

**High-Resolution Record of Vegetation and Climate Change During the Holocene in
Southwestern Québec**

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Geography

Amanda Lee Lagace

Supervisor:
Konrad Gajewski

Committee Members:
Anders Knudby
Elena Ponomarenko

Department of Geography, Environment, and Geomatics
Faculty of Arts
University of Ottawa

Acknowledgments

I would like to thank Dr. Konrad Gajewski for helping me through the struggles and challenges that arose during this project and for putting up with my rebuttals, ramblings and “no – I’m not doing that!” along the way. I could not have asked for a better supervisor – you knew when I needed to be pushed (although reluctantly), or provided words of encouragement when I was lost and overwhelmed.

A special thank you to my committee members Dr. Anders Knudby and Dr. Elena Ponomarenko for their constructive feedback and the National Science and Engineering Research Council (NSERC) Discovery Grant for funding this research. And thanks to Natalie Paquette and Dr. Karen Neil for their research and data which contributed to this project.

To the “dirty hippies” of the Laboratory of Paleoclimatology and Climatology, I thank each and every one of you for your support and friendship over the past two years! You all made the lab a wonderful place to work. I feel privileged to have had the chance to meet all of you and could not imagine a more encouraging environment. Thank you to Michelle B, Mercedes, Paige, Michelle C, and Charlene for all the laughs and the unwavering support. Thank you to Camille for the collaboration and help – I could not have done it without you. To Karen – thank you for being there every step of the way and encouraging me when I doubted myself. This experience would have been very different without all of you 😊

I would like to especially thank my parents (Donna and Gerry Lagacé) for their love and support during this adventure and all the ups and downs that accompanied it. I would not have made it through without you in my corner every step of the way – and I dedicate this thesis to you.

-A

Abstract

A varved sediment sequence spanning the past ~11.0 ka was collected from Lac Noir (45.77N, 75.13W, 168 m a.s.l.) in southwestern Québec. A high-resolution pollen record documents the post-glacial vegetation history of the region over the course of the Holocene. The record shows an initial open spruce woodland, the establishment of the boreal and mixed conifer-hardwood forest into the area, as well as the expansion and contractions of tree populations in response to climate variability during the Holocene. The well known *Tsuga* decline at Lac Noir lasted 500 years starting at 5.5 ka and it took 1 460 years for hemlock to recover. The highest frequency of fire activity occurred during the early Holocene, and the lowest in the mid-Holocene. The late Holocene saw an increase in fire frequency, which could be attributed to a drier climate in eastern North America during this period. The impact of climate variability, fire disturbances and possible biotic factors on the Lac Noir vegetation are examined.

Table of Contents

Acknowledgments	ii
Abstract	iii
Table of Contents	iv
List of Tables	vi
List of Figures	vii
List of taxa common names and definitions	x

Chapter 1	Introduction	1
Chapter 2	Literature review	3
	2.1 Palynology as a tool for paleoenvironmental analysis	3
	2.2 Postglacial Vegetation and Climate History of Québec	5
	2.3 Fire History.....	10
Chapter 3	Methodology	14
	3.1 Site Selection and Field Methods	14
	3.2 Laboratory Methods	15
	3.2.1 Magnetic Susceptibility	15
	3.2.2 Varve Counting and Cross Dating	16
	3.2.3 Radiocarbon Dating (¹⁴ C)	17
	3.3 Development of Lac Noir Chronology	17
	3.4 Pollen Identification and Analysis	18
	3.4.1 Pollen Processing.....	18
	3.4.2 Pollen Identification.....	19
	3.5 Micro-charcoal Analysis	19
	3.6 Paleoclimate Reconstruction	21
	Appendix: Table and Figures	23

Chapter 4	High-Resolution Record of Vegetation Change During the Holocene in South-Western Québec.....	28
	4.1 Introduction	28
	4.2 Methodology	31
	4.3 Results.....	34
	4.3.1 Varve Chronology Development and Verification	34
	4.3.2 Magnetic Susceptibility and Varve Thickness	36
	4.3.3 Pollen record	36
	4.3.4 Micro-charcoal	38
	4.3.5 Principal Components Analysis	39
	4.3.6 Climate Reconstructions	40
	4.4 Discussion	41
	4.5 Conclusion	51
	4.6 Acknowledgments	53
	Appendix: Tables and Figures	54
Chapter 5	Summary.....	70
References	74

List of Tables

Table	Caption	Page
3.1	Annual laminations (varves) counted in sediment cores collected from Lac Noir, Québec. Counts (conducted by two researchers independently) and percentage differences for individual drives and between distinct marker beds. In the case where a marker bed located between the end of a drive and the beginning of another; each researcher counted the varves per core for a total of four counts. Drive 0 chronology (0-0.91 m) was developed by Paquette and Gajewski (2013).	23
3.2	Radiocarbon dates and calibrated ages BP (before 1950 CE) based on organic material collected from Lac Noir, Québec sediment core. *Beta-276987 and Beta-276988 were collected by Paquette and Gajewski (2013). UOC-5305 collected from basal clay section.	24
4.1	Annual laminations (varves) counted from sediment cores collected from Lac Noir, Québec. Counts (conducted by two researchers independently) and percentage differences for individual drives and between distinct marker beds. In the case where a marker bed located between the end of a drive and the beginning of another; each researcher counted the varves per core for a total of four counts. Drive 0 chronology (0-0.91 m) was developed by Paquette and Gajewski (2014).	54
4.2	Radiocarbon dates and calibrated ages BP (before 1950 CE) based on organic material collected from Lac Noir, Québec sediment core. *Beta-276987 and Beta-276988 were collected by Paquette and Gajewski (2013). UOC-5305 collected from basal clay section.	55
4.3	Loading and eigenvalues for a principal components analysis based on pollen percentages from Lac Noir, Québec.	56

List of Figures

Figure	Caption	Page
3.1	Map showing the location of Lac Noir in southwestern Québec. The red dot shows the coring location in the deepest part of the lake (16.2m). Inset map shows the location of the lake in relation to Ottawa, Ontario Canada. (Map created in ArcMap using Topographic base maps)	25
3.2	A drive from the Lac Noir sediment core with pins representing 10-yr intervals based on the annual laminations counts (varves)	26
3.3	Magnified view of the annual laminations (varves) from Lac Noir sediment core using a Leica Wild M3C stereo microscope. Coloured pins represent 10-yr intervals.	27
4.1	Map showing the location of Lac Noir in southwestern Québec. The red dot shows the coring location in the deepest part of the lake (16.2m). Inset map shows the location of the lake in relation to Ottawa, Ontario Canada. (Map created in ArcMap using Topographic base maps)	57
4.2	Visual representation of the 2 sediment cores (10 drives) retrieved from Lac Noir, Québec (September 2012).	58
4.3	Varve chronology for Lac Noir core (black line). A chronology (grey shading) was independently created based on the AMS ^{14}C dates (grey markers) using the BACON package (Blaauw, Christen, 2011) of the R program (Team, R. C., 2013). The dotted grey lines represent the 95% confidence interval for the radiocarbon chronology. The red line is a 2 nd order polynomial regression fit through the ^{14}C dates; see text for details. Varve Chronology from K Neil (Neil and Gajewski, 2018), as described in the methods. The radiocarbon chronologies were used only for verification of the annual nature of the varves; the varve chronology was exclusively used for this study	59
4.4	Magnetic susceptibility and varve thickness for Lac Noir, Québec based on average values from the overlapping drives from the two sediment cores. Magnetic susceptibility starts at 555 varve years. (Data from zone 6 is from Paquette and Gajewski, 2013).	60

- 4.5** Pollen percentage diagram for Lac Noir, Québec. Only major taxa are shown and aquatic pollen are not included. Light grey lines are 5x exaggeration applied to pollen taxa representing a small portion of the pollen sum for easier visualization. (Data for zone 6 from Paquette and Gajewski, 2013). **61**
- 4.6** Principal Components Analysis (PCA) scores, key pollen taxa, and the associated zones for Lac Noir, Québec. The zones were established by transitions in the time series of the scores. The explained variance for each axis is labelled in brackets. Refer to Table 3 for the loadings. (Data from zone 6 from Paquette and Gajewski, 2013). **62**
- 4.7** Micro-charcoal size characteristics from Lac Noir, Québec, total charcoal concentration and influx and z-scores (from the R package Paleofire; Blarquez et al, 2014). Size classes are (1) $219 \leq x < 438 \mu\text{m}^2$, (2) $438 \leq x < 875 \mu\text{m}^2$, (3) $875 \leq x < 1750 \mu\text{m}^2$, (4) $1750 > x \mu\text{m}^2$. Note changes in scale. (Data for zone 6 from Paquette and Gajewski, 2013). **63**
- 4.8** Principal components analysis of pollen percentages from Lac Noir, Québec. (A) Biplot of pollen percentages transformed using a Hellinger transformation. Dots represent the scores and arrows represent the loadings. (B) Scores showing clusters that form the basis of the zones. **64**
- 4.9** Summary diagram showing principal components scores, key pollen taxa, and the associated zones for Lac Noir, Québec. The zones were established by breaks in the time series of the scores. The explained variance for each axis is labelled in brackets. Refer to Table 3 for the loadings. (Data from zone 6 from Paquette and Gajewski, 2013). **65**
- 4.10** Pollen percentages of taxa used for paleoclimate reconstructions, summer temperature (June, July, August), annual precipitation and squared chord distance (SCD; $\times 100$ of the best analogue with the fossil sample) for Lac Noir. Reconstructions are based on the 5 closest analogues using the Modern Analogue Technique and the North American Modern Pollen Database (Whitemore et al, 2005; version 1.8). The vertical axes for temperature and precipitation are plotted at 17.5°C and 915 mm, respectively, which are the mean for the record. (Data for zone 6 based on Paquette and Gajewski (2013)). **66**

- 4.11** Paleo-environmental summary for Lac Noir, Québec, including varve thickness, magnetic susceptibility, total concentration and influx of pollen and micro-charcoal. Reconstructions of summer temperatures (June, July, August) and annual precipitation, were estimated using the modern analogue technique using the squared chord distance (SCD) as the dissimilarity metric. Principal component scores with the corresponding explained variance of each axis shown in brackets were used to define the zones. The vertical axis for temperature and precipitation baseline is plotted at 17.5°C and 915 mm, respectively, which are the mean for the record. Note changes to scale. Data for zone 6 based on Paquette and Gajewski (2013) **67**
- 4.12** Summary diagram from zone 2 (10 400 – 7 500 ka), illustrating the vegetation response to the “8.2 cooling event” in the region of Lac Noir, Québec. Key pollen and micro-charcoal characteristics are shown, including pollen percentages of major taxa, total pollen influx and concentration as well as the reconstructed summer temperatures (June, July and August) and the annual precipitation. Paleoclimate reconstructions are based on the 5 closest analogues using the Modern Analogue Technique and the North American Modern Pollen Database (Whitmore et al., 2005; version 1.8). The vertical axis for temperature and precipitation is plotted at 16.6°C and 729 mm respectively representing the mean for the specific time period. **68**
- 4.13** Summary diagram for zone 4 (5 600 – 3 500 ka) illustrating the regional response of the vegetation to the global “4.2” drought events. Key pollen and micro-charcoal characteristics are shown, including pollen percentages of major taxa, total pollen influx and concentration as well as the reconstructed summer temperatures (June, July and August) and the annual precipitation. Paleoclimate reconstructions are based on the 5 closest analogues using the Modern Analogue Technique and the North American Modern Pollen Database (Whitmore et al., 2005; version 1.8). The vertical axis for temperature and precipitation is plotted at 17.7°C and 930 mm, respectively, representing the mean for the specific time period. **69**

List of taxa common names and terms used in this thesis

Arboreal Pollen (AP)	Pollen from trees
<i>Abies balsamea</i>	Balsam fir
<i>Acer</i>	Maple
<i>Ambrosia</i>	Ragweed
<i>Alnus</i>	Alder
<i>Betula</i>	Birch
<i>Carpinus/Ostrya</i>	Hornbeam
<i>Cupressaceae</i>	A conifer tree family; in this region includes juniper and northern white cedar
<i>Cyperaceae</i>	Sedges
<i>Fagus</i>	Beech
<i>Fraxinus</i>	Ash
<i>Larix</i>	Larch
Non-Arboreal Pollen (NAP)	Pollen not from trees (eg. Including shrubs and herbaceous taxa)
<i>Picea glauca</i>	White spruce
<i>Picea mariana</i>	Black spruce
<i>Pinus banksiana (diploxylon)</i>	Jack pine (diploxylon are pines with two fibrovascular bundles per leaf)
<i>Pinus resinosa (diploxylon)</i>	Red pine (two fibrovascular bundles per leaf)
<i>Pinus strobus (haploxylon)</i>	Eastern white pine (one fibrovascular bundle per leaf)
<i>Poaceae</i>	Grasses
<i>Populus</i>	Poplar (aspen)
<i>Quercus</i>	Oak
<i>Tsuga canadensis</i>	Hemlock
Spores	Single-celled asexual reproductive grains produced from non-flowering plants
<i>Ulmus</i>	Elm

Chapter 1 – Introduction

Numerous studies have focused on the large-scale changes in the vegetation of North America during the Holocene. These studies have documented the migration of tree taxa in response to a changing climate following deglaciation (e.g., Bernabo and Webb, 1977; Prentice et al, 1991; Overpeck et al 1992; Jackson et al, 2000). These syntheses are based on accumulating a database of many time-series studies of local lake vegetation history.

Pollen deposited in sediment can be used to identify how an environment has evolved and how it was transformed by climate changes over the course of the Holocene (Birks and Birks, 1980). Pollen analysis is based on the idea that the pollen deposited and extracted from sediment can be used to infer the vegetation and environment in which it was produced (Birks and Birks, 2001). Vegetation changes can be attributed to changes in climate, introduction of a new species, or a disturbance in the area (Faegri and Iverson, 1989, p. 165).

In southwestern Québec, a few studies have documented changes in vegetation through the Holocene through the analysis of pollen records from lake sediment cores (Mott, 1977; Mott, Farley-Gill, 1981; Richard, 1994; Muller and Richard, 2001, Lavoie et al, 2015). Other studies have produced high-resolution records detailing the vegetation and climate history of the area over the last 1 000 - 3 000 years (Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014; Marlon et al, 2017). However, for the mid- and early Holocene, the available records have low temporal resolution and provide only a broad-scale reconstruction of the vegetation history. There are no quantitative climate reconstructions older than the past 1 000 years (Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014).

This thesis, which is in article format, will investigate the post-glacial history of the vegetation including levels of fire activity at Lac Noir in southwestern Québec over the course of

the Holocene at a centennial and decadal scale. It is based on the pollen analysis of a lake sediment core. The presence of annual laminae (varves) in the cores from Lac Noir provides a unique opportunity to study the response of pollen taxa at a high temporal resolution (Ojala, 2012; Paquette and Gajewski, 2013), as the chronology is more precise than those based solely on radiocarbon dates. Previous work has identified vegetation and climate changes of the past 1 000 years in the region (Lafontaine-Boyer and Gajewski, 2014; Paquette and Gajewski, 2012); my study will focus primarily on the early and middle Holocene, which has not been as well studied in comparison to the late Holocene. The fire activity history of the region throughout the Holocene will be examined by the analysis of micro-charcoal in order to determine the fire history and its relation to forest composition.

After a literature review and methods, the findings of the study will be presented in scientific article format, followed by a summary chapter concluding the thesis.

Chapter 2 – Literature Review

Palynology as a tool for paleoenvironmental analysis

One of the most remarkable traits of pollen grains is how well they are both preserved and transported, and this makes them the most important tool in the study of paleoecology (Birks and Birks, 1980). Pollen analysis is based on the observation that pollen grains can be identified and used to reconstruct the vegetation and environment from which they were produced in (Faegri and Iverson, 1989). Although few pollen grains can be identified to species, the identification of pollen grains is made to the lowest possible taxonomic level (Faegri and Iverson 1989).

The process of performing a pollen analysis is well known and the various components have been studied. Pollen are well dispersed and can usually be easily recovered and identified from anaerobic environments, including the sediments of lakes (Hicks, 1998). Different taxa will produce different amounts of pollen, and wind pollenating species will produce more pollen than species relying on insects for pollination (Birks and Birks, 1980). Pollen production of a tree located in a forest versus a tree in a field will be different, with the former producing fewer pollen grains due to the competition for light and space in the canopy (Faegri and Iverson, 1989).

There is seasonal variation among the species of tree in their pollen phenology. For example, *Corylus*, *Taxus*, and *Alnus* tend to disperse pollen around March; April is dominated by *Ulmus* and *Betula*, followed by *Quercus* in May and herbaceous pollen such as *Poaceae* and *Asteraceae* will flower later in the summer and early autumn (Birks and Birks, 1980); which can vary depending on region and year. There is annual variation in pollen production which is directly related to the climate of the year before (e.g., Grousse-Brauckman, 1978).

Shorter growing seasons, late season droughts, as well as cold snaps in the spring can also affect the pollen production (Aber and Melillo, 1991). In northern boreal forests, climate, especially temperature, have an effect on the amount of pollen produced. Temperature contributes to the quantity of pollen created in the year before the pollen is dispersed and deposited into a lake (Hicks, 2001). As a result, it is best to look at pollen counts and influx values averaged over a series of years; the average values are more likely to give an accurate representation of the location of boundaries such as treelines or of the abundance of taxa in the area (Hicks, 2001).

The dispersal of pollen is affected by atmospheric conditions including turbulence and the wind speed and direction. Properties of the pollen are important also, including the pollen grain terminal falling velocity, which depends on the weight and shape of the pollen, as well as the height and strength of the pollen source (Birks and Birks, 1980). In ordinary meteorological conditions, the largest amounts of pollen will be deposited nearer to the source, a few hundred meters from the originating tree, with less and less pollen deposited farther out, to a maximum distance many tens to thousands of km or more (Birks and Birks, 1980; Faegri and Iversen, 1989). The “pollen rain” refers to the process where pollen grains fall out of the atmosphere and blanket a surface (Faegri and Iversen, 1989). In comparing deposition of pollen between small and large lakes, smaller lakes are more likely to act as catchments for local and shoreline taxa, while the greater surface area of a large lake will allow for a greater chance to act as a catchment for pollen transported from long distances (Faegri and Iversen, 1989). In the case of deposition in a lake, pollen is subject to horizontal and vertical movement before it is deposited into the sediment of the lake basin (Birks and Birks, 1980). In most cases deciduous taxa pollen are evenly distributed evenly across a lake bottom. Aquatic taxa and *Salix* are more often found in the shallow portions of a lake and near the originating source (Birks and Birks, 1980).

The resilient pollen exine is, in most cases, preserved after sedimentation and can be used to identify pollen grains to family, genus, or in some cases species, despite the biological, chemical and physical process grains are exposed to in the natural environment (Birks and Birks, 1980). The preservation of pollen creates the opportunity to use it as a proxy to investigate past vegetation and climate relationships (Davis et al, 2013).

Postglacial Vegetation and Climate History of Québec

Following the retreat of the Laurentide Ice Sheet and before the isostatic uplift, the land was depressed sufficiently to be covered by a large proglacial lake, the Champlain Sea, fed by the Atlantic Ocean (Mott and Farley-Gill, 1981). The Champlain Sea reached as far as Gatineau Park, and its presence deposited a layer of sediment (Leda Clay) throughout the region. Radiocarbon dates from a Quaternary pollen profile of the Ottawa region confirmed the existence of the Champlain Sea east of the Gatineau Park until $12\,200 \pm 160 - 11\,600 \pm$ cal yr BP, with uplift in the region most likely occurring approximately 11 000 years ago (Mott and Farley-Gill, 1981; Rust and Romanelli, 1975).

i. Vegetation history of southwestern Québec

The development of the vegetation across Canada was affected by the paleogeographic changes associated with deglaciation and the climate history of the particular region. The climate associated with the early Holocene enabled a north-ward migration of a boreal-type forest in the region, as the Laurentide ice sheet continued to retreat (Bartlein et al, 1983). During the early Holocene, between 11 000 cal yr BP - 7 000 cal yr BP, pollen records indicate an abundance of *Picea* and herb pollen (e.g., *Gramineae*, *Chenopodiineae*, *Artemisia*, *Ambrosia*, *Compositae* and *Plantago*) (Bernabo and Webb, 1977).

The initial increase of *Picea* in the early Holocene was followed by an increase in *Pinus*. *Pinus* remained the dominant species through the early Holocene and would continue to migrate northward, while *Quercus* continued to establish itself in the region (Bernabo and Webb, 1977). The vegetation at the end of the early Holocene can therefore be described as a forest dominated by *Pinus*, and *Quercus*. During this time, other taxa, including *Betula*, *Acer*, *Fagus* and *Tsuga*, were increasing in abundance. Most of the species presently found in the area had migrated into the region by 9 000 cal yr BP (Ritchie, 1987).

During the mid-Holocene (7 000- 4 000 cal yr BP) the region and its vegetation underwent more gradual transitions than during the early Holocene (Bernabo and Webb, 1977). *Picea* continued to decrease, as did *Pinus*, while forest communities with dominant trees taxa including *Betula*, *Acer*, *Fagus* and *Tsuga* were fully established in the region (Bernabo and Webb, 1977). To the north, the modern-day boreal forest reached its present-day range and tree limit approximately 5 000 years ago (Ritchie, 1987).

The late Holocene, from 4 000 cal yr BP to the present, saw an expansion southward of *Picea* and other taxa of the boreal forest in northeastern Canada (Bernabo and Webb, 1977). *Pinus* remained the dominant species in north-eastern North America and *Quercus* decreased in abundance. The prairie-forest border, as seen in the percentages of herb pollen, was displaced westward. Overall changes in the vegetation in north-eastern North America were small in comparison to changes that would occur with the arrival of Europeans (Bernabo and Webb, 1977). The cutting and burning of forests for agricultural purposes during European colonization led to a decrease in *Pinus*, *Quercus*, and an increase in herbaceous plants in many areas. *Picea* population remained stable during this period; however, *Pinus* and *Tsuga*, and deciduous taxa such as *Quercus*, *Betula*, *Acer*, and *Fagus* continued to decrease (Bernabo and Webb, 1977).

ii. *Climate history of southwestern Québec*

The Holocene experienced long-term changes in the latitudinal and seasonal distribution of incoming solar radiation related to the Milankovitch orbital variations, which had an affect on the climate and the vegetation (Ritchie, 1987). From 16 000 cal yr BP – 6 000 cal yr BP the northern hemisphere saw an increased seasonal cycle of solar radiation with maximum levels achieved at 9 000 cal yr BP. This led to the hemisphere receiving 8% more incoming solar radiation in summer, resulting in higher land surface temperature in North America, with mean temperatures in July reaching levels 2.5°C higher than present day (ie 20th Century) temperatures (Ritchie, 1987; Kutzbach and Guetter, 1986). The warmer temperatures allowed for *Picea* to migrate further northward from the tree lines limits in the United States (Ritchie, 1987).

