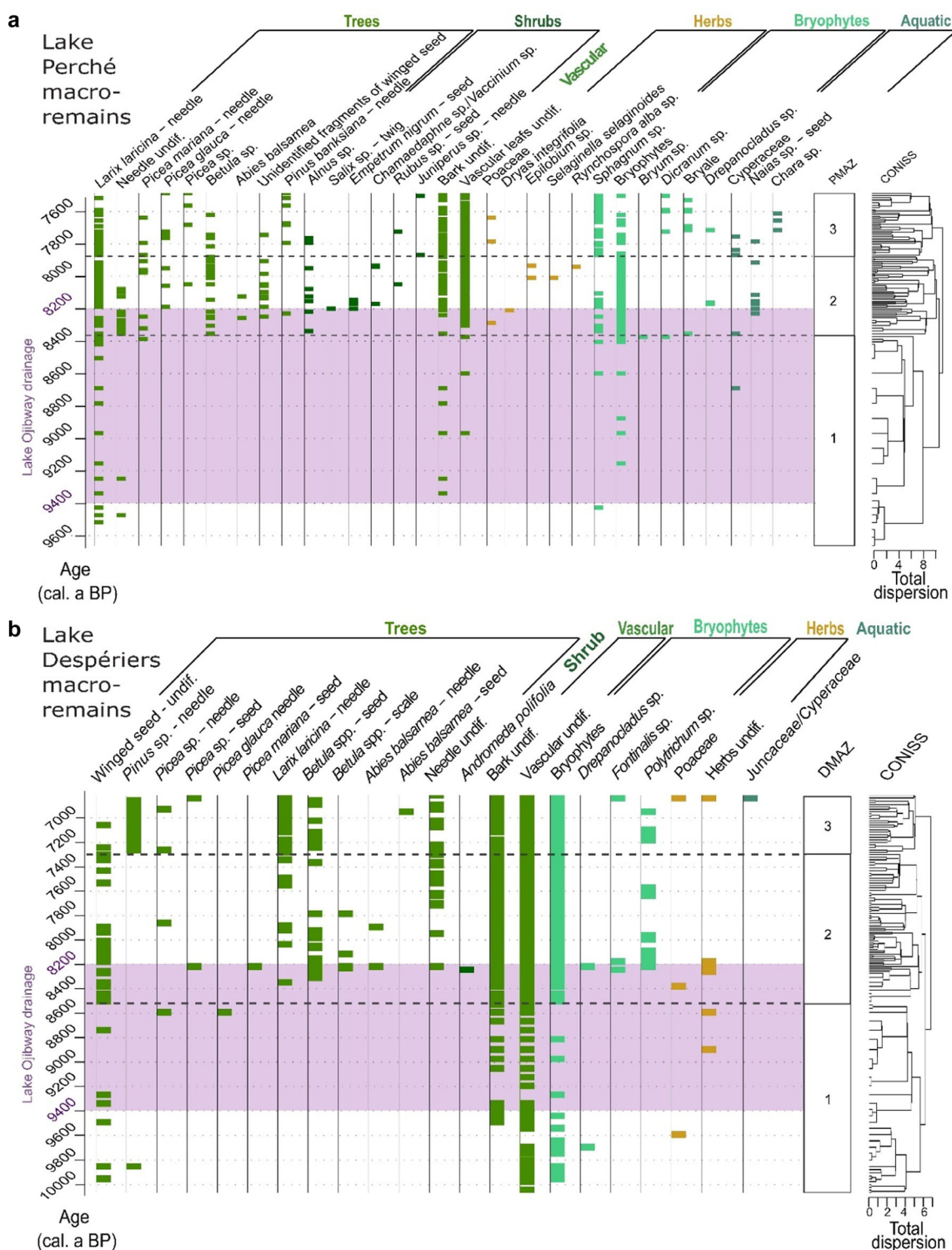
## Results

### Age–depth models

The age–depth models present a similar linear trend, with mean sedimentation rates of 44 and 53 a cm<sup>-1</sup> for Lakes Perché and Despériers, varying from 144 to 98 a cm<sup>-1</sup> between the beginning of organic matter accumulation and 8500 cal a BP and then reaching 23 and 37 a cm<sup>-1</sup> between 8500 and the most recent sediments analyzed, respectively. Basal ages were at or close to the transition with silt for both lakes (557.5 and 294.5 cm depth for Lakes Perché and Despériers, respectively). The studied sequences spanned from 9657 to 6503 cal a BP for Lake Perché (Fig. S1a) and from 10 060 to 6850 cal a BP for Lake Despériers (Fig. S1b). More details about sediment dating can be found in Vogel et al. (2023).

### Plant macro-remains: local vegetation establishment

The macro-remains found at Lake Perché ranged from 9680 to 7500 cal a BP and are divided into three macro-remains assemblage zones (PMAZs) with transitions around 8380 and 7880 cal a BP (Fig. 2a).



**Figure 2.** Macro-remains at different sampling depths in the Lake Perché (a) and Lake Despériers (b) sediment sequences. Taxa are organized by groups and by order of appearance. The macro-remains assemblage zones based on CONISS are shown to the right. The purple-shaded area indicates the period when the level of proglacial Lake Ojibway gradually decreased until its final drainage ca 8200 cal a BP. [Color figure can be viewed at wileyonlinelibrary.com]

*PMAZ 1 (ca 9680 – ca 8380 cal a BP)*

Low diversity was found in PMAZ 1 compared to PMAZ 2 and PMAZ 3 (see Fig. 5). The earliest vegetation macro-remains identified were *Larix laricina* needles around 9520 cal a BP, followed by *Sphagnum* sp. fragments around 9420 cal a BP, and a Cyperaceae fragment ca 8700 cal a BP (Fig. 2a). Other macro-remains found were two unidentified needles ca 9480 and 9240 cal a BP, bark fragments ca 9380 cal a BP, bryophyte fragments ca 9180 cal a BP, and bark and vascular elements after 9000 cal a BP (Fig. 2a).

*PMAZ 2 (ca 8380–7880 cal a BP)*

*Larix laricina*, *Sphagnum* sp. and bryophytes remained present in PMAZ 2. More taxa of conifer and deciduous trees were found, including *Picea mariana* ca 8400 cal a BP, *Betula* spp. (three taxa possible) ca 8380 cal a BP, *Abies balsamea* ca 8280 cal a BP, *Pinus banksiana* ca 8220 cal a BP and *Picea glauca* ca 8190 cal a BP. The first shrubs to be recorded were *Alnus* spp. (*Alnus viridis* subsp. *crispa* and *Alnus incana* subsp. *rugosa*) ca 8350 cal a BP, followed by *Empetrum nigrum* and *Salix* sp. ca 8200 cal a BP, *Chamaedaphne* sp. or *Vaccinium* sp.

ca 8180 cal a BP, and *Rubus* sp. ca 8050 cal a BP. Cyperaceae fragments were identified at the transition between PMAZ 1 and PMAZ 2, then Poaceae were found ca 8290 cal a BP, followed by *Dryas integrifolia* ca 8200 cal a BP, *Epilobium* sp. and *Selaginella selaginoides* ca 8000 cal a BP, and *Rynchospora* sp. ca 7940 cal a BP. *Bryum* sp., *Dicranum* sp. and bryophytes (type bryale) appeared at the transition between PMAZ 1 and PMAZ 2 ca 8380 cal a BP. Aquatic plant fragments were found around 8220 cal a BP, i.e. *Naias* sp. seeds (Fig. 2a).

#### PMAZ 3 (ca 7880–7500 cal a BP)

Needles of *Larix laricina*, *Picea* spp. (two taxa possible), *Betula* sp. and *Pinus banksiana* (more frequent than in PMAZ 2) were still found in PMAZ 3, but no *Abies balsamea* macro-remain was recorded. *Alnus* sp., *Rubus* sp. and *Juniperus* sp. were also found, while for non-arboreal taxa, only Poaceae remained in PMAZ 3. For bryophytes, no *Bryum* sp. was recorded, and concerning the aquatic taxa, Cyperaceae and *Naias* sp. remained present, and *Chara* sp. was first recorded ca 7720 cal a BP.

The macro-remains found at Lake Despériers ranged from 10 050 to 6800 cal a BP and are also divided into three macro-remains assemblage zones (DMAZs) with transitions around 8500 and 7300 cal a BP (Fig. 2b).

#### DMAZ 1 (10 050–8500 cal a BP)

As reported for PMAZ 1, DMAZ 1 has lower diversity than DMAZ 2 and DMAZ 3. The earliest macro-remain identified was a *Pinus* sp. needle ca 9850 cal a BP, followed by *Picea glauca* and *Picea* sp. needles ca 8600 cal a BP. Bryophyte fragments were first recorded ca 9900 cal a BP, and *Drepanocladus* sp. was identified ca 9700 cal a BP. Poaceae fragments were found ca 9650 cal a BP and herbs ca 8900 cal a BP (Fig. 2b).

#### DMAZ 2 (8500–7300 cal a BP)

*Larix laricina* was recorded ca 8350 cal a BP, *Betula* spp. (three taxa possible) ca 8320 cal a BP, *Abies balsamea* and *Picea* sp. needles ca 8220 cal a BP, and the shrub *Andromeda polifolia* var. *latifolia* ca 8230 cal a BP. Bryophytes *Drepanocladus* sp., *Fontinalis* sp. and *Polytrichum* sp. were recorded around 8,200 cal a BP, but only *Polytrichum* sp. remained present thereafter. Poaceae fragments were found ca 8390 cal a BP and herb fragments ca 8300 cal a BP (Fig. 2b).

