A 2300-year reconstruction of environmental change from Parc national du Mont-Orford, southeastern Québec, using high-resolution pollen, charcoal and X-ray fluorescence records

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ABSTRACT

A 2300-year reconstruction of environmental change from Parc national du Mont-Orford, southeastern Québec, using high-resolution pollen, charcoal and X-ray fluorescence records

Claire O'Neill Sanger

We used a high-resolution lacustrine pollen record from Étang Fer-de-Lance (45°21'21.9"N, 72°13'35.3"W), southern Québec, Canada, together with microcharcoal, to infer forest dynamics, climate and human impacts over the past 2300 years. The lake is located in the sugar maple-basswood domain of the Northern Temperate Forest. We found that *Fagus grandifolia* (American beech) and *Tsuga canadensis* (eastern hemlock) significantly declined over the past 700 years. Over the last millennium, *Picea glauca* (white spruce), *Picea mariana/rubens* (black and red spruce), and *Pinus strobus* (eastern white pine) significantly increased. Using the modern analog technique (MAT), we found a warm and dry first millennium AD, a somewhat less warm and less dry Medieval Climate Anomaly, and a cold and wet Little Ice Age. The signal for human modification of the landscape first appeared at ~AD 1550-1650 as increases in *Ambrosia* (ragweed) and Poaceae (grasses) from Indigenous agriculture. The signal of European settler landscape modification appeared at ~AD 1770 as the beginning of a steep, "classic" *Ambrosia* rise. It intensified over the subsequent 250 years as further increases in non-arboreal pollen taxa and early successional *Acer* (maple) species. Microcharcoal analysis showed that fire is a natural part of the sugar maple-basswood domain with a mean fire return interval of 515 years.

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Contributions of Authors

As first author, I was responsible for the conception, design, data analysis and the writing of the manuscript related to this thesis. The manuscript was co-authored by Kayden Schwartz, who analyzed the charcoal record of the core and Dr. Jeannine-Marie St-Jacques and Dr. Matthew Peros, who advised on experimental design, statistics, editing, and revisions to the manuscript.

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1. Introduction

Climate change is rapidly altering the terrestrial landscape of the Earth. Its expected impacts on the distribution of tree species in Canada pose a new level of uncertainty for forest management, conservation and the many industries that depend on them (Natural Resources Canada, 2018). To respond to these impacts, forestry scientists, ecologists, climate scientists and governments alike are calling for ecosystem management strategies informed by long-term paleo-environmental data (Sustainable Forest Development Act of Québec (Article 1), 2010). Looking at historic interactions between forest ecosystems and climate enables us to establish pre-industrial and pre-European settlement environmental baselines to assess whether current changes are outside of the normal range of environmental variability and predict future species changes (Willis and Birks, 2006; Boucher et al., 2009; Grondin et al., 2018).

The field of palynology has utilized fossilized pollen as a proxy in creating these much-needed long-term paleo-environmental datasets. In northeastern North America, many studies have used pollen analysis successfully to reconstruct whole Holocene forest dynamics (Richard, 1975; Mott, 1977; Richard, 1978; Gajewski, 1987; Lavoie and Richard, 2000; Muller and Richard, 2001; Muller et al., 2003; Houle et al., 2012; Lavoie and Richard, 2017). These works have provided excellent records of post-glacial vegetation and have deepened our understanding of the migration of trees following the retreat of ice sheets. Lafontaine-Boyer and Gajewski (2014) have argued, however, that the resolution of such studies is not fine enough to capture short periods of driving climate variation that can greatly affect forest composition.

The high-resolution pollen reconstructions of Lafontaine-Boyer and Gajewski (2014) and a few other researchers in southern Québec have shown how higher-resolution pollen analysis can deepen our understanding of decadal to century-scale environmental variability over the last two millennia – including the transition from the Medieval Climate Anomaly (MCA) to the Little Ice Age (LIA) (Houle et al., 2012; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski 2014). By filling the research gap of high-resolution pollen analysis in southeastern Québec, this study aims to answer the question of how sensitive the sugar-maple hardwood forest has been to environmental change over the common era (last 2000 years), while also exploring the effects of pre- and post-European settlement land-use changes on the forest composition. In addition to pollen, high-resolution charcoal and x-ray fluorescence records are also analyzed to reconstruct fire and erosional events. High-resolution reconstructions that capture decadal-centennial scale vegetation and environmental changes can give insight into the impacts of current global warming on forests which are occurring at accelerating rates.

2. Literature Review

2.1 Pollen as a paleo-environmental proxy

Responding to the need for long-term environmental datasets for baselines, paleo-environmental studies produce records of past environments far beyond the limited period of recorded instrumental observations by studying the variability of naturally archived paleo-environmental proxies. These proxy records provide a long-term temporal perspective that is crucial for informing ecosystem management strategies (Willis and Birks, 2006). Paleo-environmental proxies, themselves, are defined as natural phenomena which are dependent on environmental conditions such as forest history or climate, and which incorporate into their very structure a measure of this dependency (Bradley, 2015). Using their variability, these proxies allow researchers to infer past environmental variations.

Compared to other forms of terrestrial paleoenvironmental data, pollen records are the most spatially extensive and widely accessible (Whitmore et al., 2005). Pollen grains function well as environmental proxies as they are annually dispersed and, if retained in an anaerobic environment, such as lake or bog sediment, their structures are well preserved (Moore et al., 1991). Primarily transported by wind, if deposited in temperate latitudes in a site where sediments are accumulating, pollen grains become part of the environment's stratigraphic record and are archived annually in sediment layers (Bradley, 2015). These past pollen records can be used to reconstruct forest dynamics or climate, as vegetation distribution is substantially controlled by climate. Therefore, by using fossilized pollen to reconstruct a species' past distribution, one is also gaining knowledge of past biomes and climate (Prentice et al., 1996).

Pollen records have been used to reconstruct past forest histories spanning the entire Holocene, the Pleistocene and even earlier (Mott, 1977). In southern Scandinavia, regional pollen diagrams were used to study the arrival and spread of *Fagus sylvatica* L. (European beech) and *Picea abies* (L.) H. Karst. (Norway spruce) through the region over the last 4000 years (Bradshaw and Lindbladh, 2005). Such palaeoecological studies are able to observe slow forest ecosystem processes that are hard to capture through standard ecological methods but can be crucial to ecosystem function.

Palynology has also been used to understand human impacts on vegetation by detecting settlement and land use changes, such as forestry and agriculture, through the presence of crop and weed species associated with agricultural or pastoral environments (Moore et al., 1991). Some palynological studies have even been successful in detecting human influence on landscapes where archaeological evidence is limited or difficult to obtain (Munoz et al., 2010; Blarquez et al., 2018). For example, by using pollen records at Crawford Lake in southern Ontario, researchers were able to establish the effects of Iroquoian and then later European farming on forest composition (McAndrews and Boyko-Diakonow, 1989). They found that while Indigenous agriculture was less extensive than European farming, it also left a long-term impact on the forest succession with the development of a *Populus* (poplar), *Quercus* (oak) and *Pinus* (pine) seral community.

2.2 Holocene-scale pollen analysis in southern Québec

Over the past 50 years in southern Québec, much research has gone into producing pollen records that span the whole Holocene and that capture environmental variability in response to orbital forcing (Mott, 1977; Muller et al., 2003; Lavoie and Richard, 2000; Lavoie and Richard, 2017). Pierre Richard, in particular, has worked extensively on coring and reconstructing pollen profiles from numerous small lakes in southern Québec; his work provides excellent low-resolution postglacial climate reconstructions and vegetative histories for the region (e.g.

Richard, 1975; Richard, 1978; Lavoie and Richard, 2000; Muller and Richard, 2001; Muller et al., 2003; Houle et al., 2012; Lavoie and Richard, 2017).

Pollen assemblages over the course of the late Glacial Period to Holocene show that over the past 14,000 years Québec has experienced a variety of vegetative stages. In southern Québec, Muller and Richard (2001) studied fifteen pollen diagrams to compare post-glacial vegetation responses in the St. Lawrence lowlands. Their findings determined four sequential major plant formations over the course of the Holocene: tundra, boreal forest, mixed forest and deciduous forest (Figure 2.1). Herbaceous tundra followed by shrubby tundra was recorded between ~ 13,400 - 10,200 cal. BP (Pollen Zone 1) with the sites being dominated by *Salix* L. (willow), Cyperaceae Juss. (sedge), and *Alnus* Mill. (alder) taxa (Muller and Richard, 2001). Shrubby tundra taxa was succeeded by a period of boreal forest which began to develop between ~12,800 – 11,500 cal. BP (Pollen Zone 2) throughout the St. Lawrence lowlands. The open mixed boreal forest dominated by *Populus* and *Picea mariana* (Mill.) Britton, Sterns & Poggenburg (black spruce) pollen represented a stage of afforestation in the region. Muller and Richard (2001) found this period to be followed by series of successional mixed deciduous forests across the St. Lawrence lowlands (Pollen Zone 3a-d). Beginning around 9300 cal. BP the sites exhibited a transition to the *Acer saccharum* Marsh. (sugar maple) dominated deciduous forests that are present today in the region. Their study also found a correlating period of human deforestation amongst most of their sites starting between AD 1700 – 1750 (Pollen Zone 3e). The clearance of the land is attributed to the European settlement of the St. Lawrence lowlands and created major anthropogenic shifts in the forests as light requiring weedy taxa quickly invaded. Studies such as Muller and Richard (2001) are crucial in our understanding of long-term forest dynamics throughout the Holocene.

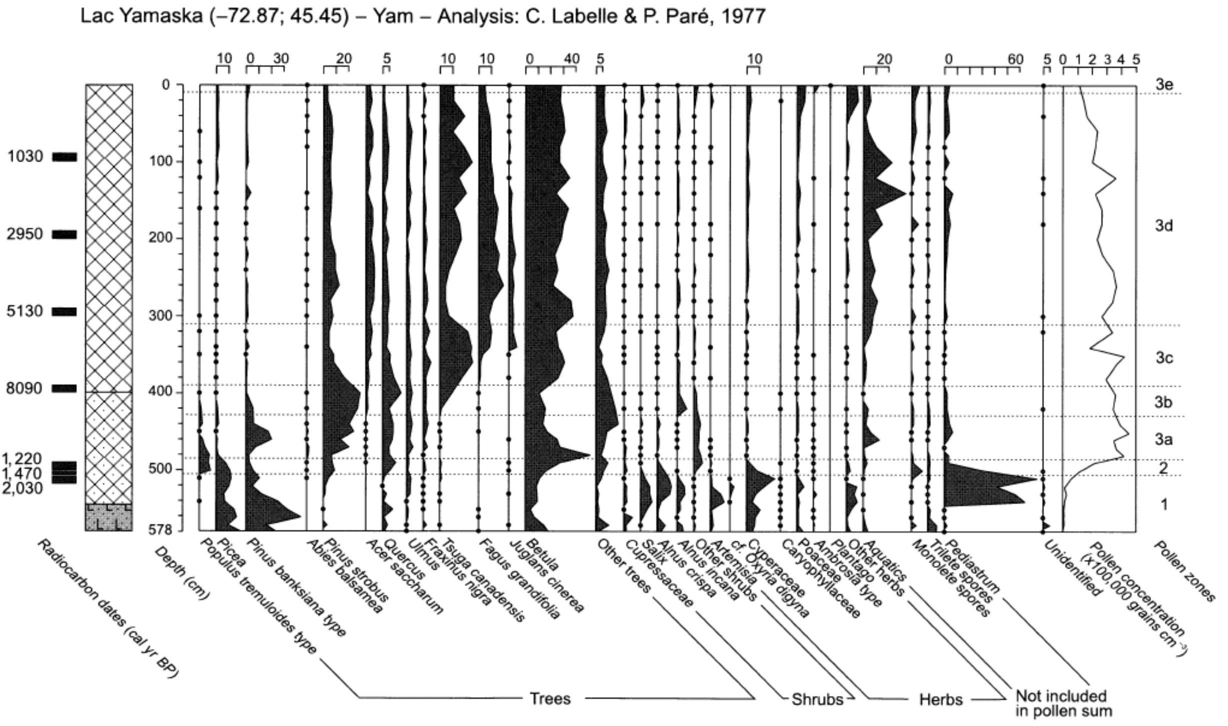

Figure 2.1. The pollen stratigraphy from Lac Yamaska taken from Muller and Richard (2001) is one of the fifteen cores analysed in their study and is representative of whole Holocene vegetation dynamics of the St. Lawrence lowlands.

2.3 Environmental variability over the last millennium and high-resolution pollen analysis in southern Québec

There has, however, been much less high-resolution pollen research in Québec, and vegetation-climate interactions over the past two millennia at decadal to century scales are not well understood (Paquette and Gajewski, 2013). Unlike whole Holocene analysis, high-resolution (sub-centennial) pollen analysis, particularly when located at a sensitive ecotone, has the ability to record short-period climate variations and disturbances that can significantly influence forest composition and production (Lafontaine-Boyer and Gajewski, 2014). In west-central Minnesota, continuously sampled, high-resolution pollen analysis (every 2 – 4 years) was used to detect sub-centennial droughts and the sharp transition in temperature between the Little Ice Age and the Medieval Climate Anomaly at the ecotone of the northern coniferous-southern deciduous forest (St. Jacques et al., 2008). This demonstrates the ability and high accuracy of high-resolution reconstructions to capture variability of temperature and effective moisture at sensitive ecotones. In Québec, the limited high-resolution work that has been done (Houle et al., 2012; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014) (only in southwestern and south-central Québec) has proven how useful high-resolution pollen analysis is for reconstructing decadal to centennial-scale environmental variability.

Over the past millennium, the northern Atlantic regions experienced a transition from the Medieval Climate Anomaly to the Little Ice Age, both preceding the large anthropogenic global warming trend that has been evident over the last century. The Medieval Climate Anomaly (MCA) was a period of warmer climate affecting Europe and the high latitude north Atlantic regions between AD ~ 800 – 1300 (Ruddiman, 2008). The MCA was followed by a period of cooling between AD ~ 1400 –1800, which has been named the Little Ice Age (LIA). These temperature changes are detectable through high-resolution pollen analysis of lacustrine sediments, and these studies have shown the impacts that this climate variability has had on and continues to have on forest composition in southern Québec and northern New England. A high-resolution pollen reconstruction from Lac Noir in the Gatineau Hills of south-central Québec found that the transition to the LIA greatly reduced pollen production for a number of tree species for about 50 years (Paquette and Gajewski, 2013). Taxa such as *Tsuga* Carrière (hemlock)*, Acer* L. (maple) and *Fagus* L. (beech) all experienced declines during the LIA and still have not recovered to pre-LIA levels. These finding are consistent with another study from Lac Brulé (located 20 km away from Lac Noir) which found the significant decrease of *Tsuga, Acer* and *Fagus* to be accompanied by an increase in conifer and shrub taxa, reflecting the onset of the LIA around AD 1375 (Lafontaine-Boyer and Gajewski, 2014). The increase in *Alnus* and high values of *Pinus strobus* L. (Eastern white pine) and *Picea* Mill. (spruce) around the same time as the decline in *Tsuga*, *Acer* and *Fagus* found at the two lakes suggests the cold dry conditions typical of the LIA. A study on Piseco Lake in the southern Adirondack mountains, New York, similarly also observed a decline in *Tsuga* after 1430 CE which they attribute to more generally dry conditions in the Little Ice Age (Grochocki et al., 2019)

How forests have responded to past climatic changes can be used as analogs for future forest composition responses to our current climate crisis. Paquette and Gajewski (2013) compared the rapidity of the change between the MCA and the LIA to the global warming experienced today. They call for more detailed (i.e., higher-resolution) analysis of this transition between the MCA and LIA to provide insight into rapid climate changes and how they affect conifer-hardwood forest ecosystems (Paquette and Gajewski, 2013). As the MCA exhibited temperatures akin to temperatures already reached by the anthropogenic global warming that we are presently experiencing, forest vegetation conditions during, as well as, while transitioning out of the Medieval Climate Anomaly, could be used as analogs for future vegetative responses to climate change (Mann, 2002). Studying the transition between two periods of climate anomalies, such as the MCA and the LIA, may allow us to predict future vegetative responses to climate change as we experience our current rapid anthropogenic global warming.