Ice wedges associated with the Laurentide ice sheet after its deglaciation in the region resulted in permafrost conditions. These conditions are associated with the dominance of herb pollen in the area and tundra-like conditions following deglaciation preceding the establishment of the boreal forest (Dionne, 1975; Péwé, 1983). The ice-free land in the maritime region created a climate gradient between the maritime and Great Lakes-St Lawrence region. This climate gradient resulted in a slow expansion of *Picea*, *Betula*, *Abies* and *Populus* taxa into southwestern Québec (Ritchie, 1987). Overall the early Holocene can be characterized as having a warmer climate by 2°C, and 125 mm less precipitation annually (Ritchie, 1987).

The climate over the last 10 000 years in North America can be divided into four parts based on climate shifts which occurred approximately every 2 500 years (Viau et al, 2006). There was a rapid warming until 8 000 cal yr BP, followed by a cooling from 8 000 cal yr BP- 6 000 cal yr BP. The cooler interval was followed by an abrupt warming during the middle of the Holocene,

followed by a slight cooling after 3 000 cal yr BP (Viau et al, 2006). Superimposed on this four-part structure are millennial-scale climate variations and the Little Ice Age (LIA) and Medieval Climate Anomaly Period (MCA) are the most recent examples of the millennial-scale temperature variations in North America (Viau et al, 2006). In addition, there are climate variations of other scales. An example of an abrupt climate variation is the 8.2 ka cold event, which saw a decrease in temperatures in some parts of the world. It is thought to be associated with a sudden increase of meltwater from the collapse of the ice dome located over the Hudson-Bay region (Gregoire et al, 2012). The rapid influx of meltwater would have resulted in a change in the atmosphere and circulation systems and can be linked to the brief cooling period (Barber et al, 1999; Dean et al, 2002; Alley and Agustsdittor, 2005; Matero et al, 2017).

The increase in *Tsuga* and *Pinus strobus* in the region could be used to conclude that summer mean temperatures were warmer between 9 000 cal yr BP – 5 000 cal yr BP (Ritchie 1987). The northern migration of *Tsuga* at 5 000 cal yr BP and until the LIA indicates the region experienced warmer summers than the present day (Ritchie, 1987). The mid- to late-Holocene saw the initial transition into a cooler than present day climate starting between 3 000 cal yr BP - 6 000 cal yr BP, which is associated with an increase in *Picea*, and *Abies* (Ritchie, 1987; Webb et al., 1983). A drought, perhaps with near-global impacts, at 4 200 years ago was identified and has shown to have had impacts on the environment and vegetation at the time in some regions. The drought resulted in lower water tables levels, and resulted in drier conditions and climate in central North America (Booth et al, 2005, Shuman and Burrell, 2017).

iii. *Lac Noir: The last 1000 years*

Paquette and Gajewski (2013) published a pollen record of the past 1 000 years from Lac Noir in southwestern Québec and noted the changes in vegetation in the region in response to climate variations such as the LIA and MCA. During this time period, the area was dominated by arboreal taxa including *Pinus*, *Tsuga*, *Betula* and *Fagus*. From 990 - 1560 AD *Tsuga* and *Fagus* pollen percentages were high in the area, while *Pinus haploxylon*, *Picea*, and *Abies* had lower values. *Betula* showed no long-term trend over the last 1 000 years (Paquette and Gajewski, 2013). *Acer* pollen percentages were higher between 990 – 1560 AD, and *Acer* had lower pollen percentages (lowest at 0.6%) between 1310 - 1560 AD). Total pollen accumulation rate (PAR) was higher between 990-1560 AD, especially for hardwood species, before a decrease around 1560 AD (Paquette and Gajewski, 2013). Between 1560 – 1810 AD, *Acer* had lower percentages than it had in the previous time period. *Pinus haploxylon* percentages were relatively high during this time period, with two notable peaks at ~1580 AD (29%), and ~1770 AD (41%) (Paquette and Gajewski, 2013). *Pinus diploxylon* increased overall during this period, but experienced slight variations in its percentages. *Tsuga* and *Fagus* percentages decreased quickly ~1580 AD, before a slight resurgence in their percentages at 1740 AD and 1760 AD. Total PAR for hardwoods and *Tsuga* were low during this time period and *Abies*, *Picea*, *Pinus* and *Alnus* accumulation rates increased (Paquette and Gajewski, 2013). Overall it was concluded there was a small increase in total PAR from 1560-1810 AD, followed by a decrease from leading into 2010 AD. They also noted an increase in herbaceous pollen including *Ambrosia*, *Poaceae*, *Plantaginaceae* and *Rumex* at ~1810 AD, with the highest values occurring 1860-1920 AD, which correlates with European settlement in the region (Gajewski et al, 1985, 1987; Muller and Richard, 2001).

Lac Brulé is located approximately 25 km west of Lac Noir, and the vegetation changes in the area have also been studied (Lafontaine-Boyer and Gajewski, 2014). As is the case with Lac Noir, the Lac Brulé region was dominated by *Tsuga*, *Acer* and *Fagus* preceding and leading into the MCA followed by an increase in boreal pollen and *Alnus* during the LIA (Lafontaine-Boyer and Gajewski, 2014). Both regions saw an increase in *Ambrosia* following the arrival of Europeans ~ 1860 AD. Since there are no farms located in the close vicinity of either of the lakes, Lafontaine-Boyer and Gajewski (2015) suggest the rise of *Ambrosia* is related to European presence within the general region, for example along the river valleys. Although the two lakes are relatively close together, each experienced a different timing to the onset in the decline of *Tsuga*; the decline in the *Tsuga* population began in 1375 AD at Lac Brulé, and 200 years later at Lac Noir (Lafontaine-Boyer, 2014). The Lac Brulé region saw a decrease in *Tsuga* around the same time there was an increase in charcoal accumulation, suggesting a fire may have had an impact on the *Tsuga* in the area (Lafontaine-Boyer and Gajewski, 2014). No such peak was found in the charcoal levels around Lac Noir, and Paquette and Gajewski suggest *Tsuga* declined due to the cooling of the LIA (2013).

Fire History

The frequency of fire varied throughout the Holocene, and in many cases, changes occurred in response to climate change (Whitlock et al, 2003). Terrestrial ecosystems are sensitive to fire disturbances, coniferous forests more so than hardwood forests (Spurr and Barners, 1980; Wright and Bailey, 1982; Talon et al, 2005). Boreal forests tend to experience more high intensity crown fires which create the opportunity for forest regeneration and the introduction of new successions (Flannigan, 2015). High intensity crown fires associated with Boreal forests in North America are

more likely to result in the loss of most trees in the area and the establishment of a new forest dynamic (Rogers et al, 2015).

There are three different types of fire which can result in the creation of charcoal and potentially deposited into lake sediment: surface fire, crown fire, and ground fire (Scott, 2000). A ground fire can be fueled by foliage, limbs, logs, brush, grass, duff and roots of trees. Crown fires move along the uppermost portion of the trees and can be fueled by foliage, branches, snags and moss (Scott, 2000). Crown fires can also result from a high intensity surface fire that has spread to the crowns of the trees in the area. Deciduous trees have higher moisture contents in the leaves, resulting in the crown portion of the tree being less likely to burn. Some species of coniferous trees have thicker bark and fewer lower branches, enabling them to withstand the fire and prevent fires from reaching the canopies. They may also have serotinous cones which allow for seeding of the area after a high intensity fire (Flannigan, 2015). Due to the climate, moist conditions, and tree taxa populating the conifer-hardwood forest of southeastern Canada, most fires would not have a large affect on forest dynamics due to the low level of flammability of the forests (Long et al., 2011; Carcaillet and Richard, 2000; Fuller, 1997; Clark et al., 1996; Hély et al., 2000).

The present-day fire intervals are approximately every 90 years in the mixed wood region of western Québec (Bergeron et al, 2004). Southwestern Québec experiences more fires ranging in sectors from >10 ha and 1 000 – 100 000 ha than the coniferous boreal forest to the north. The coniferous boreal forest to the north experiences larger fires (1000-100 000 ha) due to its forest composition.

During the Holocene, eastern North America experienced lower levels of fire activity in comparison to both the rest of the North America and to present-day activity (Power et al, 2008).

There have been fewer fires recorded in the North America boreal forest since the end of the LIA (Grenier et al, 2005). Records from 30 lake sites in eastern Canada indicate that there was a high frequency of fires during the early-Holocene compared to present-day fire regimes (Carcaillet et al, 2001; Ali et al, 2008; Power et al, 2008). Fire frequencies decreased further during the middle Holocene by ~8 000 cal yr BP, while the late Holocene experienced a fire frequency similar to those of the present day (Power et al, 2008). The Great Lakes region to the has experienced a slight increase in the number of forest fires, which has led researchers to conclude that global climate trends are not directly having an affect on the frequency of forest fires, but on the types of species that are populating the two regions (Grenier, 2005).

There were eight fires on site in southern Québec region during the early and mid-Holocene until 6 300 cal yr BP, with evidence of a higher rate of occurrence in the early Holocene than in the late Holocene (Talon, 2005). Little evidence of fire activity was found after 6 300 cal yr BP in the region leading to the conclusion that that fires were not large enough to have a significant impact on the environment (Talon et al, 2005). A study in southern Québec recorded 11-17 fires in the region over the Holocene, with the highest frequency occurring between 9 700- 5000 cal yr BP, however, smaller fires may not have been detected by the analysis and more fires could have occurred (Payette et al, 2017). Periods of drought and drier conditions resulted in more fires, and the establishment of fire-resistant species. In comparison, wetter and cooler climates during periods of the Holocene resulted in lower frequencies of fires with the establishment of more fire-sensitive species. The low frequency in southwestern Québec since the LIA has been attributed to the general climate warming, and the lower number of droughts in the area.

Paquette and Gajewski (2013) studied the fire history of Lac Noir over the past 1 ka and noted only one peak in charcoal accumulation rates, but no change in the forest composition

between 1120-1140 AD. They concluded the charcoal fragments in the lake sediment were either from small fires in the region, and pollen still accumulated in the lake from other sources around or lake, or that was the fire was elsewhere. Fire frequency in the region increased with the arrival of European and burning of land associated with agricultural purposes (Bernabo and Webb, 1977). Charcoal fragments found in the core from Lac Brulé showed a fire in the area occurred around 1375 AD, but there was no other indication or evidence of long-term changes in the fire regime (Lafontaine-Boyer and Gajewski, 2014). In addition, local Indigenous populations, and the arrival of Europeans would have impacted the area and resulted in higher herb pollen amounts due to land clearing, burning and farm abandonment. This was seen in the rise of *Ambrosia* at 1860 AD in the Lac Brulé and Lac Noir studies (Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014). Overall, changes or significant numbers of forest fires would not be expected in the region over the last 2 000 years, as forest dynamics are not greatly affected by fires in this region due to the low level of flammability of the conifer-hardwood species (Burns and Honkala, 1990; Fuller, 1997; Hély et al, 2000).

Chapter 3 - Methodology

3.1. Site Selection and Field Methods

Lac Noir (45.7756N, 75.1347W, 168 m a.s.l.) is located in southwestern Québec approximately 60 km north east of Ottawa, Ontario, at an elevation of 168m (Figure 3.1). It is located within the Papineau regional municipality and falls under the regional administration of the Outaouais (Le Gouvernement du Québec, 2016). It was formerly known as Lac Blais until its name and status were rescinded in 1981 and formally changed to its current name of Lac Noir (Le Gouvernement du Québec, 2016).

Lac Noir is found within the Great Lakes-St. Lawrence forest region, between the St. Lawrence lowlands and the Laurentian Highlands (Braun, 1950; Rowe, 1972). The region is a conifer-hardwood forest which acts as a transition zone between the deciduous forests to the south and the boreal forests to the north, and is dominated by species in the genera of *Pinus*, *Picea*, *Tsuga*, *Acer*, *Quercus*, *Betula*, and *Fagus* (Braun, 1950; Burns and Honkala, 1990; Rowe, 1972). There is a chain of rolling hills associated with the Laurentian Highlands (100m) which enclose the area, and a hill (400m in height a.s.l) adjacent to the lake on its western banks. The eastern side of Lac Noir consists of agricultural land in the valley of La Petite Nation region, and two summer cabins can be found on the lake (Paquette and Gajewski, 2013). Lac Noir measures approximately 300m in width and 450m in length and is ~16.2m in the deepest portion of the lake (Paquette and Gajewski, 2013).

The closest weather station is to the west in the Notre Dame de la Paix municipality in Québec (ID 7035666: Environment and Climate Change Canada, 2018). Over the 30-year period

of 1981-2010, the average summer temperature (June, July, August) was 17.9°C and the area receives 986 mm of precipitation per year (Environment and Climate Change Canada, 2018).

3.1.2 Field Collection

Sediment cores were collected from Lac Noir in 2012. Two parallel cores were collected in one-meter sections (“drives”) from the deepest part of Lac Noir using a modified Livingstone-type piston corer (Figure 3.2). The extracted cores totalled ~5.24m in length and contained the sediment-water profile at the top, a sequence of laminated sediments and ~30 cm of clay at the bottom. This led to the conclusion that the sediment cores would represent the full postglacial history of Lac Noir. The cores were wrapped in plastic wrap and aluminum foil for preservation and stored in a refrigerator at the Geography Department at the University of Ottawa. Inspection of the drives retrieved from Lac Noir confirmed the presence of laminations, which were subsequently determined to be annual (varves) and was therefore used to create a high temporal resolution chronology.

3.2 Laboratory Methods

3.2.1 Magnetic Susceptibility

The magnetic susceptibility of the core was analyzed at 1-cm intervals using a Bartington MS2C meter and loop sensor (Bartington Instruments, Witney, Oxon, England) (Sandgren and Snow, 2001). This instrument is used to detect the variations in the magnetic properties of the sediment; these variations can be used to correlate cores from the same lake as well as quantify and characterize sediment influx (Thompson, 1973; Thompson, 1980). Once the sequences were aligned, the magnetic susceptibility data from the two sequences were averaged to produce a curve depicting the variations in susceptibility over the Holocene (Figure 4.3).

3.2.2 Varve Counting and Cross Dating

The cores from Lac Noir were almost entirely varved, with the exception of a 14 cm section in drive 5. The annual deposits, “couplets”, are represented by a light and dark layer of sediment representing the summer and winter deposits and are typically only formed in lakes that are undisturbed at the bottom (O’Sullivan, 1983). In some cases, the varve couplets can have a distinctive colour and/or thicknesses, which are referred to as marker beds (if they are >0.5mm in thickness) or marker layers (Ojala et al, 2012). Marker beds ranged in colour from light grey to white and were typically as wide as a single varve. Marker layers were darker grey and black and spanned the width of 20-30 varves. Marker layers and beds, in conjunction with magnetic susceptibility, can be used to cross-date and correlate the two sequences in order to establish a varve-based chronology (Ojala et al, 2012).

Annual laminae were counted and pins inserted into the sediment core to represent 10-year intervals. The varve counts for the Lac Noir sediment cores were primarily counted by Dr. Karen Neil, and I counted a select number of the drives and marker layers to provide an independent estimate of the chronology and enable computation of standard error of the chronology. Dr. Neil and I did not systemically count more or fewer varves than the other during this process, suggesting the differences between our counts could be treated as random error. Ojala et al (2012) considered an acceptable standard error for varve counts to be between 1-4%. Most of the resolved varve counts fell between the acceptable ranges (Ojala et al, 2012) with the exception of drive six, which had a standard error of 6.7% (Table 1). The total number of varves counted established a chronology spanning the past ~11.6 ka.

Upon completion of counting and cross-dating the varves, the distance between the pins (10-year intervals) was measured using an Acu-Rite linear encoder and Quick-Check readout with Measure J2X software to determine the thickness of each decadal interval. These measurements were used to determine the sediment accumulation rate. A small section from the deepest portion of the core was disturbed (~4cm) with no visible laminations, and the number of years for this portion were estimated using the average varve thickness of the section above it.

3.2.3 Radiocarbon Dating (^{14}C)

To determine if the laminations were truly annual (i.e., varves), an independent chronology was estimated using radiocarbon dating. One cc of sediment was collected from 1-cm cross sections at ~20-cm increments down the core. The subsampled material was sieved with a 90 μm Nitex® mesh using deionised water and organic material was collected under a dissection microscope. The majority of the 1-cm cross sections did not provide sufficient amounts of organic material to be dated, as a result additional sediment was collected from adjacent 1-cm increments. In two individual cases an intact coniferous needle was extracted from drive and used as the material for carbon dating. The collected organic material was sent to A.E. Lalonde Accelerator Mass Spectrometry (AMS) Laboratory at the University of Ottawa for dating (Crann et al 2017).

Table 2 shows the dates returned from the AMS lab and its corresponding depth, as well as two dates from a previous study of the past 1 000 years by Paquette and Gajewski (2013). There were no reversals, and all the dates fall within chronological order. Overall, the dates were considered acceptable and a ^{14}C -based chronology was developed, as described below. This exercise was solely to verify the annual nature of the varves; all subsequent work was based entirely on the varve chronology.

3.3 Development of the Lac Noir Chronology

The radiocarbon dates returned from the AMS lab were used to establish a calibrated radiocarbon chronology using the R package “BACON” (**B**locked **A**daptive **C**omputationally **E**fficient **O**utlier **N**ominators; Blaauw and Christen, 2011). In addition, an alternate chronology was developed using a second-order polynomial regression, a commonly used method for deriving age-depth curves in paleoecology. The BACON, polynomial regression, and the varve chronology were then compared, and the similarities between the three gave us confidence in the accuracy of the varve chronology. Using any of the age-depth curves would have produced comparable results and we concluded that the laminae were varves and could therefore be used to create a high-resolution history of the study region.

3.4 Pollen Identification and Analysis

3.4.1 Pollen Processing

Pollen were extracted from a series of levels in the core. The subsamples were collected at 100-year intervals in order to obtain a complete history of the vegetation succession in the region and at 20-year intervals from areas of key interest associated with known climatic events or major transitions (3.5-4.5 ka; the 4.2 ka event and 7.5-8.5 ka; the 8.2 ka event).

The samples were processed following standard pollen extraction protocols (Faegri and Iversen, 1989). Samples of 0.5 cc of material were extracted from the sediment cores using a calibrated brass sampler. The 0.5 cc sub-samples were processed in a series of steps to remove carbonates, silica and non-pollen organic material using 10% Hydrochloric Acid, 10% Potassium Hydroxide, Hydrofluoric Acid, and Acetolysis solution. Samples were subsequently dried in 95% Ethanol, and transferred to Tertiary butanol, which was allowed to evaporate. The samples were

stained using 1% saffranin, preserved in a silicon fluid and mounted on a slide for analysis. Exotic *Lycopodium* spikes were added to each sample at the beginning of processing; this step is used to determine the concentration of the pollen grains in the sediment (Faegri and Iversen, 1989).

3.4.2 Pollen Identification

The pollen slides were analyzed under a microscope at magnification of 400x, with critical identifications made at 1000x under oil immersion. All pollen grains were identified and counted along a series of transects across the microscope slide. An average of 533 pollen grains (excluding aquatics) were counted per level in order to ensure the major taxa were estimated with sufficiently small error bars. Pollen grains were identified to at the very least the family or genus level, and in some cases to species using standard texts and a reference collection (McAndrews, et al, 1973; Faegri and Iversen, 1989; Moore et al, 1991). Pollen and spores were totaled and represented as percentages. Pollen concentration and accumulation rates (PAR) were computed and the varve thickness was used to estimate the sedimentation rate (Maher, 1980; Bennett and Willis, 2001):

$$\text{pollen concentration} = \frac{\text{total pollen sum} * \text{exotic added}}{\text{exotic counted}}$$

$$\text{pollen accumulation rate} = \text{pollen concentration} * \text{sedimentation rate}$$

3.5 Microcharcoal Analysis

Charcoal and pollen can be used to reconstruct the fire history of the region as well as the vegetation history (Birks, 1997; Bradshaw et al, 1997). Charcoal fragments are evidence of burning, and fluctuations in their concentration and influx can be interpreted as disturbances in an area (Whitlock and Larsen, 2001). Macro and micro-charcoal found in lake sediment cores can be used to infer local and regional fire events (Talon et al, 2005).

Charcoal fragments can be transported considerable distances, depending on particle size, weight and form (Talon et al, 2005). Microscopic charcoal is generally transported over longer distance and is representative of fires in a region, while macroscopic charcoal (>0.5mm) remains within the local area and is representative of a fire in the vicinity of the site (Ohlson, and Tryterud, 2000; Clark, 1988; Whitlock and Millspaugh, 1996). Pisaric (2002) found that in some cases charcoal can be transported up to 10s of km in distance, so the presence of charcoal within sediment cannot be used to draw definitive conclusions that a fire took place in close proximity to the lake. The transportation of charcoal, and the size of charcoal fragments (macro- or microscopic charcoal) must be considered when concluding whether a fire occurred within a region, or within direct proximity to the study site.