#### DMAZ 3 (7300–6800 cal a BP)

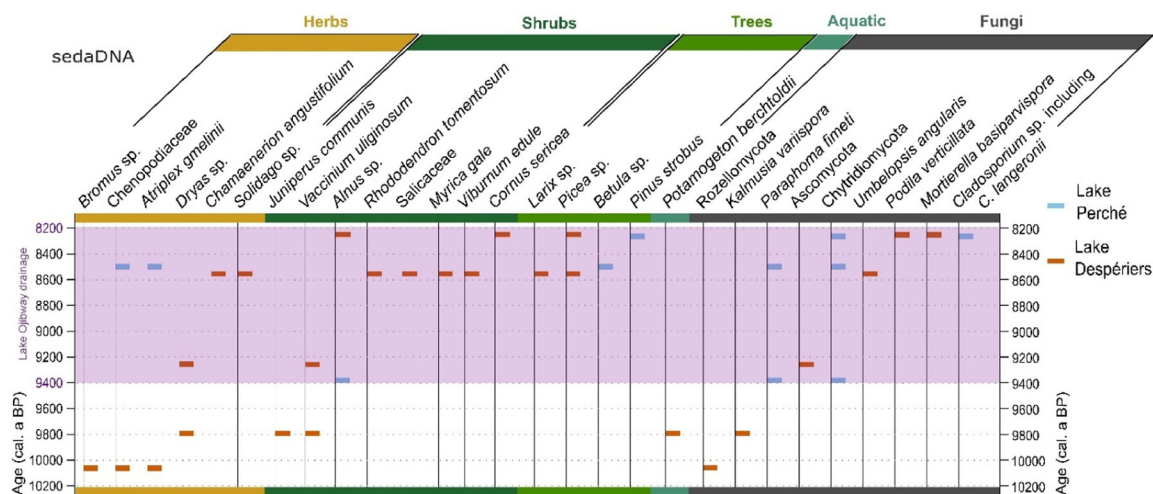
In addition to the tree species already recorded in DMAZ 2 (*Larix laricina*, *Betula* sp., *Abies balsamea* and *Picea* sp.), *Pinus* sp. needles were continuously recorded in DMAZ 3 and characterized the transition between DMAZ 2 and DMAZ 3. *Andromeda polifolia* and *Drepanocladus* sp. were not recorded, but a fragment of aquatic Juncaceae or Cyperaceae was first recorded ca 6800 cal a BP (Fig. 2b).

#### SedaDNA: local vegetation and fungi dynamics

A total of six and 17 vascular plant taxa and three and six fungi taxa were identified with the sedaDNA metabarcoding at Lake Perché and Lake Despériers, respectively (Figs. 3 and S2). Control samples recorded the presence of *Allium schoenoprasum* (L.) and unassigned sequences that could not be clustered in terms of fungi ASVs, which is reassuring pertaining to contamination. While we could not perform cluster analyses on the sedaDNA data, because we only sampled three or five levels in each sediment core, we can still glimpse the community dynamics of plants and fungi at each lake.

At Lake Perché, the earliest taxa identified with sedaDNA ca 9380 cal a BP are *Alnus* sp., a pioneer shrub species, and Chytridiomycota fungi including *Paraphoma fimeti*. Then, ca 8500 cal a BP, some herb taxa were identified: Chenopodiaceae and *Atriplex gmelinii*, with *Betula* sp. and the same fungi taxa as at the previous level. Then, ca 8270 cal a BP, *Pinus strobus* was identified along with Chytridiomycota and ascomycetes of the genus *Cladosporium*, including *Cladosporium langeronii*.

At Lake Despériers, the first taxa identified ca 10 060 cal a BP were herbs (*Bromus* sp., Chenopodiaceae and *Atriplex gmelinii*), along with a fungus taxon within the Rozellomycota. Then, ca 9800 cal a BP, *Dryas* sp., *Juniperus communis* and *Vaccinium uliginosum* were identified along with the aquatic taxon *Potamogeton berchtoldii* and the fungus *Kalmusia variispora*. Then, ca 9250 cal a BP, *Dryas* sp., *Vaccinium uliginosum* and sequences belonging to taxonomically unassigned ascomycetes were detected. Later, ca 8550 cal a BP, herb taxa were identified (*Chamerion angustifolium* and *Solidago* sp.), along with shrubs (*Rhododendron tomentosum*, Salicaceae, *Maica gale* and *Viburnum edule*). Tree taxa were also identified (*Larix* sp. and *Picea* sp.). The Zygomycete *Umbelopsis angularis* was identified. This taxon is part of the Mucorales, which include a high



**Figure 3.** SedaDNA record for Lake Perché (blue) and Lake Despériers (orange) for both vascular plants and fungi primers (Table S2) based on the age–depth models (Fig. S1). The purple-shaded area indicates the period when the level of proglacial Lake Ojibway gradually decreased until its final drainage ca 8200 cal a BP. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

diversity of decayers from a wide range of forest ecosystems. In the most recent level, ca 8250 cal a BP, *Alnus* sp. and *Cornus sericea* were found, along with *Picea* sp. and the fungus *Podila verticillata*, within the Mucorales (Zygomycete), as well as another saprotroph (Fig. 3).

### Pollen analysis: local and regional vegetation dynamics

A total of 48 terrestrial taxa were identified in the Lake Perché sequence, with a single pollen grain remaining unidentified (Table S3). Arboreal pollen (AP), including trees and shrubs, dominated the pollen assemblages and represented on average 93% of the taxa identified (from 89 to 97%). The pollen diagram was divided into five pollen assemblage zones (PAZs) (Fig. 4).

#### PAZ 1 (9680–9650 cal a BP)

The first pollen assemblage zone was quite short and was dominated by *Pinus banksiana*, whose concentration was maximal at the time. *Picea glauca*, *Betula papyrifera*, herbs and NPPs also had high percentages, and pollen concentration was maximal in PAZ 1 (90 000 grains cm<sup>-3</sup>).

#### PAZ 2 (9650–8690 cal a BP)

The second pollen assemblage zone was co-dominated by *Pinus banksiana* (decreasing) and *Picea mariana* (maximal). AP percentages and influx were high and steady. *Betula papyrifera*, herbs and NPPs also had high percentages. Pollen grains identified as *Juniperus communis* reached their maximum in this zone, *Pinus strobus* and *Larix laricina* were also present. Pollen concentration decreased until 9500 cal a BP and then increased, while *Alnus* spp. increased in the second part of PAZ 2.

#### PAZ 3 (8690–8220 cal a BP)

*Pinus banksiana*, stable with a peak ca 8390 cal a BP, co-dominated PAZ 3 with *Alnus* spp., which peaked at the same time. *Picea mariana* (decreasing), *Betula papyrifera* (increasing) and herbs also had high percentages. Some tree taxa such as *Larix laricina*, *Pinus strobus* and *Abies balsamea* were present at the beginning of PAZ 3 and decreased around 8390 cal a BP. NPP and AP percentage and influx reached their minimum (ca 4 and 66%, respectively) at that time. Pollen concentration remained stable.

#### PAZ 4 (8220–7730 cal a BP)

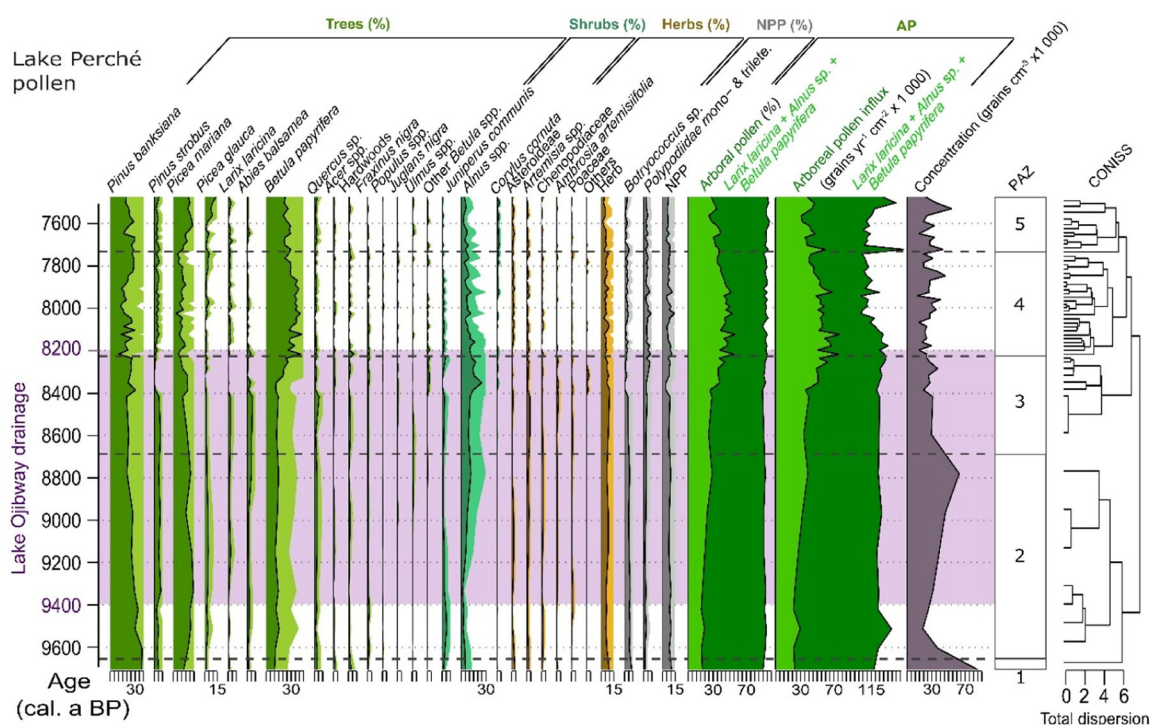
*Betula papyrifera* reached its maximum in PAZ 4 and then decreased after 7850 cal a BP. *Betula papyrifera* co-dominated the zone with *Pinus banksiana* increasing after 7850 cal a BP. *Picea mariana* and *Alnus* spp. decreased in PAZ 4 compared to PAZ 3. *Larix laricina*, *Pinus strobus*, herbs and NPPs remained stable.