2.4 Paleoecological evidence of European settlement in southern Québec

Fossilized pollen records of non-arboreal pollen (NAP) in eastern North America have also been used to determine the more recent effect of European settlement on regional vegetation. Anthropogenic marker species, such as *Ambrosia artemisiifolia* L. (native ragweed), *Rumex* L. (dock), and *Plantago major* L. (introduced plantain), as well as other shade-intolerant pioneer species of weeds and grasses are used to detect the arrival and establishment of European-colonial settlement (Houle et al., 2012). The '*Ambrosia* rise', the sharp increase in NAP, is linked to land clearance for European-style agriculture and the construction of road networks (Lavoie et al., 2007; Lafontaine-Boyer and Gajewski, 2014). In southeastern Québec, the *Ambrosia* rise has been found to have begun between AD 1700 and AD 1860, corresponding with European settlement in the region (Muller and Richard, 2001; Houle et al., 2012; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014; Blarquez et al., 2018).

In the Hull-Gatineau region of southern Québec, Blarquez et al. (2018) found that while the European settlement of the region was characterized by the appearance of anthropogenic NAP marker species, sites with significant Indigenous influence over the last millennium were marked by the presence of many of the same anthropogenic marker species, as well as increased charcoal deposition from agricultural clearance. It is therefore important to recognize the impact that burning and land use for extensive agriculture by Indigenous nations may have had on the landscape as well prior to European settlement.

2.5 Need for high-resolution research in southeastern Québec

Parc national du Mont-Orford in southeastern Québec provides an opportune environment in which to conduct high-resolution, pollen-based environmental reconstruction and fill in the current research gap which exists for the area. Situated in the sugar maple-basswood domain, located approximately 50 km between the colder sugar maple - yellow birch domain, and the warmer sugar-maple-bitternut hickory domain of the maple-dominated hardwood forests subzone of southeastern Québec, Parc national du Mont-Orford contains a forest composition sensitive to temperature change (Figure 2.2) (Gauvin and Bouchard, 1983; Ressources Naturelles Québec, 2003). These forest domains are defined by different annual mean temperatures and growing season lengths. The sugar maple-yellow birch domain is defined by a cooler annual average temperature (2.5-4℃) and has a shorter growing season (170-180 days) compared to the sugar maple-basswood domain (with an average annual temperature of 4-5℃ and a growing season of 180-190 days per year). The more southerly sugar-maple-bitternut hickory domain has an average annual temperature of 5-7℃ and a growing season of 190-200 days per year. Hence, past climatic changes should be represented in changes in taxa dominating the pollen records from this sensitive region (Leboeuf, 2016).

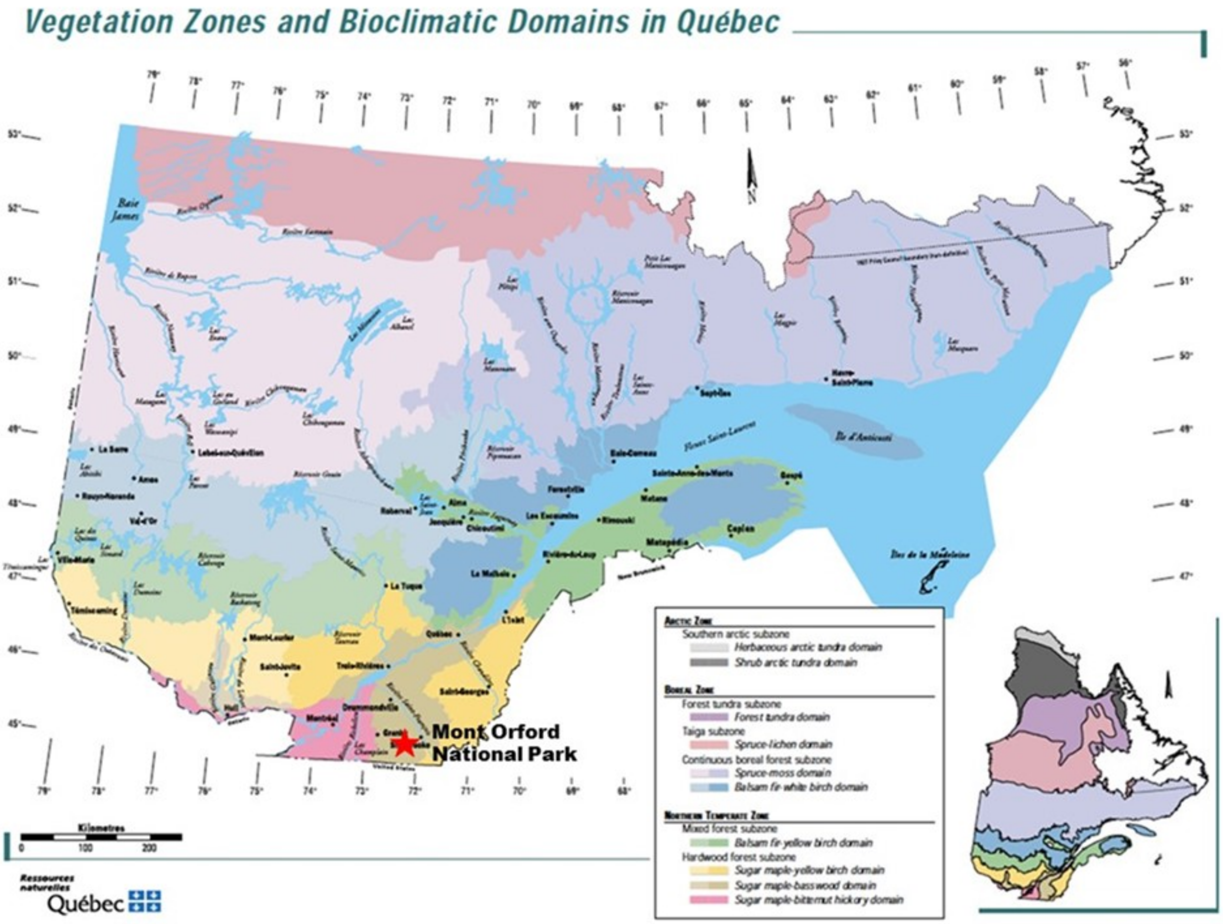

Figure 2.2. Vegetation Zones and Bioclimatic Domains in Québec. The study site located in Parc national du Mont-Orford is situated within the transition zone between the sugar maple-yellow birch, sugar maple-basswood and the sugar maple-bitternut hickory domains of the hardwood forest subzone. (Source: Ressources Naturelles Québec. 2003. Adapted by author).

Established in 1938, Parc national du Mont-Orford is surrounded by the fertile agricultural lands of the Eastern Townships (Kesteman, 1998). While the violent conflict between English and French settlers (and the Abenakis who allied themselves with France) is well documented, the exact sequence of the history of the Townships' pre-European settlement is unclear. Very little archeological research has been conducted to explore the relationship of the Abenakis and of other groups of Iroquois and Algonquin peoples with this territory but written and oral histories show that between the 16th and 18th century, the Abenakis, among other First Nations including the Algonquins and Iroquois, frequented the Eastern Townships on a seasonal basis for the purpose of fishing, trapping and hunting (Gélinas, 2018; Musée des Abénakis, 2019). North of the Eastern Townships, the St. Lawrence Iroquoians are known to have been cultivating maize in the St. Lawrence valley between AD 1200 – 1600 but their extent into the Eastern Townships is unknown (Tremblay, 2006). In addition to reconstructing forest responses to temperature change in the region over the past 2300 years, high-resolution pollen analysis has the potential to detect ecological evidence of pre-European land uses.

2.6 Conclusion

Paleoenvironmental research that reconstructs forest ecosystem responses to past climate variability can help us better understand multi-centennial-scale forest dynamics and thereby hopefully mitigate the impacts of current climate change on southeastern Québec forests. While lower-resolution pollen analysis in Québec has provided important records of whole Holocene climate variability, it unfortunately does not have the temporal resolution to capture decadal to centennial-scale change. Our current rate of climate change necessitates a more thorough understanding of forest vegetation responses to rapid temperature change in order to prepare conservation strategies that will equip resource-dependent industries for an uncertain future. Building on a body of work created by the community of paleoenvironmental scientists working with pollen records in eastern North America, this project aims to fill current research gaps by conducting high-resolution pollen analysis of the environmental variability over the last two millennia in the mixed hardwood-maple forests of southeastern Québec.

3. Research Questions

As few studies in Québec have been able to document a clear Medieval Climate Anomaly (AD 800-1300) and Little Ice Age (AD 1400-1800) (Houle et al., 2012; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014), this research project aims to further identify these periods of warming and cooling by exploring the main research question: How sensitive have the sugar maple-hardwood forests of southeastern Québec been to environmental variations over the last two millennia?

As vegetation changes during the Medieval Climate Anomaly and the transition to the Little Ice Age can be used as an analogue for future forest changes caused by warming during the 21st century, two further questions that this study will address are:

1) How did forest composition change during the Medieval Climate Anomaly and the Little Ice Age in southeastern Québec?

   and

2) have recent forest composition changes over the past 120 years been within the region's normal range of environmental variability, or have they most likely been caused by human activities?

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4. Manuscript

Reconstructed high-resolution forest dynamics, climate and human impacts for the past 2300 years from the *Parc national du Mont-Orford,* southeastern Québec, Canada

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Abstract

We used a high-resolution lacustrine pollen record from Étang Fer-de-Lance (45°21'21.9"N, 72°13'35.3"W), southern Québec, Canada, together with microcharcoal, to infer forest dynamics, climate and human impacts over the past 2300 years. The lake is located in the sugar maple-basswood domain of the Northern Temperate Forest. We found that *Fagus grandifolia* (American beech) and *Tsuga canadensis* (eastern hemlock) significantly declined over the past 700 years. Over the last millennium, *Picea glauca* (white spruce), *Picea mariana/rubens* (black and red spruce), and *Pinus strobus* (eastern white pine) significantly increased. Using the modern analog technique (MAT), we found a warm and dry first millennium AD, a somewhat less warm and less dry Medieval Climate Anomaly, and a cold and wet Little Ice Age. The signal for human modification of the landscape first appeared at ~AD 1550-1650 as increases in *Ambrosia* (ragweed) and Poaceae (grasses) from Indigenous agriculture. The signal of European settler landscape modification appeared at ~AD 1770 as the beginning of a steep, "classic" *Ambrosia* rise. It intensified over the subsequent 250 years as further increases in non-arboreal pollen taxa and early successional *Acer* (maple) species. Microcharcoal analysis showed that fire is a natural part of the sugar maple-basswood domain with a mean fire return interval of 515 years.

Key words: Anthropocene; charcoal; Common Era; high-resolution pollen analysis; Little Ice Age; Medieval Climate Anomaly; North America; paleoclimatology; pre-Contact Indigenous agriculture; vegetation dynamics

4.1 Introduction

Post-glacial vegetation records spanning the late Glacial Period and Holocene have been well documented throughout eastern Canada (Richard, 1975; Mott, 1977; Richard, 1978; Lavoie and Richard, 2000; Muller and Richard, 2001; Muller et al., 2003; Houle et al., 2012; Lavoie and Richard, 2017). While these studies have led us to understand the migration of trees to lands newly exposed by the retreating Laurentide Ice Sheet, the resolution of many of these studies is insufficient to further understand forest dynamics at a shorter and more recent timescale (Lafontaine-Boyer and Gajewski, 2014). In order to better understand forest dynamics over decadal to centennial periods, finer temporal-and spatial-scaled paleoenvironmental studies are needed (e.g., St-Jacques et al., 2008a; 2008b). The limited high-resolution pollen research that exists in southern Québec has proven effective in capturing vegetation dynamics and responses to short periods of climate variation, particularly during the late Holocene with climate events such as the Little Ice Age (LIA) and the Medieval Climate Anomaly (MCA) (Houle et al., 2012; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014), although studies of this nature are relatively sparse.

Pollen-climate transfer functions applied to sedimentary pollen records have allowed climate reconstructions over the entire Holocene (Kaufman et al., 2020). At a finer scale, high-resolution (multi-decadal) pollen analysis can also be used to reconstruct recent climate, particularly when done at sensitive ecotones (Shuman et al., 2018). For example, St-Jacques et al. (2008a; 2008b; 2015) used high-resolution pollen analysis (every 4 years) to detect sub-centennial droughts and the sharp transition between the LIA and the MCA at the ecotone of the northern coniferous-southern deciduous forest in Minnesota. In southwestern Québec, Paquette and Gajewski (2013) and Lafontaine-Boyer and Gajewski (2014) have reconstructed multi-decadal climate variability for the past two millennia inferred from high-resolution pollen analysis. More such studies from southern Québec will only be informative in this region where there is a current debate as to whether the LIA and MCA occurred here at all (Hausmann et al., 2011; Van Bellen et al., 2018).

Although forest fire is commonly thought to be a feature of western North American or boreal landscapes, fire is also a natural part of the northeastern deciduous forest (Clark and Royall, 1996). Some limited research using microcharcoal from lake sediments to infer forest fires has been done in southwestern Québec and northern New England, but none in densely-populated southeastern Québec (e.g., Clark and Royall, 1996; Clifford and Booth, 2013; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014; Stager et al., 2016; Blarquez et al., 2018). Given the many forest types of southern Québec (*Ressources Naturelles Québec*, 2003), there is a need for paleo-fire studies from each forest type to better understand the natural fire-vegetation relationship, a relationship that can only be studied using paleo-methods because of modern fire suppression. A benefit of such further studies would be that in densely-populated southern Québec, where wildfire has been relatively infrequent in historical times, fire-risk assessments have incorporated little-to-no pre-historical data and little is known about long-term fire-climate relationships.

The purpose of this study is to investigate forest vegetation dynamics, climate change and forest fire frequencies over the last 2300 years using high-resolution pollen and microcharcoal records from a small lake, *Étang Fer-de-Lance* situated in southeastern Québec, Canada. From the high-resolution pollen record, we inferred temperature and moisture changes over the past two millennia. This study produced paleo-environmental records in this region previously unstudied at high resolution, and helps determine how sensitive the local sugar-maple hardwood forests have been to climate change over the last two millennia. In addition, we investigated the relationship between vegetation and fire from the eastern sugar maple-basswood domain (Ressources Naturelles Québec, 2003), a forest type from which no paleo-fire records previously existed, as well as the effects of historical land-use changes in the region on forest vegetation.