Lycopodium spikes added to the pollen subsamples during the processing stage were also used to determine the estimated concentration of charcoal fragments in a unit volume of sediment. Microscopic charcoal was counted on the pollen slides under a light microscope at 40x magnification and were divided into 4 classes sizes: class 1 ($12.5 \mu\text{m} \times 17.5 \mu\text{m} = 218.75 \mu\text{m}^2$), class 2 ($25.0 \mu\text{m} \times 17.5 \mu\text{m} = 437.5 \mu\text{m}^2$), class 3 ($25 \mu\text{m} \times 35 \mu\text{m} = 875 \mu\text{m}^2$), and class 4 ($50 \mu\text{m} \times 35 \mu\text{m} = 1750 \mu\text{m}^2$) (Whitlock and Larsen, 2002). These measurements were done by creating a grid based on the previously outlined class size using the imaging software NIS Elements. The size class method was used for counting micro-charcoal on the pollen slides from Lac Noir. This method is based on sorting the counted micro-charcoal particles into predetermined size classes and summing the individual size class to get the total area of charcoal (Waddington, 1969; Swaine, 1973; Whitlock and Larsen, 2001). It is common for micro-charcoal particles to be broken up during pollen processing and the size class method accounts for the damage by creating a total charcoal area based on summing all the charcoal classes together. Micro-charcoal particles smaller

than 90 µm are not counted and included in the sizes classes or sum total because of their high abundance and low statistical contribution to the sum area of charcoal (Whitlock and Larsen, 2001). Other studies have shown to use different particle sizes classes with the same ability to make inferences about fire activity from using the total charcoal area of the micro-charcoal (Waddington, 1981; Swain 1973, 1978, 1980; Sarmaja-korjonen, 1991; Vachula et al, 2018). The micro-charcoal counts were plotted and analyzed in a similar to way as the pollen data (Patterson III et al, 1987; Swain, 1973; Amundson, and Wright, 1979). Significant peaks in the charcoal accumulation are indicative of fire activity, while smaller peaks can be attributed to noise (Whitlock and Larsen, 2001). Local high intensity fires can be seen in the charcoal data as a significant peak in charcoal accumulation as well as an increase in magnetic susceptibility and varve thickness (Rummery et al, 1979; Cwynar, 1987; Rummery at el, 1983; Igleseias, et al, 2015).

$$\text{microcharcoal concentration} = \frac{\text{total microcharcoal sum} * \text{exotic added}}{\text{exotic counted}}$$

$$\text{microcharcoal accumulation} = \text{microcharcoal concentration} * \text{sedimentation rate}$$

3.6 Paleoclimate reconstructions

Summer (June, July, August) temperatures and annual precipitation were reconstructed using the Modern Analogue Technique and the North America Modern Pollen Database version 1.8 (Sawada, 2006; Whitmore et al., 2005). Modern samples within the region of 50°-100°W longitude and 20°-50°N latitude in the North American Modern Pollen Database were extracted. The area chosen included the eastern half of North America, to ensure not any possible analogue could be selected but only those most related and with similar taxa to the study region. Pollen taxa

that had a minimum 5% representation in at least one level of the Lac Noir cores were used; this resulted in 18 pollen taxa: *Abies*, *Acer*, *Alnus*, *Ambrosia*, *Betula*, *Curpressaceae*, *Cyperaceae*, *Fagus*, *Fraxinus*, *Larix*, *Caprinus/Ostraya*, *Picea*, *Pinus*, *Poaceae*, *Quercus*, *Tilia*, *Tsuga* and *Ulmus*. The value of the paleoclimate reconstructions was computed based on the 5 closest analogues. When only 1 and 3 analogues were used, comparable results were obtained.

Appendix: Tables

Table 3.1 – Annual laminations (varves) counted in sediment cores collected from Lac Noir, Québec. Counts (conducted by two researchers independently) and percentage differences for individual drives and between distinct marker beds. In the case where a marker bed located between the end of a drive and the beginning of another; each researcher counted the varves per core for a total of four counts. Drive 0 chronology (0-0.91 m) was developed by Paquette and Gajewski (2013).

Drive number or 'drive-marker bed' ID	Varve Count 1	Varve Count 2	Varve Count 3	Varve Count 4	Difference Interval	Percentage Error
0	-	-	-	-	-	2.3
6	710	761	-	-	-51	6.7
1	898	880	-	-	18	2.0
7	812	800	-	-	12	1.5
2	1469	1540	-	-	-71	4.6
10	1835	1760	-	-	75	4.3
8-A to 8-B	159	163	-	-	-4	2.5
8-H to 8-I / 3-A to 3-B	189	194	192	196	-7	3.6
3-I to 3-J / 9-A to 9-B	173	174	179	175	-6	3.4
9-G to 9-H / 4-A to 4-B	121	121	124	126	-5	4.1
4-G to 4-H	219	222	-	-	-3	1.4
5-BB to 5-DD	318	312	-	-	6	1.9

Table 3.2 - Radiocarbon dates and calibrated ages BP (before 1950 CE) based on organic material collected from Lac Noir, Québec sediment core. *Beta-276987 and Beta-276988 were collected by Paquette and Gajewski (2013). UOC-5305 collected from basal clay section.

Lab Id	Depth (cm)	¹⁴ C age	¹⁴ C error (±)	Cal BP (% probability)
* Beta-276987	41-42	580	40	660 - 520 (95%)
* Beta-276988	77-78	980	40	960 - 790 (95%)
UOC-5286	160-163	2 346	168	2 770 - 1 989 (95.4%)
UOC-5287	200-203	2 599	43	2 790 - 2 692 (78.6%) 2 636 - 2 614 (4.2%) 2 594 - 2 466 (12.7%)
UOC-5288	220-223	3 201	141	3 731 - 3 063 (93.3%)
UOC-5289	240-242	3 310	51	3 644 - 3 445 (91.4%)
UOC-5290	260-261	3 660	30	4 085 - 3 899 (95.4%)
UOC-5291	280-283	4 159	64	4 844 - 4 524 (95.4%)
UOC-5292	300-302	4 134	26	4 821 - 4 568 (95.0%)
UOC-5293	320-322	4 639	38	5 469 - 5 302 (95.4%)
UOC-5294	340-341	4 894	58	5 748 - 5 577 (87.9%) 5 534 - 5 480 (6.9%)
UOC-5295	360-361	5 183	25	5 990 - 5 907 (95.4%)
UOC-5296	380-382	5 492	63	6 414 - 6 180 (94.2%)
UOC-5297	400-403	6 170	71	7 251 - 6 896 (95.4%)
UOC-5298	420-421	6 708	43	7 660 - 7 500 (95.4%)
UOC-5299	432-433	7 149	27	8 014 - 7 936 (95.4%)
UOC-5300	448-449	7 621	27	8 450 - 8 379 (95.4%)
UOC-5301	480-482	8 769	155	10 214 - 9 526 (95.4%)
UOC-5302	500-502	9 078	65	10 434 - 10 152 (93.2%)
UOC-5303	511-512	9 404	33	10 728 - 10 555 (95.4%)
UOC-5304	522-524	9 610	35	11 159 - 11 050 (24.5%) 11 039 - 10 775 (70.9%)
UOC-5305*	540-543	10 080	82	11 997 - 11 315 95.4%)

Figures

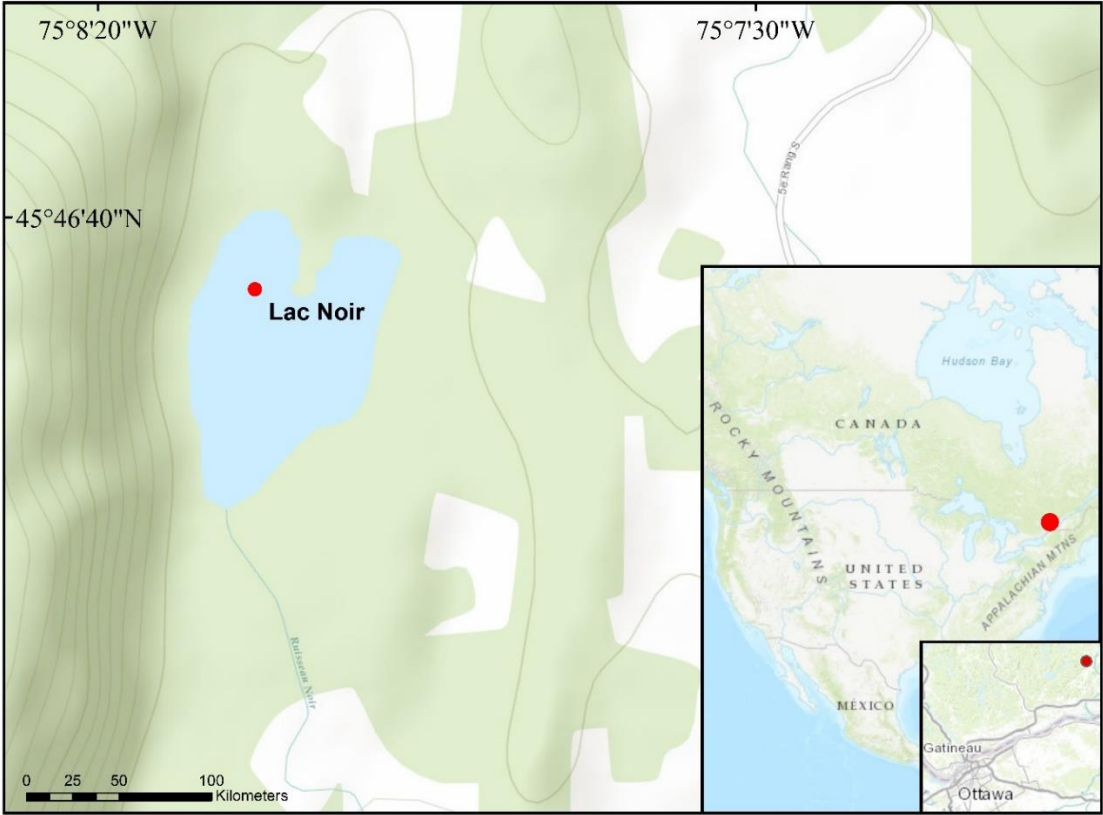


Figure 3.1 Map showing the location of Lac Noir in southwestern Québec. The red dot shows the coring location in the deepest part of the lake (16.2m). Inset map shows the location of the lake in relation to Ottawa, Ontario Canada. (Map created in ArcMap using Topographic base maps)



Figure 3.2 A drive from the Lac Noir sediment core with pins representing 10-yr intervals based on the annual laminations counts (varves).



Figure 3.3 Magnified view of the annual laminations (varves) from Lac Noir sediment core using a Leica Wild M3C stereo microscope. Coloured pins represent 10-yr intervals. Picture taken by Dr. K. Neil (2017)

Chapter 4 – High-Resolution Record of Vegetation Change during the Holocene in southwestern Québec

4.1 Introduction

Numerous studies have documented the ecological development of forests in northeastern North America over the course of the Holocene following the retreat of the Laurentide ice sheet (Mott-Farley, Gill, 1981; Ritchie 1987; Fulton et al, 1987; Fuller, 1997; Richard, 1994; Muller and Richard, 2001, Lavoie et al, 2013). Pollen deposited in sediment can be used to identify how an environment has evolved and how it was transformed by climate changes over the course of the Holocene (Birks and Birks, 1980; Faegri and Iverson, 1989). To further examine the vegetation and disturbance history of southwestern Québec, a high-resolution pollen and micro-charcoal analysis was conducted from a sediment core extracted from the region. These data were used to make a quantitative climate reconstruction for the area.

Studies have documented the major trends in the development of the vegetation including the abundance of *Picea* and herbaceous pollen in the early Holocene as the region transitioned from an open spruce-woodland, to boreal forest, to the mixed conifer-hardwood forest seen today (Bernabo and Webb, 1977; Mott and Farley-Gill, 1981; Ritchie, 1987; Fuller 1997; Muller and Richard, 2001, Oswald and Fuller 2011; Lavoie et al, 2015). There was an initial phase with high amounts of non-arboreal pollen (NAP), which also included large quantities of *Populus* pollen. This was interpreted as extensive populations of this tree expanding into the region, and it was eventually replaced by *Pinus* (Peros et al 2008; Mott, 1977; Mott and Farley-Gill 1981 Richard, 1994; Fuller 1997, Muller and Richard 2001). Deciduous taxa such as *Betula*, *Quercus*, and *Fraxinus* along with *Pinus* then migrated into the region and continued to slowly increase in

abundance by the end of the early Holocene, leading to a forest with a closed canopy. A sharp decline in *Tsuga* occurred between 6.20 - 4.80 ka, and it took *Tsuga* over 1 000 years to recover (Mott and Farley-Gill, 1981; Jackson and Whitehead, 1991; Fuller, 1997; Haas and McAndrews, 2000, Oswald and Foster, 2002; Lavoie et al, 2015; Day et al, 2013). The exact cause that led to the decrease in *Tsuga* pollen in all pollen diagrams from eastern North America is still being examined but leading hypotheses have attributed the decline to either a pathogenic outbreak, pests, or a warming and drier climate (Davis 1981; Anderson et al, 1986; Bhiry and Filion, 1996; Shuman et al, 2004 Foster et al, 2006; Zhao et al 2010, Booth, 2012; Marsicek, 2013; Oswald et al, 2016). Some studies have speculated that the drier climate at the time of the collapse weakened the trees enough for insects and/or disease to have a devastating impact (Foster et al 2006; Day et al, 2013). Peaks in *Fagus*, *Acer* and *Betula* pollen were observed as successional species replacing *Tsuga* following its decline (Mott and Farley-Gill, 1981; Davis 1981; Ritchie 1987). The late-Holocene saw the continued dominance of the mixed conifer-hardwood forest with a decrease of deciduous taxa and increase of boreal taxa associated with neoglaciation, the Medieval Climate Anomaly and Little Ice Age (Gajewski, 1988; Paquette and Gajewski, 2013; Trouet et al, 2013; Lafontaine-Boyer and Gajewski, 2014). An extensive deforestation in the St. Lawrence lowlands and increase in herbaceous pollen started between 250-200 years ago and is associated with the arrival of the Europeans into the region (Muller and Richard 2001; Muller and Richard, 2001 Oswald and Foster, 2011; Paquette and Gajewski, 2013; Lafontaine-Boyer and Gajewski, 2014).

Charcoal analysis of sediment cores from the region and elsewhere in eastern North America have shown higher fire activity during the early Holocene than in the late Holocene (Richard, 1994; Power et al, 2008). In one site in southern Québec, Talon (2005) documented at least eight forest fires over the course of the early and mid-Holocene, with highest frequencies in

the early Holocene and with little evidence of fires in the late Holocene. The lack of charcoal in the late Holocene sediments is not necessarily evidence of lack of fire during this period, but rather that the fires were not severe enough to have had a significant impact on the forest (Talon et al, 2005). The establishment of the mixed conifer–hardwood forest, which has a higher proportion of deciduous taxa than the conifer dominated forests of the early Holocene, probably contributed to the decreased number of forest fires in the mid and late Holocene due to its low flammability (Hély et al, 2001).

The climate in North America has varied throughout the Holocene and this has had an impact on the vegetation in the region. The early Holocene had low levels of precipitation related to greater summer insolation in southern Québec and across eastern North America, and a shift from dry to more wet summers around 9 000 cal yr BP in southern Québec (Richard, 1994; Muller, et al, 2003). Note that these reconstructions are based on pollen data, although there are independent sources that also have come to similar conclusions. There was a noticeable warming during the mid Holocene with peak summer temperature occurring 3 000 – 2 500 years ago, which was then followed by a cooler and wetter climate in the late-Holocene associated with Neoglacial cooling (Muller et al, 2003; Viau et al, 2006; Trouet et al 2013).

Studies in southwestern Québec examining the ecological development of the forest and its disturbance history have either been high-temporal-resolution studies focusing on the past 1 000 years, or lower-resolution studies of the entire Holocene (Mott and Farley-Gill; Muller and Richard, 2001; Paquette and Gajewski, 2013; Lafontaine and Gajewski, 2014, Lavoie et al, 2015). A recent study by Neil and Gajewski (2018) examined the diatom response to climate and terrestrial vegetation changes at Lac Noir and identified the aquatic ecosystem’s history of the

lake. This study showed the influence of terrestrial ecosystems on lake chemistry and the local aquatic community.

The purpose of this study is to produce a high-resolution pollen study spanning the Holocene. A sediment core with annual laminations (varves) was extracted from Lac Noir in southwestern Québec and provided a unique opportunity to create a precise and high-resolution chronology, which could be used to study the vegetation response to climate variations at centennial scales.

4.2 Methodology

4.2.1 Study Site

Lac Noir (45.7756N, 75.1347W, 168 m a.s.l.) is located in the southwestern region of Québec approximately 60 km north east of Ottawa, Ontario (Figure 4.1). It measures 300m in width, 450m in length and has a maximum depth of 16.2 m. The lake is bordered on the western margin by a hill (400 m a.s.l.), and agricultural land can be found within a km to the east of the lake.

The Lac Noir watershed is situated within the Great Lakes-St. Lawrence forest region, bounded by the St. Lawrence lowlands and the Laurentian Highlands (Braun, 1950; Rowe, 1972; Mott, 1977). The forest in this region can be characterized as conifer-hardwood, and is dominated by *Pinus*, *Tsuga canadensis*, *Acer*, *Quercus*, *Betula* and *Fagus*. The region is a transition Zone between the boreal forest to the north, and the deciduous forest to the south (Braun, 1950; Ritchie 1990; Richard, 1993). The Notre Dame de la Paix weather station to the west of Lac Noir recorded an average temperature in the summer months (June, July, August) over the past 30 years (1981-

2010) of 17.9°C, and an average of 985.5 mm of precipitation (ID 7035666: Environment and Climate Change Canada, 2018).

4.2.2 Core collection and Correlation

A 0.9m frozen sediment core was originally collected from Lac Noir and used for pollen analysis (Paquette and Gajewski, 2013). This study produced a high temporal resolution study (10-yr interval) which documented the vegetation's response to climate variability over the last past 1 000 years in the region. In 2012, a Livingston piston corer was used to extract two sediment sequences from the deepest part of the lake, each sequence measuring over 5.24 m in length and almost entirely varved (Figure 4.2). The uppermost section of the cores which contained the water/sediment interface was collected in a clear plastic tube. The remainder of the core was collected in 1 m sections using a Livingstone square rod sampler. The deepest portion of the sediment was primarily composed of clay (~30cm) leading to the conclusion that the sediment sequence represents the full history of the lake and surrounding region. The presence of varves provided a unique opportunity, as they can produce an accurate chronology, which can be used to identify past environmental change at a high resolution scale (Ojala et al, 2012).

These cores have also been used for a diatom analysis of Lac Noir (Neil and Gajewski, 2018). Magnetic susceptibility was measured along the sediment drives using a Bartington MS2C meter and loop sensor (Bartington Instruments, Witney, Oxon, England) with the exception the upper segment of the topmost core, as it was too unconsolidated to pass through the sensor. The drives were then cross-dated using peaks in magnetic susceptibility in addition to unique marker layers/beds identified in the sediment drives.

The varves were counted and cross-dated between the two sequences, described in the Results. Pins were inserted into the sediment drives to represent 10-year intervals, which were then measured using an Acu-Rite linear encoder and Quick-Check readout with Measure J2X software to determine the thickness of each decadal interval. These measurements were used to determine the sedimentation accumulation rate.

4.2.3 Pollen Identification and Analysis

Samples of 0.5cc of sediment were extracted using a calibrated brass sampler at 100-year intervals and were processed following standard pollen extraction protocols (Faegri and Iversen, 1989). Additional samples were extracted at 20-yr intervals at pre-selected periods of interest associated with known climate changes at 4.2 ka and 8.2 ka. Pollen extraction protocols involved using 10% Hydrochloric Acid, 10% Potassium Hydroxide, Hydrofluoric Acid, and Acetolysis solution to remove carbonates, silica and organic material. Samples were stained with 1% safranin and stored in Si oil for preservation (Faegri and Iversen, 1989). Pollen percentages were calculated based on the sum of arboreal (AP), non-arboreal (NAP) and spore counts. An average of 533 pollen grains per level (excluding aquatics) were counted in order to establish an accurate representation of the depositional environment. Two exotic *Lycopodium* spore tablets were also added to each sample in order to calculate pollen concentration. Since each sample comprised of 10-year segments, accurate estimates of pollen accumulation rates (PAR) could be made (Stockmarr, 1971; Faegri et al 1989).

4.2.4 Micro-charcoal Analysis

Micro-charcoal was counted and measured on the pollen slides (Whitlock and Larsen, 2002). Charcoal fragments were categorized into one of four classes based on their particle size, measured

using a grid created in the imaging software NIS-elements version 3.0. The charcoal size classes are as follows: class 1 ($12.5 \mu\text{m} \times 17.5 \mu\text{m} = 218.75 \mu\text{m}^2$), class 2 ($25.0 \mu\text{m} \times 17.5 \mu\text{m} = 437.5 \mu\text{m}^2$), class 3 ($25 \mu\text{m} \times 35 \mu\text{m} = 875 \mu\text{m}^2$), and class 4 ($50 \mu\text{m} \times 35 \mu\text{m} = 1750 \mu\text{m}^2$) and are included in a charcoal sum total (Paquette, 2013; Whitlock and Larsen, 2002).

4.2.5 Statistical Analysis

A principal component analysis was used to identify and summarize trends in the pollen assemblages and to establish biostratigraphic zones used in the pollen diagrams. In the pollen and micro-charcoal diagrams, data of the past 1 000 years by Paquette and Gajewski (2013) were combined with the new data presented here to produce a complete history of the entire Holocene.

Reconstructions of summer temperature (June, July and August) and annual precipitation was estimated using the Modern Analogue Technique (MAT). Modern pollen samples from latitudes between 50° - 100° W longitude, and 20° - 50° N latitude were extracted from the North American Modern Pollen Database to identify candidates for the modern analogues (Whitmore et al, 2005; Sawada, 2006). A total of 18 pollen taxa that had a minimum representation of at least >5% in one sample over the course of the Holocene were used to compute the climate reconstructions based on five analogues. Reconstructions with three and one analogue and additional pollen taxa were also conducted but minimal differences were noted.

4.3 Results

4.3.1 Varve Chronology Development and Verification

In total, 11 160 varves were counted on each of the two sediment sequences (5.24 m each) collected from Lac Noir. Distinct markers layers and beds were visible and used to correlate the

two cores. Marker layers were usually light grey to white in colour and were typically as thick as single varve. Marker beds were distinguished by darker shades of grey and black than the typical varve couplets visible in the cores and spanned the width of up to 20-30 varves.

Two researchers independently counted the varves in order to construct the varve chronology and enable computation of the standard error of the varve counts (Neil, 2018; Neil and Gajewski 2018). One researcher (Neil) counted all the varves of the Lac Noir core. The second (Lagacé) then counted varves from specific drives and between documented marker layers and beds (Table 4.1). The difference in the number of varves counted by the two people ranged between 1.5-6.7% (Table 4.1) and can be considered within the acceptable margin of error (Ojala, 2012). One person did not systematically count more or fewer varves than the other during this process, suggesting the errors are random.

A small section, less than 4 cm in length, and located in the deepest portion of the core was disturbed and had no visible varves. For this section, the number of years was estimated by using the average accumulation rate of the varved section located immediately above the disturbed area. There was also a ~30cm deposit of clay found below the oldest counted varve (11 160 varve years before 2010). A radiocarbon date was collected from this section of the core (5.4m) and dated at $11\ 650 \pm 347$ cal yr BP (UOC-5305). No samples were analyzed from this section.

A Bayesian age-depth model (Figure 4.3) was produced using the 22 AMS ^{14}C dated samples collected from Lac Noir. The independent chronology created in R using BACON was used to validate the varve chronology (Blaauw, Christen, 2011; R Core Team, version 3.4.0, 2014). The maximum difference in age between the varve chronology and the Bayesian age model was <500 years. In addition, a second order polynomial regression was fitted to the ^{14}C dates to

establish a second independent chronology, and the largest difference between the regression model and the varve chronology was <450 years. All three models produced comparable chronologies (Figure 3) and it was concluded that the laminations were annual and the varve chronology was acceptable. In the remainder of this paper, only the varve chronology was used to describe the stratigraphic changes at Lac Noir and ages are written as ka (1 000 years before present; where present is defined as 2010).