#### PAZ 5 (7730–7440 cal a BP)

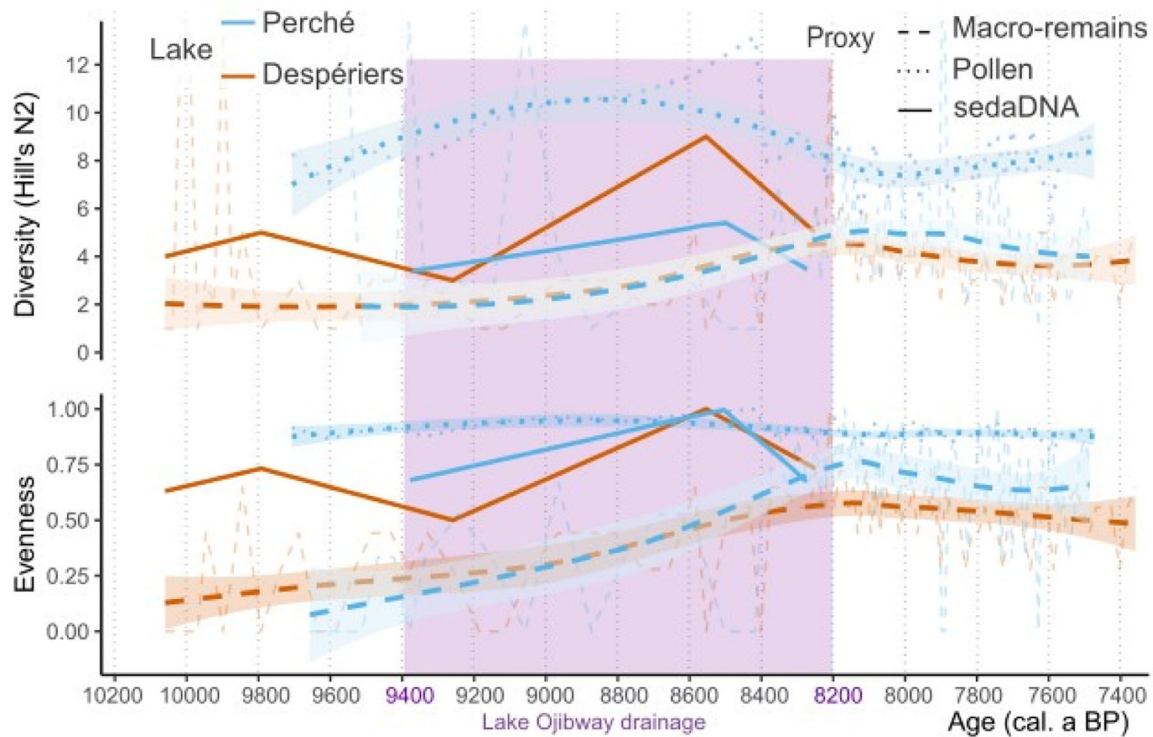
PAZ 5 was co-dominated by *Picea mariana* (increasing), *Betula papyrifera* (decreasing) and *Pinus banksiana*. *Picea glauca* and *Corylus cornuta* increased, and *Alnus* spp., NPPs and herbs had high percentages. AP, both percentage and influx, increased and reached maximum values. *Larix laricina*, *Abies balsamea* and *Pinus strobus* remained stable (Fig. 4).

### Biodiversity indices: intra-core diversity (alpha diversity)

Lakes Perché and Despériers presented similar diversity trends for macro-remains, with an increase of Hill's N2 from the basal part of the sequence until 8250 and 8100 cal a BP, before slightly decreasing until the end of the sequences (Fig. 5). At Lake Perché, the N2 values for pollen were higher due to the larger number of species identified, and showed a different



**Figure 4.** Pollen percentages and influx for Lake Perché. NPP = non-pollen palynomorphs; AP = arboreal pollen; PAZ = pollen assemblage zones based on CONISS clustering. See Table S2 for more details on pollen group formation. The purple-shaded area indicates the period when the level of proglacial Lake Ojibway gradually decreased until its final drainage ca 8200 cal a BP. [Color figure can be viewed at wileyonlinelibrary.com]



**Figure 5.** Biodiversity indices with Hill's N2 for Lake Perché (blue) and Lake Despériers (orange) for the macro-remains (dashed line), pollen (dotted line) and sedaDNA (solid line), and their respective evenness. The purple-shaded area indicates the period when the level of proglacial Lake Ojibway gradually decreased until its final drainage ca 8200 cal a BP. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/jqs.3682)]

trend with an increase until 8900 cal a BP and a decrease until 8100 cal a BP and a slight increase until the end of the record. At Lake Despériers, sedaDNA diversity first increased and then decreased at the beginning of the sequence. Then, both sedaDNA records increased until 8500 and 8600 cal a BP for Lakes Perché and Despériers, respectively, and then decreased until ca 8200 cal a BP. The evenness trends for macro-remains and sedaDNA were similar to their diversity trends, while pollen evenness remained somewhat stable (Fig. 5).

### Fire history

FF differed between lakes (Fig. 6). At Lake Perché, FF first decreased until 8600 cal a BP, from 10 to 5 fires 1000 years<sup>-1</sup>, then increased until 7500 cal a BP up to 9 fires 1000 years<sup>-1</sup>, before decreasing again until the end of the record ca 6500 cal a BP when it reached its minimum (4 fires 1000 years<sup>-1</sup>) (Fig. 6a). At Lake Despériers, FF remained relatively stable between 7 and 8 fires 1000 years<sup>-1</sup> (Fig. 6b). Charcoal concentrations were generally higher at Lake Despériers than at Lake Perché. CharAnalysis detected 21 and 25 fire events at Lakes Perché and Despériers, respectively. (Fig. 6). Among these, 13 and 11 events were identified as local fires by the CSD method at Lake Perché and Lake Despériers, respectively (Fig. 6). The earliest local fire at Lake Perché was detected ca 8360 cal a BP and corresponded to the maximal values of charcoal concentration and charcoal influx (Fig. 6a). Other fire events occurred after the final drainage of Lake Ojibway (Fig. 6a). The earliest local fire event recorded at Lake Despériers occurred ca 9820 cal a BP, i.e. 400 years before the level of Lake Ojibway started to decrease. Six other local fire events occurred at the site while the level of Lake Ojibway was progressively decreasing, and three after final drainage (Fig. 6b).

## Synthesis

### Pre-afforestation phase (10 000–9500 cal a BP)

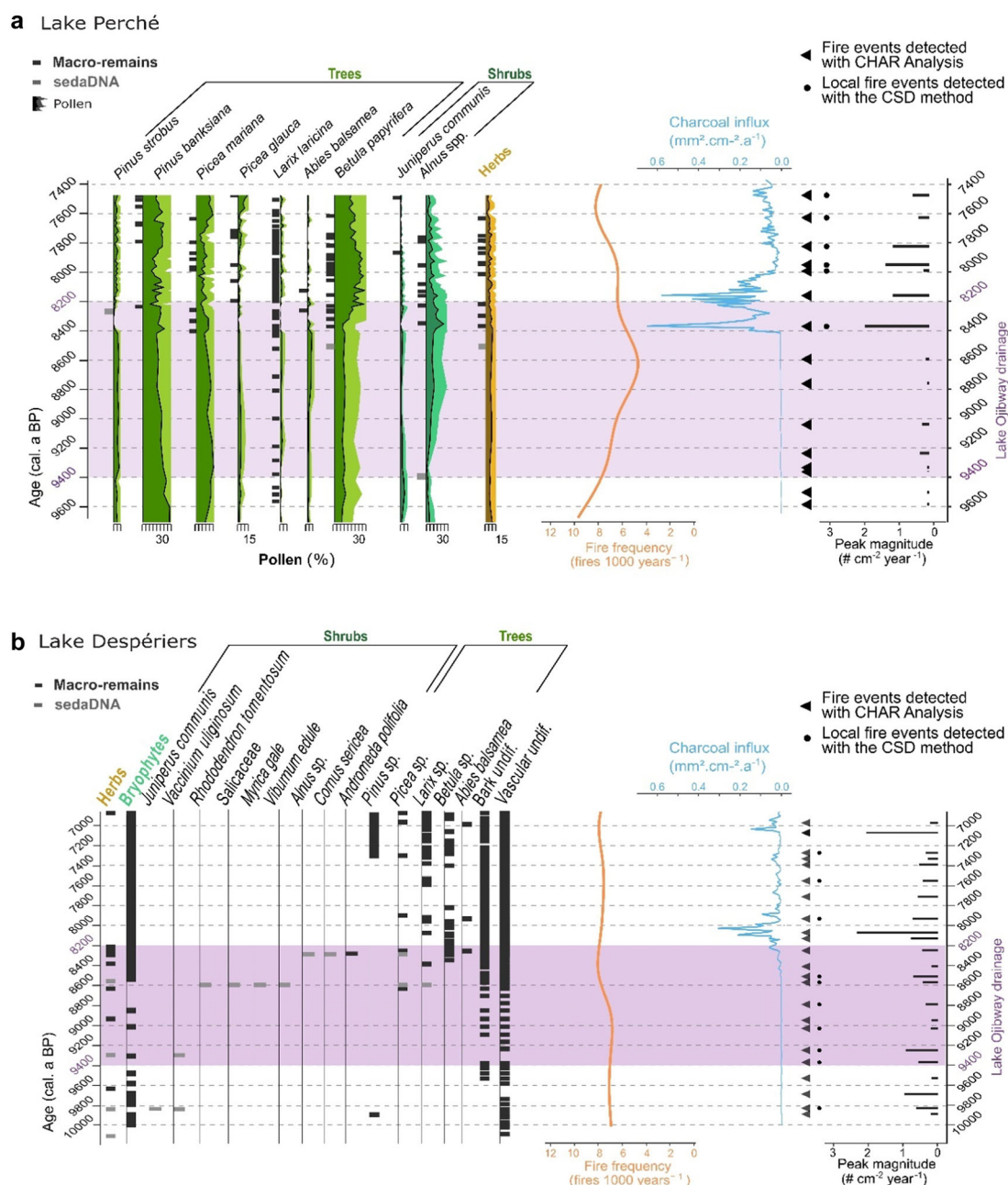
Both lakes present a first phase during which no tree and few plants were recorded, and during which biodiversity and species evenness were generally lower than in later periods. No fire was recorded at Lakes Perché and Despériers during this phase prior to afforestation, probably because of its short duration, and because of the low biomass present.