4.2 Study area and methods

4.2.1 *Study area*

Étang Fer-de-Lance (45°21'21.9"N, 72°13'35.3"W) is a small 1 km long and 250 m wide lake which features a minerotrophic peatland situated in the *Parc national du Mont-Orford*, 20 km west of Sherbrooke in the Eastern Townships of Québec, Canada (Figure 4.1). The park is part of the southwestern limit of the Appalachian Mountain range in Québec and is characterized by broad valleys surrounded by the peaks of *Mont-Orford* (maximum altitude of 853 m), *Pic de l'Ours* (740 m) and *Mont Chauve* (600 m) (Gauvin and Bouchard, 1983; SEPAQ, 2019). The geology of Mont-Orford is marked by the presence of igneous ophiolite left behind during the initial phases of the development of the Appalachian Mountains when oceanic crust was preserved within the forming mountain range (Haldar and Tišljar, 2014; SEPAQ, 2019). Today, the Parc national du Mont-Orford covers a total area of 59.5 km^2.

The Mont-Orford region has an average annual temperature of 5.6°C and an average annual precipitation of 1142.3 mm (Government of Canada, 2019). Situated within the eastern sugar maple-basswood domain of the hardwood forest subzone of Northern Temperate Forest between the colder eastern sugar maple-yellow birch domain (~50 km northeast) and the warmer sugar maple-bitternut hickory domain (~50 km southwest), the park is a location that should be sensitive to centennial-scale temperature change, to which the composition of its forests should respond to readily (Gauvin and Bouchard, 1983; Ressources Naturelles Québec, 2003; SEPAQ, 2019).

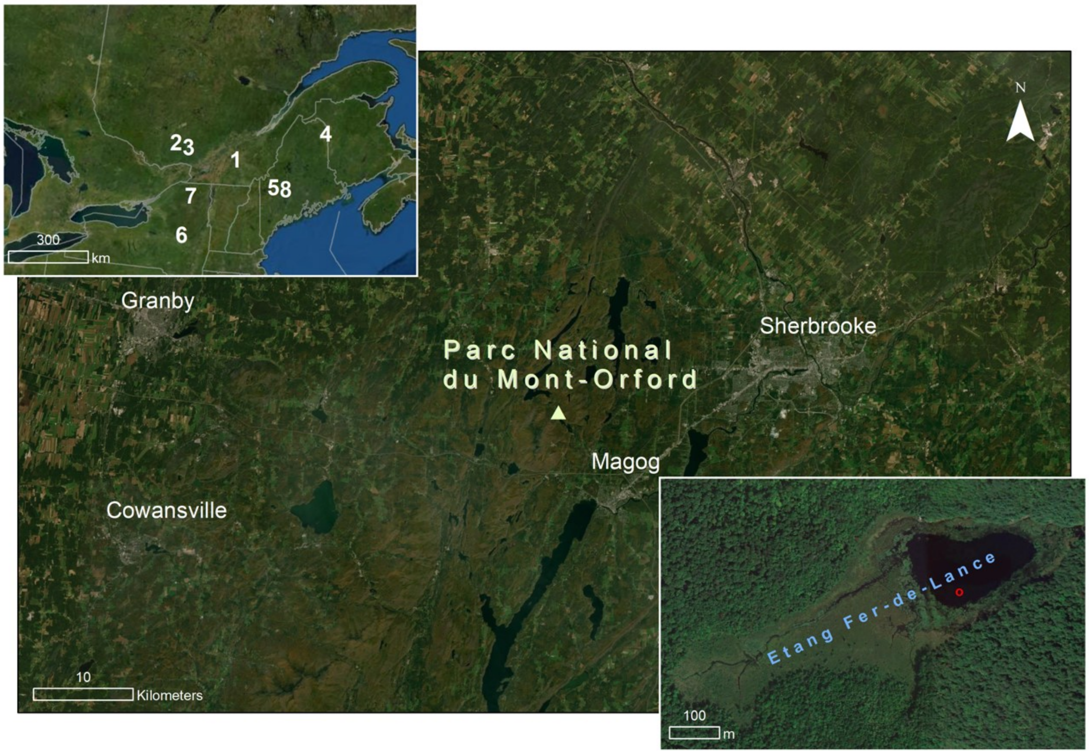

Figure 4.1. Location of Étang Fer-de-Lance (yellow triangle) in the Parc national du Mont-Orford and in southeastern Québec (1) in upper-left inset). Also in upper-left inset are shown: 2) Lac Noir, 3) Lac Brulé, 4) Conroy Lake, 5) Basin Pond, 6) Clear Pond, 7) Wolf Lake and 8) Sidney Bog. Red circle on the lower-right inset map shows the location where the core was extracted from Étang Fer-de-Lance. Floating macrophytes in shallow water make lake appear smaller than it is.

Étang Fer-de-Lance has a maximum depth of 3.9 m and the lake is at an elevation of 288 m and is situated between two streams, *Ruisseau des Hêtres* and *Ruisseau des Hourdes*, in a valley bordered by the Pic de l'Ours (740 m) and Mont Chauve (599 m). The small lake is only accessible by foot or all-terrain vehicle. Hiking trails on the north side of the lake lead to a raised platform that overlooks the lake and the northeast end of the lake features a beaver dam which has created an 83 cm drop in the water level from the lake to where it connects with Ruisseau des Hourdes.

Currently, the north shore of Étang Fer-de-Lance is populated by a stand of *Pinus strobus* L. (white pine) and some solitary *Picea glauca* (Moench) Voss (white spruce) trees. *Pinus rigida* Mill. (pitch pine) grows along the water on the north shore, and there is a *Tsuga canadensis* (L.) Carrière (eastern hemlock) grove approximately 10 m inland up the slope on the north shore. The south shore is dominated by *Thuja occidentalis* L. (eastern white cedar) and *T. canadensis*, while on the slightly higher plateau 20 m inland, *Acer rubrum* L. (red maple), *Acer saccharum* Marsh. (sugar maple) and *Betula alleghaniensis* Britt. (yellow birch) trees dominate. Though little is known about the occupation of the area before European settlement, prior to the creation of the park in 1938, the area was predominantly used for forestry and agriculture (Gauvin and Bouchard, 1983; SEPAQ, 2019).

4.2.2 *Field methods*

Three sediment cores were extracted from the deepest point near the center of Étang Fer-de-Lance (45°21’22.1” N 072°13’ 35.1” W) in June 2018 using a push core (transparent tube with piston) and a Livingstone piston corer (Figure 4.2). Prior to each core being driven, the depth of the lake was measured using a Laylinn Speedtech SM-5 Depthmate Water Portable Sounder and Depth Meter and GPS coordinates were taken using a Garmin eTrex 10 GPS. The surface sediment core FDL2 was extracted with the push corer and extruded on-site into Ziploc bags with a sampling resolution of 1 cm. The cores extracted with the Livingstone piston corer (FDL-P2 and FDL-P3) were immediately transferred into hard plastic tubing lined with plastic wrap and aluminum foil and left intact for analysis. All cores were transported unfrozen to the *Climate and Environmental Change Research Laboratory* at Bishop’s University, and then permanently stored in a refrigerator. High-resolution pollen and charcoal analyses were conducted on all three cores. At the time of the coring, a survey of the vegetation surrounding Étang Fer-de-Lance was conducted for reference purposes to assist the modern pollen counts.

4.2.3 *Laboratory methods: chronology*

Eleven ^{14}C and twelve ^{210}Pb dates were obtained from plant macrofossils and surface sediment samples, respectively, throughout the core (Figure 4.2). Radiocarbon analysis was performed on the plant macrofossils by the A.E. Lalonde AMS Laboratory at the University of Ottawa, and the ^{14}C dates were calibrated using OxCal v4.3 and the IntCal13 calibration curve (Bronk Ramsey, 2009; Reimer et al., 2013). The ^{210}Pb dates were obtained from the first 40 cm of the surface core FDL2 and processed at Geotop at the *Université du Québec à Montréal*. The ^{210}Pb activity is measured as disintegrations per minute per gram (dm/g). The ^{210}Pb method for dating sediment samples has been demonstrated on both varved and unvarved sediments (Sorgente et al., 1999). In order to account for possible compaction of the core due to the weight of sequential yearly deposits of sediment, the constant rate of supply (CRS) model was used to interpret the ^{210}Pb depth profile (Ghaleb, 2009). The ^{14}C and ^{210}Pb dates were used to produce an age-depth model which provides age estimates for all other depths of the core. The age-depth model was made using the R package Bacon (version 2.4.0), using Bayesian methods to reconstruct accumulation rates of sediments and ages were calculated to a 1 cm resolution throughout the depth of the core (Blaauw and Christen, 2011).

4.2.4 *Laboratory methods: pollen analysis*

Samples of 1.25 cm^3 of sediment were taken for pollen analysis at 2-4 cm intervals along the core. Each sample was spiked with one *Lycopodium* tablet (batch 3862 from the University of Lund) in order to use the exotic marker grain method (Benninghoff, 1962; Bonny, 1972) to permit the calculation of the pollen concentration throughout the core (Moore et al., 1991).

Samples were treated in order to remove as much non-pollen components of the sediment as possible while preserving the pollen grains (Faegri and Iverson, 1989; LacCore, 2016). The procedure included HCl to remove carbonates, KOH and acetolysis to remove non-pollen organic matter, and HF to remove silicates. Pollen samples were stained using safranin and mounted in silicone oil on microscope slides for pollen analysis (Faegri and Iverson, 1989).

High taxonomic resolution pollen counts were conducted with a minimum sum of 500 pollen grains from each sample. Pollen slides were counted at 400x or 800x using a Leica DM 2500 LED microscope at the *Climatology, Hydrology and Paleo-Environmental Laboratory* at Concordia University. Regional vegetation and pollen guides (Richard, 1970; McAndrews et al., 1973; Bassett et al. 1978; Gauvin and Bouchard, 1983; Farrar, 1995; Lindbladh et al. 2002; Leboeuf, 2016) were used as references for pollen taxonomy. *Picea* (spruce) was split into *P. glauca* and *P. rubens/mariana* (red/black spruce) following Lindbladh et al. (2002). *Pinus* (pine) pollen grains were identified as subgenus *Pinus* Haploxylon or subgenus *Pinus* Diploxylon to distinguish between *P. strobus* (Haploxylon) and other Diploxylon species of *Pinus* possibly present, i.e. *P. rigida* Mill., *Pinus resinosa* Ait. (red pine), and *Pinus banksiana* Lamb. (jack pine) (Richard, 1970; McAndrews et al., 1973). As modern species lists show that *B. alleghaniensis*, *Betula papyrifera* (Marsh.) (paper birch) and *Betula populifolia* (Marsh.) (grey birch) are all present in the Mont-Orford region, and they have pollen grains of overlapping sizes (Richard, 1970; Gauvin and Bouchard, 1983), *Betula* pollen grains were identified to genus level and labelled as "*Betula* spp".

Constrained Clustering with Incremental Sum of Squares (CONISS) was used to separate the pollen stratigraphy into distinct zones (Juggins, 2019). Principal Component Analysis (PCA) ordination using the correlation matrix was used to confirm the CONISS pollen zones and to calculate the species scores and the sample scores of the main principal components to better understand the temporal variation of the pollen record. These analyses were done on the taxa with at least one occurrence greater than or equal to 5%.

Visually detected changes in pollen percentages of ecologically key taxa between pollen zones were done using Welch two-sample two-sided *t*-tests assuming unequal variances after verification that the data were normally distributed and no significant autocorrelation was present. If significant lag-1 autocorrelation was present but the data was normally distributed, adjusted *t*-tests were used with the effective sample sizes adjusted for autocorrelation (Santer et al., 2000). Otherwise, lower-power Wilcoxon rank sum tests were used.

We reconstructed past climate, i.e., summer (JJA) average temperature and annual precipitation, using the modern analog technique (MAT). For the pollen-climate calibration set, we used version 1.72 of Whitmore et al. (2005), together with the squared-chord distance metric. For the calculations, we used C2 software (Juggins, 2007). A total pollen sum of 52 arboreal and terrestrial herbaceous pollen taxa from the Étang Fer-de-Lance core was used for the analog computations. Although we used the finest resolution possible given the taxonomic decisions of the earlier researchers whose work forms the pollen-climate training set to conserve as much climate information as possible, we had to merge the *Picea* taxa. Modern pollen data spanning between 64° and 80° W longitude and 41° and 49° N latitude were extracted as potential candidates for modern analogs, resulting in 620 sites in the pollen-climate calibration set. The average of the first three analogs was used to compute the reconstructed climate variables. The fifth percentile of the distribution of pair-wise dissimilarities observed from the training-set samples was used as the definition of acceptable close analogs (Simpson, 2012). We then compared our reconstructions to other high-resolution sedimentary reconstructions from within a

350 km radius to examine regional past patterns in temperature and moisture. We define high-sampling resolution analysis as at least four pollen or other proxy samples per century. We used MAT in order to be able to directly compare our results to other high-resolution climate reconstructions from the area (i.e., Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014).

4.2.5 *Laboratory methods: charcoal*

Fire occurrence intervals were based on analysis of sedimentary microcharcoal. Contiguous samples of 1 cm^3 were analyzed for their charcoal content along the entire core. Samples were soaked ~12 hours in sodium hexametaphosphate $(NaPO_3)_6$ and then ~12 hours in aqueous 6% sodium hypochlorite (NaClO) to deflocculate and bleach the sediment. Charcoal particles were sieved with a 150 mm Nitex© mesh, then counted and measured using a Leica M80 stereoscope paired with an image analysis system (WinSeedle©, Regent Instruments, Québec, Québec). We used charcoal area because charcoal abundance could be subject to fragmentation during preparation, causing errors. Fire occurrence reconstruction was done using CharAnalysis 0.9 software in Matlab© (Higuera, 2009; Higuera et al., 2009). CharAnalysis was used to calculate an evenly-spaced interpolated charcoal accumulation rate record (CHAR), and to remove the low-frequency charcoal background signal (BCHAR) (which corresponds to long-term variation in charcoal production, secondary charcoal transport, the sedimentation process, mixing and sampling). We determined BCHAR with a 400-year window width and a robust LOWESS smoother, and subtracted BCHAR from CHAR to get residual CHAR values. The residual CHAR peaks then passing a locally-defined 95% threshold based on a Gaussian mixed model were considered representative of one or more local fires (Higuera et al., 2009).

4.3 Results

4.3.1 *Sediment cores and age-depth model construction*

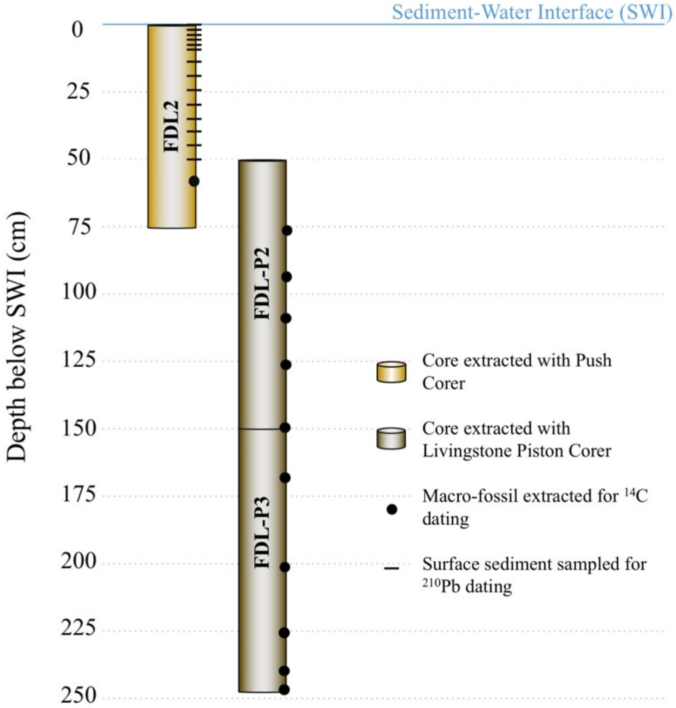

Figure 4.2. Diagram depicting the sediment cores and their depths extracted from Étang Fer-de-Lance, Québec, and the location of material extracted for radiocarbon and ^{210}Pb dates used to establish the core chronology.