4.3.2 Magnetic Susceptibility and Varve Thickness

The highest levels of magnetic susceptibility occurred in the oldest portion of the core at ~11.10 ka and reached a level of 43.5 cgs (Figure 4.4). Susceptibility then significantly decreased to ~2.5 cgs by ~9.40 ka. There was a small peak in cgs between 8.90 ka -8.40 ka, followed by a smaller peak around ~ 7.5 ka. Subsequently, magnetic susceptibility remained stable.

Varve thickness was relatively stable between 11.10 ka – 5.50 ka with an average thickness of ~0.35mm (Figure 4). There was a gradual increase in varve thickness from 5.50 ka to 4.40 ka reaching an average thickness of ~0.55mm for the 10-year intervals. This was followed by a decrease from 4.30 ka to 3.50 ka with a low value of ~0.42 mm and an increase from 3.10 ka to values of ~1.3 mm occurring at ~1.00 ka. Varve thickness once again declined until 0.60 ka where it then began to increase again in the uppermost sediments (Figure 4.4).

4.3.3 Pollen record

Over the course of the Holocene the forest in Lac Noir has transitioned from an open-spruce woodland dominated by *Picea* in the early Holocene, which is inferred from the higher levels of herbaceous pollen (Figure 4.5). The forest then transitioned to a boreal forest as indicated by the presence of *Picea* and included the expansion of *Pinus*, to a mixed conifer-hardwood forest

with *Betula*, *Quercus*, and *Tsuga*. The northern expansion of the boreal forest saw *Pinus diploxylon* also expand further into the area closing the forest canopy and replacing *Picea* as the dominant taxa in the region by 10.00 ka (Figure 4.5). In the mid-Holocene a mixed conifer-hardwood forest was established with *Betula* and *Tsuga* replacing *Pinus* and *Picea*. The mid-Holocene also saw the decline and partial recovery of *Tsuga*. The late Holocene was characterized by the continued presence of conifer-hardwood taxa in the region including *Betula*, *Tsuga*, *Quercus*, *Fagus*, *Acer*, *Pinus* and the long distant transport of *Picea*. An abrupt increase in *Poaceae* and other NAP at the end of the late Holocene denotes the arrival of the Europeans in the region.

Zones were created based on biostratigraphic changes in the pollen assemblages in order to help in the description of the pollen record. These zones were based on the changes in the PCA scores (discussed below). The description of general pollen characteristics and zones are listed in the table below.

General description of pollen assemblage Zones

<i>Zone</i>	<i>Years (ka)</i>	<i>Pollen</i>
1	11.1 – 10.4	(gradual increase in Pollen Accumulation Rates; PAR) Abrupt decrease in the amount of <i>Pinus diploxylon</i> from 47% at 11.00 ka to 18% by 10.70 ka. As well, as an increase in <i>Picea glauca</i> from 9-23% in this time period. A gradual increase in <i>Betula</i> and <i>Quercus</i> and the highest levels of <i>Cyperaceae</i> and <i>Poaceae</i> , are recorded, indicating an open spruce-woodland.
2	10.4 – 7.4	(high and variable PAR) <i>Pinus</i> and <i>Picea</i> taxa remained relatively constant during this Zone. Peaks in <i>Pinus diploxylon</i> and <i>Picea glauca</i> at 8.26 and 8.3 ka respectively. <i>Betula</i> decreased to its lowest recorded levels between 8.40 – 7.50 ka. and <i>Tsuga</i> had an abrupt increase at the end of this Zone, starting at 7.70 ka.

3	7.4 – 5.6	<p><i>(high and variable PAR)</i></p> <p>Gradual decrease in <i>Pinus</i> and <i>Picea</i> and while other AP taxa, including <i>Betula</i>, remained constant, and with a slight increase in <i>Tsuga</i> which reached its highest levels (~41%) at 6.10 ka</p>
4	5.6 – 3.2	<p><i>(high and variable PAR, significant decrease at 3.60 ka)</i></p> <p><i>Pinus</i> and <i>Picea</i> remained stable with slight decreases by the end of this Zone. <i>Tsuga</i> sharply decreased at ~5.45 ka, with the decline to lowest values taking 400 years. It remained low (<5%) until it gradually started to increase around 3.50 ka. <i>Betula</i> and <i>Quercus</i> increased slightly during this zone.</p>
5	3.2 – 1.0	<p><i>(gradual increase in PAR), peak at 3.12 ka)</i></p> <p><i>Pinus</i> and <i>Picea glauca</i> continued to decrease to levels comparable to the present. <i>Betula</i>, <i>Tsuga</i>, <i>Quercus</i>, and other AP increased during this time period.</p>
6	1.0 - 0	<p><i>(high and variable PAR)</i></p> <p>This period is discussed in Paquette and Gajewski, 2013. <i>Betula</i> was the dominant taxa during this period reaching its highest levels. There is an abrupt increase in <i>Pinus haploxyton</i> around 0.18 ka, and <i>Tsuga</i> and <i>Fagus</i> abruptly decrease around ~0.43 ka. There is a significant increase in <i>Ambrosia</i> and other NAP taxa around ~0.10 ka which coincides with the arrival of Europeans in the region</p>

4.3.4 Micro-charcoal

The charcoal values in Zone 6 were taken from Paquette and Gajewski (2013) using slightly different methods; as a result, the absolute values are not directly comparable. To account for methodological differences in micro-charcoal estimation, z-scores are typically used (Blarquez et al, 2014). The micro-charcoal influx was normalised using the R package Paleofire (Blarquez et al, 2014), and was done separately for the two sections. This standardization of the micro-charcoal data provided the opportunity to identify overall trends of the fire history for the region across the Holocene.

Micro-charcoal influx and concentration varied considerably over the Holocene with higher frequencies and variability occurring in Zone 2 (10.40 ka -7.40 ka)(Figure 4.7). The z-scores showed relatively high values in Zones 2 and 4 and low values in 1, 3, 5 and 6. In Zones 2 and 4, maximum values were reached in the middle of the zone, with decreases in the upper part that continued into the subsequent zone. Overall, there was a higher frequency of fire activity in the early Holocene (Zone 2) than the mid and late Holocene. Micro-charcoal values continued to decrease in Zone 6, except for the uppermost levels, which dates the European period. There were significant peaks in charcoal influx at 7.88 ka (Zone 2), 6.60 ka (Zone 3), and 3.68 ka (Zone 4). The biostratigraphic Zone boundaries established by the PCA from the pollen assemblages is not synchronous with the charcoal changes (discussed below).

4.3.5 Principal Components Analysis

Principal components analysis was used to summarize changes in the pollen percentages and locate zone boundaries (Figure 4.8a and 4.8b). The first four components explained 64% of the variance (Table 4.3). The first component explained 29% of the variance while components 2, 3, and 4 explained 16%, 10% and 7% respectively (Table 4.3). The first component was negatively correlated with *Fagus*, *Acer*, *Picea*, *Betula*, and *Tsuga* and positively correlated with *Larix*, *Cyperaceae*, and *Pinus*, which indicates that the major changes in the pollen record are between pollen taxa of the deciduous-hardwood and boreal forests, with the exception of *Picea* (Table 4.3). The second component was negatively correlated with *Alnus*, *Ambrosia*, *Poaceae*, *Populus* and *Cupressaceae* and is indicative of a disturbance. The third component was negatively correlated with *Tilia* and *Ulmus*, *Quercus* and *Carpinus/Ostrya* and positively correlated with *Abies* and *Poaceae*. Component 4 was negatively correlated with *Larix* and positively correlated with *Alnus*, and *Ambrosia*. Although components 3 and 4 explain less of the

variance than the preceding components, they do show the *Ambrosia* rise associated with the arrival of the Europeans at the end of the late Holocene.

Scores for the first component remained positive from Zones 1-3, remained near zero and oscillated between small positive and negative values in Zones 4 and 5, and remained negative in Zone 6 (Figure 9). Second component scores were negative in Zone 1 and transitioned abruptly from negative to positive in Zone 2. The scores then continued to oscillate between positive and negative values in Zones 3, 4, and 6. Scores were predominantly negative in Zone 5 (Figure 4.9). Scores of component 3 were mainly positive in Zones 1 and 2, and negative in Zones 4-5. They returned to larger positive values in Zones 6. Scores of component four were negative in Zone 1, and remained very low in absolute value until the last portion of Zone 6 when they changed to positive values.

4.3.6 Climate Reconstruction

A reconstruction of summer (JJA) temperature and annual precipitation was created from the pollen percentage data using the modern analogue technique. A total of 18 pollen taxa which had a minimum of 5% representation in at least one level were used: *Abies*, *Acer*, *Alnus*, *Ambrosia*, *Betula*, *Curpressaceae*, *Cyperaceae*, *Fagus*, *Fraxinus*, *Larix*, *Caprinus/Ostraya*, *Picea*, *Pinus*, *Poaceae*, *Quercus*, *Tilia*, *Tsuga* and *Ulmus*. The squared chord distance (SCD) was used as the distance measure. Values of the SCD ranged between 5 and 16, suggesting that good analogues were found for all samples; note that these were computed on percentages, so the possible range of values is from 0-200 (Figure 4.10).

The mean average summer temperature (JJA) over the course of the Holocene in southwestern Québec was ~17.5°C and was used as a baseline to compare and distinguish the

changes in temperature. Over the past 30 years the average summer temperature recorded at Notre Dame de la Paix (the closest station to Lac Noir) was 17.9°C and had an annual precipitation level of 986 mm. (ID 7035666: Environment and Climate Change Canada, 2018). Zone 1 (11.10 ka - 10.40 ka) and Zone 2 (10.40 -7.50 ka) had lowest mean summer temperatures, with average values of 16.4°C and 16.7°C respectively. Zone 3 (7.50 ka - 5.60 ka) was marked by an abrupt increase in temperature, reaching average values of 18.2°C. Zone 4 (5.60 ka - 3.5 ka) had a mean summer temperature of 17.7°C, and temperatures increased again in Zone 5. However, there was a slight but distinct cooling in Zone 4 between 5.60 ka - 6.50 ka, with a mean summer temperature of 17.7°C. Zone 5 had the highest mean summer temperature of 18.3°C between 3.50 ka -1.00 ka. Zone 6 (1.00 ka - 0.00 ka) had an overall cooling trend and recorded an average summer mean temperature of 17.6°C.

The mean total annual precipitation over the course of the Holocene was 916 mm which is lower than modern recorded precipitation over the past 30 years of 985 mm (Figure 4.10). Zone 1 (11.10 ka - 10.40 ka) and Zone 2 (10.40 ka -7.50 ka) were relatively drier than the mid- and late Holocene. Zone 1 had an annual precipitation level of 827 mm and Zone 2 had the lowest annual precipitation level at 753 mm. Precipitation increased in Zone 3 (7.50 ka - 5.60 ka) reaching a value of 950 mm. In Zone 4 (5.60 ka - 3.50 ka), Zone 5 (3.50 ka - 1.00 ka), and Zone 6 (1.00 ka - 0.00 ka) there was a continued increase in the annual precipitation with mean values of 950 mm, 969 mm, 995 mm in respectively.

4.4 Discussion

Over the past 11 000 years there was a series of shifts in forest composition from an open-spruce woodland, to boreal forest, to mixed conifer-hardwood vegetation in southwestern Québec.

These changes are represented by the variability in the dominant pollen taxa, such as, *Picea*, *Pinus*, *Betula*, *Tsuga*, and *Quercus* throughout the Holocene.

Deglaciation in southern Québec occurred at ~13 000 cal yr BP and was almost immediately followed by the creation of the Champlain Sea as an extension of the Atlantic Ocean as a result of isostatic depression, and which fully receded from the region by 11 600 cal yr BP (Anderson, 1987; Anderson, 1988, Rodrigues 1992, Richard; 1994; Parent and Ochietti, 2007). During the time of the Champlain Sea, glacio-marine clay was deposited into the area. This clay deposit is presumably seen at the base of the sediment core collected from Lac Noir. Above this 30 cm clay layer, lake sediment was deposited, and due to conditions within the lake, it was varved. The varved portion of the sediment core measured 5.24 m. Radiocarbon dating of organic material sampled from the clay sediment returned a date of $11\ 600 \pm 82$ cal yr BP (median age; 11 997 - 11 315 (95.4%)). The oldest varve count from the sediment core was 11.16 ka. The varve chronology, deposit of marine and lack of marine diatom species present in the lowest portion of the core indicates that the sediments deposited into Lac Noir were deposited in freshwater conditions at the beginning of the early Holocene after the Champlain Sea had fully retreated from the region (Neil and Gajewski, 2018).

Early Holocene

Zone 1

The high amounts of birch, poplar and shrub pollen, as well as low spruce percentages in Zone 1 represents an open-spruce woodland landscape and the afforestation phase of the region (Fuller, 1997, Muller and Richard, 2001, Lavoie et al 2015). The high levels of herbaceous pollen in this zone can be used to infer that the canopy of forest had not yet closed (Figure 4.5). It is

possible pine and oak pollen recorded in this zone were representative of trees growing in the region by this time (Mott and Farley-Gull, 1981; Fuller, 1997). Other studies in the regions also show spruce, pine, larch, poplar and sedges dominating the landscape, and the abundance of sedges began to decrease between 11.00 ka - 10.50 ka (Mott and Farley-Gill, 1981; Ritchie, 1987; Fulton 1987; Richard, 1994; Fuller, 1997; Haas and McAndrews, 2000; Muller and Richard, 2001; Lavoie et al, 2015). Birch and pine values were relatively high in Zone 1, perhaps due to populations of dwarf birch in the region and long distant transport of pine pollen from populations further south of the study region.

The *z*-scores for micro-charcoal in Zone 1 were negative, interpreted as less than the average amount of fire activity, consistent with an open woodland forest (Figure 4.7). The climate reconstruction for this zone showed temperatures much cooler than the average for the Holocene, and the region received less precipitation (Figure 4.10). The afforestation of the region was well underway by the end of the early Holocene and leading into the mid-Holocene.

Zone 2

Spruce and jack pine were well established in the region by 10.50 ka (Zone 2) marking the transition from open woodland forest to boreal forest at Lac Noir (Figure 4.5). Birch pollen decreased as pine and spruce increased between 9.40 ka -7.58 ka. A similar decrease in birch was noted in southern Ontario, and at Ramsay Lake in the Gatineau region around 9 000 cal BP (Mott, Farley-Gill, 1981; Fuller, 1997). Other sites around the Montréal Lowlands also noted decreases in birch during this period, however the replacement species included pine, spruce, elm, oak and hemlock (Muller and Richard, 2001). In one of the study sites there was no increase in spruce (Muller and Richard 2001). PAR continued to increase through this zone as the boreal forest

became fully established. Thus, around the region, a boreal-type forest was established, with perhaps different mixtures of subdominant species depending on the region. The differences in timing may be attributed to distance from source populations or local mesoclimates, but also due to chronological errors in the varve counts used for the chronology.

In Zone 2, highest levels of fire activity occurred between 10.40 ka - 7.50 ka (Figure 4.7). Peaks in micro-charcoal z-scores at 9.10 ka, 8.80 ka, and 7.88 ka correlate with slight decreases in PAR and based on the lack of significant changes in pollen percentages for any of the pollen taxa, these could be related to small fires or fires elsewhere in the region (Figure 4.11). The establishment of the boreal forest would have made the region more susceptible to larger fire events, as fire is an important component of boreal forests (Hély et al 2001). Other studies have noted the eastern boreal forest in North America had the highest level of fire activity between 10.0 ka -7.50 ka (Carcaillet et al, 2001; Ali et al, 2008; Power et al, 2008). Talon et al (2005) noted that eight fires had occurred in the early Holocene in southern Québec prior to 6 300 cal yr BP. The temperatures during the summer months began to increase during Zone 2 but remained below the mean temperature of the Holocene while precipitation remained well below the mean amount for the Holocene (Figure 4.10). This indicates that the summer months were becoming warmer and still dry. The drier climate during the early Holocene would also be more conducive to fire activity, particularly coniferous taxa that are more susceptible to fire than deciduous taxa and the lower levels of precipitation could have provided an environment with high probability of ignition (Carcaillet and Richard, 2000; Whitlock and Larsen, 2001; Talon et al, 2005).

During this time period, there was a short-lived global cooling event at 8.2ka linked to the discharge of meltwater caused by the collapse of ice domes over Hudson-Bay, and which is believed to have had an impact on the climate system and in turn on the vegetation in North

America (Barber et al, 1999; Dean et al, 2002; Alley and Agustsdittor, 2005; Gregoire et al, 2012; Matero et al, 2017). Zone 2 is marked with high and variable PAR gradually increasing by the end of the zone. Although the vegetation at Lac Noir recorded a minor decrease in PAR between 8.32 ka - 8.20 ka, and a minor increase in jack pine between 8.26 ka - 8.24 ka there was no significant decrease in deciduous tree pollen which would indicate a change in forest composition (Figure 4.12). There was also no significant decrease in magnetic susceptibility and varve thickness to indicate that this climate anomaly had an impact on the vegetation (Figure 4.12). Other studies have shown that the 8.2 ka cooling event had a minimal and gradual impact on the vegetation, or have not observed and noted a significant change that could be associated with this event (Mott and Farley-Gill, 1981; Ritchie, 1987; Fuller, 1997; Muller and Richard, 2001; Lavoie and Filion, 2001; Dean et al, 2002; Lavoie et al 2015). Overall, by the end of the early Holocene the taxa associated with a mixed-forest were expanding into southern Québec and at Lac Noir (Overpeck et al, 1992; Lavoie et al, 2015).

Mid-Holocene

Zone 3

Birch increased abruptly at 7.50 ka from 4%-16% and then fluctuated between 8-16% for the remainder of the Zone (Figure 4.5). Based on the macrofossils found in a nearby sediment core dated from this time, these may have come from paper birch (Lavoie et al, 2015). Oak, beech, maple and other deciduous trees increased slightly during the mid-Holocene, or remained stable during this Zone and continued to dominant the forest composition. These taxa tend to be underrepresented in the pollen rain, so although they are found in low percentages, they could have contributed/originated from a significant component of the forest. Jack pine (diploxylon pollen

type) underwent a rapid decrease from 37% to 7.9% from 7.40 ka - 5.60 ka and remained low for the remainder of the Holocene (Figure 4.5).

Hemlock abruptly increased from 6% in 7.78 ka to 25% in 7.40 ka and maintained a relatively high abundance (> 17%) throughout the remainder of Zone 3 (Figure 4.5). Other studies in the region show *Tsuga* fully established in the region between 8 000-7 000 cal yr BP and reaching >20% by no later than 7 000 cal yr BP (Mott and Farley-Gill, 1981; Ritchie 1987; Jackson and Whitehead, 1991; Fuller 1997; Muller and Richard, 2001; Lavoie et al, 2015). During this time there were several declines in *Tsuga* of up to 15- 20% including one between 6.70 ka - 6.30 ka and another between 6.00 ka - 5.60 ka (Figure 4.5) with the second minor decrease coinciding with small declines noted in other studies (Fuller, 1997; Oswald and Foster, 2000). Fuller (1997) noted the first short-lived decrease in hemlock occurred in southern Ontario at 6 000 cal yr BP, and Oswald and Foster (2000) dated the decline to ~ 6 000 cal yr BP in northern New England. The minor decline in hemlock from 6.0 ka - 5.60 ka and observed in other regions was short lived in comparison to the abrupt decrease in hemlock that occurred later (5.50 ka) and is thought to have contributed to the larger collapse of *Tsuga* (Fuller, 1997; Hass and McAndrews, 2000; Muller and Richard, 2001; Oswald and Foster, 2011).

Micro-charcoal z-scores showed lower fire activity in Zone 3 than in previous Zones (Figure 4.7) and this is most likely related to the full establishment of the mixed forest which would have increased the fire resiliency of the forest (Burns and Honkala, 1990; Hély 2000). There is a notable peak in micro-charcoal at 6.60 ka, however there is no corresponding change in varve thickness (Figure 4.11). This indicates either the fire was not local to the Lac Noir area, or was a small and short lived fire with no significant impact on the vegetation. Despite the warming temperatures during this zone there was also an increase in precipitation associated with wetter

summer months which could have reduced the availability of fuel in the forest and further suppressed fire activity in the forest (Figure 4.11)(Carcaillet and Richard, 2000). The vegetation at Lac Noir was relatively stable throughout at time with the exception of the first hemlock decline which may have been related to a minor drought event (Oswald and Foster, 2002; Shuman and Marsicek, 2016). Overall precipitation increased in Zone 3, which would have further contributed to the lack of fire activity. The pollen-based climate reconstruction also shows an increase in summer temperatures (Figure 4.9). Some of the warmest summer temperatures documented by the paleoclimate reconstruction from the pollen at Lac Noir occurred in Zone 3, which corresponds with the warm climate of the mid-Holocene reconstructed across much of North America (Shuman, 2004, Viau et al 2006)

The pollen reconstruction also noted a decrease in annual precipitation from 1 063mm to 935 mm between 5.90 ka - 5.70 ka coinciding with an increase in the average summer temperatures between 6.10 ka - 5.80 ka from 18.1°C to 18.9°C and a decrease in PAR from 5.80 ka - 5.60 ka (Figure 4.11). The warmer summer temperatures along with the decrease in precipitation most likely contributed to the minor decrease in hemlock from 6.00 ka - 5.60 ka at Lac Noir (Figure 4.11)(Oswald and Foster, 2002). It could be that the drier conditions were more detrimental to the younger hemlock seedlings in the understory than it was for the older trees in the canopy. This could have contributed to the larger subsequent decline at 5.50 ka because the hemlock populations may not have had enough to recover from the minor 6.00 ka drought (Haas and McAndrews, 2000; Shuman et al, 2009; Oswald and Foster, 2011).