At Lake Perché, the pre-afforestation phase lasted from ca 9700 to ca 9500 cal a BP and no plant macro-remain was recorded (Fig. 7). Pollen concentration was high, suggesting an open vegetated landscape, further supported by high relative abundance of herbs, the presence of heliophilous shrubs such as *Juniperus* sp. (Richard, 1980) and long-distance pollen dispersers such as *Pinus* spp.

At Lake Despériers, the pre-afforestation phase began earlier and lasted from ca 10 060 to ca 9850 cal a BP (Fig. 7). Only unidentified plant fragments and herb DNA were recorded. Rozellomycota DNA was identified, from a lineage encompassing poorly specific parasitic fungi sometimes found in anoxic waters and ice-covered lakes (Aitken et al., 2008; Rojas-Jimenez et al., 2017). *Kalmusia variispora* was also present, a parasite fungus of ligneous plants such as *Alnus* sp., *Larix* sp. and Salicaceae (von Hippel et al., 2022).

### Afforestation and diversification phase (9500–8200 cal a BP)

The afforestation phase was characterized at both sites by an increase in plant diversity and species evenness relative to the previous phase. At Lake Perché, *Larix laricina* was first recorded (macro-remain) ca 9500 cal a BP, accompanied by *Alnus* sp. (Fig. 7), suggesting humid soil conditions (Johnston, 1990). Some vascular and bryophyte taxa were sporadically recorded.



**Figure 6.** Summary results of the vegetation and fire dynamics at (a) Lake Perché and (b) Lake Despériers, with pollen for Lake Perché and for both lakes: macro-remains (black) and sedaDNA (grey) records of main taxa identified. The purple-shaded area illustrates the period when the level of proglacial Lake Ojibway gradually decreased until its final drainage ca 8200 cal a BP. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

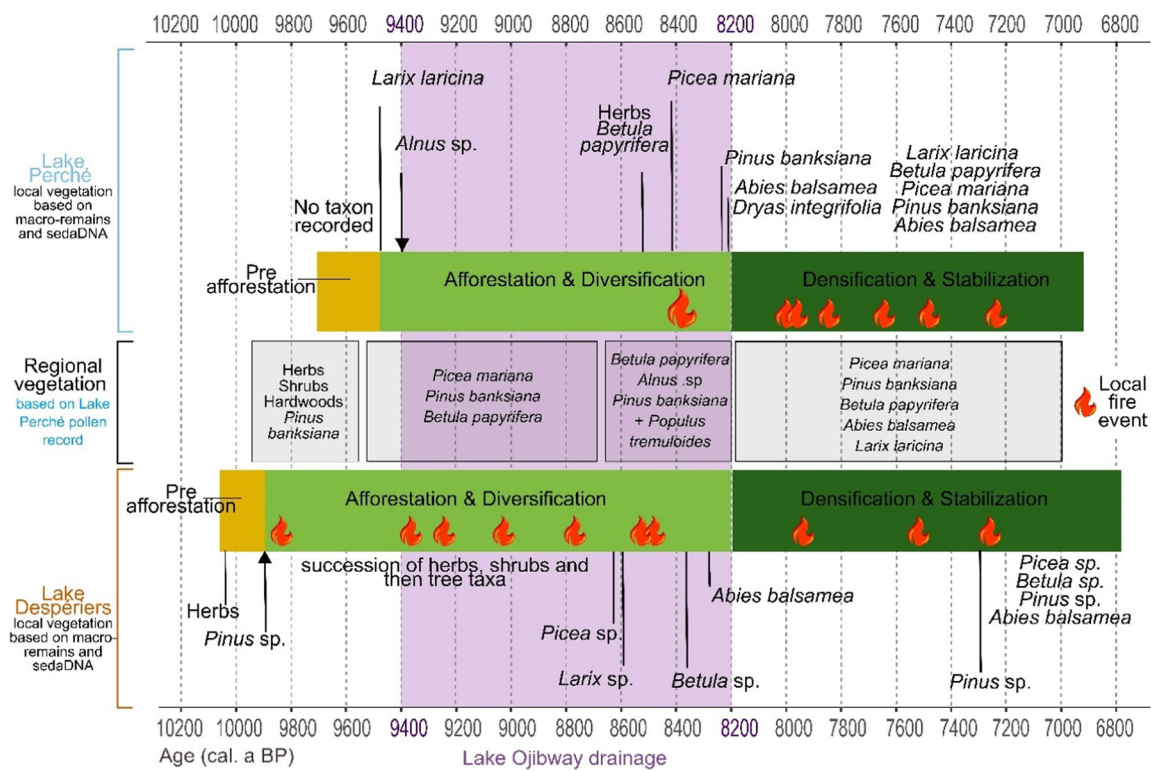
The identified fungi DNA further points to a disturbed and cold environment where organic matter started to accumulate. Chytridiomycota fungi are mostly aquatic and associated with plants or animals, either as parasites or as decayers (Shearer et al., 2007; Rojas-Jimenez et al., 2017; Lepère et al., 2019). The presence of herb pollen, the high *Pinus* spp. pollen percentages and the presence of *Paraphoma fimeti*, a fungal endophyte of various gymnosperm species and a parasite of *Pinus* sp. pollen grains (Wurzbacher et al., 2014), all suggest an open landscape dominated by herbs with scattered trees. No local fire was recorded at Lake Perché during the afforestation phase.

At Lake Despériers, the afforestation phase started with *Pinus* sp. locally recorded ca 9900 cal a BP, along with several unidentified winged seeds (Fig. 7), suggesting a drier environment than at Lake Perché. The presence of *Dryas* sp. suggests the environment was still somewhat cold. The earliest local fire was recorded ca 9820 cal a BP, followed by six other local fires

until 8500 cal a BP. They were probably low-severity surface fires (Schulze et al., 2005) as the charcoal peak magnitude was low. Herbs, and then shrubs and associated fungi increased until ca 9250 cal a BP, and other tree species (*Picea* sp. and *Larix* sp.) established ca 8550 cal a BP with their associated saprophytes. The Zygomycete *Umbelopsis angularis* was also detected ca 8550 cal a BP. This taxon is part of the Mucorales, which include a high diversity of decayers from a wide range of forest ecosystems with cold and disturbed soils (Sukdeo et al., 2018), sometimes associated with *Picea* spp. and *Pinus* spp. roots (Meyer and Gams, 2003; Lindahl et al., 2007).

#### Forest densification and stabilization (8200–7,000 cal a BP)

Following the afforestation phase, the watersheds around Lakes Perché and Despériers experienced densification and



**Figure 7.** Chronological representation of the main colonization phases on the studied paleo-islands. The purple-shaded area indicates the period when the level of proglacial Lake Ojibway gradually decreased until its final drainage ca 8200 cal a BP. [Color figure can be viewed at wileyonlinelibrary.com]

stabilization. *Betula papyrifera* and *Abies balsamea*, two species emblematic of the boreal mixedwoods, established during this period at both sites, before the final drainage of Lake Ojibway (Fig. 7). *Pinus sp.*, *Picea sp.* and *Larix laricina* were still abundant, and the vegetation was similar to what can be observed currently around both lakes (Table 1). Decayer fungi were still present at both sites (Chytridiomycota, *Cladosporium langeronii*, *Podila verticillata* and *Mortierella basiparvispora*). The pollen and macro-remain records show higher correspondence during this phase, suggesting that local and regional vegetations became similar. Forest fires continued to occur around Lake Despériers, and fires were recorded at Lake Perché as well. High peak magnitude could indicate that crown fires occurred in response to increased biomass and tree cover. Fire frequencies were similar and reached ca 7 fires 1000 years<sup>-1</sup> (Fig. 6), suggesting that conditions converged toward mesic conditions at both sites.