The three sediment cores extracted from Étang Fer-de-Lance span 0-247 cm below the SWI (Figure 4.2). The first push core, FDL2, is 76 cm long and spans 0-76 cm below the SWI. The deeper second piston core, FDL_P2, is 101 cm long and spans 50-151 cm below the SWI, while the third and deepest piston core, FDL_P3, has a length of 96 cm and spans 151-247 cm. There is a 26 cm overlap between FDL2 and FDL_P2. Figure 4.2 depicts the alignment and depths of the three sediment cores extracted from Étang Fer-de-Lance and the location of the terrestrial plant macro-fossils and sediment samples used for radiocarbon and ^{210}Pb dating to construct the core chronology. The alignment of FDL2 and FDL_P2 was confirmed by pollen counts from both cores within the overlap; however, the final stratigraphies and statistical analysis only use pollen counts from FDL2 in the section of overlap. The aligned three sediment cores will henceforth be referred to as "the core" in this manuscript. The cores are a uniform dark black in color and have an organic gyttja consistency throughout.

Of the 14 sediment samples submitted for ^{210}Pb dating, 12 yielded measurable dates (Supplemental Table 1). The ^{210}Pb samples dated from AD 1880 – 2018, establishing the chronology of the first 40 cm of the core and accounting for the first 139 years of sediment accumulation. The ^{210}Pb activity results reflect the ideal case where ^{210}Pb activity declines exponentially with the increase in depth, due to radioactive decay as it decreases from 35.404 ± 2.297 dpm/g at 2.5 cm to 1.627 ± 0.138 dpm/g at 50 cm below the SWI (Supplemental Figure 1), with the exception of the first sample at 0.5 cm below the SWI (Sorgente et al., 1999; Ghaleb, 2009). The outlier ^{210}Pb activity of 29.224 ± 1.909 dpm/g at the initial sample at 0.5 cm is likely due to mixing with water and dilution of the surface sediment sample.

Table 4.1. The 11 AMS-dated radiocarbon samples from terrestrial plant fragments from Étang Fer-de-Lance, Québec. Dates given in years AD and BC.

Depth below SWI[a] (cm)	**Sample type**	**Lab ID[b]**	**Raw age (^{14}C yr AD/BC)**	**Fraction modern carbon (F^{14}C)**	**Calibrated age range (yr AD/BC)**
60-61	seed capsule	UOC-7571	AD 1677 ± 37	0.9666 ± 0.0045	AD 1488 – 1603 (50.4%) AD 1610 – 1669 (37.8%) AD 1780 – 1799 (6.3%) AD 1944... (1.0%)[c]
76-77	wood	UOC-7573	AD 1421 ± 38	0.9363 ± 0.0044	AD 1313 – 1357 (26.2%) AD 1387 – 1444 (69.2%)
95-96	*Betula* seed	UOC-7574	AD 839 ± 70	0.8709 ± 0.0076	AD 713 – 744 (2.1%) AD 765 – 1036 (93.3%)
110-111	wood	UOC-7575	AD 115 ± 85	0.7957 ± 0.0085	AD 2 – 389 (95.4%)
126-127	wood	UOC-11314	AD 820 ± 19	0.8687 ± 0.0021	AD 878 – 980 (95.4%)
150-151	conifer needle	UOC-7576	AD 34 ± 84	0.7878 ± 0.0082	145 – 143 BC (0.1%) 109 BC – AD 260 (92.3%) AD 279 – 325 (3.0%)
168-169	wood	UOC-7577	136 BC ± 61	0.7712 ± 0.0058	352 – 291 BC (7.5%) 229 BC – AD 52 (87.9%)
201-202	*Betula* seed	UOC-7578	AD 177 ± 50	0.8019 ± 0.0049	AD 131 – 381 (95.4%)
226-227	*Betula* seed	UOC-7579	553 BC ± 81	0.7322 ± 0.0074	795 – 414 BC (95.4%)
240-241	*Betula* seed	UOC-7208	265 BC ± 40	0.7589 ± 0.0038	385 – 190 BC (95.4%)
246-247	conifer needle	UOC-7207	272 BC ± 42	0.7582 ± 0.0039	388 – 195 BC (95.4%)

[a] SWI (Sediment Water Interface).
[b] Radiocarbon analysis done by the A. E. Lalonde AMS Laboratory at the University of Ottawa, and calibration was done using the OxCal v4.3 and the IntCal13 calibration curve.
[c] Seuss Effect

The uncalibrated ages of all 11 samples submitted for ^{14}C dating were included in the age depth model and calibrated using the IntCal13 calibration curve for northern hemisphere terrestrial samples (Table 1 and Figures 2 and 3; Blaauw and Christen, 2011). The 12 ^{210}Pb dates were also included in the age depth model of the core (Figure 4.3). The age-depth model of the core spans ~365 BC – ~AD 2018. Plotted in grey are the mean 95% confidence intervals of this model which have a mean of 290 years, ranging from a minimum of 4 years (at 1.5-2 cm) to a maximum of 469 years (at 170 cm). All but one of the 11 ^{14}C dates overlap with the Bayesian age-depth model's 95% confidence range.

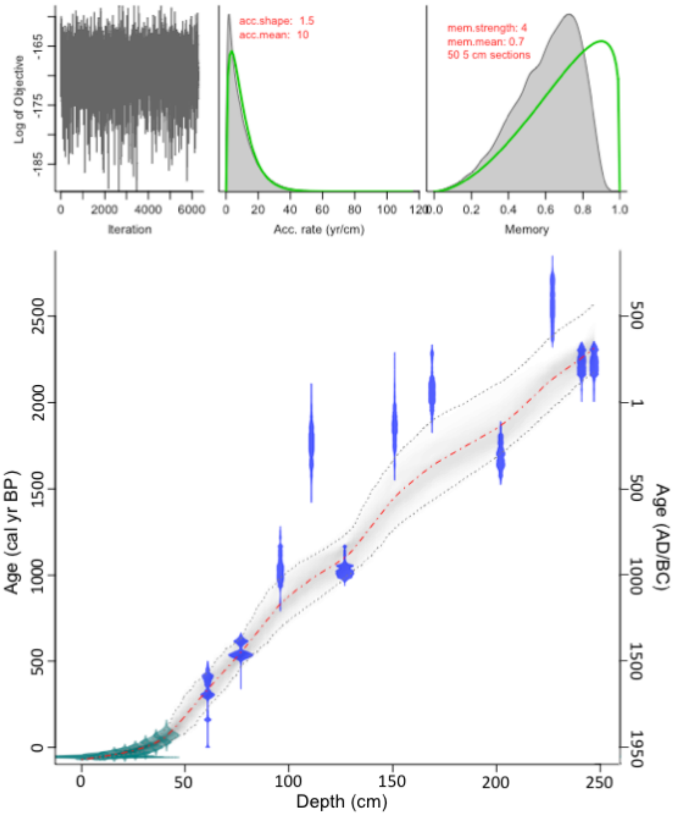

Figure 4.3. Age-depth model for the Étang Fer-de-Lance core using the R package Bacon. The age-depth model includes ^{210}Pb (green) and ^{14}C (blue) dates. The outer grey dotted lines represent the model's 95% confidence interval and the central red dotted line is the best fit model.

4.3.2 *Pollen results*

In total, 102 samples were counted from the core, yielding an average sample interval of 23.5 years. Pollen assemblages at Étang Fer-de-Lance show that its forest has been dominated over the last 2300 years by a mix of both coniferous and deciduous arboreal taxa, with dominants *Betula* spp., *Tsuga canadensis, Fagus grandifolia* Ehrh. (American beech), *Picea glauca*, *Picea mariana* (Mill.) Britton, Sterns & Poggenburg (black spruce) and/or *Picea rubens* Sarg. (red spruce) (Figure 4.4). A full pollen percentage diagram is presented in Supplemental Figure 2. Constrained Clustering with Incremental Sum of Squares (CONISS) and principal component analysis (PCA) were used to divide the pollen percentage diagram of the taxa with at least one occurrence greater than or equal to 5% into three pollen zones, with the first zone split into two subzones (Figures 4.4 and 4.5). CONISS and PCA on the full pollen assemblage of all 52 taxa gave identical results.

Between ~365 BC – ~AD 1300 (Pollen Zone 1, 85.5 – 247.5 cm), concurrent with the first millennium AD and the Medieval Climate Anomaly (MCA), *Betula* spp. and *T. canadensis* maintained high percentages throughout, apart from a short decline in *Betula* percentages between ~AD 70 – 130 (Figure 4.4). *Fagus grandifolia* has a significantly higher average percentage in Pollen Zone 1 (11.0%) than compared to the subsequent 700 years (6.9%) (Table 4.2). The percentage of the *Acer* spp. (*Acer saccharum*, *Acer rubrum* L. (red maple), *Acer pensylvanicum* L. (striped maple), *Acer spicatum* Lam. (mountain maple), *Acer saccharinum* L. (silver maple) and *Acer negundo* L. (Manitoba maple)) remains low throughout Pollen Zone 1. While *P. mariana/rubens* shows no change throughout Zone 1, *P. glauca* increased over the course of the first millennium AD, rising from 0.2% to 10.2%. *Pinus* Haploxylon and *Pinus* Diploxylon are both present with low percentages throughout Pollen Zone 1, but beginning in ~AD 897, *Pinus* Haploxylon began an increase which continued into the second millennium. *Alnus* spp. (*Alnus crispa* (Cryander ex Ait.) Turr. ex Ait. and *Alnus rugosa* (Du Roi) R.T. Clausen), Poaceae (grasses) and Cyperaceae (sedges) have low percentages and show no long-term trend, while *Ambrosia*-type pollen is barely present throughout Pollen Zone 1.

Table 4.2. Comparisons of pollen percentages between pollen zones of Étang Fer-de-Lance. Regular *t*-tests were used if the normality assumption was met and no autocorrelation present. If autocorrelation was present but the data was normal, a *t*-test adjusted for autocorrelation was used. Otherwise a Wilcoxon rank sum test was used. Non-significance denoted by n.s. Not applicable denoted by n.a.

Taxon	**Trend**	***test statistic***	***p-value***	***df***
Comparisons between Pollen Zone 1 and combined Pollen Zones 2 and 3				
F. grandifolia	↓	8.14	1.5×10^{-12}	95.0
Comparisons between Pollen Zone 1 and Pollen Zone 2				
Betula spp.	↓	1.86	0.08	21.3
T. canadensis	↓	1.92	0.07	27.4
F. grandifolia	↓	3.26	0.004	19.3
P. glauca[1]	↑	89.5	3.9×10^{-6}	n.a.
P. mariana/rubens	↑	-3.27	0.004	16.5
Pinus Haploxylon	↑	-3.97	0.0008	19.2
Pinus Diploxylon	n.s.	-1.30	0.21	18.7
total pollen influx[1]	↓	594.5	0.006	n.a.
Comparisons between Pollen Zone 2 and Pollen Zone 3				
T. canadensis[2]	↓	4.85	0.0003	13.0
F. grandifolia	↓	2.30	0.03	21.2

[1] Wilcoxon rank sum test using W-statistic
[2] *t*-test adjusted for autocorrelation

Both CONISS and PCA divide Pollen Zone 1 into subzones 1A and 1B at ~AD 129. The visual demarcation between these two subzones is subtle but *F. grandifolia* is higher in subzone 1A and declines in subzone 1B, while *P. glauca* is lower in subzone 1A and higher in subzone 1B. As well, a sharp decline in *Betula* occurs at and prior to ~AD 129.

Total pollen influx is relatively high throughout Pollen Zone 1 with two major peaks at ~AD 129 and ~AD 266 (Figure 4.4). There is however a dip in total pollen influx between ~AD 400 and ~AD 700 (Supplemental Figure 3).

Between ~AD 1300 - 1600 (Pollen Zone 2; 62.5 - 82.5 cm), concurrent with the early Little Ice Age (LIA), the average *Betula* species percentage (33.2%) significantly decreases compared to Pollen Zone 1 (37.4%) (Figure 4.4 and Table 4.2). Mean percentages of *T. canadensis* also significantly decline from Pollen Zone 1 (23.9%) in comparison to Pollen Zone 2 (21.1%). Importantly, mean *F. grandifolia* percentages significantly decline gradually throughout Pollen Zone 2 (8.2%) relative to its mean values in Pollen Zone 1 (11.0%). The *Acer* species' percentages remain consistent with their low pollen percentages of the preceding 1600 years. *Picea glauca* (8.9%) increases significantly between ~AD 1300 – 1600, relative to its prior mean percentage (3.0%), as does *P. mariana/rubens* which increases from an average percentage of 4.6% in Pollen Zone 1 to 7.1% in Pollen Zone 2. *Pinus* Haploxylon significantly increases gradually throughout Pollen Zone 2 with a mean of 3.3%, relative to its previous mean percentage of 1.5%. On the other hand, the percentage of *Pinus* Diploxylon does not increase significantly between Pollen Zone 1 (1.4%) and Pollen Zone 2 (1.9%). *Alnus* spp., Poaceae and Cyperaceae continue to have low percentages and show no long-term changes throughout Pollen Zone 2, and *Ambrosia*-type percentages remain negligible, but sporadically present. The total pollen influx is significantly lower in Pollen Zone 2 (7.9 x 10^4 grains/cm^2/year) relative to Pollen Zone 1 (17.7 x 10^4 grains/cm^2/year).

Between ~AD 1600 – 2018 (Pollen Zone 3; 0 – 60.5 cm), concurrent with the late LIA and European arrival and settlement, there is a striking increase in non-arboreal pollen (NAP) as *Ambrosia*-type pollen, Poaceae and Cyperaceae begin to increase at the beginning of Pollen Zone 3 (Figure 4.4). The *Ambrosia* rise in this pollen zone is characterized by two distinct periods of increase: an early *Ambrosia* rise beginning at ~AD 1647 (58.5 cm) and lasting until ~AD 1759 (50.5 cm) is comprised of relatively stable percentages ranging from 0.5 – 0.8%. A subsequent more “classic” *Ambrosia* rise begins at ~AD 1773 (49.5 cm) and increases from 1.4% to 6.3% by ~AD 1940, after which it declines slightly while still maintaining relatively high percentages. *Betula* is relatively constant throughout this last zone. From a mean of 8.2% in Pollen Zone 2, *F. grandifolia* percentages significantly decline further in Pollen Zone 3 (a mean of 6.2%) (Table 4.2). *Acer* percentages increase throughout Pollen Zone 3, particularly over the last 100 years between ~AD 1900 – 2018. This increase is primarily due to an increase in *Acer rubrum* (Supplemental Figure 2). *Quercus* percentages also increase during the most recent 150 years (Supplemental Figure 2). *Tsuga canadensis, P. glauca* and *P. mariana/rubens* all initially decline in Pollen Zone 3, but then increase circa ~AD 1800 AD and then gradually decline. *Pinus* Haploxylon maintains relatively high percentages from the 1600s until ~AD 1866 when it declines until present day. *Alnus* shows a gradual percentage increase beginning in the early 1800s and peaks at 5.6% in the present. Total pollen influx dips during the late LIA, ~AD 1600 - ~AD 1800 (Supplemental Figure 3).