Zone 4

Zone 4 is distinguished by an abrupt decline in hemlock which is one of the most notable changes in the vegetation during the Holocene. Studies in the region have dated the hemlock decline as starting as early as 5 700 cal yr BP and as late as 5 100 cal yr BP (Mott and Farley-Gill, 1981; Ritchie, 1987; Jackson and Whitehead, 1991; Fuller, 1997; Haas and McAndrews, 2000, Lavoie et al, 2015). Muller and Richard showed the start of the abrupt decline in hemlock ranged from 6.20 cal yr BP- 4.80 cal yr BP in southern Québec, with the most likely age being 5 500 cal yr BP, based on a clustering of radiocarbon dates from the studies (2001). The collapse of hemlock at Lac Noir occurred between 5.50 ka - 5.00 ka, and hemlock decreased during this period from 35%-4% over the span of 500 years (Figure 4.5). Some studies concluded that this decline occurred abruptly; Oswald and Foster (2011) noted that hemlock decreased from >25% at 5 500 cal yr BP to less than 1% in a 70-year span. Other studies have concluded that the hemlock decline was a long-term process taking several hundred years (Mott and Farley-Gill 1981; Fuller, 1997; Haas and MacAndrews, 2001; Toney et al, 2003; Muller and Richard 2001; Oswald and Foster, 2011; Oswald et al, 2018). The period of low hemlock values lasted between 1 000-1 500 years in most regions, while at Lac Noir it took hemlock ~ 1 460 years to recover (Figure 4.5). Overall the collapse of hemlock at Lac Noir occurred abruptly over 500 years and persisted for a significant period of time (>1 400 years) time before its recovery. The cause of the hemlock decline is attributed to a combination of factors including a pathogen, insects, and a warm and drier climate Davis 1981; Anderson et al, 1986; Bhiry and Fillion, 1996; Shuman et al, 2004 Foster et al, 2006; Zhao et al 2010, Booth, 2012; Marsicek, 2013; Oswald et al, 2016). The increase of benthic diatom species at Lac Noir indicate a brief dry period between 5.50 ka -5.00 ka (Neil and Gajewski, 2018), suggesting a drier climate was one of the factors influencing the hemlock decline.

Eastern white pine increased from 2% - 29% between 5.80 ka – 5.10 ka (Figure 4.5). There was an increase in PAR of birch, oak, maple, elm, and alder from 4.9-3.64 ka, which coincides with their replacement of hemlock in the canopy following its decline (Figure 4.6). This was followed by a decrease in PAR of all taxa in the region at 3.60 ka, and a decrease in varve thickness which could indicate drought like conditions (Figure 4.11)(Jacques et al, 2008). There was also a significant peak in micro-charcoal influx at 3.68 ka which preceded the decrease in PAR (Figure 4.11). The lack of change in the pollen percentages during the period from 4.60 ka -3.60 ka implies that any fires were most likely somewhere in the region and did not have a direct or significant impact on the forest around Lac Noir (Figure 4.11). The middle Holocene was also still experiencing wetter summer months which would have continued to suppress fire activity in the fire along despite the warmer temperatures in this zone (Figure 4.11)(Carcaillet and Richard, 2000).

The climate reconstructions for annual precipitation show the highest values at 4.80 ka (1 275 mm) and 4.60 ka (1 155 mm) (Figure 4.10). There were also cooler periods within Zone 4, for example, at 4.70 ka - 4.50 ka (17.3°C) and 3.70 ka - 3.60 ka (17.0°C) which coincide with a cooling trend across mid-latitude North America from 5.2 ka - 4.8 ka. There were also drier phases representing potential droughts at 4.24 ka, 3.94 ka, and 3.52 ka with annual precipitation of 836 mm, 891 mm, 807 mm respectively (4.10).

Zone 4 is associated with the 4 200 global drought which was marked by warmer and drier conditions and led to lower water table levels in some regions in northeastern North America (Booth et al, 2005; Shuman and Burrell, 2017). The vegetation in the region of Lac Noir did not seem to be highly impacted by this drought and showed no significant change (Figure 4.13). There was a minor increase in varve thickness from 4.35 ka - 4.10 ka, where it increased from 0.52 mm

to 0.64 mm (Figure 4.13). Increases in varve thickness have been shown to be related to drought conditions and the increase in Lac Noir from 4.35 ka to 4.10 ka could be related to the 4 200 drought and warming conditions (Jacques et al, 2008).

Late Holocene

Zone 5

By the late Holocene, hemlock had re-established itself as a key species in the mixed conifer-hardwood forests at Lac Noir and across most of eastern North America, although it never reached the levels as it had before the decline (Figure 4.5) (Jacobson et al, 1987; Mott and Farley-Gill, 1981; Fuller, 1997; Muller and Richard 2001; Oswald and Foster, 2011). Birch, oak, pine and other taxa continued to dominate the forests in southwestern Québec (Mott and Farley-Gill 1981; Fuller, 1997; Muller and Richard, 2001.) Red and jack pine decreased further in Zone 5 suggesting they were not growing in the region at this time. Oak continued to increase, and other hardwood taxa remained relatively stable and with high values (Figure 4.5). Eastern white pine continued to slightly decrease from the relatively high values in the mid Holocene (Zone 4).

PAR gradually increased over the course of Zone 5, reaching its maximum at 1.10 ka (Figure 4.6). The PAR of taxa characteristic of the conifer-hardwood forest were high and increased throughout this period, while the PAR of jack pine was minimal and white pine was low (Figure 10). In Zone 5 there was a reconstructed increase in temperature and precipitation, based on the pollen assemblages, and fire activity was relatively low (Figure 4.11). Other studies have shown an increased frequency of fires during this period, starting around 2.50 cal yr BP (Swain, 1973; Carcaillet and Richard, 2000); at Lac Noir there was only a small increase in the z-scores. The significant portion of deciduous trees found in the mixed conifer-hardwood forest established at

Lac Noir by the mid and late-Holocene would have contributed to the fire resiliency of the vegetation and forest (Hély et al, 2001, Carcaillet et al, 2001). The minor increase in micro-charcoal z-scores could be attributed to the possible drought like conditions and the drier summers seen across eastern North America that could have made the forest minimally more susceptible to forest activity (Carcaillet and Richard, 2000)(Figure 4.7).

The vegetation and fire history of the past 1ka is discussed in Paquette and Gajewski (2013) and Lafontaine-Boyer and Gajewski (2014).

4.5 Conclusions

Since the collapse and retreat of the Laurentide Ice Sheet and the Champlain Sea, the vegetation at Lac Noir has progressed from open spruce-woodland, to boreal forest, to the mixed conifer-hardwood forest found in the landscape today. The high-resolution varve chronology constructed for this study created a unique opportunity to observe and identify the response of the local vegetation to climate variability. The vegetation composition at Lac Noir has shown to be similar to other studies in the region with only some minor variations (Mott and Farley-Gill, 1981; Fuller 1997, Muller and Richard, 2001; Lavoie et al, 2015).

In the early Holocene, Lac Noir was an open spruce-woodland. This was followed by the northward expansion of the boreal forest, and the closing of the canopy in the region. There was a minor increase in jack pine between 8.26 ka - 8.24 ka, and a decrease in PAR from 8.32 ka - 8.20 ka which could be attributed to the 8.20 ka global cooling event (Figure 4.12). By the end of the early Holocene, the modern mixed conifer-hardwood forest was already starting to replace the boreal forest and dominate the landscape. The mid-Holocene saw a minor decline in hemlock from 6.00 ka - 5.60 ka, followed by an abrupt decrease from 5.50 ka - 5.00 ka, and the period of reduced

hemlock lasted 1 460 years at Lac Noir (Figure 4.5). The late Holocene saw the continued dominance of the mixed conifer-hardwood forest, potential drought conditions recorded in the varve thickness from 4.35 ka - 4.10 ka (Figure 4.13), and a sudden opening of the forests with the arrival of the Europeans (Figure 4.11).

There were higher rates of fire activity in the early Holocene than in the middle and late Holocene which can be attributed to the lower levels of precipitation and higher summer solar radiation (Figure 4.7) (Carcaillet and Richard, 2000; Carcaillet et al, 2001, Long et al, 2011). In addition to the wetter summer months during the middle Holocene the mixed conifer-hardwood forests established in the region by these times would have made the forest more resilient to fire activity. Therefore, any fire activity occurring after the establishment of these forests would not have a large or significant impact on the forest composition in the region (Burns and Honkala, 1990; Clark et al., 1996; Fuller, 1997; Carcaillet and Richard, 2000; Hély et al., 2000; Long et al., 2011). The end of the late Holocene saw an increase in fire activity in the region despite the increase in precipitation and temperatures (Figure 4.11). Carcaillet and Richard (2000) concluded the increase in fire activity starting in 3 ka BP in Québec could be due to an increase in seasonality resulting in higher levels of precipitation during the winter months, and drier summers. There was no overall significant relationship between the peaks in micro-charcoal influx or z-score and the reconstructed climate conditions for Lac Noir except that they were found during periods of lower precipitation or warmer temperatures. The majority of the micro-charcoal peaks for zones 3-6 occurred during periods of warmer temperatures despite there also being varying levels of precipitation but in most cases there are higher levels fire activity when the surface litter is very dry as a result of low levels of precipitation, higher summer temperatures and wind (Figure 4.11)

(Harrington et al, 1983; Flannigan and Harrington 1988; Clark, 1989; Payette et al, 1989; Harrington and Flannigan, 1993; Carcaillet and Richard 2000).

Overall, vegetation changes in the Lac Noir region were not only influenced by climate but were also impacted by other variables including pests, pathogens and fire disturbances, which contributed to the forest variability and succession at Lac Noir during the Holocene.

Acknowledgments

This project was funded by a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). We thank Francois Fortier and Peter Langlois for access to the lake, Natalie Paquette for her data from the lake, and to Dr. Neil for the development of the varve chronology.

Appendix: Tables

Table 4.1 Annual laminations (varves) counted from sediment cores collected from Lac Noir, Québec. Counts (conducted by two researchers independently) and percentage differences for individual drives and between distinct marker beds. In the case where a marker bed was disrupted by the end of a drive and the beginning of another; each researcher counted the varves per core for a total of four counts. Drive 0 chronology (0-0.91 m) was developed by Paquette and Gajewski (2014).

Drive number or 'drive-marker bed' ID	Varve Count 1	Varve Count 2	Varve Count 3	Varve Count 4	Difference Interval	Percentage Error
0	-	-	-	-	-	2.3
6	710	761	-	-	-51	6.7
1	898	880	-	-	18	2.0
7	812	800	-	-	12	1.5
2	1469	1540	-	-	-71	4.6
10	1835	1760	-	-	75	4.3
8-A to 8-B	159	163	-	-	-4	2.5
8-H to 8-I / 3-A to 3-B	189	194	192	196	-7	3.6
3-I to 3-J / 9-A to 9-B	173	174	179	175	-6	3.4
9-G to 9-H / 4-A to 4-B	121	121	124	126	-5	4.1
4-G to 4-H	219	222	-	-	-3	1.4
5-BB to 5-DD	318	312	-	-	6	1.9

Table 4.2 Radiocarbon dates and calibrated ages BP (before 1950 CE) based on organic material collected from Lac Noir, Québec sediment core. *Beta-276987 and Beta-276988 were collected by Paquette and Gajewski (2013). UOC-5305 collected from basal clay section.

Lab Id	Depth (cm)	¹⁴ C age	¹⁴ C error (±)	Cal BP (% probability)
* Beta-276987	41-42	580	40	660 - 520 (95%)
* Beta-276988	77-78	980	40	960 - 790 (95%)
UOC-5286	160-163	2 346	168	2 770 - 1 989 (95.4%)
UOC-5287	200-203	2 599	43	2 790 - 2 692 (78.6%) 2 636 - 2 614 (4.2%) 2 594 - 2 466 (12.7%)
UOC-5288	220-223	3 201	141	3 731 - 3 063 (93.3%)
UOC-5289	240-242	3 310	51	3 644 - 3 445 (91.4%)
UOC-5290	260-261	3 660	30	4 085 - 3 899 (95.4%)
UOC-5291	280-283	4 159	64	4 844 - 4 524 (95.4%)
UOC-5292	300-302	4 134	26	4 821 - 4 568 (95.0%)
UOC-5293	320-322	4 639	38	5 469 - 5 302 (95.4%)
UOC-5294	340-341	4 894	58	5 748 - 5 577 (87.9%) 5 534 - 5 480 (6.9%)
UOC-5295	360-361	5 183	25	5 990 - 5 907 (95.4%)
UOC-5296	380-382	5 492	63	6 414 - 6 180 (94.2%)
UOC-5297	400-403	6 170	71	7 251 - 6 896 (95.4%)
UOC-5298	420-421	6 708	43	7 660 - 7 500 (95.4%)
UOC-5299	432-433	7 149	27	8 014 - 7 936 (95.4%)
UOC-5300	448-449	7 621	27	8 450 - 8 379 (95.4%)
UOC-5301	480-482	8 769	155	10 214 - 9 526 (95.4%)
UOC-5302	500-502	9 078	65	10 434 - 10 152 (93.2%)
UOC-5303	511-512	9 404	33	10 728 - 10 555 (95.4%)
UOC-5304	522-524	9 610	35	11 159 - 11 050 (24.5%) 11 039 - 10 775 (70.9%)
UOC-5305*	540-543	10 080	82	11 997 - 11 315 95.4%)

Table 4.3 Loading and eigenvalues for a principal components analysis based on pollen percentages from Lac Noir, Québec.

	PC1	PC2	PC3	PC4
<i>Fagus</i>	-1.78	0.06	0.30	-0.33
<i>Acer</i>	-1.66	-0.03	0.065	0.06
<i>Picea</i>	-1.58	-0.40	-0.02	-0.70
<i>Betula</i>	-1.56	-0.73	0.28	0.02
<i>Tsuga</i>	-1.29	0.32	-0.31	-0.31
<i>Fraxinus</i>	-1.14	-0.12	0.34	0.09
<i>Tilia</i>	-0.93	-0.12	-0.95	0.06
<i>Ulmus</i>	-0.74	0.09	-0.89	0.08
<i>Alnus</i>	-0.20	-1.24	-0.70	0.81
<i>Ambrosia</i>	-0.03	-1.15	0.51	0.99
<i>Poaceae</i>	0.10	-1.29	0.69	0.67
<i>Populus</i>	0.15	-1.21	0.29	-0.33
<i>Quercus</i>	0.18	-0.37	-1.56	0.39
<i>Carpinus/Ostrya</i>	0.33	-1.03	-1.06	-0.37
<i>Abies</i>	0.33	-0.84	0.46	-0.34
<i>Cupressae</i>	0.53	-1.27	0.17	-0.69
<i>Larix</i>	0.91	-0.61	-0.25	-0.99
<i>Cyperaceae</i>	1.32	-0.55	-0.06	-0.48
<i>Pinus</i>	1.72	0.66	-0.04	0.30
Eigenvalue	5.60	3.00	1.90	1.33
Proportion Explained	0.29	0.16	0.10	0.07
Cumulative Proportion	0.29	0.45	0.55	0.62

Figures

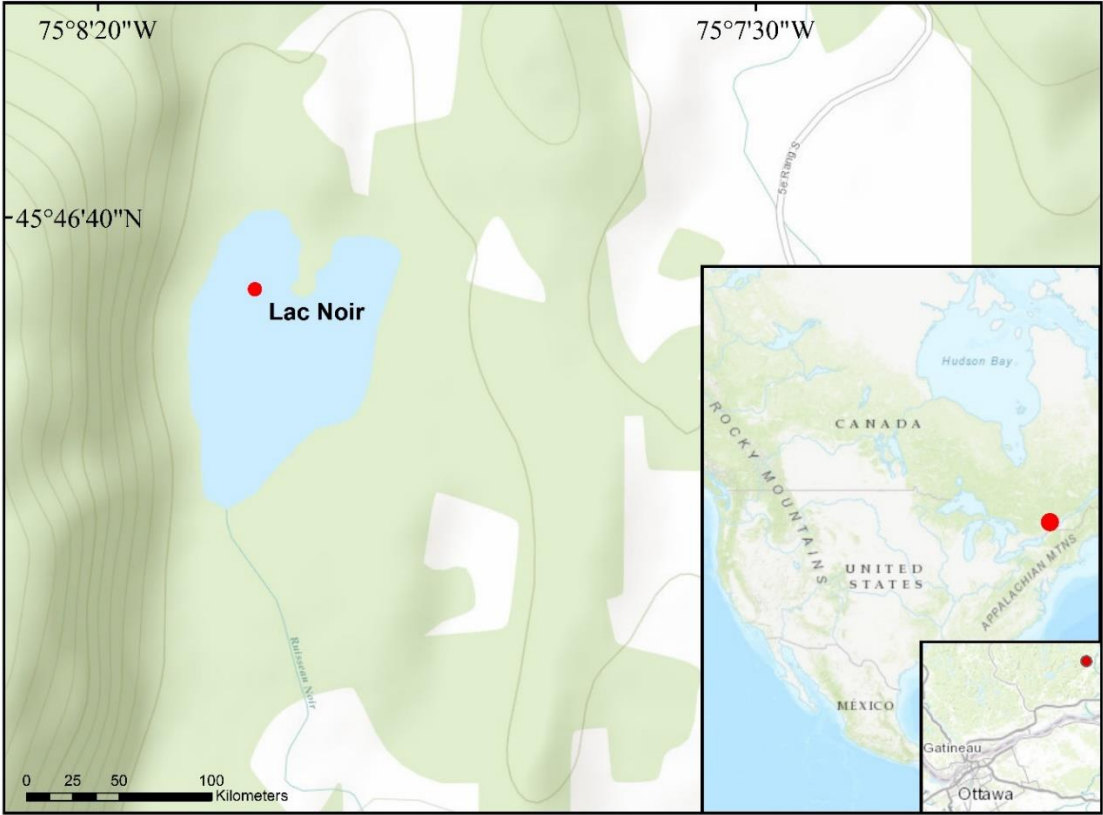


Figure 4.1 Map showing the location of Lac Noir in southwestern Québec. The red dot shows the coring location in the deepest part of the lake (16.2m). Inset map shows the location of the lake in relation to Ottawa, Ontario Canada. (Map created in ArcMap using Topographic base maps)

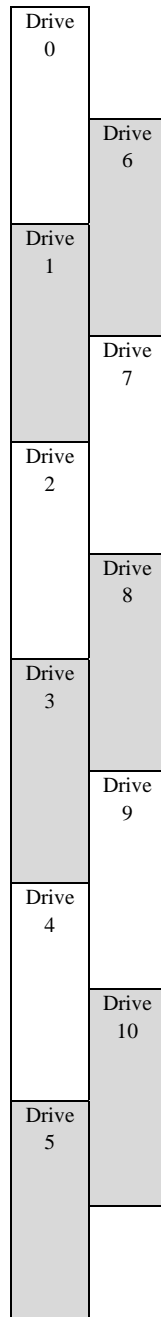


Figure 4.2 Visual representation of the 2 sediment cores (10 drives) retrieved from Lac Noir, Québec (September 2012).

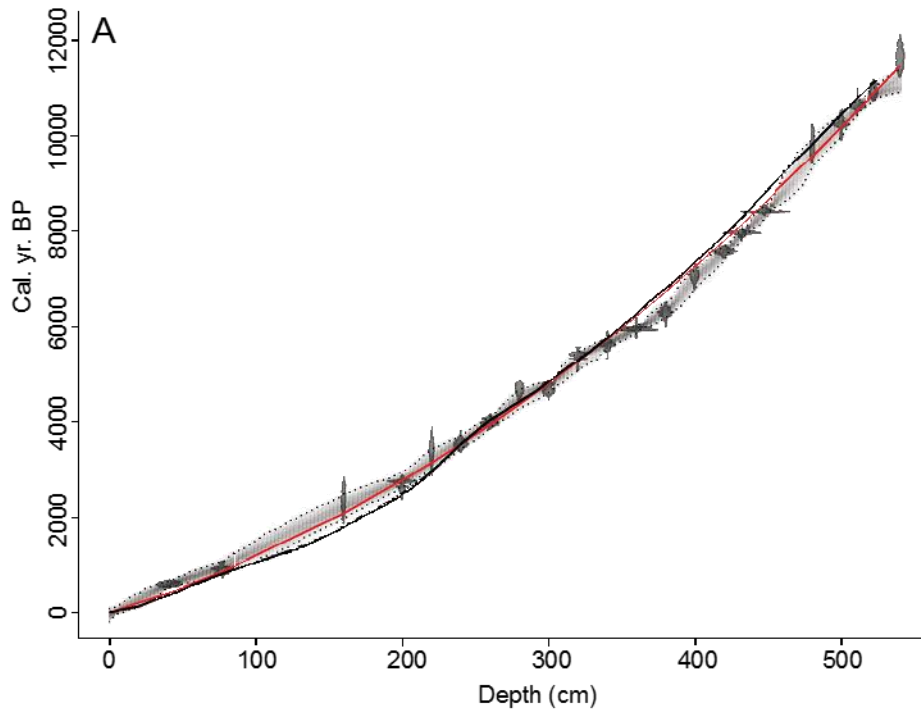


Figure 4.3 Varve chronology for Lac Noir core (black line). A chronology (grey shading) was independently created based on the AMS ¹⁴C dates (grey markers) using the BACON package (Blaauw, Christen, 2011) of the R program (Team, R. C., 2013). The dotted grey lines represent the 95% confidence interval for the radiocarbon chronology. The red line is a 2nd order polynomial regression fit through the ¹⁴C dates; see text for details. Varve Chronology from K Neil (Neil and Gajewski, 2018), as described in the methods. The radiocarbon chronologies were used only for verification of the annual nature of the varves; the varve chronology was exclusively used for this study

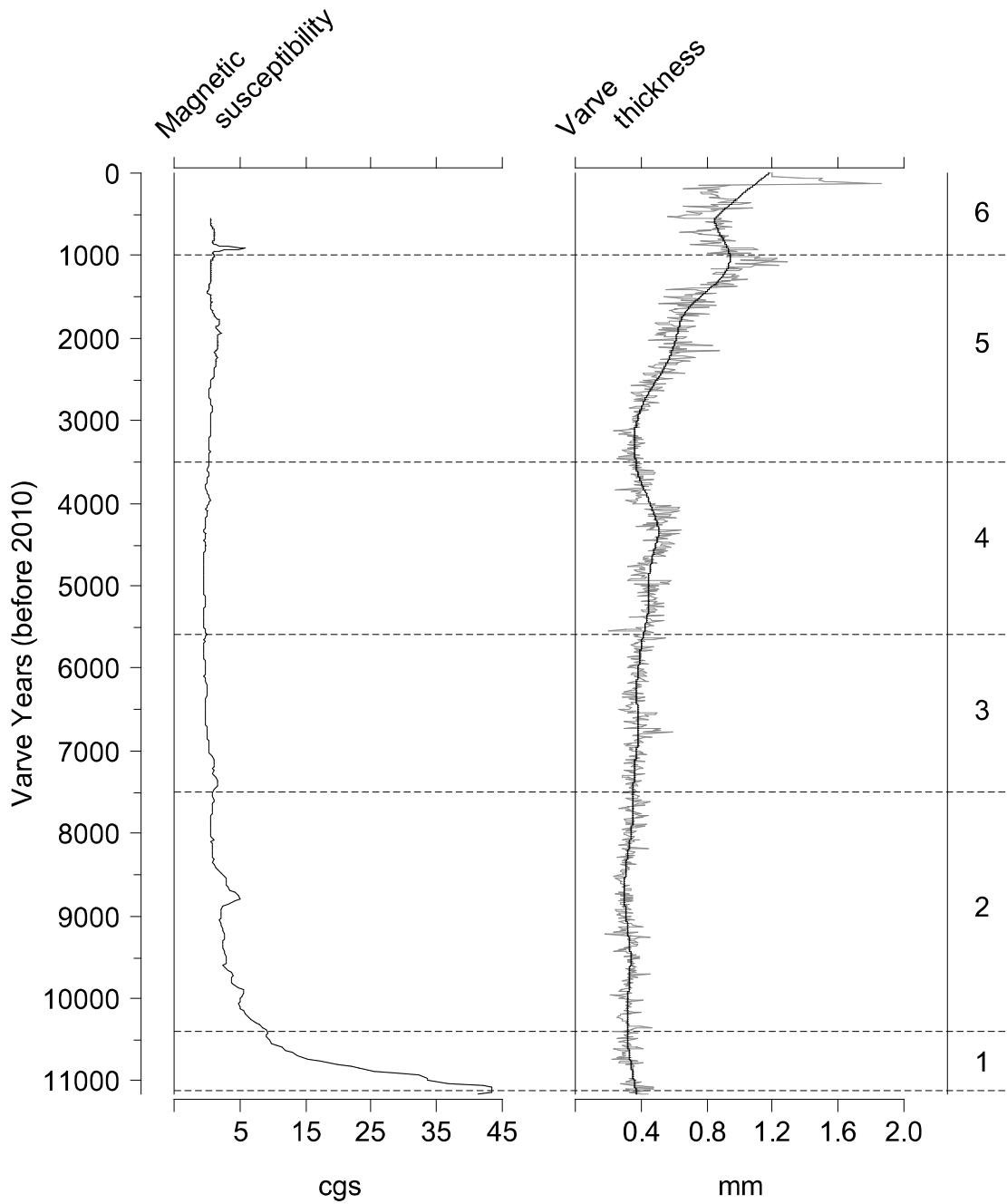


Figure 4.4 Magnetic susceptibility and varve thickness for Lac Noir, Québec based on average values from the overlapping drives from the two sediment cores. Magnetic susceptibility starts at 555 varve years. (Data from zone 6 is from Paquette and Gajewski, 2013).