## Discussion

### Comparison of vegetation establishment patterns on paleo-islands and adjacent lowland sites

Both paleo-islands recorded a tundra-like pre-afforestation phase, which has not been recorded at nearby lowland sites, where vegetation colonization either started with the direct development of the boreal mixedwoods or first went through a quick open forest phase (Terasmae and Anderson, 1970; Richard, 1980; Liu, 1990; Carcaillet et al., 2001; Ali et al., 2008; Paillard et al., 2023). Open forests were recorded on the paleo-islands starting from ca 9500 cal a BP when proglacial Lake Ojibway started to drain. Possible local warming and drying induced by the progressive drainage of the proglacial lake (Hostetler et al., 2000) could have facilitated tree establishment and accelerated afforestation on the paleo-islands. Open forests were followed by the establishment of the boreal mixedwoods

ca 8500 cal a BP (Fig. 2), before a regional cooling event ca 8200 cal a BP (Clarke et al., 2004; Carrivick and Tweed, 2013). Hence, when proglacial Lake Ojibway completely drained ca 8200 cal a BP, the paleo-islands already harbored fully fledged boreal mixedwoods which could rapidly colonize the newly liberated lowlands. *Populus* spp. were recorded at most of the lowland sites during the afforestation phase (Richard, 1980; Liu, 1990; Carcaillet et al., 2001; Ali et al., 2008; Paillard et al., 2023), but apparently not on the studied paleo-islands. This could be due to the fragility of *Populus* pollen grains and macro-remains (Dark, 2023) and does not necessarily entail absence.

### Proxy complementarity

Our study confirmed the utility of a multi-proxy approach to vegetation reconstruction, as few genera were recorded by all proxies (pollen, macro-remains, sedaDNA) in each core (Fig. S2). The approaches based on sedaDNA remain exploratory, and low-frequency contamination could have occurred and remained undetected (Alsos et al., 2020). However, our methods do not seem to have impaired our main conclusions on local vegetation dynamics. Proxy complementarity allowed us to detect more taxa from local and regional sources (Jørgensen et al., 2012; Pedersen et al., 2013; Garcés-Pastor et al., 2019; Parducci et al., 2019; Fracasso et al., 2022). Even if pollen grains (indicators of both local and regional vegetation) contain DNA, they represent only a small proportion of the sedaDNA extracted from sediment cores (Capo et al., 2021). In addition, while sedaDNA and macro-remains are both proxies of local vegetation, they do not necessarily allow for the detection of the same species assemblages (Capo et al., 2021). Moreover, sedaDNA analysis allows us to detect taxa that do not produce pollen and whose macro-remains are too small to be found in sedimentary records, such as fungi (Talas et al., 2021). Our analyses indeed revealed the presence of several fungal taxa within the lineages Chytridiomycota, Zygomycota and Ascomycota. Strikingly, the

metabarcoding analysis did not detect the presence of mycorrhizal fungi, despite their ubiquitous presence in boreal plant communities and their potential in species-rich communities dominated by basidiomycetes (Nagati et al., 2018). This may be due to fragile structures, such as basidiomycetes spores, not being conserved in lake sediments (Crossay et al., 2018), compared to highly resistant and water-adapted oospores, zygospores and pigmented ascospores (Wyatt et al., 2013). Macro-remains and sedaDNA also allowed us to detect the local presence of *Larix laricina*, whose pollen is poorly conserved in sediments (Sjögren et al., 2008). This proved to be important, as *Larix laricina* was the first tree species to colonize one of the studied paleo-islands and appeared to play a key role in the early stages of afforestation.

Another advantage of the multi-proxy approach is that it allows for a more precise interpretation of vegetation signals at different scales. For example, an increase of *Betula papyrifera* pollen percentages matched the first records of this species' macro-remains, indicating that earlier lower pollen percentages represented long-distance dispersal. A similar finding was reported from nearby sites (Liu, 1990; Ali et al., 2008; Paillard et al., 2023). Although a sharp increase in pollen records can indicate local establishment of a species (Davis, 1981), validation with macro-remains allows us to pinpoint a more precise threshold to infer local presence. For some taxa (*Picea* spp. and *Pinus* spp.), macro-remains were found at a time when their pollen percentages actually decreased (8900 cal a BP). This apparent contradiction can be explained by forest densification at the time which blocked some of the pollen input of long-distance dispersers such as *Picea* and *Pinus*. This suggests that the regional pollen signal became proportionally less important than the local pollen signal. Local vegetation increase is further supported by the increased diversity of sedaDNA and macro-remains.

### Soil and fire dynamics on paleo-islands

Macro-remains, pollen, sedaDNA and biodiversity indices reveal progressive vegetation establishment on the paleo-islands, first with a treeless tundra-like phase when organic matter started to accumulate, followed by an open forest which later transitioned to a denser forest akin to the current boreal mixedwoods found in the area. Progressive vegetation densification probably led to soil stabilization, as suggested by a decrease in geochemical proxies of soil erosion on the paleo-islands (Vogel et al., 2023). Soil stabilization following postglacial afforestation was also recorded in other boreal and subalpine environments (Bradshaw et al., 2000; Magyari et al., 2014; Schwörer et al., 2014; Myrstener et al., 2021; Baig and Gavin, 2023).

Fire dynamics differed on the two studied paleo-islands, resulting in different vegetation development trajectories, both of which ultimately culminated in the boreal mixedwoods that are typical in the region today. At Lake Perché, no local fire was recorded during the first ca 1300 years of vegetation history, which explains the long-term persistence of an open forest dominated by *Larix laricina* and *Alnus* sp., which are known to be ill-adapted to fire and rather associated with wet environments (Schirmer et al., 2016). Then, after the first local fire occurred ca 8400 cal a BP, fire-adapted taxa were also recorded (*Pinus banksiana*, *Picea mariana*, *Betula papyrifera*). This introduced diversity to the system, as reflected by the increase in Hill's N2 at the time. Fires have previously been shown to trigger changes in plant communities (Yeboah et al., 2016; Remy et al., 2017). The relatively high proportion of *Betula papyrifera* kept fire frequencies relatively low, allowing the establishment of late-successional species such as *Abies balsamea*.

At Lake Despériers, fires occurred at the beginning and throughout the afforestation phase, which explains why open *Pinus banksiana* forests dominated the landscape for ca 1400 years. *Pinus banksiana* is a well-known fire-adapted species, whose postglacial migration was shown to depend on fire occurrence (Asselin et al., 2003). This is why it occurred early at Lake Despériers, but much later at Lake Perché. Then, after ca 8500 cal a BP, the environment around Lake Despériers became wetter, as indicated by increased bryophytes. Higher humidity resulted in a slight decrease in fire frequency and concomitant increase in diversity (higher values of Hill's N2), including tree species less adapted to fire such as *Abies balsamea*.

### Conclusion

Using a multi-proxy approach, we recorded for the first time a pre-afforestation phase at the beginning of the vegetation colonization process in the Abitibi region, which appears to be exclusive to paleo-islands. This confirmed our hypothesis that paleo-islands recorded progressive vegetation establishment, including an initial tundra-like non-arboreal phase. While the two paleo-islands followed different vegetation development trajectories (notably influenced by different fire histories), both ended with the development of boreal mixedwoods earlier than in the adjacent lowlands, in line with our second hypothesis. The complementarity of the proxies we used (pollen, macro-remains, sedaDNA, charcoal) allowed us to decipher how the paleo-islands were instrumental to the rapid colonization of the lowlands by boreal mixedwoods after the final drainage of proglacial Lake Ojibway. This work thus shows the potential importance of islands for promoting post-glacial rates of plant dispersal in areas formerly covered by proglacial lakes.

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### Data availability statement

The data that support the findings of this study are openly available in Neotoma database and here at <https://data.mendeley.com/datasets/scfj66rg46/1>.

### Supporting information

Additional supporting information can be found in the online version of this article.

**Table S1.** Radiocarbon dates obtained from Lakes Perché and Despériers cores (Vogel et al., 2023).

**Table S2.** Primer sequences used and associated PCR conditions.

**Table S3.** Pollen taxa not shown or shown as a group in Fig. 4.

**Figure S1.** Calibrated age–depth models based on the radiocarbon dates (Table 2) obtained from basal sediments (brown = organic sediments and olive-grey = mineralogic sediments) at (a) Lake Perché and (b) Lake Despériers. The purple rectangle illustrates the period when the level of

proglacial Lake Ojibway gradually decreased until its final drainage ca 8200 cal a BP (modified from Vogel et al., 2023).

**Figure S2.** Distribution of the identified genera among the three proxies used: pollen, macro-remains and sedaDNA for (a) Lake Perché and (b) Lake Despériers.

**Abbreviations.** ANP, Aigüebelle National Park; AP, Arboreal Pollen; cal. a BP, Calibrated year Before Present; CSD, Charcoal Size Distribution; DMAZ, Despériers Macro-remains Assemblage zone; DNA, DeoxyriboNucleic Acid; FF, Fire Frequency; HB, Hudson Bay; JB, James Bay; NPP, Non-Pollen Palynomorph; PAZ, Pollinic Assemblage Zone; PMAZ, Perché Macro-remains Assemblage zone; sedaDNA, sedimentary ancient DNA.