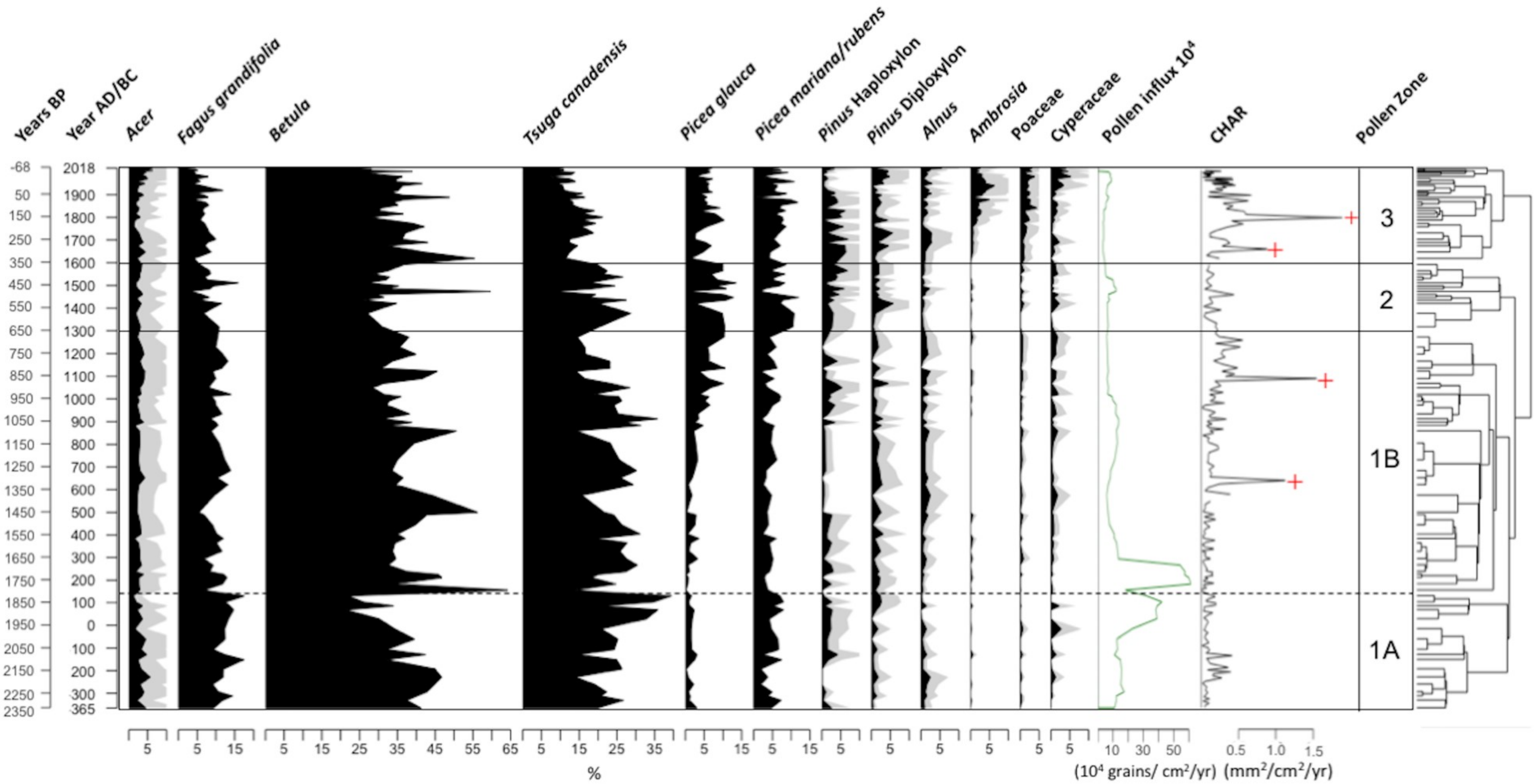

Figure 4.4. Pollen percentage diagram for principal taxa from Étang Fer-de-Lance, Québec. Shown are pollen percentages of main taxa (total pollen sum > 5% at least once in the record). Light grey areas show an exaggeration of 3x. The 5-point moving average of pollen influx (10^4 grains/cm^2/year) and charcoal accumulation rate (CHAR) (mm^2/cm^2/year) are plotted as well. Significant charcoal peaks indicated with a red cross.

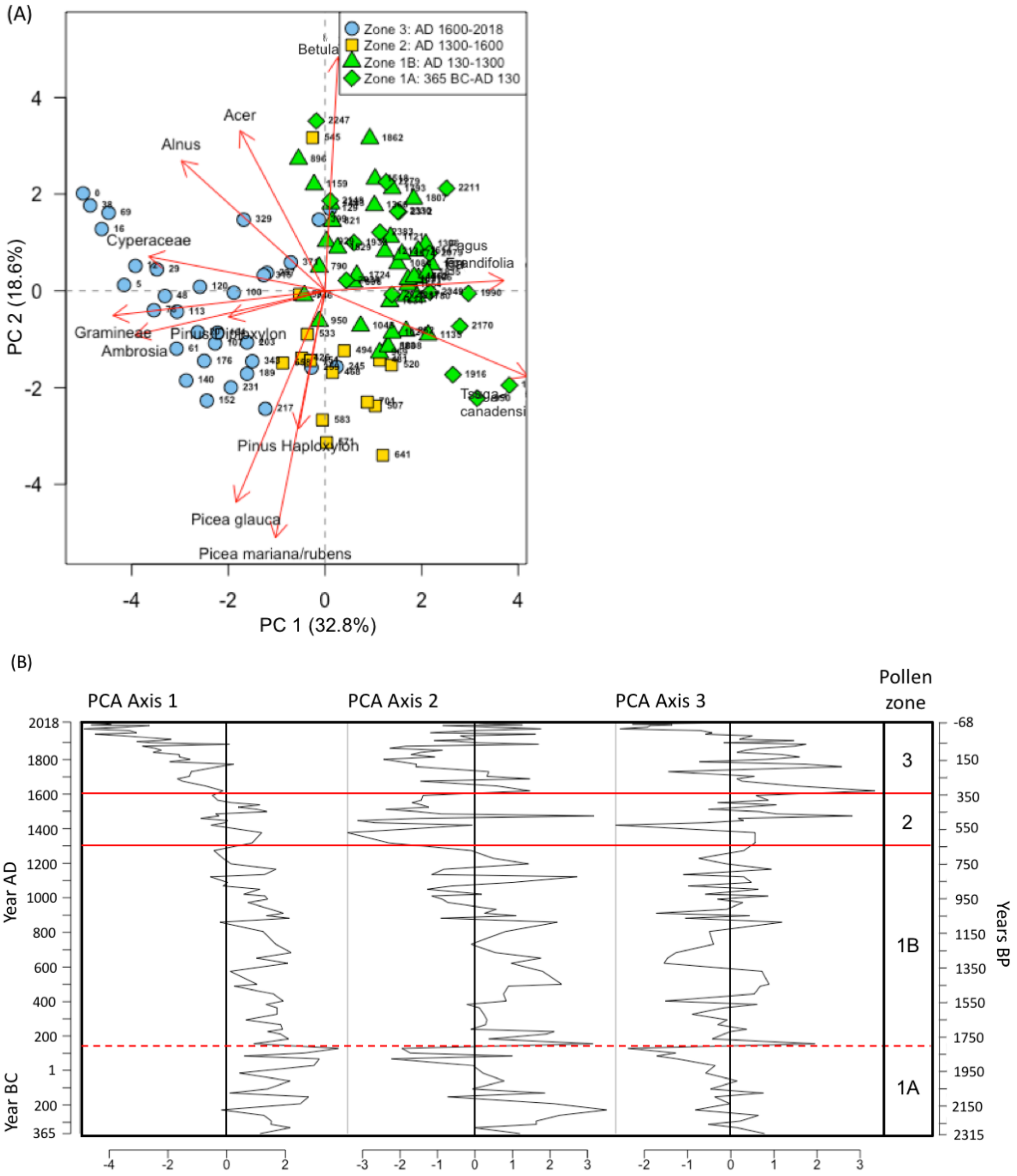

Figure 4.5. (A) PCA biplot of Étang Fer-de-Lance pollen percentages with symbols denoting the pollen zones of the observations. Negative numbers denote years BC. (B) Étang Fer-de-Lance PCA sample scores (unsmoothed) for the first three principal components (~365 BC – ~AD 2018). Pollen zones and subzones shown with red lines.

Table 4.3. Species scores from principal component analysis (PCA) of Étang Fer-de-Lance pollen percentages (~365 BC – ~AD 2018).

Taxon	**Axis 1**	**Axis 2**	**Axis 3**
Acer spp.	-0.18	0.33	-0.24
Fagus grandifolia	0.37	0.02	-0.03
Betula spp.	0.03	0.48	0.46
Tsuga canadensis	0.42	-0.18	-0.24
Picea glauca	-0.18	-0.48	0.11
Picea mariana/rubens	-0.10	-0.51	0.01
Pinus Haploxylon	-0.05	-0.29	0.46
Pinus Diploxylon	-0.20	-0.05	-0.54
Alnus spp.	-0.30	0.27	-0.01
Ambrosia-type pollen	-0.39	-0.09	0.04
Poaceae	-0.43	-0.05	0.01
Cyperaceae	-0.36	0.07	-0.28

Principal component analysis (PCA) was used to uncover the main patterns of variation in the pollen percentage data (Figure 4.5 and Table 4.3). The first three PCA axes explain 62% of the total variation in the data. PCA Axis 1 explains 32.8 % of the total variation in the pollen and is defined by *T. canadensis, F. grandifolia* (highest positive 1st axis species scores), and the disturbance indicator taxa: Poaceae, *Ambrosia*-type pollen, Cyperaceae and *Alnus* spp. (lowest negative 1st axis species scores). PCA Axis 1 is defined by successional stage. PCA Axis 2 explains 18.6% of the pollen variation and is defined by the deciduous pollen of *Betula* spp. and *Acer* spp. (highest positive 2nd axis species scores), and the coniferous pollen of *P. glauca* and *P. mariana/rubens* (lowest negative 2nd axis species scores). PCA Axis 2 separates the hardwoods from the softwoods. PCA Axis 3 explains 10.4% of the pollen variation and is defined by *Betula* spp. and *Pinus* Haploxylon (highest positive 3rd axis species scores) and *Pinus* Diploxylon and Cyperaceae (lowest negative 3rd axis species scores). The eigenvalue scree plot (not shown) shows that subsequent PCA axes are not important.

The pollen zonation (Figure 4.4) is based on this PCA ordination and CONISS (Figures 4 and 5), with the demarcation between Pollen Zones 2 and 3 defined by PCA Component 1, and the demarcation between Pollen Zones 1 and 2 defined by PCA Component 2. Sample scores for PCA Component 1 are positive throughout Pollen Zone 1, transition to negative through Pollen Zone 2, and decline sharply in Pollen Zone 3. The sample scores for PCA Component 2 are predominately positive in Pollen Zone 1, and then are predominantly negative in Pollen Zone 2. Sample scores for PCA Component 3 oscillate between positive and negative until ~AD 1500, becoming increasingly positive between ~AD 1500 – 1900. The division of Pollen Zone 1 into subzones 1A and 1B is principally defined by the sample scores for PCA Component 3 which are largely negative for subzone 1A and largely positive for subzone 1B. There also is a negative dip in the PCA Component 2 scores around this subdivision. A PCA using the covariance matrix with a square root transform on the percentages of the taxa with abundances ≥ 5% gave similar results, as did a PCA using the correlation matrix on all 52 taxa, so these are not shown further.

4.3.3 *Climate reconstructions*

The reconstructed summer temperature shows a warm first millennium AD, a slightly cooler MCA, and a distinct cold LIA (Figure 4.6). The reconstructed warm first millennium AD spans ~365 BC – ~AD 934 with summer temperatures almost always above the pre-1899 average of 16.8 °C, the slightly cooler MCA spans ~AD 973 - 1421 with summer temperatures oscillating above and below average, and the distinct cold LIA spans ~AD 1435 – 1801 with summer temperatures almost consistently below average. The reconstructed annual precipitation shows a gradually wetting climate, with a mean annual precipitation of 1016 mm during the first millennium AD, the MCA with a mean of 1062 mm, the LIA with a mean of 1084 mm and the 1800s with a mean of 1109 mm (Figure 4.6). Reconstructed JJA precipitation showed very similar results (results not shown). Pollen subzone 1A is slightly cooler and wetter than the subsequent 600 years in subzone 1B. Post-1898, the climate reconstructions become unreliable due to increasing amounts of historically well-documented human-caused landscape modification. Analog matchings between the down-core samples and the training set were close, with only four samples having a minimum distance greater than that of 5% of the training set (22.88). Of these four samples with poor analogs (out of a total of 102), two were from the most recent three decades and two from the early first millennium AD. The training set when run on itself using leave-one-out cross-validation had a $R^2 = 0.79$ and a root mean squared error of prediction $RMSEP = 0.87$ °C for JJA mean temperature, and a $R^2 = 0.49$ and $RMSEP = 1112$ mm for annual precipitation. Analysis using a pollen-climate calibration set spanning between 50° and 100° W longitude and 20° and 50° N latitude gave very similar results.