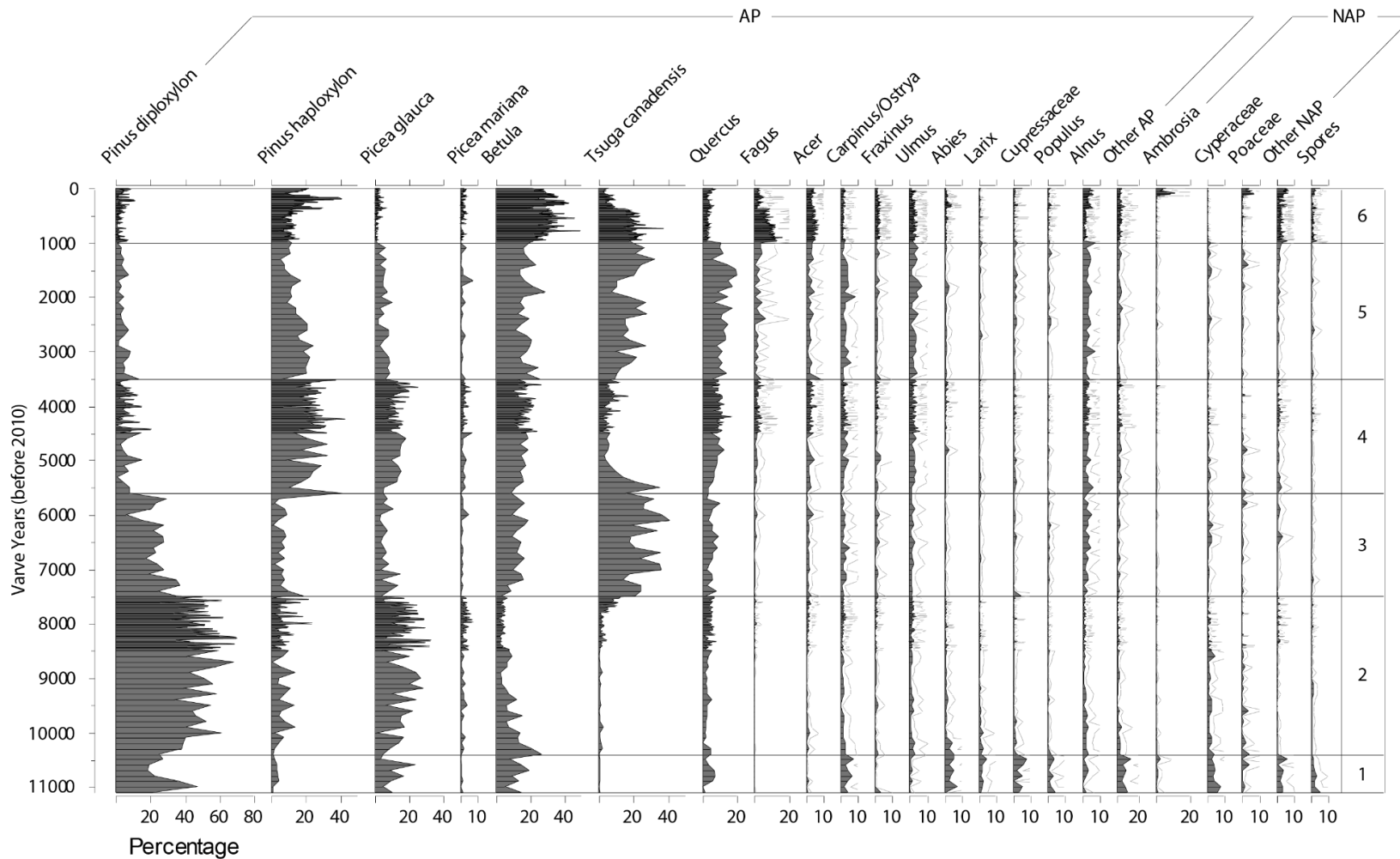


Figure 4.5 Pollen percentage diagram for Lac Noir, Québec. Only major taxa are shown and aquatic pollen are not included. Light grey lines are 5x exaggeration applied to pollen taxa representing a small portion of the pollen sum for easier visualization. (Data for zone 6 from Paquette and Gajewski, 2013).

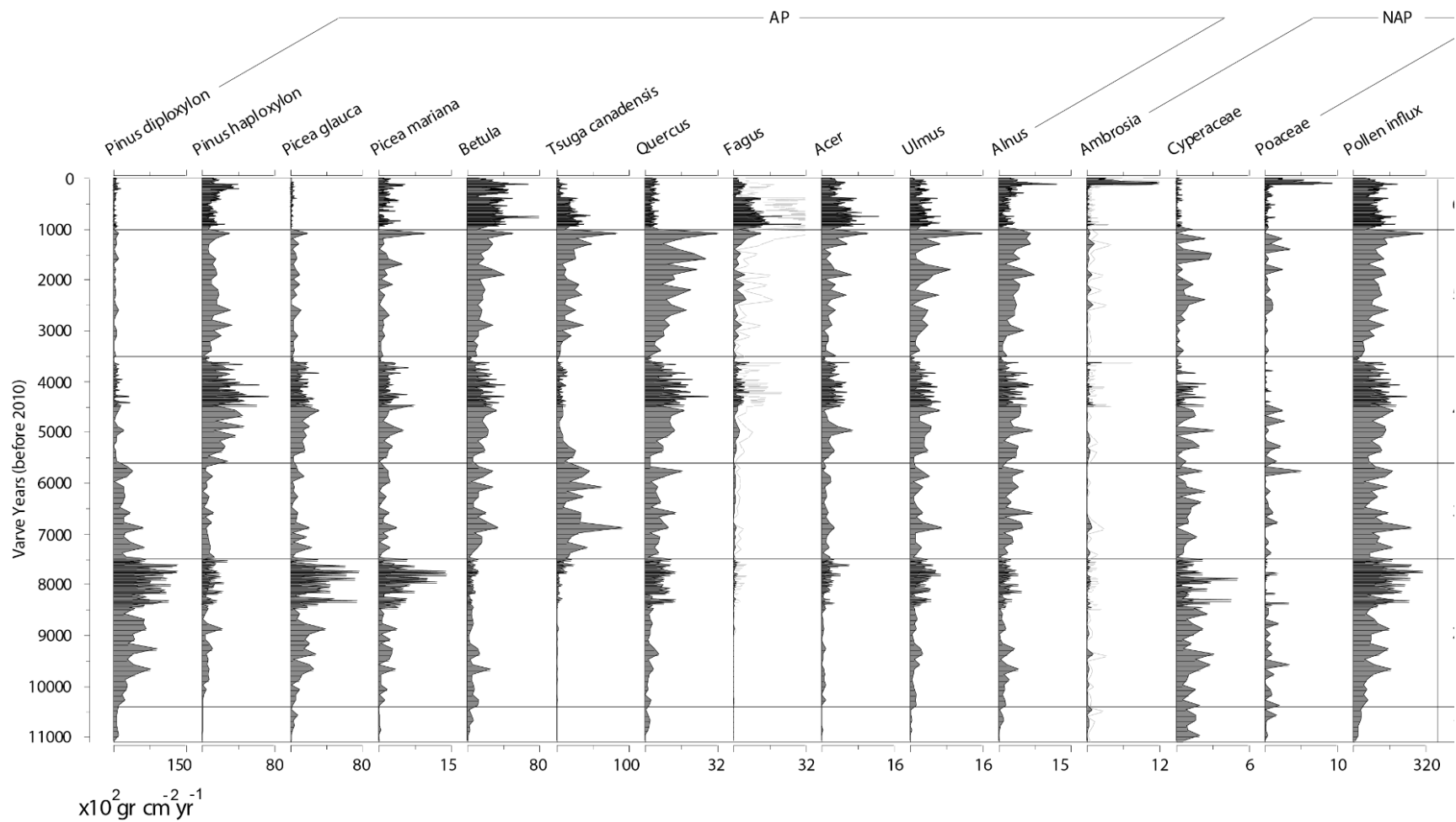


Figure 4.6 Pollen accumulation rates (PAR) of major taxa from Lac Noir, Québec. Total pollen influx includes the sum of AP (arboreal) + NAP (non-arboreal). (Data for Zone 6 from Paquette and Gajewski, 2013).

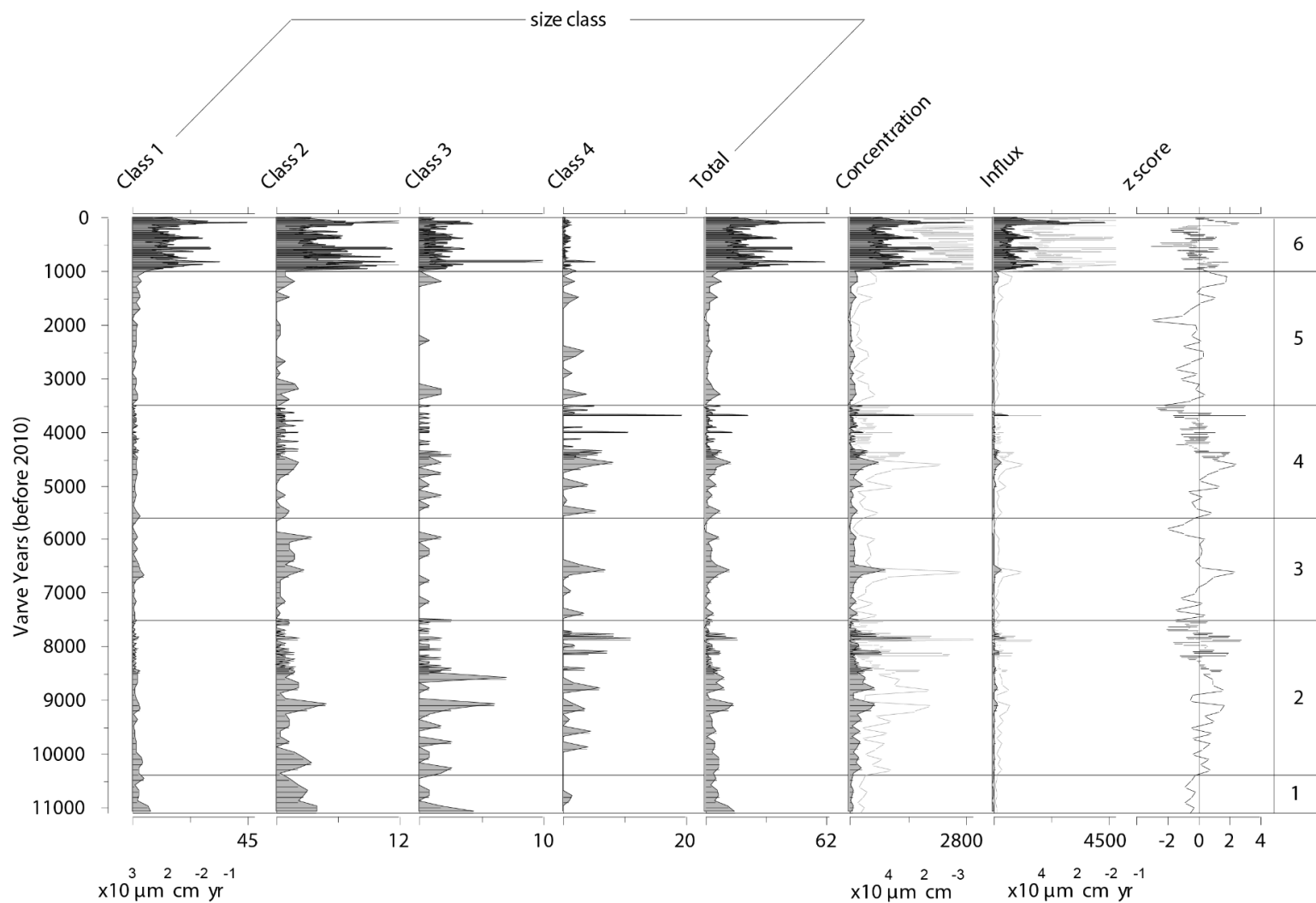


Figure 4.7 Micro-charcoal size characteristics from Lac Noir, Québec, total charcoal concentration and influx and z-scores (from the R package Paleofire; Blarquez et al, 2014). Size classes are (1) $219 \leq x < 438 \mu\text{m}^2$, (2) $438 \leq x < 875 \mu\text{m}^2$, (3) $875 \leq x < 1750 \mu\text{m}^2$, (4) $1750 > x \mu\text{m}^2$. Note changes in scale. (Data for Zone 6 from Paquette and Gajewski, 2013).

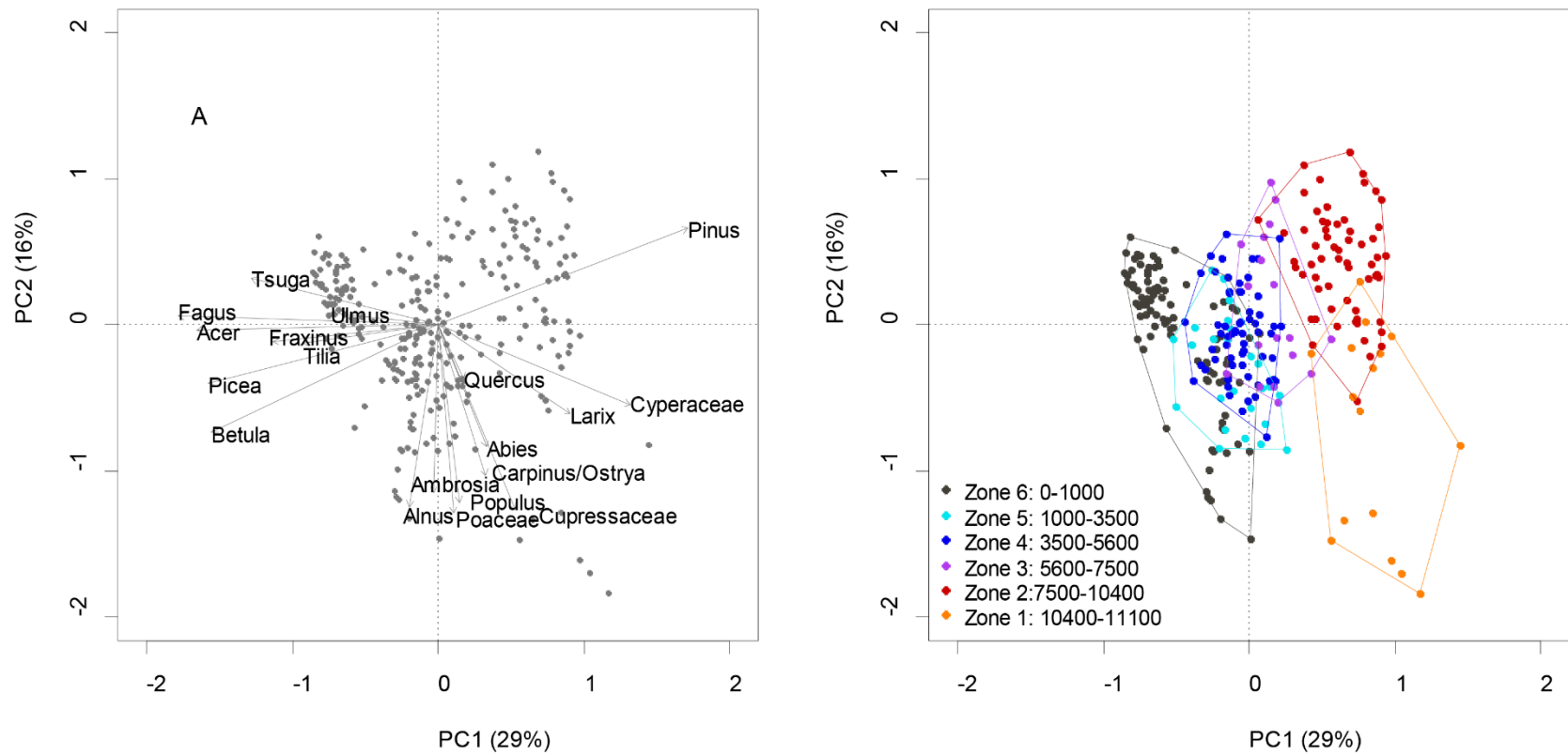


Figure 4.8 Principal components analysis of pollen percentages from Lac Noir, Québec. (A) Biplot of pollen percentages transformed using a Hellinger transformation. Dots represent the scores and arrows represent the loadings. (B) Scores showing clusters that form the basis of the zones.

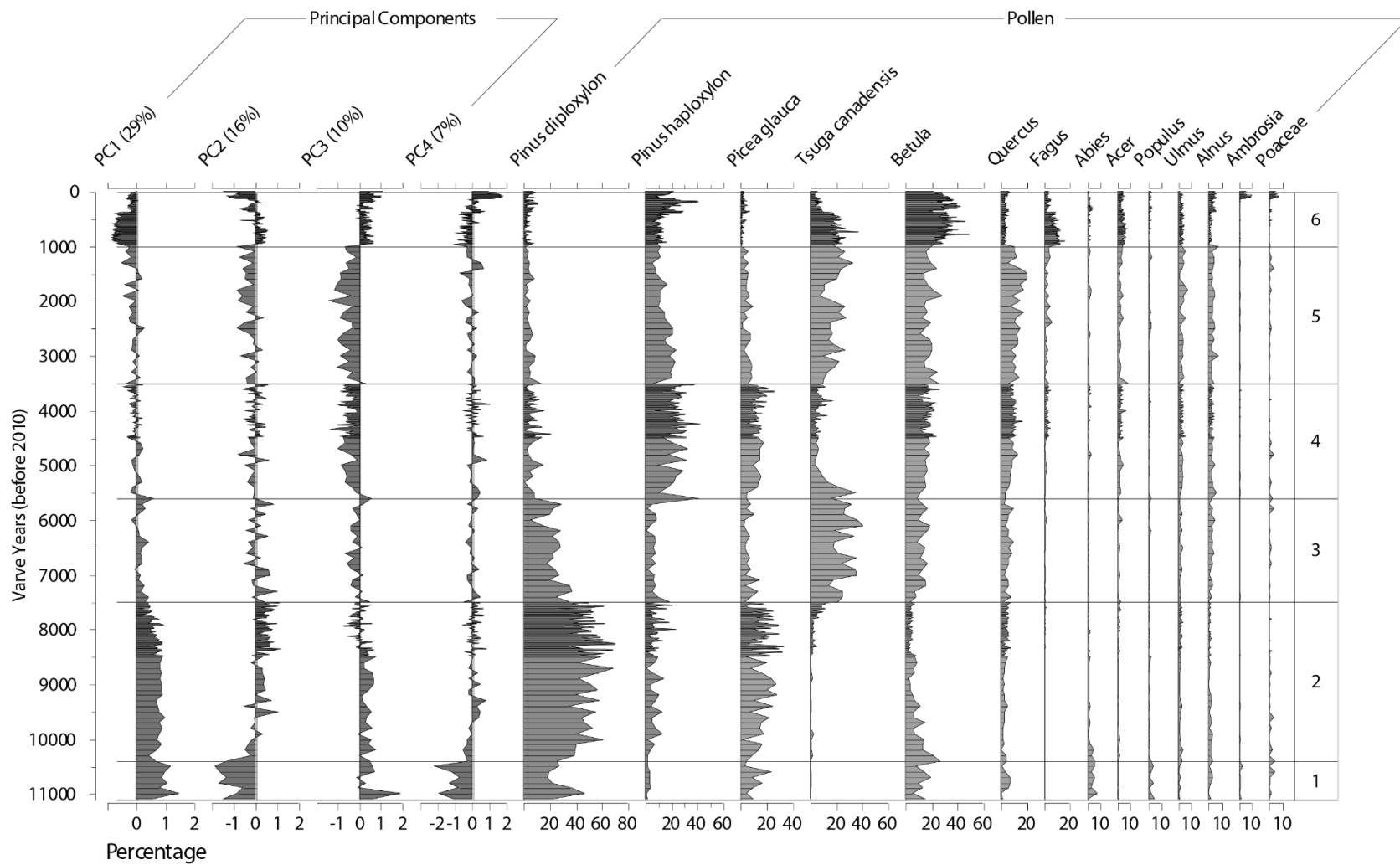


Figure 4.9 Summary diagram showing principal components scores, key pollen taxa, and the associated zones for Lac Noir, Québec. The zones were established by breaks in the time series of the scores. The explained variance for each axis is labelled in brackets. Refer to Table 3 for the loadings. (Data from zone 6 from Paquette and Gajewski, 2013).