## References

- Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T. & Curtis-McLane, S. (2008) Adaptation, migration or extirpation: climate change outcomes for tree populations: Climate change outcomes for tree populations. *Evolutionary Applications*, 1, 95–111. Available at: <https://doi.org/10.1111/j.1752-4571.2007.00013.x>
- Ali, A.A., Asselin, H., Larouche, A.C., Bergeron, Y., Carcaillet, C. & Richard, P.J.H. (2008) Changes in fire regime explain the Holocene rise and fall of *Abies balsamea* in the coniferous forests of western Québec, Canada. *The Holocene*, 18, 693–703. Available at: <https://doi.org/10.1177/0959683608091780>
- Alsos, I.G., Sjögren, P., Brown, A.G., Gielly, L., Merkel, M.K.F., Paus, A. et al. (2020) Last Glacial Maximum environmental conditions at Andøya, northern Norway; evidence for a northern ice-edge ecological “hotspot”. *Quaternary Science Reviews*, 239, 106364. Available at: <https://doi.org/10.1016/j.quascirev.2020.106364>.
- Asselin, H. & Payette, S. (2005) Detecting local-scale fire episodes on pollen slides. *Review of Palaeobotany and Palynology*, 137, 31–40. Available at: <https://doi.org/10.1016/j.revpalbo.2005.08.002>
- Asselin, H., Payette, S., Fortin, M.-J. & Vallée, S. (2003) The northern limit of *Pinus banksiana* Lamb. in Canada: explaining the difference between the eastern and western distributions. *Journal of Biogeography*, 30, 1709–1718. Available at: <https://doi.org/10.1046/j.1365-2699.2003.00935.x>
- Baig, J. & Gavin, D.G. (2023) Postglacial vegetation and fire history with a high-resolution analysis of tephra impacts, High Cascade Range, Oregon, USA. *Quaternary Science Reviews*, 303, 107970. Available at: <https://doi.org/10.1016/j.quascirev.2023.107970>.
- Bellemain, E., Davey, M.L., Kausrud, H., Epp, L.S., Boessenkool, S., Coissac, E. et al. (2013) Fungal palaeodiversity revealed using high-throughput metabarcoding of ancient DNA from arctic permafrost. *Environmental Microbiology*, 15, 1176–1189. Available at: <https://doi.org/10.1111/1462-2920.12020>
- Birks, H.J.B., Felde, V.A., Bjune, A.E., Grytnes, J.-A., Seppä, H. & Giesecke, T. (2016) Does pollen-assemblage richness reflect floristic richness? A review of recent developments and future challenges. *Review of Palaeobotany and Palynology*, 228, 1–25. Available at: <https://doi.org/10.1016/j.revpalbo.2015.12.011>
- Birks, H.J.B. & Line, J.M. (1992) The use of rarefaction analysis for estimating palynological richness from quaternary pollen-analytical data. *The Holocene*, 2, 1–10. Available at: <https://doi.org/10.1177/095968369200200101>
- Blaauw, M., Christen, J., Aquino Lopez, M.A., Vazquez, J.E., Gonzalez, O.M., Belding, T. et al. (2022) rbacon package.
- Bradshaw, E.G., Jones, V.J., Birks, H.J.B. & Birks, H.H. (2000) Diatom responses to late-glacial and early-Holocene environmental changes at Kråkenes, western Norway. *Journal of Paleolimnology*, 23, 21–34.
- Brooks, G.R. (2020) Evidence of a strong paleoearthquake in ~9.1 ka cal BP interpreted from mass transport deposits, western Quebec – northeastern Ontario, Canada. *Quaternary Science Reviews*, 234, 106250. Available at: <https://doi.org/10.1016/j.quascirev.2020.106250>
- Brouard, E., Roy, M., Godbout, P.-M. & Veillette, J.J. (2021) A framework for the timing of the final meltwater outbursts from glacial Lake Agassiz-Ojibway. *Quaternary Science Reviews*, 274, 107269. Available at: <https://doi.org/10.1016/j.quascirev.2021.107269>.
- Callahan, B.J., McMurdie, P.J., Rosen, M.J., Han, A.W., Johnson, A.J.A. & Holmes, S.P. (2016) DADA2: High resolution sample inference from Illumina amplicon data. *Nature Methods*, 13, 581–583. Available at: <https://doi.org/10.1038/nmeth.3869>
- Capo, E., Giguet-Covex, C., Rouillard, A., Nota, K., Heintzman, P.D., Vuillemin, A. et al. (2021) Lake Sedimentary DNA Research on Past Terrestrial and Aquatic Biodiversity: Overview and Recommendations. *Quaternary*, 4, 6. Available at: <https://doi.org/10.3390/quat4010006>
- Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S. & Prairie, Y.T. (2001) Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? *Journal of Ecology*, 89, 930–946. Available at: <https://doi.org/10.1111/j.1365-2745.2001.00614.x>
- Carrivick, J.L. & Tweed, F.S. (2013) Proglacial lakes: character, behaviour and geological importance. *Quaternary Science Reviews*, 78, 34–52. Available at: <https://doi.org/10.1016/j.quascirev.2013.07.028>
- Chao, A., Henderson, P.A., Chiu, C.-H., Moyes, F., Hu, K.-H., Dornelas, M. et al. (2021) Measuring temporal change in alpha diversity: A framework integrating taxonomic, phylogenetic and functional diversity and the iNEXT.3D standardization. *Methods in Ecology and Evolution*, 12, 1926–1940. Available at: <https://doi.org/10.1111/2041-210X.13682>
- Clark, J.S., Fastie, C., Hurtt, G., Jackson, S.T., Johnson, C., King, G.A. et al. (1998) Reid’s Paradox of rapid plant migration. *BioScience*, 48, 13–24. Available at: <https://doi.org/10.2307/1313224>
- Clarke, G.K.C., Leverington, D.W., Teller, J.T. & Dyke, A.S. (2004) Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200BP cold event. *Quaternary Science Reviews*, 23, 389–407. Available at: <https://doi.org/10.1016/j.quascirev.2003.06.004>
- Core Team, R. (2022) *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing <https://www.R-project.org/>
- Crossay, T., Cilia, A., Cavaloc, Y., Amir, H. & Redecker, D. (2018) Four new species of arbuscular mycorrhizal fungi (Glomeromycota) associated with endemic plants from ultramafic soils of New Caledonia. *Mycological Progress*, 17, 729–744. Available at: <https://doi.org/10.1007/s11557-018-1386-5>
- Dalton, A.S., Margold, M., Stokes, C.R., Tarasov, L., Dyke, A.S., Adams, R.S. et al. (2020) An updated radiocarbon-based ice margin chronology for the last deglaciation of the North American Ice Sheet Complex. *Quaternary Science Reviews*, 234, 106223. Available at: <https://doi.org/10.1016/j.quascirev.2020.106223>
- Dark, P. (2023) Pollen and macroscopic plant remains as indicators of local and regional environments, In: *Handbook of Archaeological Sciences*. John Wiley & Sons, Ltd. pp. 271–288. <https://doi.org/10.1002/9781119592112.ch14>
- Davis, M.B. (1981) Quaternary history and the stability of forest communities. In: West, D.C., Shugart, H.H. & Botkin, D.B. (Eds.) *Forest Succession: Concepts and Application*, Springer Advanced Texts in Life Sciences. New York, NY: Springer. pp. 132–153. [https://doi.org/10.1007/978-1-4612-5950-3\\_10](https://doi.org/10.1007/978-1-4612-5950-3_10)
- Djamali, M. & Cilleros, K. (2020) Statistically significant minimum pollen count in Quaternary pollen analysis; the case of pollen-rich lake sediments. *Review of Palaeobotany and Palynology*, 275, 104156. Available at: <https://doi.org/10.1016/j.revpalbo.2019.104156>
- Dyke, A.S. (2004) An outline of North American deglaciation with emphasis on central and northern Canada, In: *Developments in Quaternary Sciences*. Elsevier. pp. 373–424. [https://doi.org/10.1016/S1571-0866\(04\)80209-4](https://doi.org/10.1016/S1571-0866(04)80209-4)
- Epp, L.S., Boessenkool, S., Bellemain, E.P., Haile, J., Esposito, A., Riaz, T. et al. (2012) New environmental metabarcodes for analysing soil DNA: potential for studying past and present ecosystems. *Molecular Ecology*, 21, 1821–1833. Available at: <https://doi.org/10.1111/j.1365-294X.2012.05537.x>
- Faegri, K., Kaland, P.E. & Krzywinski, K. (1989) *Textbook of pollen analysis*. Wiley.
- Fracasso, I., Dinella, A., Giammarchi, F., Marinchel, N., Kołaczek, P., Lamentowicz, M. et al. (2022) Climate and human impacts inferred from a 1500-year multi-proxy record of an alpine peatland in the South-Eastern Alps. *Ecological Indicators*, 145, 109737. Available at: <https://doi.org/10.1016/j.ecolind.2022.109737>
- Garcés-Pastor, S., Wangenstein, O.S., Pérez-Haase, A., Pélachs, A., Pérez-Obiol, R., Cañellas-Boltà, N. et al. (2019) DNA metabarcod-