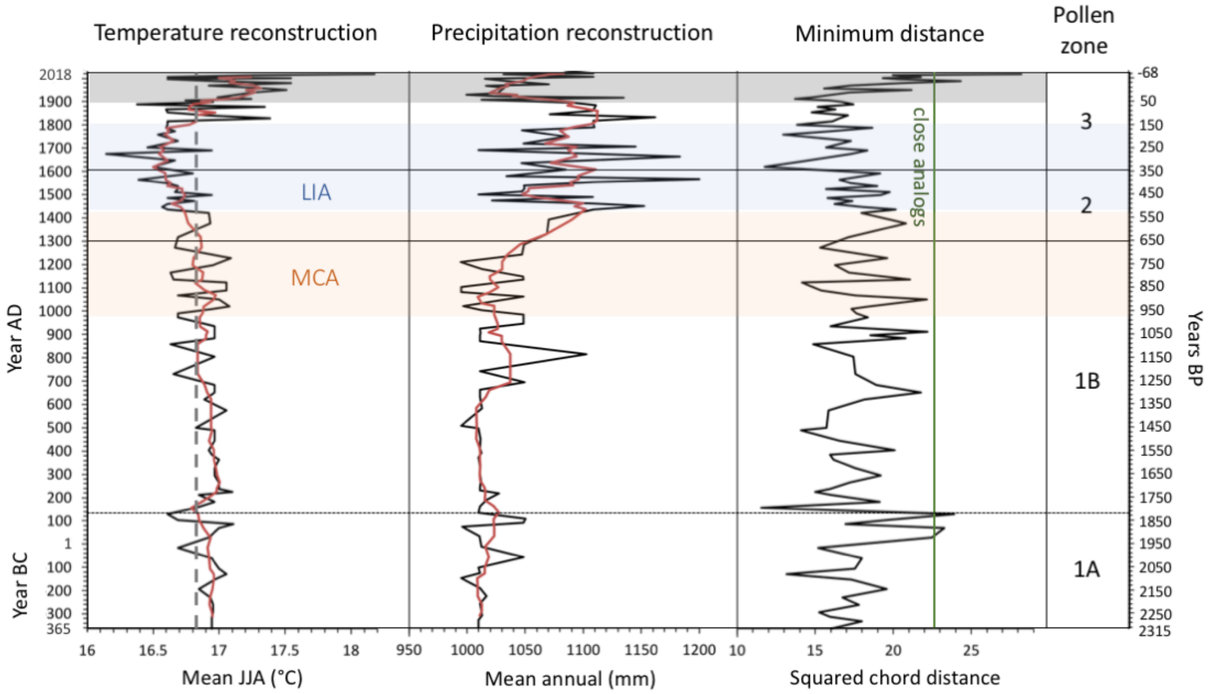

Figure 4.6. Reconstructed summer (JJA) temperature and mean annual precipitation for Étang Fer-de-Lance, Québec, using the modern analog technique (MAT), together with minimum squared chord distance for the closest analog. The red lines are 5-point smoothers. Samples with a minimum squared chord distance of less than 22.9 are considered to have close analogs.

4.3.4 *Charcoal analysis results*

Charcoal particles were present throughout the entire core, showing that fire is naturally present in the Mont-Orford forest landscape (Figure 4.4). Unsurprisingly, the charcoal accumulation rate (CHAR) record increases during the European period (Pollen Zone 3). The decomposition of the CHAR record into background charcoal and local fires shows that significant local fires occurred at ~AD 645, ~AD 1088, ~AD 1658, and ~AD 1798 (Figure 4.4). Assuming that significant fire peaks prior to ~AD 1760 (the beginning of denser European settlement in the region) are naturally ignited fires, this produces a mean natural fire return interval of 515 years for this forest type in the Mont-Orford region.

4.4 Discussion

4.4.1 *Dating*

The age-depth model is robust for the second millennium AD with relatively tight 95% confidence limits of ± 100 years, but somewhat less so for the first millennium AD, with a broader range of radiocarbon dates, and hence broader 95% confidence intervals of ± 250 years (Figure 3). Some of this spread is perhaps due to having to radiocarbon date wood which might be older than the sediments if the wood comes from the center of long-lived trees. This error however might be partially offset if the heavier wood settled deeper than lighter seeds or leaves in the soft surface sediments. Additionally, wood does provide two of the tightest radiocarbon dates. We radiocarbon dated wood for lack of anything else. The ^{210}Pb-based portion of the age-depth model is robust (Supplemental Table 1 and Supplemental Figure 1). Fortunately, our most interesting results occurred in the second millennium AD where the age-depth model is more robust.

4.4.2 *Vegetation history*

The results of our study highlight the enduring dominance of the hardwood forest subzone in the Mont-Orford region over the last 2300 years. While the major taxa have remained relatively similar over the first 1600 years of the record, the pollen zones established by CONISS and PCA identify key vegetation changes tied to climatic and human events throughout this time period. Notably our record captures a clear increase in conifer taxa (*Picea glauca, Picea mariana/rubens* and *Pinus* Haploxylon) beginning in the late first millennium AD and a decrease in *Fagus grandifolia* and *Tsuga canadensis* over the last 700 years.

Our pollen record captures a relatively constant first millennium AD for most taxa with vegetation in the region being dominated by *Betula spp*, *T. canadensis* and to a lesser extent *F. grandifolia* (Figure 4.4). Though not separated for this study, species of *Betula* known in the region include *B. alleghaniensis, B. papyrifera,* and *B. populifolia* and could all possibly have been present throughout the first millennium (Gauvin and Bouchard, 1983). While there is some variation in the various taxa percentages in the first millennium, these variations are smaller than the changes of the second millennium AD. The general stability of the first millennium AD for the pollen taxa in Étang Fer-de-Lance is supported by other studies in southern Québec that also captured relatively undifferentiated first millennia AD (Houle et al., 2012; Lafontaine-Boyer and Gajewski, 2014). At Lac Clair, southcentral Québec, Houle et al. (2012), in their 1,800-year-long study, found that main tree taxa percentages were less variable prior to AD 1500 before showing subsequent significant changes. A 1,400-year-long study at Lac Brulé, southwestern Québec, similarly found little variation in pollen percentages until the early second millennium (Lafontaine-Boyer and Gajewski, 2014). While we observe little change in pollen percentages during the first millennium AD, there were distinct changes in the pollen influx (Figure 4.4) and increased pollen accumulation rates of deciduous taxa: *Acer spp., Betula spp., F. grandifolia* and

Alnus spp. (Supplemental Figure 3). Pollen influx rates from Étang Fer-de-Lance were highest between ~16 BC and ~AD 266 which is suggestive of higher pollen and forest biomass production caused by warmer temperatures at the beginning of the first millennium (Grochocki et al., 2019). These pollen influx rates are characteristic of hardwood-dominated mixed forest (Davis et al., 1975). There is a decline in total pollen influx ~AD 400-700 which is coincident with the Dark Ages Cold Period (Helama et al., 2017), but our climate reconstructions show no change here. This period frequently appears as a cold and wet period in northern Québec (e.g., Loisel and Garneau, 2010).

After consistently low percentages of *P. glauca* between ~365 BC and ~AD 991, we see a rise in *P. glauca* beginning around ~AD 910 and persisting throughout the second millennium (Figure 4.4). The rise in *P. mariana/rubens* occurs slightly later at around ~AD 1300 (Figure 4.4). These rises are consistent with studies across adjacent Maine which also found a resurgence in *Picea* over the past 1000 years (Davis et al, 1975; Gajewski et al., 1987; Schauffler and Jacobson, 2002; Lindbladh et al., 2003; Lafontaine-Boyer and Gajewski, 2014; Grochocki et al., 2019; Nolan, 2019). In more southern upstate New York and Vermont, the *Picea* increase occurs earlier still from the beginning of the first millennium AD to AD 700 (Gajewski et al., 1987; Oswald et al., 2018; Grochocki et al., 2019). In southwestern and southcentral Québec, the rise was found to be a little later - ~AD 1300 (Houle et al., 2012; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014). As *Picea* were some of the first trees to have recolonized North American landscapes following the retreat of the Laurentide Ice Sheet, this recent northwards resurgence of *Picea* follows a subsequent decline in its presence attributed to unfavorable early-to-mid Holocene climate characterized by high seasonality (Lindbladh et al., 2003). The increase of *Picea* beginning in the first millennium AD is indicative of a general cooling due to orbital forcing and decreasing of seasonality (Gajewski, 1987, 1988; Ruddiman, 2008). While previous studies have documented the resurgence of *Picea* pollen around AD 1000 -1300, few studies have investigated the unique responses of the different species of *Picea* (excepting Lindbladh et al., 2003; Houle et al., 2012). By separating *P. glauca* pollen from *P. mariana/rubens* pollen (the two latter species are morphologically very similar), our records capture this differential return of *Picea* species during the late Holocene. It has been speculated that colder and moister coastal areas and the higher altitudes of the Appalachian and Adirondack Mountains served as refugia for the *Picea* species in New England (and possibly southern Québec) during the unfavorable growing conditions of the mid-Holocene (Schauffler and Jacobson, 2002; Lindbladh et al., 2003).

Pinus Haploxylon (here *Pinus strobus*) also increases at Étang Fer-de-Lance ~AD 1300. The high-resolution Knob Hill Pond core from upstate Vermont also shows an increase in *P. strobus* ~AD 1200 (Oswald et al., 2018). Paquette and Gajewski (2013) and Lafontaine-Boyer and Gajewski (2014) also observed an increase in this species at Lacs Noir and Brulé, but at a later date – AD 1500. Unlike the broad New England and southern Québec increase in *Picea* in the late Holocene, there is no corresponding increase in *P. strobus* with some relatively nearby higher-resolution site showing no increase (i.e., Lac Clair) or declines (i.e., Mont Shefford; Richard, 1978). *Pinus* Diploxylon (i.e., *Pinus resinosa*, *Pinus rigida*, *Pinus banksiana*) non-significantly increases at this time as well.

The abrupt increase of *Picea* and *P. strobus* is accompanied by declining percentages of other dominant taxa. Both *F. grandifolia* and *T. canadensis* saw a further decline in their percentages beginning ~AD 1500 and continued to decline into the modern era. This decline of *F. grandifolia* and *T. canadensis* is found in other high-resolution studies from northeastern

North America and is attributed to the beginning of the LIA (Gajewski, 1987; Campbell and McAndrews, 1993; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014; Oswald et al., 2018; Grochocki et al., 2019). Our findings match results from southwestern Québec that found relatively high *F. grandifolia* and *T. canadensis* pollen percentages in the first millennium AD which then significantly declined in the mid-second millennium AD and have not returned to previous peak percentages (Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014). At varved Lac Brulé, this decline in *F. grandifolia* and *T. canadensis* occurred ~AD 1375, while at varved Lac Noir, the changes began ~AD 1550. This abrupt decrease in these earlier sub-dominant taxa and an increase in more boreal conifer pollen, supports the suggestion that there was a rapid transition between an earlier warmer MCA and the cooler LIA experienced in Québec, which had great effect on the vegetation (Paquette and Gajewski, 2013).

With the exception of the studies mentioned above, much of the pollen work previously done in Québec has been low-resolution whole Holocene reconstructions (Richard, 1975; Richard, 1978; Lavoie and Richard, 2000; Muller and Richard, 2001). While yielding illuminating whole Holocene results, the resolution of these studies are probably unable to easily capture the presence of a distinct MCA and LIA within Québec. By filling the lack of high-resolution pollen records in southeastern Québec, our findings help clarify the presence of a MCA and a distinct early LIA that previous low-resolution cores had difficulty detecting.

4.4.3 ***Ambrosia rises and the Human-modified Period***

4.4.3.1 *Ambrosia rises*

Pollen Zone 3 begins in ~AD 1600 with an increase of shade intolerant and disturbance characteristic taxa due to the beginning of the Human-modified Period which has likely overshadowed the vegetative response of the late LIA in southeastern Québec. Étang Fer-de-

Lance exhibits an *Ambrosia* rise occurring in two steps and captures signs of possible Indigenous agriculture in the broader Mont-Orford region prior to European settlement of the Eastern Townships in the late AD 1700's. Our pollen record from the small lake captures an initial early rise in *Ambrosia* beginning ~AD 1650 and then a second, more abrupt, classic *Ambrosia* rise beginning ~AD 1770 and peaking in ~AD 1940. The initial rise in *Ambrosia* is accompanied by an earlier rise in Poaceae beginning ~AD 1550, which provides further reason that this first increase in *Ambrosia*-type pollen is linked to Indigenous farming rather than early French farming. Stager et al. (2016) found increased erosion in Wolf Lake in the late 1600s and early 1700s which they also attributed to Indigenous agriculture (Figure 1). Several of the Montréal lowlands sites of Muller and Richard (2001) also show similar early *Ambrosia* and Poaceae rises, but given their lower resolution and dating control this is less certain.

There are mixed Indigenous accounts as to who controlled the region as First Nations from both the Wabanaki and Haudenosaunee Confederacies historically occupied much of the region (Gélinas, 2018). Well known for their extensive field planting of crops of maize, beans and squash, the Haudenosaunee used a combination of controlled burns and stone axes to clear forest and brush for fields (Tremblay, 2006; Haudenosaunee Confederacy, 2020). The Abenakis (part of the Wabanaki Confederacy) also practiced agriculture and grew maize. However, without any archeological evidence of permanent settlements until the 19th century, their relationship with the Eastern Townships is believed to have been mostly for seasonal fishing and trapping (Gélinas, 2018; Musée des Abénakis, 2019). Montréal was founded in AD 1642 on the site of St-Laurent Iroquoian Hochelaga (Tremblay, 2006) but remained very small for many years because of its precarious military position. During the French Colonial Regime, due to frequent wars between the Abenakis (with their French allies) and the Haudenosaunee (with their

English allies), it is hard to establish precisely which nations would have been practicing agriculture in the Mont-Orford region of the Eastern Townships between AD 1650 – 1770. There was no permanent French settlement in the region because of incessant warfare. *Nouvelle France* fell in AD 1760 to the British, causing the end of the French Regime. In the ensuing peace, European settlement began to increase in the Eastern Townships.

The second *Ambrosia* rise, beginning ~AD 1770, is more characteristic of the classic *Ambrosia* rises captured in southern Québec studies marking the onset of extensive European agriculture (Muller and Richard, 2001; Lavoie et al., 2007; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014). Although the genus is native to eastern North America, *Ambrosia*-type pollen expanded greatly with non-Indigenous settlement and associated land disturbances and provides a reliable marker for European settlement (Grimm and Jacobson, 2003). The dating of our classic *Ambrosia* rise at ~AD 1770 is within the time-frame of the *Ambrosia* rise dated by Muller and Richard (2001) in the Monteregian Hills northwest of Mont-Orford. Their 15-core study determined that the regional *Ambrosia* rise occurred between AD 1750 – 1800 as the result of European-caused deforestation and agriculture. Further north in southwestern Québec, Lacs Noir and Brulé show an *Ambrosia* rise between AD 1810 - 1860 corresponding to the time of settlement in that region (Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014). In the Eastern Townships, settlement by Europeans began formally in the late 1700s with the Constitutional Act of 1791 stipulating that Crown land would be surveyed into townships and ceded to settlers (St-Onge and Will, 2019). In this second *Ambrosia* rise, our record likely captures the beginning of the Loyalist settlement from Vermont in the Mont-Orford region at Magog in AD 1776 (Figure 4.1).

4.4.3.2 *Further European impacts over the last 200 years*

In addition to increasing pioneering weedy taxa with high light demands, such as *Ambrosia,* Poaceae and Cyperaceae, the land disturbance of European settlers in the region has had lasting impacts on the forest composition. Over the last 200 years, Étang Fer-de-Lance shows a significant increase in *Acer spp.* pollen, particularly *A. rubrum, A. pensylvanicum* and *A. saccharum*, following the second rise of *Ambrosia* (Supplemental Figure 2). Using early European land settlement surveys, Danneyrolles et al. (2019) show how anthropogenic disturbances, such as agricultural clearing, logging, and anthropogenic fires, have collectively influenced forest dynamics in southern Québec by benefiting disturbance-adapted, early-successional, short-lived and fast-growing tree species, such as *Acer spp*. Gauvin and Bouchard (1983) also identified *Acer spp.* as a marker of forestry in their vegetational survey of the Parc national du Mont-Orford. They found that park sectors that had been disturbed by forestry had been reclaimed by successional communities of *Acer spp., Betula spp.* and *Populus spp*. These anthropogenic disturbances and the increase of *Acer spp*. and other successional species come at the expense of long-lived late-successional taxa, such as *T. canadensis* and *F. grandifolia* (Finkelstein et al., 2006; Boucher et al., 2009; Danneyrolles et al., 2019). The Étang Fer-de-Lance pollen record detects the arboreal species shifts and dynamics described by these forest inventory studies, as early-and mid-successional *Acer spp.* increase at the peak of the *Ambrosia* rise with concomitant declines in late-successional *T. canadensis* and *F. grandifolia*, declines which have not yet stabilized. To the best of our knowledge, this study is the first study in southern Québec to link sedimentary pollen results to those from early settlement forest inventory studies, showing the benefits of high-taxonomic resolution palynology. Additionally, there has been an increase in *Quercus* over the last 150 years, which is considered to be a tree species characteristic of disturbances (Supplemental Figure 2).