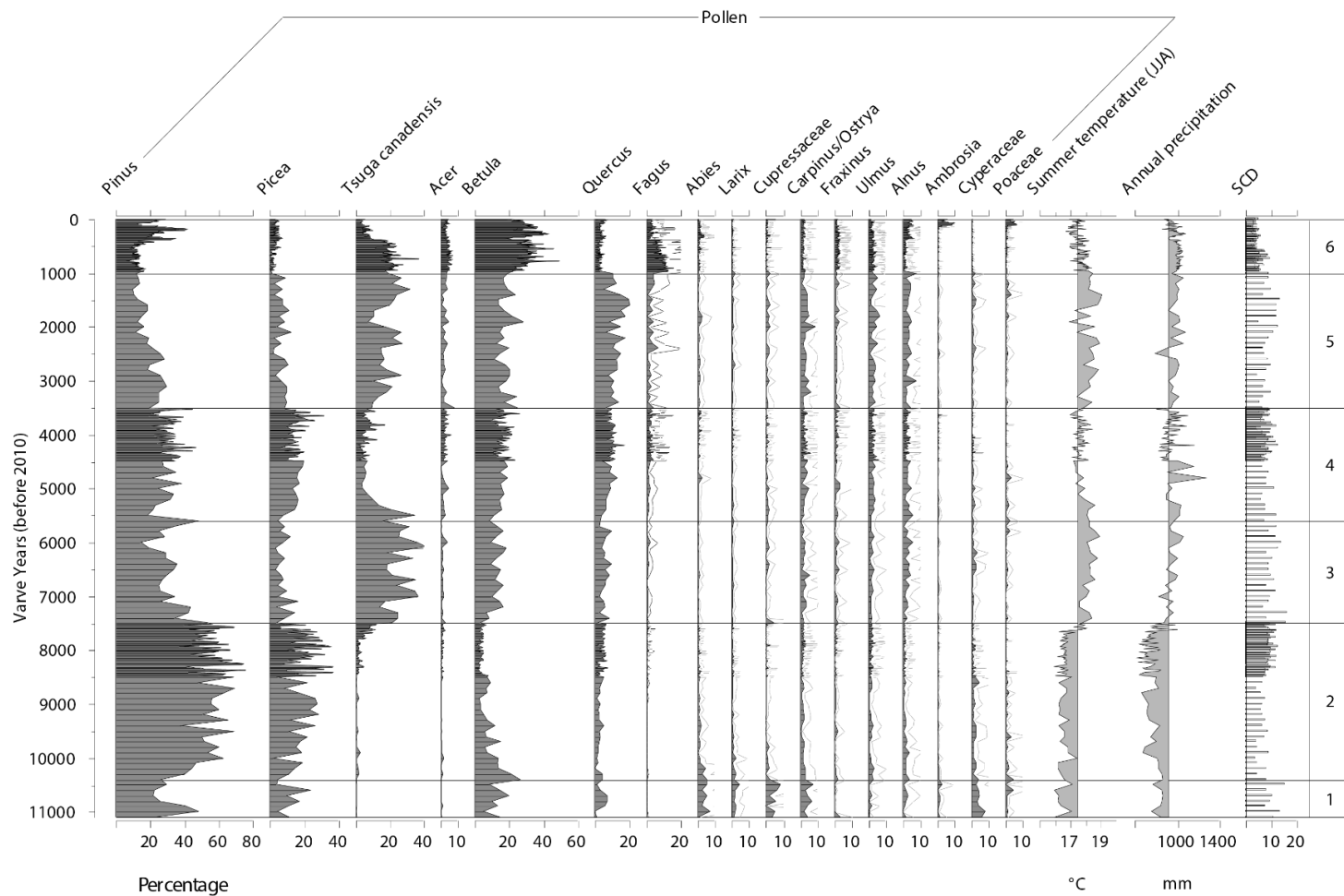


Figure 4.10 Pollen percentages of taxa used for paleoclimate reconstructions, summer temperature (June, July, August), annual precipitation and squared chord distance (SCD; x100 of the best analogue with the fossil sample) for Lac Noir. Reconstructions are based on the 5 closest analogues using the Modern Analogue Technique and the North American Modern Pollen Database (Whitemore et al, 2005; version 1.8). The vertical axes for temperature and precipitation at plotted at 17.5°C and 915 mm, respectively, which are the mean for the record. (Data for zone 6 based on Paquette and Gajewski (2013)).

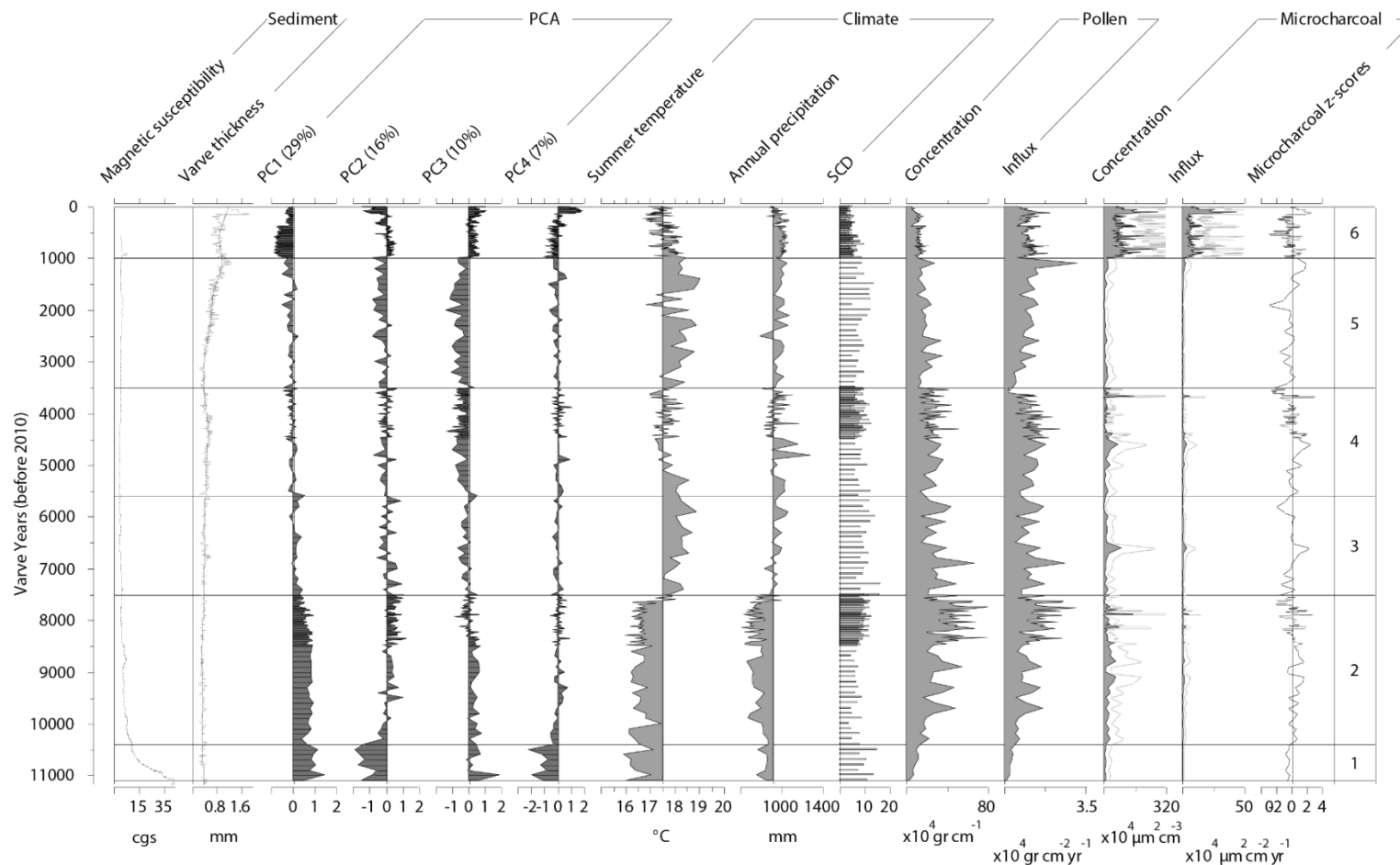


Figure 4.11 Paleoenvironmental summary for Lac Noir, Québec, including varve thickness, magnetic susceptibility, total concentration and influx of pollen and micro-charcoal. Reconstructions of summer temperatures (June, July, August) and annual precipitation, were estimated using the modern analogue technique using the squared chord distance (SCD) as the dissimilarity metric. Principal component scores with the corresponding explained variance of each axis shown in brackets were used to define the zones. The vertical axis for temperature and precipitation baseline is plotted at 17.5°C and 915 mm, respectively, which are the mean for the record. Note changes 64to scale. Data for zone 6 based on Paquette and Gajewski (2013)

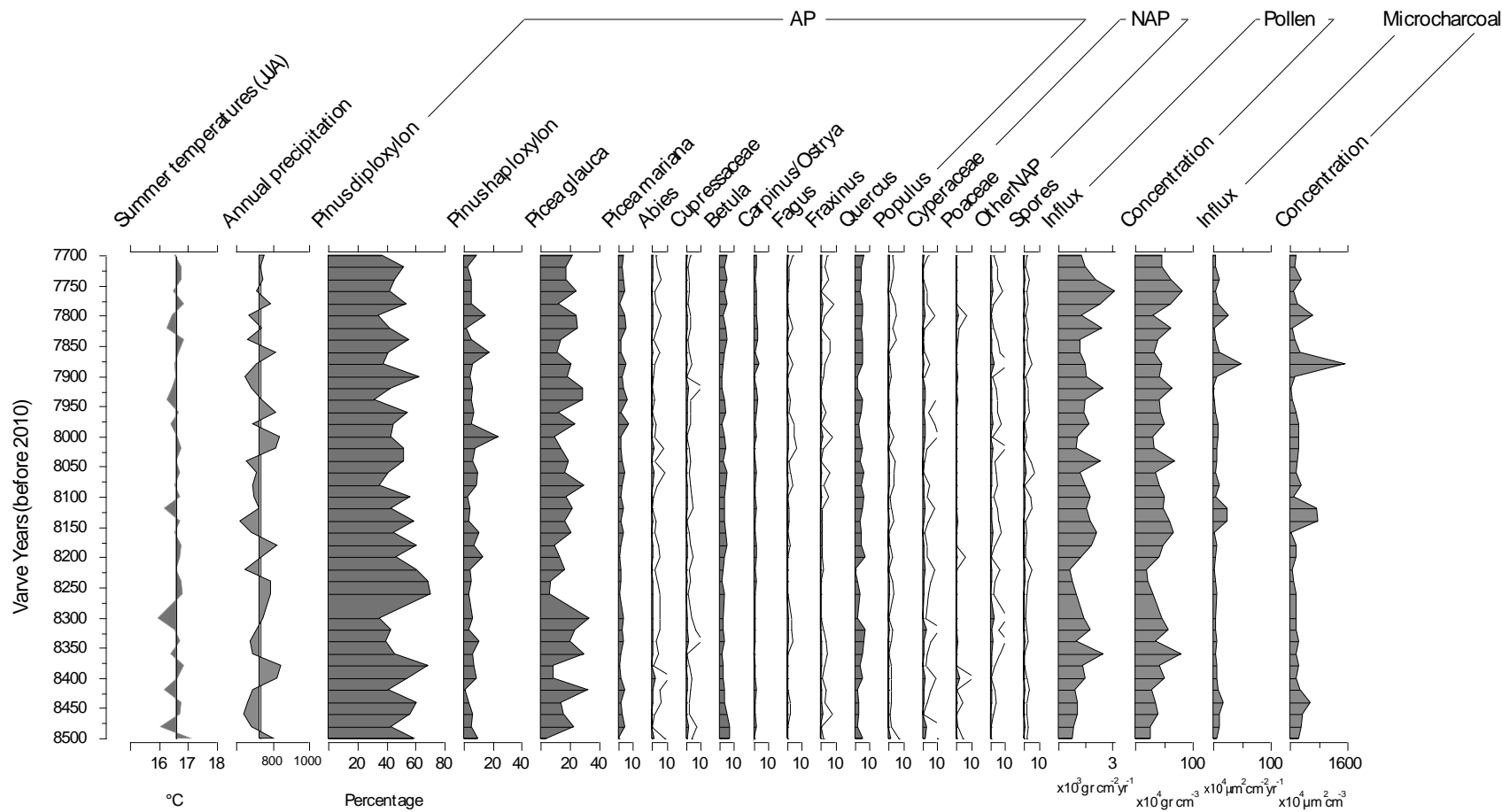


Figure 4.12 Summary diagram from zone 2 (10 400 – 7 500 ka), illustrating the vegetation response to the “8.2 cooling event” in the region of Lac Noir, Québec. Key pollen and micro-charcoal characteristics are shown, including pollen percentages of major taxa, total pollen influx and concentration as well as the reconstructed summer temperatures (June, July and August) and the annual precipitation. Paleoclimate reconstructions are based on the 5 closest analogues using the Modern Analogue Technique and the North American Modern Pollen Database (Whitmore et al., 2005; version 1.8). The vertical axis for temperature and precipitation is plotted at 16.6°C and 729 mm respectively representing the mean for the specific time period.

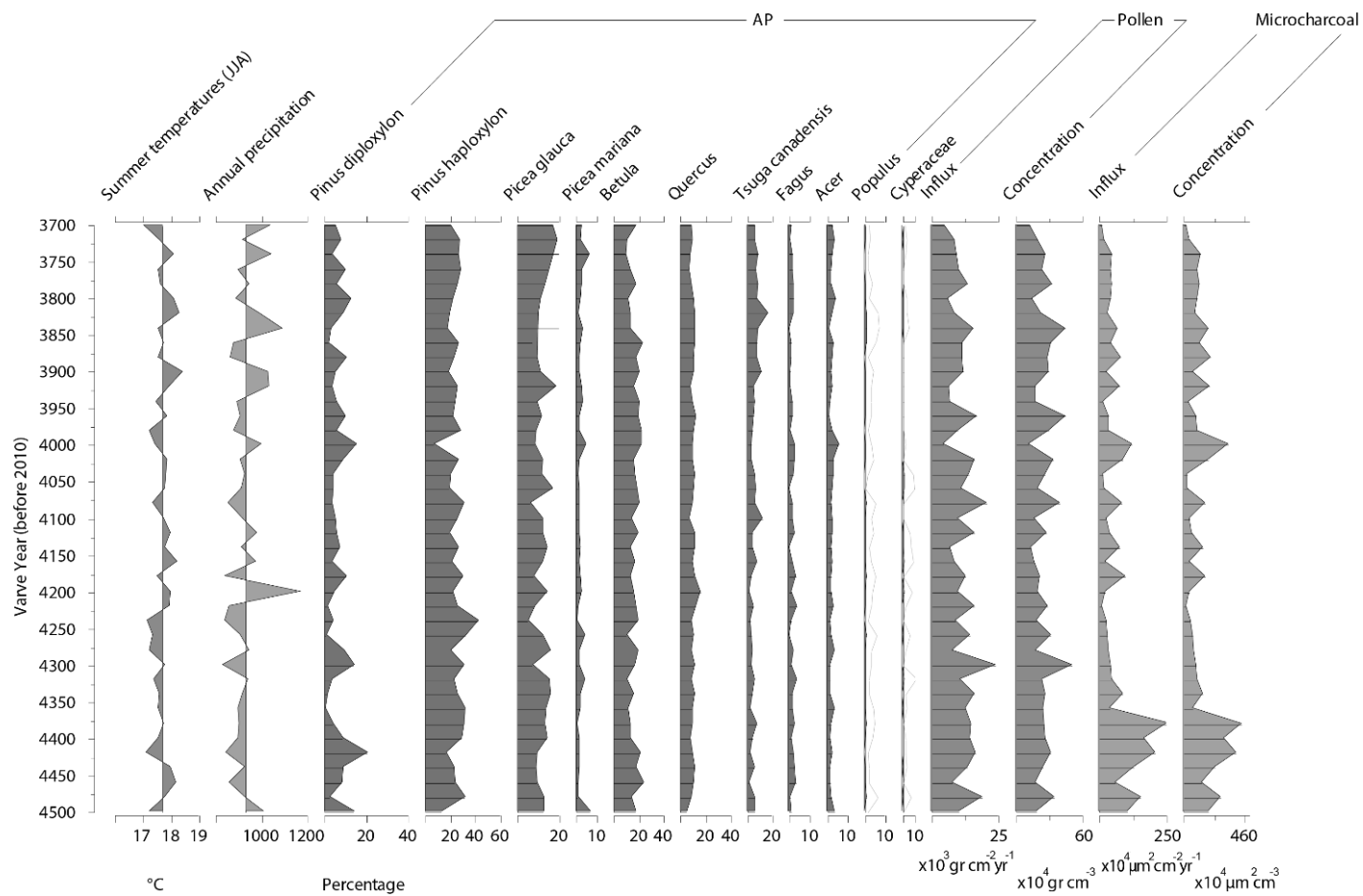


Figure 4.13 Summary diagram for zone 4 (5 600 – 3 500 ka) illustrating the regional response of the vegetation to the global “4.2” drought events. Key pollen and micro-charcoal characteristics are shown, including pollen percentages of major taxa, total pollen influx and concentration as well as the reconstructed summer temperatures (June, July and August) and the annual precipitation. Paleoclimate reconstructions are based on the 5 closest analogues using the Modern Analogue Technique and the North American Modern Pollen Database (Whitmore et al., 2005; version 1.8). The vertical axis for temperature and precipitation is plotted at 17.7°C and 930 mm, respectively, representing the mean for the specific time period.

Chapter 5- Summary

Two sediment cores were collected from Lac Noir in southwestern Québec in order to study and identify the vegetation response to climate variability over the course of the Holocene. Samples were analyzed at 100-year intervals to establish a complete Holocene history for the region, as well as a 20-year intervals at specific areas of interest associated with climate anomalies identified in other regions (8.2 cooling event, and 4.2 warming event).

The 5.4 m sediment cores collected from Lac Noir were almost entirely varved, with the exception of a small section (<4cm) between 5.12 - 5.16 m. The varves were cross-dated by aligning unique marker layers and marker beds in order to develop the varve chronology for Lac Noir. Twenty-two radiocarbon dates and a 2nd order polynomial regression were used to create an independent chronology to confirm the validity of the varve chronology. The varve chronology created a unique opportunity to identify and examine the vegetation history in the region with a high precision and resolution study and was used to describe the stratigraphic changes at Lac Noir.

Over the past 11 000 years the Lac Noir region transitioned from an open-spruce woodland, to a boreal forest, to the modern mixed conifer-hardwood forest seen in the region today. *Pinus*, *Picea*, *Tsuga* and *Betula* and other arboreal taxa have dominated the pollen record and have marked the significant and subtle changes in the forest over time. Principal components analysis was used to establish zones throughout the Holocene in order to identify periods of change based on the pollen assemblage analysis. Zone 1 in the early Holocene was associated with an open-spruce woodland. It was dominated by herbaceous pollen and *Picea*, and had long distant transport of *Betula*, *Pinus* and other arboreal taxa. Zone 2 saw the migration and establishment of the boreal forest into the region with a minor increase in *Pinus* between 8.26 ka - 8.24 ka. It is possible this increase was related to the perceived cooling of the global climate system caused by the influx of

meltwater from the collapse of the ice domes over Hudson-Bay. However, no other taxa showed a response during this period and it can be concluded that this cooling event did not have a significant impact on the vegetation at Lac Noir. Zone 3 was characterized by the abrupt increase in *Tsuga*, the gradual decline of *Pinus* which could be associated with the general warming trend and the transition from the boreal forest to the mixed-conifer hardwood forest. Zone 4 recorded the collapse of the *Tsuga* population which is thought to be related to a pest/pathogenic outbreak and/or a drier climate. Zone 5 saw the continued recovery of *Tsuga* and the increased dominance of other hardwood taxa, including *Betula*, *Quercus*, and *Fagus* and Zone 6 saw the transition from the Medieval Climate Anomaly, into the Little Ice Age and the arrival of Europeans into the region (*Ambrosia* rise).

The micro-charcoal analyzed from the Lac Noir regions showed that the region experienced higher frequencies of fire activity in the early Holocene than it did in the middle or late Holocene and is most likely related to the forest type, lower levels of precipitation and increased levels of solar radiation during the summer months. Boreal forests are more susceptible to fire activity than a mixed conifer hardwood forest. The middle Holocene registered the lowest frequency of fire activity in the region which can be attributed to a stabilizing climate and the increased levels of precipitation. The late Holocene had a higher frequency of fire than the middle Holocene despite the mixed conifer-hardwood forest which may be related to the drier conditions during summer months. The drier climate would have made the normally fire-resistant taxa more susceptible to fire.

PAR showed a significant increase in production starting in the early Holocene and was relatively stable for much of the Holocene. There was a minor increase in PAR after the *Tsuga* collapse which aligns with increases in PAR of *Quercus*, *Betula* *Pinus* and *Ulnus* and is probably

as a result of these taxa responding to the openings left in the canopy from the loss of *Tsuga*. The PAR for these and other hardwood taxa continued to increase even following the resurgence of the *Tsuga* population further substantiating the dominance of the mixed conifer-hardwood forest in the region. There is a considerable decrease in PAR and varve thickness at ~3.60 ka which could have be related to drought and lower water levels, however there is no significant change in the pollen taxa to signal a change or response by the taxa to this climate event. There is also a decrease in varve thickness from 4.35 ka - 4.10 ka which could be evidence of the 4.2 ka drought event (Booth et al, 2005; Shuman and Burrell, 2017).

The paleoclimate reconstructions for the average summer month temperatures (June, July, August) and annual precipitation was based on the pollen assemblages analyzed at Lac Noir. These pollen-based reconstructions indicate the early Holocene experienced a cooler and drier climate than present day. The mid and late Holocene saw a warming trend and increased levels of precipitation which started at 7.40 ka. The warmer temperatures and increased levels of precipitation in the mid-Holocene aligned with the swift establishment of *Tsuga*, and the slightly lower levels of precipitation at the end of the mid-Holocene corresponds with the collapse of *Tsuga*. The paleoclimate reconstruction for the late Holocene show a warming in the summer months and an increased amount of precipitation, which contrasts with the general cooling noted in other studies (Ritchie, 1987; Diaz et al, 1989; Muller et al, 2003).