- ing reveals modern and past eukaryotic communities in a high-mountain peat bog system. *Journal of Paleolimnology*, 62, 425–441. Available at: <https://doi.org/10.1007/s10933-019-00097-x>
- Godbout, P.-M., Roy, M. & Veillette, J.J. (2020) A detailed lake-level reconstruction shows evidence for two abrupt lake drawdowns in the late-stage history of the eastern Lake Agassiz-Ojibway basin. *Quaternary Science Reviews*, 238, 106327. Available at: <https://doi.org/10.1016/j.quascirev.2020.106327>
- Godbout, P.-M., Roy, M., Veillette, J.J. & Schaefer, J.M. (2017) Cosmogenic <sup>10</sup>Be dating of raised shorelines constrains the timing of lake levels in the eastern Lake Agassiz-Ojibway basin. *Quaternary Research*, 88, 265–276. Available at: <https://doi.org/10.1017/qua.2017.40>
- Grimm, E.C. (1987) CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences*, 13, 13–35. Available at: [https://doi.org/10.1016/0098-3004\(87\)90022-7](https://doi.org/10.1016/0098-3004(87)90022-7)
- Harnik, P.G., Maherali, H., Miller, J.H. & Manos, P.S. (2018) Geographic range velocity and its association with phylogeny and life history traits in North American woody plants. *Ecology and Evolution*, 8, 2632–2644. Available at: <https://doi.org/10.1002/ece3.3880>
- Higuera, P.E., Brubaker, L.B., Anderson, P.M., Brown, T.A., Kennedy, A.T. & Hu, F.S. (2008) Frequent fires in ancient shrub tundra: implications of paleorecords for Arctic environmental change. *PLoS One*, 3, e0001744. Available at: <https://doi.org/10.1371/journal.pone.0001744>
- Hill, M.O. (1973) Diversity and evenness: A unifying notation and its consequences. *Ecology*, 54, 427–432. Available at: <https://doi.org/10.2307/1934352>
- Hostetler, S.W., Bartlein, P.J., Clark, P.U., Small, E.E. & Solomon, A.M. (2000) Simulated influences of Lake Agassiz on the climate of central North America 11,000 years ago. *Nature*, 405, 334–337. Available at: <https://doi.org/10.1038/35012581>
- Johnston, W.F. (1990) *Larix laricina* (Du Roi) K. Koch – Tamarack, in: *Silvics of North America*. pp. 141–151.
- Juggins, S. & Juggins, M.S. (2019) Package “rioja”.
- Jørgensen, T., Haile, J., Möller, P., Andreev, A., Boessenkool, S., Rasmussen, M. et al. (2012) A comparative study of ancient sedimentary DNA, pollen and macrofossils from permafrost sediments of northern Siberia reveals long-term vegetational stability. *Molecular Ecology*, 21, 1989–2003. Available at: <https://doi.org/10.1111/j.1365-294X.2011.05287.x>
- Kölgel, U., Nilsson, R.H., Abarenkov, K., Tedersoo, L., Taylor, A.F.S., Bahram, M. et al. (2013) Towards a unified paradigm for sequence-based identification of fungi. *Molecular Ecology*, 22, 5271–5277. Available at: <https://doi.org/10.1111/mec.12481>
- Lepère, C., Domaizon, I., Humbert, J.-F., Jardillier, L., Hugoni, M. & Debroas, D. (2019) Diversity, spatial distribution and activity of fungi in freshwater ecosystems. *PeerJ*, 7, e6247. Available at: <https://doi.org/10.7717/peerj.6247>
- Lévesque, P.E.M., Diné, H. & Larouche, A. (1988) Guide to the identification of plant macrofossils in Canadian peatlands, Publication/Land Resource Research Centre, Research Branch, Agriculture Canada. Land Resource Research Centre, Research Branch, Agriculture Canada, Ottawa, Ont.
- Li, D. (2018) Package “hillR” 14.
- Lindahl, B.D., Ihrmark, K., Boberg, J., Trumbore, S.E., Höglberg, P., Stenlid, J. & Finlay, R.D. (2007) Spatial separation of litter decomposition and mycorrhizal nitrogen uptake in a boreal forest. *New Phytologist*, 173, 611–620. Available at: <https://doi.org/10.1111/j.1469-8137.2006.01936.x>
- Liu, K.-B. (1990) Holocene paleoecology of the boreal forest and Great Lakes-St. Lawrence forest in Northern Ontario. *Ecological Monographs*, 60, 179–212. Available at: <https://doi.org/10.2307/1943044>
- Magyari, E.K., Veres, D., Wennrich, V., Wagner, B., Braun, M., Jakab, G. et al. (2014) Vegetation and environmental responses to climate forcing during the Last Glacial Maximum and deglaciation in the East Carpathians: attenuated response to maximum cooling and increased biomass burning. *Quaternary Science Reviews*, 106, 278–298. Available at: <https://doi.org/10.1016/j.quascirev.2014.09.015>
- Marshall, S.J., Tarasov, L., Clarke, G.K.C. & Peltier, W.R. (2000) Glaciological reconstruction of the Laurentide Ice Sheet: physical processes and modelling challenges. *Canadian Journal of Earth Sciences*, 37, 26.
- McAndrews, J.H. (1973) *Key to the Quaternary pollen and spores of the Great Lakes region*. [Ottawa]: Royal Ontario Museum.
- MERN - Système d'information géomorphologique. (2022) Zones morphosédimentologiques indicatives de la géologie du Quaternaire en Abitibi (Québec).
- Meyer, W. & Gams, W. (2003) Delimitation of Umbelopsis (Mucorales, Umbelopsidaceae fam. nov.) based on ITS sequence and RFLP data. *Mycological Research*, 107, 339–350. Available at: <https://doi.org/10.1017/S0953756203007226>
- Moore, P.D. & Webb, J.A. (1978) *An illustrated guide to pollen analysis*. Hodder and Stoughton
- Mortensen, M.F., Birks, H.H., Christensen, C., Holm, J., Noe-Nygaard, N., Odgaard, B.V. et al. (2011) Lateglacial vegetation development in Denmark—New evidence based on macrofossils and pollen from Slotseng, a small-scale site in southern Jutland. *Quaternary Science Reviews*, 30, 2534–2550. Available at: <https://doi.org/10.1016/j.quascirev.2011.04.018>
- Myrstener, E., Ninnes, S., Meyer-Jacob, C., Mighall, T. & Bindler, R. (2021) Long-term development and trajectories of inferred lake-water organic carbon and pH in naturally acidic boreal lakes. *Limnology and Oceanography*, 66, 2408–2422.
- Nagati, M., Roy, M., Manzi, S., Richard, F., Desrochers, A., Gardes, M. et al. (2018) Impact of local forest composition on soil fungal communities in a mixed boreal forest. *Plant and Soil*, 432, 345–357. Available at: <https://doi.org/10.1007/s11104-018-3806-3>
- Nutz, A., Lajeunesse, P., Ghienne, J.-F., Schuster, M., Brouard, E., Dietrich, P. et al. (2020) Deglacial to paraglacial history of the Lake Saint-Jean lowlands: A geomorphological perspective. In: Slaymaker, O. & Catto, N. (Eds.) *Landscapes and Landforms of Eastern Canada*. Cham: Springer International Publishing. pp. 145–158. [https://doi.org/10.1007/978-3-030-35137-3\\_5](https://doi.org/10.1007/978-3-030-35137-3_5)
- Oksanen, J., Simpson, G.L., Blanchet, G.F., Kindt, R., Legendre, P., Minchin, P.R. et al. (2022) Package “vegan.”
- Ordonez, A. & Williams, J.W. (2013) Climatic and biotic velocities for woody taxa distributions over the last 16 000 years in eastern North America. *Ecology Letters*, 16, 773–781. Available at: <https://doi.org/10.1111/ele.12110>
- Oris, F., Ali, A.A., Asselin, H., Paradis, L., Bergeron, Y. & Finsinger, W. (2014) Charcoal dispersion and deposition in boreal lakes from 3 years of monitoring: Differences between local and regional fires. *Geophysical Research Letters*, 41, 6743–6752. Available at: <https://doi.org/10.1002/2014GL060984>
- Paillard, J., Richard, P.J., Blarquez, O., Grondin, P. & Bergeron, Y. (2023) Postglacial establishment and expansion of marginal populations of sugar maple in western Québec, Canada: Palynological detection and interactions with fire, climate and successional processes. *The Holocene*, 33, 09596836231183065. Available at: <https://doi.org/10.1177/09596836231183065>
- Parducci, L., Alsos, I.G., Unneberg, P., Pedersen, M.W., Han, L., Lammers, Y. et al. (2019) Shotgun environmental DNA, pollen, and macrofossil analysis of Lateglacial lake sediments from Southern Sweden. *Frontiers in Ecology and Evolution*, 7, 189. Available at: <https://doi.org/10.3389/fevo.2019.00189>
- Pauvert, C., Buée, M., Laval, V., Edel-Hermann, V., Fauchery, L., Gautier, A. et al. (2019) Bioinformatics matters: The accuracy of plant and soil fungal community data is highly dependent on the metabarcoding pipeline. *Fungal Ecology*, 41, 23–33. Available at: <https://doi.org/10.1016/j.funeco.2019.03.005>
- Payette, S., Couillard, P.-L., Frégeau, M., Laflamme, J. & Lavoie, M. (2022) The velocity of postglacial migration of fire-adapted boreal tree species in eastern North America. *Proceedings of the National Academy of Sciences*, 119, e2210496119. Available at: <https://doi.org/10.1073/pnas.2210496119>
- Pedersen, M.W., Ginolhac, A., Orlando, L., Olsen, J., Andersen, K., Holm, J. et al. (2013) A comparative study of ancient environmental DNA to pollen and macrofossils from lake sediments reveals taxonomic overlap and additional plant taxa. *Quaternary Science Reviews*, 75, 161–168. Available at: <https://doi.org/10.1016/j.quascirev.2013.06.006>
- Pfeffer, W.T., Dyrgerov, M., Kaplan, M., Dwyer, J., Sassolas, C., Jennings, A. et al. (1997) Numerical modeling of Late Glacial Laurentide advance of ice across Hudson Strait: Insights into terrestrial and marine geology, mass balance, and calving flux.