4.4.4 *Climate reconstructions*

We compare the Étang Fer-de-Lance climate reconstructions to other nearby terrestrial, high-resolution, sediment-based climate reconstructions within a ~350 km radius (Figures 4.1, 4.7 and 4.8). Tree-ring-based climate reconstructions, although of even higher annual resolution, do not capture well centennial-scale climate variability in this region because of the aggressive detrending methods needed to remove stand dynamics in the northeastern closed-canopy forests and hence are not suitable for comparison (e.g., Tardif et al., 2001). The Étang Fer-de-Lance summer temperature reconstruction closely corresponds to the pollen-based reconstructions from Lacs Noir and Brulé, showing a warmer MCA than the subsequent LIA with an abrupt transition occurring between AD 1400-1500 at all three sites (Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014) (Figure 4.6). Similarly, Gajewski (1988) found a shift from a warmer MCA to a colder LIA at ~AD 1400 at Conroy Lake and Basin Pond in Maine and Clear Pond in upstate New York using pollen-based reconstructions. These three latter sites also show a generally warmer first millennium AD than the MCA, as did Étang Fer-de-Lance. Hence, we have a coherent regional pattern of a warmer MCA relative to a colder LIA with the transition between AD 1400-1500 in the high-resolution summer temperature reconstructions (Lafontaine-Boyer and Gajewski, 2014) (Figure 4.7). There is a current debate as to whether the LIA and MCA occurred in southern Québec at all, but much earlier terrestrial work is of lower resolution and may not therefore detect these climate periods (Hausmann et al., 2011; Van Bellen et al., 2018).

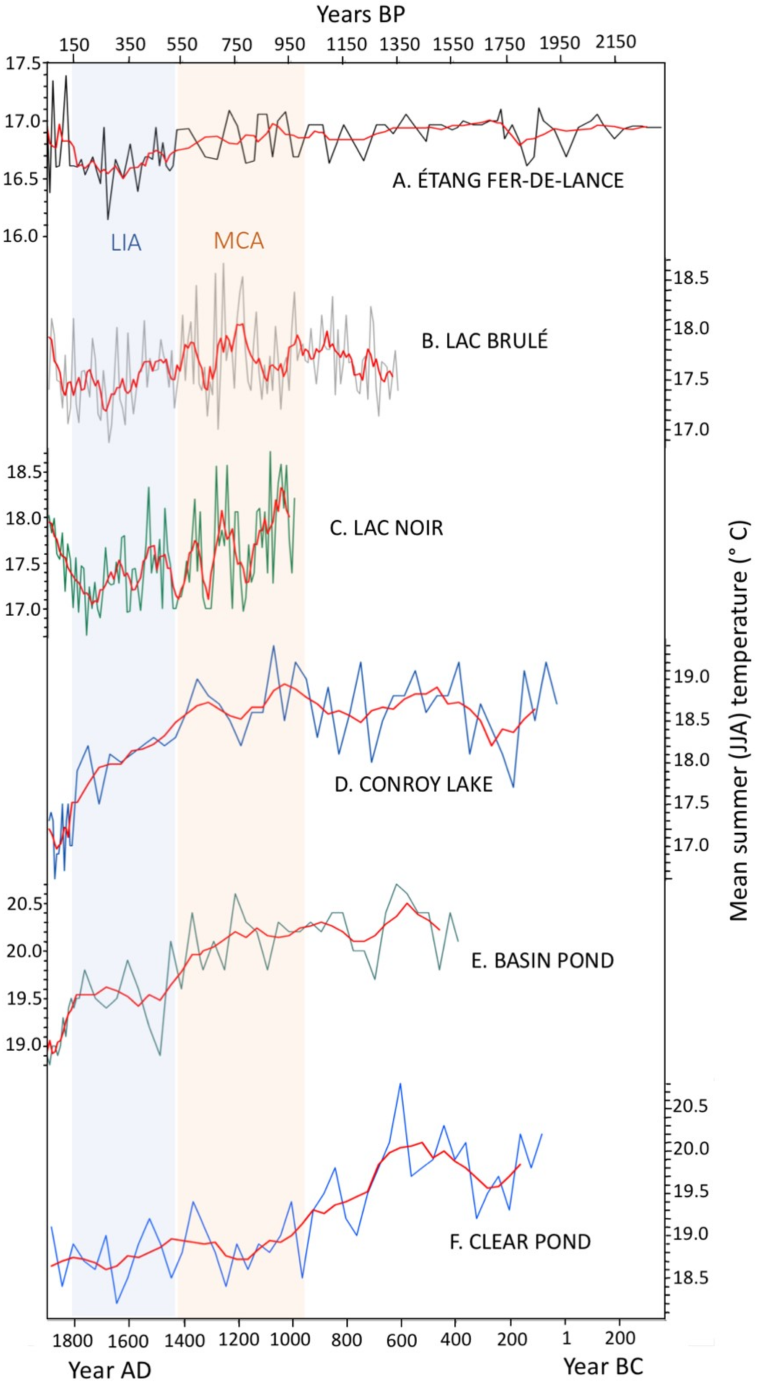

Figure 4.7. Mean summer (JJA) temperature summary of other terrestrial, high-resolution sedimentary sites within 350 km of Étang Fer-de-Lance. A. this study; B. Lac Brulé (Lafontaine-Boyer and Gajewski, 2014); C. Lac Noir (Paquette and Gajewski, 2013); D. Conroy Lake (Gajewski, 1988); E. Basin Pond (Gajewski, 1988); and F. Clear Pond (Gajewski, 1988).

The precipitation synopsis is more complex (Figure 8). The Étang Fer-de-Lance mean annual precipitation reconstruction shows a moister LIA relative to the MCA, which is then moister relative to the first millennium AD (Figure 4.6). The annual precipitation reconstruction from Conroy Lake, Maine, also shows a wetter LIA relative to the MCA (Gajewski, 1988), as do the planktonic and tychoplanktonic diatom percentage record from a sediment core from Wolf Lake in the central Adirondacks and the water-table depth reconstruction from testate amoebae from Sidney Bog (Clifford and Booth, 2013; Stager et al., 2016) (Figures 4.1 and 4.8). On the other hand, the summer precipitation reconstructions of Lacs Noir and Brulé and the annual precipitation of Basin Pond, Maine, show a drier LIA relative to the MCA, and the annual precipitation reconstruction from Clear Pond, New York, shows little difference in moisture between the LIA and MCA (Gajewski, 1988; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014). In their meta-analysis of New England high-resolution sedimentary moisture reconstructions, Shuman et al. (2018) found that generally the LIA was wetter than the MCA; however, there were records that showed the opposite or no trend. Moisture appears to be more heterogenous over relatively smaller spatial scales than temperature does. Our Étang Fer-de-Lance moisture reconstructions agree with this generally observed New England pattern (Shuman et al., 2018). Ladd et al. (2018) found no difference in annual precipitation between the LIA and MCA for our exact region and again a wetter LIA relative to the MCA in New England in their MAT-based meta-analysis of compiled pollen results.

Like Étang Fer-de-Lance, Conroy Lake and Clear Pond show a drier first millennium AD relative to the MCA, as does the planktonic diatom percentage record from Wolf Lake (Gajewski, 1988; Stager et al., 2016) (Figure 4.8). However, Basin Pond shows no substantial difference in moisture availability between the first millennium AD to the MCA. In their synthesis, Shuman et al. (2018) found that generally the 2nd millennium AD was wetter than the 1st millennium AD in their survey of most available high-resolution sedimentary records; however, again there were records that showed the opposite or no trend. Ladd et al. (2018) in their pollen-based survey found that the MCA was wetter than the Dark Age Cold Period in southeastern Canada.

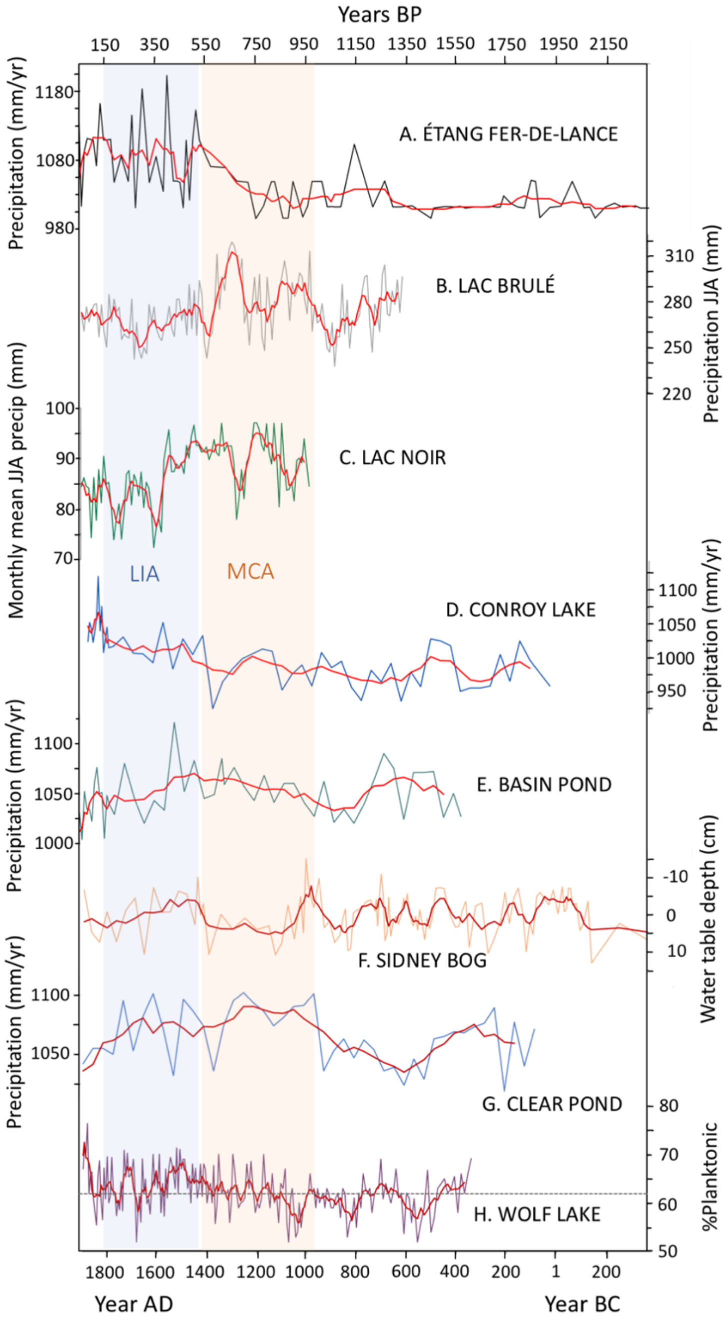

Figure 4.8. Precipitation summary of other high-resolution sedimentary sites within 350 km of Étang Fer-de-Lance. A. Annual precipitation from this study; B. JJA precipitation from Lac Brulé (Lafontaine-Boyer and Gajewski, 2014); C. Monthly mean JJA precipitation from Lac Noir (Paquette and Gajewski, 2013); D. Annual precipitation from Conroy Lake (Gajewski, 1988); E. Annual precipitation from Basin Pond (Gajewski, 1988); F. Water-table depth reconstruction residuals from Sidney Bog, with more negative residuals meaning wetter conditions (Clifford and Booth, 2013); G. Annual precipitation from Clear Pond (Gajewski, 1988); and H. Combined percentages of planktonic and tychoplanktonic diatoms from Wolf Lake, with higher values assumed to represent greater precipitation in the watershed (Stager et al., 2016). Horizontal dotted line at 62% designates mean prior to AD 1860.

A number of caveats must be mentioned with respect to the Étang Fer-de-Lance climate reconstructions. A serious issue in doing climate reconstructions based upon modern pollen-climate training sets is the fact that human-caused landscape disturbance is so great in many regions of the world (certainly in southern Québec) that vegetation no longer reflects climate in the same way that it used to prior to this major impact (St-Jacques et al., 2008b; 2015; Kujawa et al., 2016). Hence, when we use transfer functions built using modern pollen-climate training sets to infer the past climates of more pristine landscapes, there are inevitable errors that can be severe, including substantial climate signal flattening and underestimation, and bias (St-Jacques et al., 2008b; 2015). A further source of error and loss of sensitivity in our reconstructions arises from having to merge all *Picea* taxa together, even though they have different climate optima (Thompson et al., 2015) because of the low taxonomic resolution typically used by earlier researchers whose compiled results comprise the pollen training set (Whitmore et al., 2005). An additional caveat arises from the fact that 12 out of the 14 20th-century Étang Fer-de-Lance samples are shown to have close analogs in the training set even though the independent historical record makes clear the heavy human-caused regional landscape alteration (Figure 4.6). Hence, common definitions of good analogs in training sets used to assess reconstruction reliability can be problematic (Simpson, 2012). Despite these issues, reconstructing climate for the last one or two millennia using sedimentary pollen is still worthwhile; however, it is more reasonable in areas with heavy modern landscape disturbance to make relative comparisons among the mean reconstructed climate variables of past time periods such as the LIA and MCA, rather than trusting the absolute values of the reconstructions.

4.4.5 *Natural and anthropogenic fire record*

Four significant CHAR peaks mark our 2300-year fire record from Étang Fer-de-Lance (Figure 4). The CHAR peaks at ~AD 646, ~AD 1088 and ~AD 1658 are presumed to be natural in origin as they precede European settlement of the region, but pollen percentages do not show any substantial changes in forest composition due to these fires (Figure 4). The most recent significant fire event at ~AD 1798 corresponds to the early European settlement of the Eastern Townships region. As the initial settlement of the city of Sherbrooke begun in the early 1800s with the establishment of several mills (Figure 1), the CHAR peak at ~AD 1798 matches the period when early European land clearance would have been occurring (Eastern Townships Resource Centre, 2017).

The mean fire return interval (excluding the ~AD 1798 CHAR peak presumed to be of anthropogenic origin) of 515 years is typical of the hardwood forests of southeastern Canada known for a relatively moist climate and less fuel accumulation during the late Holocene (Blarquez et al., 2018). Comparatively, in the Gatineau/Outaouais region of drier southwestern Québec, Blarquez et al. (2018), recorded a mean fire return interval of 301 ± 201 years for the last 1,500 years at Folly Bog. However, prior to AD 500, they found a higher fire return interval of 135 ± 132 which we do not have at Étang Fer-de-Lance. Stager et al. (2016) found a mean fire return interval of 210 years at Wolf Lake in the central Adirondacks (Figure 4.1). We conclude from our pollen and charcoal records that while fires are a natural part of the forest landscape in the Mont-Orford area, the natural fire regime likely did not play a major role in vegetation dynamics prior to significant land clearing by European settlers. To the best of our knowledge, this is the first paleo-fire study from the eastern sugar maple-basswood domain of the hardwood forest subzone of Northern Temperate Forest (Ressources Naturelles Québec, 2003).

4.5 Conclusions

This study shows how high-resolution (bi-decadal) pollen analysis done at a high level of taxonomic resolution is able to reconstruct forest dynamics and climate over the past two millennia in southern Québec. Our working at a sensitive montane site near two ecotones defined by vegetation taxa with microscopically separable pollen permitted us to uncover distinct first millennium AD, MCA and LIA periods in the pollen-based reconstructed climate, as well as Indigenous and European settler landscape modification.

Modern forest inventories in southern Québec extend back no more than a century, hence we only have an understanding of relatively high-frequency forest dynamics, such as those in response to spruce budworm outbreaks. The only way therefore to understand centennial-scale forest dynamics is via paleo-ecological methods, such as pollen and charcoal analysis of lake sediments. Having a better grasp of longer-term forest dynamics such as those that occurred during the MCA and LIA can only help us deal with the massive changes that are expected to occur in these forests, among others, due to human-caused climate change. The forests of the MCA may be reasonable analogs for the potential forests of the present and near future. Our unsurprising take-home message to land managers is how strong modern landscape modification has become relative to natural variability in this region, with the disturbance-loving species prospering at the expense of the late-successional taxa.

4.6 Acknowledgements

This work was supported by a Natural Sciences and Engineering Research Council (NSERC) Discovery Grant 41795-2017 and a *Fonds de recherche du Québec – Nature et technologies (FRQNT) Nouveaux chercheurs* Grant to J.M. St-Jacques and funding from the Canada Foundation for Innovation and Bishop's University to M. Peros. We thank the Parc national du Mont-Orford for their collaboration in our research and securing our access to Étang Fer-de-Lance. We also thank Duane Noel, Zach Masson and Fanny Lashcari for fieldwork assistance. We also thank Michelle Garneau and Olivier Blarquez whose comments greatly improved this manuscript.

4.7 Data availability

The pollen, microcharcoal and XRF data will be archived shortly at Neotoma (https://www.neotomadb.org/data/category/explorer) and the climate reconstructions will be archived shortly at the NOAA Paleoclimatology site (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data).

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5. Conclusions

This study provides the first high-resolution pollen reconstruction of the Mont-Orford region of southeastern Québec and there are several conclusions from our study that highlight the great potential of future higher resolution studies in southern Québec. Notably, our record captures a clear early LIA period beginning around AD 1300. Declines in *Fagus grandifolia* and *Tsuga canadensis* and the resurgence of cold-tolerant boreal conifer taxa (*Picea glauca* and *Pinus strobus*) following a warmer first millennium defined by higher pollen influx supports the suggestion that Québec experienced an abrupt transition between a MCA period and the LIA (Hicks, 1999; Paquette and Gajewski, 2013). Our record further supports that *F. grandifolia* and *T. canadensis* have never returned to pre-LIA conditions.

The Étang Fer-de-Lance record also plays an important role in establishing the influence that human activities have had on the surrounding hardwood forest since the mid 17th century. The initial *Ambrosia* rise captured precedes European settlement of the Eastern Townships of Québec suggesting that the human modified period of the region began as early as AD 1650 ± 100. This early *Ambrosia* rise warrants further study as it could play a role in illuminating the human history of the Eastern Townships prior to European settlement and further our understanding of Indigenous land uses and agricultural practices around Mont-Orford. The recorded increase in *Acer spp.* beginning around AD 1800 is further evidence of the affect that human land use has had on the region. The increase in *Acer spp.* correlates with a dramatic peak in charcoal records occurring in the 1798 and accounts of forestry in the region, now occupied by Parc national du Mont-Orford (Gauvin and Bouchard, 1983). We find that fast-growing successional species such as *Acer spp*. thrive in post disturbance areas and can outcompete longer-lived late-successional taxa, such as *T. canadensis* and *F. grandifolia* contributing to their continued decline.

Further studies in southeastern Québec should apply our methods of high-resolution analysis and put emphasis on detecting the full length of the LIA and a more defined onset of the MCA.

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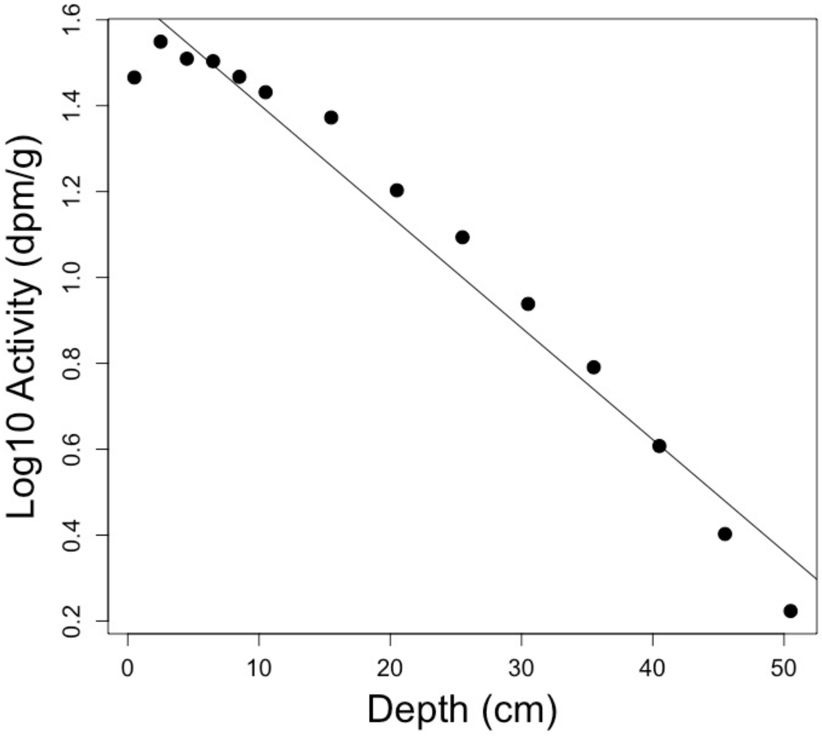
6. Supplemental data

Supplemental Table 1. The 14 ^{210}Pb dating results for surface sediments for Étang Fer-de-Lance, Québec. ^{210}Pb ages are calculated using the Constant Rate of Supply Model (CRS) model and given in years AD.

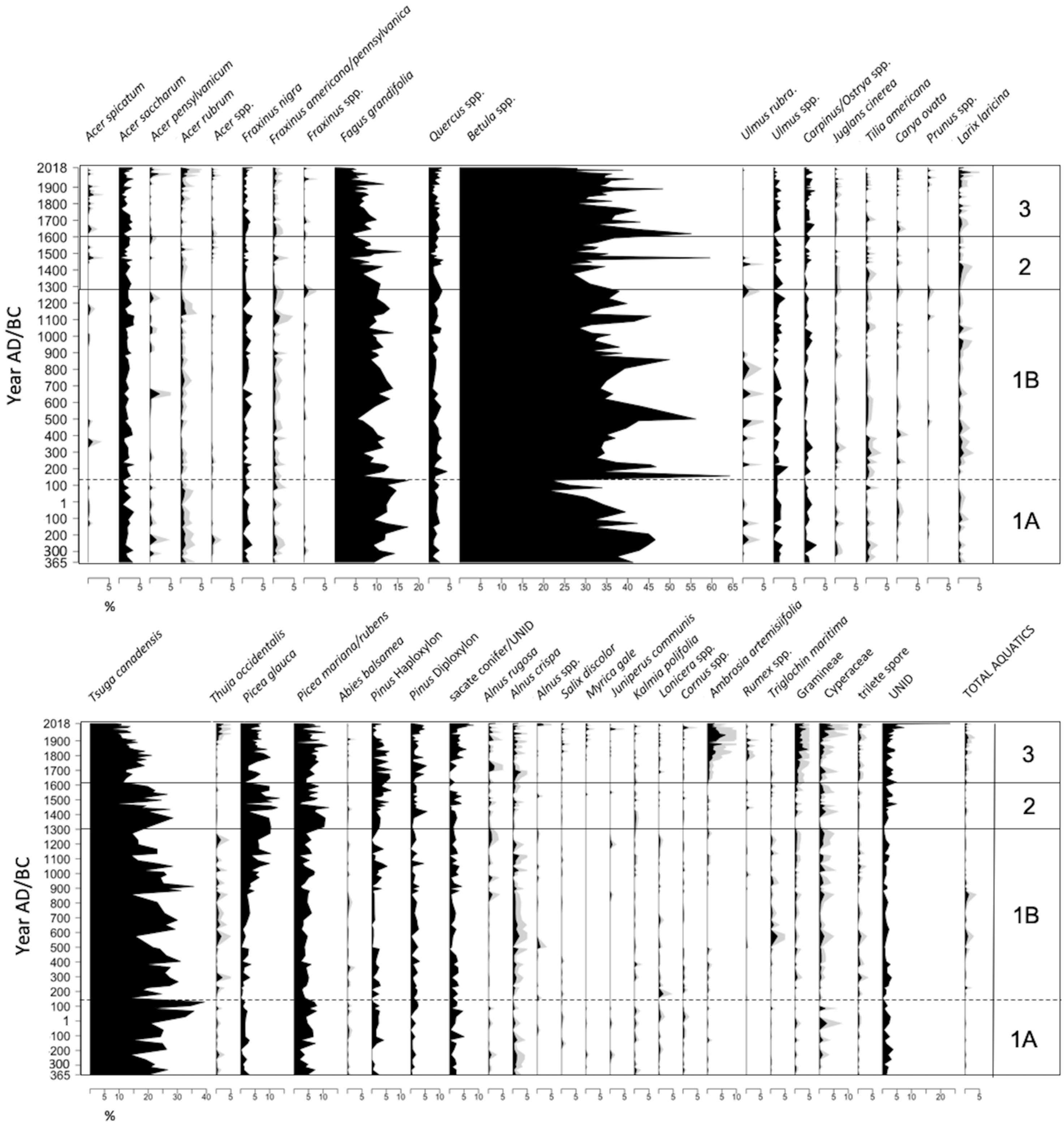
Depth below SWI (cm)	**Lab ID**[a]	**^{210}Pb (dpm/g)**	**Age (yr AD)**
0.5	9566	29.224 ± 1.909	2018 ± 0.245
2.5	9567	35.404 ± 2.297	2016 ± 1.223
4.5	9568	32.310 ± 2.155	2010 ± 2.201
6.5	9569	31.887 ± 2.105	2009 ± 3.179
8.5	9570	29.329 ± 1.873	2004 ± 4.157
10.5	9571	27.000 ± 1.734	2000 ± 5.135
15.5	9572	23.573 ± 1.538	1989 ± 7.581
20.5	9573	15.956 ± 1.003	1981 ± 10.026
25.5	9574	12.404 ± 0.789	1967 ± 12.471
30.5	9575	8.676 ± 0.573	1949 ± 14.917
35.5	9576	6.178 ± 0.395	1920 ± 17.362
40.5	9577	4.050 ± 0.278	1880 ± 19.807
45.5[b]	9578	2.527 ± 0.186	n.a.[b]
50.5[b]	9579	1.627 ± 0.138	n.a.[b]

[a] The ^{210}Pb samples were analyzed at the Geotop Lab at the Université du Québec à Montréal.

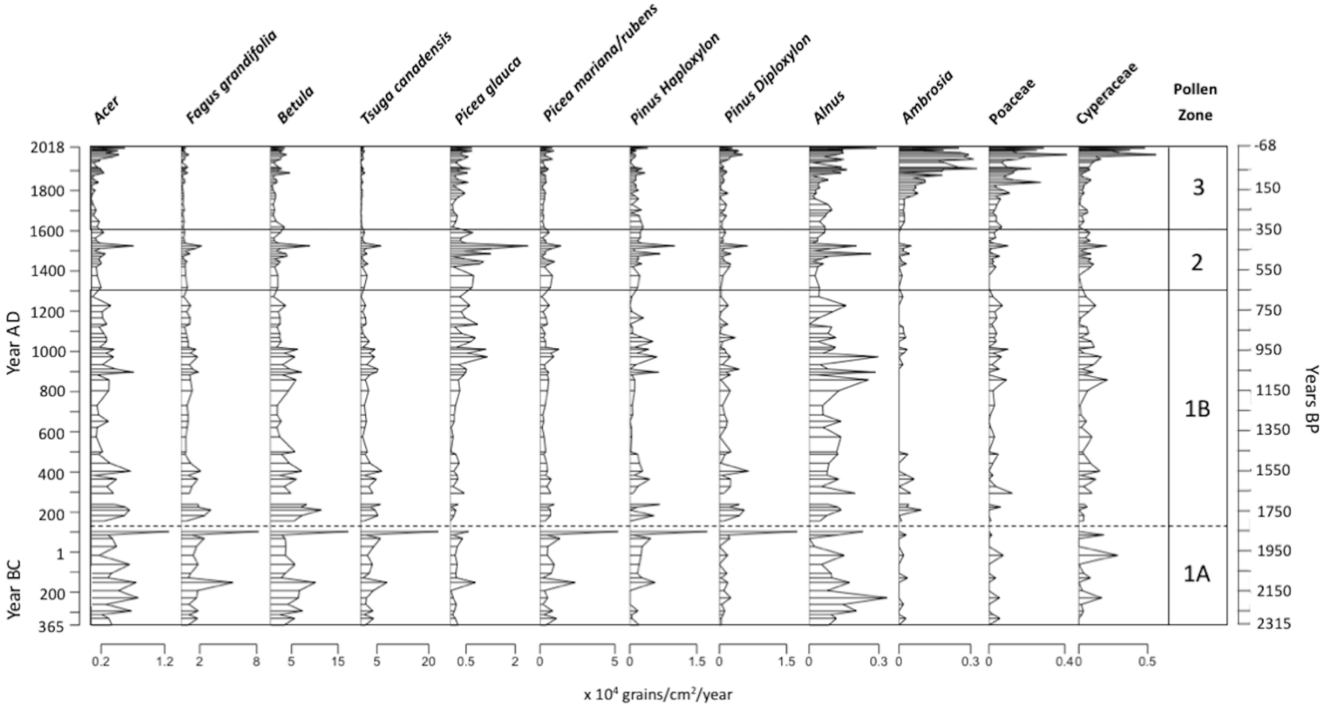
[b] None available. Sample did not yield date and was not used to construct age model.



Supplemental Figure 1. Plot of $\log_{10}$ ^{210}Pb activity (dpm/g) against core depth (cm) for Étang Fer-de-Lance core FDL2 shown with a least squares regression line ($R^2 = 0.96$, *p-value* = 5.7×10^{-10}, $n = 14$).



Supplemental Figure 2. Extended pollen graph of taxa from Étang Fer-de-Lance, southeastern Québec. Shown are pollen percentages of taxa (total pollen sum > 5% at least once in the record) split to highest reliable species resolution possible. Light grey areas show an exaggeration of 3x.



Supplemental Figure 3. Pollen accumulation rates (PAR) from Étang Fer-de-Lance, southeastern Québec. Spiking samples from AD 129 and AD 266 removed from graph for visual clarity. Total pollen influx for AD 129 was 91 x 10^4 grains/cm^2/year and for AD 266 was 223 x 10^4 grains/cm^2/year.