- Paleoceanography*, 12, 97–110. Available at: <https://doi.org/10.1029/96PA03065>
- Powell, J.A. & Zimmermann, N.E. (2004) Multiscale analysis of active seed dispersal contributes to resolving Reid's paradox. *Ecology*, 85, 490–506. Available at: <https://doi.org/10.1890/02-0535>
- Ray, K.J., Cotter, S.Y., Arzika, A.M., Kim, J., Boubacar, N., Zhou, Z. et al. (2019) High-throughput sequencing of pooled samples to determine community-level microbiome diversity. *Annals of Epidemiology*, 39, 63–68. Available at: <https://doi.org/10.1016/j.annepidem.2019.09.002>
- Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C. et al. (2020) The IntCal20 Northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon*, 62, 725–757. Available at: <https://doi.org/10.1017/RDC.2020.41>
- Remy, C.C., Fouquemberg, C., Asselin, H., Andrieux, B., Magnan, G., Brossier, B. et al. (2018) Guidelines for the use and interpretation of palaeofire reconstructions based on various archives and proxies. *Quaternary Science Reviews*, 193, 312–322. Available at: <https://doi.org/10.1016/j.quascirev.2018.06.010>
- Remy, C.C., Lavoie, M., Girardin, M.P., Hély, C., Bergeron, Y., Grondin, P. et al. (2017) Wildfire size alters long-term vegetation trajectories in boreal forests of eastern North America. *Journal of Biogeography*, 44, 1268–1279. Available at: <https://doi.org/10.1111/jbi.12921>
- Richard, P. (1970) Pollinic atlas of the trees and of some indigenous shrubs of Quebec. IV. Angiosperms (Rosaceae, Anacardiaceae, Aceraceae, Rhamnaceae, Tiliaceae, Cornaceae, Oleaceae, Caprifoliaceae). *Natur Can*, 97, 241–306.
- Richard, P. (1980) Histoire postglaciaire de la végétation au sud du lac Abitibi, Ontario et Québec. *Géographie physique et Quaternaire*, 34, 77–94. Available at: <https://doi.org/10.7202/1000385ar>
- Rojas-Jimenez, K., Wurzbacher, C., Bourne, E.C., Chiuchiolo, A., Priscu, J.C. & Grossart, H.-P. (2017) Early diverging lineages within Cryptomycota and Chytridiomycota dominate the fungal communities in ice-covered lakes of the McMurdo Dry Valleys, Antarctica. *Scientific Reports*, 7, 15348. Available at: <https://doi.org/10.1038/s41598-017-15598-w>
- Roy, M., Veillette, J.J., Daubois, V. & Ménard, M. (2015) Late-stage phases of glacial Lake Ojibway in the central Abitibi region, eastern Canada. *Geomorphology*, 248, 14–23. Available at: <https://doi.org/10.1016/j.geomorph.2015.07.026>
- Schirmermeister, L., Meyer, H., Andreev, A., Wetterich, S., Kienast, F., Bobrov, A. et al. (2016) Late Quaternary paleoenvironmental records from the Chatanika River valley near Fairbanks (Alaska). *Quaternary Science Reviews, Special Issue: PAST Gateways (Palaeo-Arctic Spatial and Temporal Gateways)*, 147, 259–278. Available at <https://doi.org/10.1016/j.quascirev.2016.02.009>
- Schulze, E.-D., Wirth, C., Mollicone, D. & Ziegler, W. (2005) Succession after stand replacing disturbances by fire, wind throw, and insects in the dark Taiga of Central Siberia. *Oecologia*, 146, 77–88. Available at <https://doi.org/10.1007/s00442-005-0173-6>
- Schwörer, C., Kaltenrieder, P., Glur, L., Berlinger, M., Elbert, J., Frei, S. et al. (2014) Holocene climate, fire and vegetation dynamics at the treeline in the Northwestern Swiss Alps. *Vegetation History and Archaeobotany*, 23, 479–496. Available at: <https://doi.org/10.1007/s00334-013-0411-5>
- Shearer, C.A., Descals, E., Kohlmeyer, B., Kohlmeyer, J., Marvanová, L., Padgett, D. et al. (2007) Fungal biodiversity in aquatic habitats. *Biodiversity and Conservation*, 16, 49–67. Available at: <https://doi.org/10.1007/s10531-006-9120-z>
- Sjögren, P., van der Knaap, W.O., Huusko, A. & van Leeuwen, J.F.N. (2008) Pollen productivity, dispersal, and correction factors for major tree taxa in the Swiss Alps based on pollen-trap results. *Review of Palaeobotany and Palynology*, 152, 200–210. Available at: <https://doi.org/10.1016/j.revpalbo.2008.05.003>
- Sukdeo, N., Teen, E., Michael Rutherford, P., Massicotte, H.B. & Egger, K.N. (2018) Soil detrital inputs increase stimulate bacterial saprotrophs with different timing and intensity compared to fungal saprotrophs. *bioRxiv*, 266684. Available at <https://doi.org/10.1101/266684>
- Taberlet, P., Coissac, E., Pompanon, F., Gielly, L., Miquel, C., Valentini, A. et al. (2007) Power and limitations of the chloroplast trnL (UAA) intron for plant DNA barcoding. *Nucleic Acids Research*, 35, e14. Available at: <https://doi.org/10.1093/nar/gkl1938>
- Talas, L., Stivrins, N., Veski, S., Tedersoo, L. & Kisand, V. (2021) Sedimentary Ancient DNA (sedaDNA) Reveals Fungal Diversity and Environmental Drivers of Community Changes throughout the Holocene in the Present Boreal Lake Lielais Svētīņū (Eastern Latvia). *Microorganisms*, 9, 719. Available at: <https://doi.org/10.3390/microorganisms9040719>
- Terasmae, J. & Anderson, T.W. (1970) Hypsithermal range extension of white pine (*Pinus strobus* L.) in Quebec, Canada. *Canadian Journal of Earth Sciences*, 7, 406–413. Available at: <https://doi.org/10.1139/e70-035>
- Veillette, J.J. (1994) Evolution and paleohydrology of glacial lakes Barlow and Ojibway. *Quaternary Science Reviews*, 13, 945–971.
- Vogel, M.F., Asselin, H., Joannin, S., Bergeron, Y., Leclercq, S., Latapy, C. et al. (2023) Early afforestation on islands of proglacial Lake Ojibway as evidence of post-glacial migration outposts. *The Holocene*, 33, 975–985. Available at: <https://doi.org/10.1177/09596836231169988>
- Vogel, M.F.S., Ali, A.A., Joannin, S., Bergeron, Y. & Asselin, H. (2024) Postglacial vegetation migration facilitated by outposts on proglacial lake islands in eastern North America. *Quaternary Science Advances*, 13, 100164. Available at: <https://doi.org/10.1016/j.qsa.2024.100164>
- Voldstad, L.H., Alsos, I.G., Farnsworth, W.R., Heintzman, P.D., Håkansson, L., Kjellman, S.E. et al. (2020) A complete Holocene lake sediment ancient DNA record reveals long-standing high Arctic plant diversity hotspot in northern Svalbard. *Quaternary Science Reviews*, 234, 106207. Available at: <https://doi.org/10.1016/j.quascirev.2020.106207>
- von Hippel, B., Stoof-Leichsenring, K.R., Schulte, L., Seeber, P., Epp, L.S., Biskaborn, B.K. et al. (2022) Long-term fungus–plant covariation from multi-site sedimentary ancient DNA metabarcoding. *Quaternary Science Reviews*, 295, 107758. Available at <https://doi.org/10.1016/j.quascirev.2022.107758>
- Willerslev, E., Davison, J., Moora, M., Zobel, M., Coissac, E., Edwards, M.E. et al. (2014) Fifty thousand years of Arctic vegetation and megafaunal diet. *Nature*, 506, 47–51. Available at: <https://doi.org/10.1038/nature12921>
- Wurzbacher, C., Rösel, S., Rychła, A. & Grossart, H.-P. (2014) Importance of saprotrophic freshwater fungi for pollen degradation. *PLoS One*, 9, e94643. Available at: <https://doi.org/10.1371/journal.pone.0094643>
- Wyatt, T.T., Wösten, H.A.B. & Dijksterhuis, J. (2013) Chapter two - Fungal spores for dispersion in space and time. In: Sariaslani, S. & Gadd, G.M. (Eds.) *Advances in Applied Microbiology*. Academic Press. pp. 43–91. <https://doi.org/10.1016/B978-0-12-407672-3.00002-2>
- Yeboah, D., Chen, H.Y.H. & Kingston, S. (2016) Tree species richness decreases while species evenness increases with disturbance frequency in a natural boreal forest landscape. *Ecology and Evolution*, 6, 842–850. Available at: <https://doi.org/10.1002/ece3.1944>