Future work

This study provides the most detailed Holocene paleoecological study from the region. However, there are unanswered questions that could be the basis of future work.

- Macro-charcoal analysis of Lac Noir would be beneficial in establishing a complete fire history for the local area. This would enable a further understanding of forest dynamics in relation to the local fire history at high resolution study.
- A high-temporal resolution study of a nearby lake within the region could be performed to see if similar trends (i.e. establishment of forest type and the vegetation response to known climate anomalies) are also being observed, or if the findings of this study are unique to Lac Noir.

This study provided a unique opportunity to study the Holocene of the vegetation in southwestern Québec response to climate variability at a high-resolution. The varve chronology in associated with pollen analysis allowed us to examine the sensitivity of the vegetation to a variety of factors including climate and fire dynamics and contribute to our understanding of the ecological environment.

References

- Aber, J., Melillo J. (1991). *Terrestrial Ecosystems*. New York: Saunders
- Ali, A. A., Asselin, H., Larouche, A. C., Bergeron, Y., Carcaillet, C., & Richard, P. J. (2008). Changes in fire regime explain the Holocene rise and fall of *Abies balsamea* in the coniferous forests of western Québec, Canada. *The Holocene*, 18: 693-703.
- Alley, R. B., & Ágústsdóttir, A. M. (2005). The 8k event: cause and consequences of a major Holocene abrupt climate change. *Quaternary Science Reviews*, 24: 1123-1149
- Amundson, D.C., Wright, H.E., Jr. (1979). Forest changes in Minnesota at the end of the Pleistocene. *Ecological Monographs*, 49: 1-16
- Anderson, R. S., R. B. Davis, N. G. Miller, and R. Stuckenrath. 1986. History of late- and post-glacial vegetation and disturbance around Upper South Branch Pond, northern Maine. *Can. J. Bot.* 64: 1977–1986
- Anderson, T.W. (1987). Terrestrial environments and age of Champlain Sea based on pollen stratigraphy of the Ottawa Valley-Lake Ontario region. In: Fulton, R.J. (ed.), *Quaternary of the Ottawa Region, Ontario and Québec*, pp. 31-42. Geological Survey of Canada Paper 86-23.
- Anderson, T.W. (1988). Late Quaternary pollen stratigraphy of the Ottawa Valley-Lake Ontario region and its application in dating the Champlain Sea. In: Gadd, N.R. (ed.), *The Late Quaternary Development of the Champlain Sea Basin*, pp. 205-224. Geological Association of Canada Special Paper 35.

- Barber, D. C., Dyke, A., Hillaire-Marcel, C., Jennings, A. E., Andrews, J. T., Kerwin, M. W.,... & Gagnon, J. M. (1999). Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature*, 400: 344
- Bartlein, P.J., Webb III, T., Fleri, E. (1983). Holocene climatic change in the northern midwest: Pollen-Derived Estimates. *Quaternary Research*, 22: 361-374
- Bennet, K.D., Willis, K.K. (2001). Pollen. In Smol, J., Birks, H. J.B., Last, W.M. (Eds) *Tracking Environmental Change using Lake Sediments, Volume 3*, pg. Dordrecht, Netherlands: Kluwer Academic Publishers
- Bergeron, Y., Gauthier, S., Flannigan, M., Kafka, V. (2004). Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Québec. *Ecology*, 85:1916-1932
- Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P. & Lesieur, D. (2001) Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Canadian Journal of Forest Research*, 31, 384– 391.
- Bergeron, Y. & Archambault, S. (1993) Decreasing frequency of forest fires in the southern boreal zone of Québec and its relation to global warming since the end of the ‘Little Ice Age’. *The Holocene*, 3, 255– 259.
- Bergeron, Y. (1991). The influence of island and mainland lakeshore landscape on boreal forest fire regime. *Ecology*, 72, 1980– 1992
- Bernabo, J.C., Webb III, T. (1977). Changing patterns in the Holocene pollen record of northeastern North America: A mapped summary. *Quaternary Research*, 8: 64-96

- Bhiry, N. and L. Filion. (1996). Mid-Holocene hemlock decline in eastern North America linked with phytophagous insect activity. *Quat. Res. (Orlando)* 45: 312–320
- Birks, H.J.B., Birks, H.H. (1980). *Quaternary Palaeoecology*. Baltimore, USA: University Park Press
- Birks, H.J.B., Birks, H.H. (2001). Future uses of pollen analysis must include plant macrofossils. *Journal of Biogeography*, 27: 31-35
- Birks, H.J.B., (1997). Reconstructing environmental impacts of fire from the Holocene sedimentary record. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (Eds.), *Sediment Records of Biomass Burning and Global Change. NATO ASI Series I: Global Environmental Change Vol. 51* Springer, Berlin: 295–311
- Blaauw, M., and J. A. Christen. (2011). Flexible Paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6:457–474
- Blaauw, M., Heegaard, E. (2012). Estimation of Age-Depth Relationships. In Smol, J., Birks, H. J.B., Last, W.M. (Eds) *Tracking Environmental Change using Lake Sediments, Volume 5*. Dordrecht, Netherlands: Kluwer Academic Publishers
- Blarquez, O., Vanni re, B., Marlon, J. R., Daniiau, A. L., Power, M. J., Brewer, S., & Bartlein, P.J. (2014). paleofire: an R package to analyse sedimentary charcoal records from the Global Charcoal Database to reconstruct past biomass burning. *Computers & Geosciences*, 72: 255-261
- Bradshaw, R.H.W., Tolonen, K., Tolonen, M. (1997). Holocene records of fire from the boreal and temperate zone of Europe. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (Eds.),

Sediment Records of Biomass Burning and Global Change. NATO ASI Series I: Global Environmental Change Vol. 51. Springer, Berlin, 347–365

Braun, E.L. (1950). Deciduous forests of eastern North America. New York, New York: Hafner Publishing Co.

Burns, R.M., Honkala, B.H. (1990). Silvics of North America. In: Agriculture Handbook 654, vol. 2. USDA, Forest Service, Washington, DC, p. 877

Booth, R, Booth, K., Brewer, S., Blaauw, M., Minckley, T.A., Jackson, S.T., (2012). Decomposing the mid-Holocene *Tsuga* decline in eastern North America. *Ecology* 93: 1841-1852

Booth, R. K., S. T. Jackson, S. L. Forman, J. E. Kutzbach, E. A. Bettis, J. Kreig, and D. K. Wright. (2005). A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages. *Holocene* 15:321–328

Bronk Ramsey C. (2009). Bayesian analysis of radiocarbon dates. *Radiocarbon* 51: 337–360

Carcaillet, C., Richard, P.J.H. (2000). Holocene changes in seasonal precipitation highlighted by fire incidence in eastern Canada. *Climate Dynamics* 16: 549-559

Carcaillet C, Bergeron Y, Richard PJH, Fréchette B, Gauthier S, Prairie YT (2001). Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? *Journal of Ecology* 89: 930–946

Carcaillet, C., Bouvier, M., Fréchette, B., Larouche, A.C. & Richard, P.J.H. (2001) Comparison of pollen-slide and sieving methods for lacustrine charcoal analyses for local and regional fire history. *The Holocene*, 11 (6), 467– 476

- Clark, J.S. (1988). Stratigraphic charcoal analysis on petrographic thin sections: application to fire history in northwestern Minnesota. *Quaternary Research* 30: 81 – 91.
- Clark, J.S., Royall, P.D. (1996). Local and regional sediment charcoal evidence for fire regimes in presettlement northeastern North America. *Journal of Ecology* 84: 365–382
- Clark JS (1989) Effects of long-term water balances on fire regime, northwestern Minnesota. *Journal Ecology* 77: 989-1 004
- Clifford, M. J., & Booth, R. K. (2013). Increased probability of fire during late Holocene droughts in northern New England. *Climatic Change*, 119: 693-704
- Crann, C.A., Murseli, S., St-jean, G., Zhao, X. (2017). First Status Report on Radiocarbon Sample Preparation Techniques at the A.E. Lalone AMS Laboratory (Ottawa, Canada). *Radiocarbon*, 59: 695-704
- Cwynar, L. C. (1987). Fire and the forest history of the North Cascade Range. *Ecology* 68, 791–802
- Cwynar, L.C. (1977) Recent history of fire of Barrow Town-ship, Algonquin Park. *Canadian Journal of Botany*, 55, 10– 21.
- Davis, M.B., (1981). Outbreaks of forest pathogens in Quaternary history. In *Proceedings of the IVth International Palynology Conference, Lucknow, India, 1976- 1977*. Birbal Sahni Institute of Paleobotany. Vol. 3, 216-228
- Davis, B., Zanon, M., Collins, P., Mauri, A., Bakker, J. et al... (2013). The European Modern Pollen Database (EMPD) project. *Vegetation History and Archaeobotany*, 22: 521-530

- Day, L. T., Oswald, W. W., Doughty, E. D., & Foster, D. R. (2013). Analysis of hemlock pollen size in Holocene lake sediments from New England. *Quaternary Research*, 79: 362-365
- Dean, W.E., Forester, R.M., Bradbury, J.P. (2002). Early Holocene change in atmospheric circulation in the Northern Great Plains: an upstream view of the 8,2 ka cold event. *Quaternary Science Reviews*, 21: 1763-1775
- Diaz, H. F., Andrews, J. T., & Short, S. K. (1989). Climate variations in northern North America (6000 BP to present) reconstructed from pollen and tree-ring data. *Arctic and Alpine Research*, 21: 45-59.
- Dionne, J.C. (1975). Paleoclimatic significance of Late Pleistocene ice-wedge casts in southern-Québec, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 17: 65-76
- Environment and Climate Change Canada: Canadian Climate Normals: 1981-2010 Station Data (Notre Dame de la Paix). Website date modified: 2018-01-11. Retrieved January 26, 2018: www.climate.weatheroffice.ec.gc.ca
- Fægri, K., Iversen, J. (1989). *Textbook of Pollen Analysis*, 3rd ed. New York: Hafner Press
- Flannigan, M., (2015). Carbon Cycle: Fire evolution split by continent. *Nature Geosciences*, 8: 167-168
- Flannigan MD, Harrington JB (1988) A study of the relation of meteorological variables to monthly provincial area burned by wildfires in Canada. *J Appl Meteorol* 27: 441-452

- Foster, D.R. (1983) The history and pattern of fire in the boreal forest of southeastern Labrador. Canadian Journal of Botany, 61, 2459– 2471
- Foster, D. R., Oswald, W. W., Faison, E. K., Doughty, E. D., & Hansen, B. C. (2006). A climatic driver for abrupt mid-Holocene vegetation dynamics and the hemlock decline in New England. Ecology, 87(12): 2959-2966.
- Fuller, J., (1997). Holocene forest dynamics in southern Ontario, Canada: fine resolution pollen data. Canadian Journal of Botany 75: 1714-1727.
- Fulton, R. J., Anderson, T. W., Gadd, N. R., Harrington, C. R., Kettles, I. M., Richard, S. H., ... & Shilts, W. W. (1987, July). Summary of the Quaternary of the Ottawa region. In International Union for Quaternary Research XII International Congress, Ottawa, Canada.
- Gadd, N. R., McDonald, B.C., Shilts, W.W. (1972). Déglaciation of southern Québec (Paper. 71-47). Hull, Québec, Geological Survey of Canada
- Gajewski, K. (2006). Is arctic palynology a "blunt instrument"? Géographie Physique Et Quaternaire, 60: 95-102
- Gajewski, K. (1988). Late Holocene climate changes in eastern North America estimated from pollen data. Quaternary Research, 29: 255–262
- Gajewski, K., (1987). Climatic impacts on the vegetation of eastern North America during the past 2000 years. Vegetation 68: 179-190.
- Gajewski, K., Winkler, M.G., Swain, A.M. (1985). Vegetation and fire history from three lakes with varved sediments in northwestern Wisconsin (USA). Review of Paleobotany and Palynology, 44: 277-292

- Gregoire, L. J., Payne, A.J., Valdes, P.J. (2012). Deglacial rapid sea level rises caused by ice-sheet saddle collapses. *Nature* 487: 219–222
- Grenier, D.J., Bergeron, Y., Kneeshaw, D. & Gauthier, S. (2005). Fire frequency for the transitional mixed wood forest of Témiskaming, Québec, Canada. *Canadian Journal of Forest Research*, 35: 656-666.
- Grousse-Brauckman, G. (1978). Absolute jährliche Polleniederschlagsmengen an verschiedenen Beobachtungsorten in der Bundesrepublik Deutschland. *Flora*, 167: 209-247
- Harrington J, Flannigan M (1993). A model for the frequency of long periods of drought at forested stations in Canada. *J Appl Meteorol* 32: 1708-1716
- Harrington JB, Flannigan MD, Van Wagner CE (1983) A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wild@re in Canada 1953-80. Information Rep PI-X-16, Canadian Forestry Service, Ottawa (ON), 65
- Harrison, S.P. (1989). Lake levels and climatic change in eastern North America. *Climate Dynamics*, 3, 157– 167
- Haas JN, McAndrews JH. (2000). The summer drought related hemlock (*Tsuga canadensis*) decline in eastern North America 5700 to 5100 years ago. In *Proceedings: Symposium on sustainable Management of Hemlock Ecosystems in Eastern North America*, June 22–24, 1999, Durham, New Hampshire, McManus K, et al. (eds). General Technical Report NE-267, Northeastern Research Station, Forest Service, U. S. Department of Agriculture: Newtown Square, PA; 81–88

- Hély, C., Bergeron, Y., Flannigan, M.D. (2000). Effects of stand composition on fire hazards in mixed wood Canadian Boreal forest. *Journal of Vegetation*, 11: 813-24
- Hicks, S. (2001). The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. *Review of Palaeobotany and Palynology*, 117: 1-29
- Hicks, S., Tinsley, H., Huusko, A., Jensen, C., Hatterstrand, M., Gerasimides, A., Kvavadze, E. (2001). Some comments on spatial variation in arboreal pollen deposition: first records from the Pollen Monitoring Programme (PMP). *Review of Palaeobotany and Palynology*, 117: 183-194
- Hicks, S. (1999). The relationship between climate and annual pollen production at northern treelines. *Chemosphere: Global Change Science* 1: 403–416
- Hicks, S. (1995). The relationship between climate and annual pollen deposition at northern tree-lines. *Chemosphere: Global Change Science*, 1: 406-416
- Huusko, A., Hicks, S. (2009). Conifer pollen abundance provides a proxy for summer temperature: evidence from the latitudinal forest limit in Finland. *Journal of Quaternary Science* 24: 522-528
- Iglesias, V., Yospin, G. I., & Whitlock, C. (2015). Reconstruction of fire regimes through integrated paleoecological proxy data and ecological modeling. *Frontiers in plant science*, 5, 785.

- Jackson, S.T., Webb, R.S., Anderson, K.H., Overpeck, J.T., Webb III, T., Williams, J.W., Hansen, B.C.S. (2000). Vegetation and environment in Eastern North America during the Last Glacial Maximum. *Quaternary Science Review*, 19: 489-508
- Jackson ST, Whitehead DR. (1991). Holocene vegetation patterns in the Adirondack Mountains. *Ecology* 72: 641-653
- Jacobson, G.L., Jr., Webb, T., 111, and Grimm, E.C. (1987). Patterns and rates of vegetation change during the deglaciation of eastern North America. In *The Geology of North America. Vol. K-3. North America and adjacent oceans during the last deglaciation*. Edited by W.F. Ruddiman and H.E. Wright, Jr. Geological Society of America, Boulder, Colo., 277-288.
- Jacques , J. M. S., Cumming, B. F., & Smol, J. P. (2008). A 900-year pollen-inferred temperature and effective moisture record from varved Lake Mina, west-central Minnesota, USA. *Quaternary Science Reviews*, 27: 781-796
- Johnson, E.A., Fryer, G.I. & Heathcott, J.M. (1990). The influence of Man and climate on frequency of fire in the interior wet belt forest, British Columbia. *Journal of Ecology*, 78, 403– 412.
- Kutzbach, J.E., Guetter, P.J. (1986). The Influence of changing orbital parameters and surface boundary conditions on the simulated climate of the past 18 000 years. *Journal of Atmospheric Sciences* 43: 1726-1759
- Lafontaine-Boyer, K., Gajewski, K. (2014). Vegetation dynamics in relation to late Holocene climate variability and disturbance, Outaouais, Québec Canada. *The Holocene* 24: 1515-1526

- Larochelle, É., Lavoie, M., Grondin, P., & Couillard, P. L. (2018). Vegetation and climate history of Québec's mixed boreal forest suggests greater abundance of temperate species during the early-and mid-Holocene. *Botany*, 96: 437-448
- Larsen, C.P.S. (1997) Spatial and temporal variations in boreal forest fire frequency in northern Alberta. *Journal of Biogeography*, 24, 663– 673.
- Lavoie, M., Pellerin, S., Larocque, M., & Bottollier-Curtet, M. (2015). Late glacial and Holocene vegetation history in the northern foothills of the Adirondack Mountains. *Ecoscience*, 22: 59-70
- Lavoie, M., and L. Filion. (2001). Holocene vegetation dynamics of Anticosti Island, Québec, and consequences of remoteness on ecological succession. *Quaternary Research* 56: 112–127
- Le Gouvernement du Québec: Commission de toponymie (2016). Lac Noir. Website Data modified: 2018-01. Retrieved from <http://www.toponymie.gouv.qc.ca/ct/accueil.aspx>
- Long, C.J., Power, M.J., McDonald, B. (2011). Millennial-scale fire and vegetation history from a mesic hardwood forest of southeastern Wisconsin, USA. *Journal of Quaternary Science* 26: 318-325
- Maher, L.J. (1980). Statistics for microfossil concentrations measurements employing samples spiked with marker grains. *Review of Palaeobotany and Palynology*, 32: 153-191
- Marlon, J. R., Pederson, N., Nolan, C., Goring, S., Shuman, B., Robertson, A., Booth, R., Bartlein, ... & Yu, Z. (2017). Climatic history of the northeastern United States during the past 3000 years, *Climate of the Past*, 13: 1355-1379

- Marsicek, J. P., Shuman, B., Brewer, S., Foster, D. R., & Oswald, W. W. (2013). Moisture and temperature changes associated with the mid-Holocene Tsuga decline in the northeastern United States. *Quaternary Science Reviews*, 80: 129-142
- Matero, I. S. O., Gregoire, L. J., Ivanovic, R. F., Tindall, J. C., & Haywood, A. M. (2017). The 8.2 ka cooling event caused by Laurentide ice saddle collapse. *Earth and Planetary Science Letters*, 473: 205-214.
- McAndrews, J.H., Berti, A.A., Norris, G. (1973). Key to the Quaternary Pollen and Spores of the Great Lakes Region. Toronto: Royal Ontario Museum Life Sciences Miscellaneous Publications.
- Moore, P.D., Webb, J.A., Collinson, M.E. (1991). Pollen Analysis, second ed. Blackwell Scientific Publications, London.
- Mott, R.J., Farley-Gill, L.D. (1981). Two Late Quaternary Pollen Profiles from Gatineau Park, Québec, Geological Survey of Canada, Paper 80–31
- Mott, R.J. (1978). Populus in late-Pleistocene pollen spectra. *Canadian Journal of Botany*, 56: 1021-1031
- Mott R. J. (1977). Late-Pleistocene and Holocene palynology in southeastern Québec. *Géographie physique et Quaternaire*, 31: 139-149
- Mott, R.J., Camfield, M. (1969). Palynological studies in the Ottawa area, (Paper 80-31) Hull, Québec: Geological Survey of Canada

- Muller, S.D., Richard, P.J.H., Talon, B., (2008). Impact of disturbance on the Holocene development of a temperate peatland (Southern Québec). *Vegetation History and Archaeobotany* 17: 713-721
- Muller, S.D., Richard, PJH, Guiot, J, de Beaulieu, J-L & Fortin, D (2003). Postglacial climate in the St Lawrence lowlands, southern Québec: pollen and lake-level evidence. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 193: 51-72
- Muller, S.D., Richard, P.J.H., (2001). Post-glacial vegetation migration in conterminous Montréal Lowlands, southern Québec. *Journal of Biogeography* 29: 1169-1193
- Neil, K. (2018). *Ecosystem Responses to Holocene Climate Variability Through the Analysis of High-resolution Lake Sediment Cores from Southwestern Québec, Canada* (Doctoral dissertation, Université d'Ottawa/University of Ottawa).
- Neil, K., & Gajewski, K. (2018). An 11,000-yr record of diatom assemblage responses to climate and terrestrial vegetation changes, southwestern Québec. *Ecosphere*, 9: 11
- Ohlson, M., Tryterud, E. (2000). Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10: 519 – 525
- Ojala, A.E.K., Francus, P., Zolitschka, B., Besonen, M., Lamoureux, S.F. (2012). Characteristics of sedimentary varve chronologies - a review. *Quaternary Science Reviews* 43: 45-60
- O'Sullivan, P.E. (1983). Annually-laminated lake sediments and the study of Quaternary environmental changes -- a review. *Quaternary Science Reviews*, 1: 245-313

- Oswald, W. W., Foster, D. R., Shuman, B. N., Doughty, E. D., Faison, E. K., Hall, B. R., ... & Truebe, S. A. (2018). Subregional variability in the response of New England vegetation to postglacial climate change. *Journal of biogeography*, 45(10): 2375-2388.
- Oswald, W. W., Doughty, E. D., Foster, D. R., Shuman, B. N., & Wagner, D. L. (2016). Evaluating the role of insects in the middle-Holocene *Tsuga* decline. *The Journal of the Torrey Botanical Society*, 144: 35-40
- Oswald, W.W., Foster, D.R. (2011). Middle-Holocene dynamics of *Tsuga canadensis* (eastern hemlock) in northern New England, USA *Holocene*, 22: 71-78
- Overpeck, J., Webb, R.S., Webb III, T. (1992). Mapping eastern North American vegetation change of the past 18ka: no-analogs and the future. *Geology*, 20: 1071-1074
- Overpeck, J., Webb, T., Prentice, I. (1985). Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogs. *Quaternary Research*, 23: 87-108
- Paquette, N., Gajewski K. (2013). Climatic change causes abrupt changes in forest composition, inferred from a high resolution pollen record, southwestern Québec, Canada. *Quaternary Science Reviews* 75: 169-180
- Payette S, Morneau C, Sirois L, Despons M (1989). Recent fire history of the northern Québec biomes. *Ecology* 70: 656-673
- Parent, M., Occhietti, S. (1988). Late Wisconsinan deglaciation and Champlain Sea invasion in the St. Lawrence Valley, Québec. *Géographie physique et Quaternaire*, 42: 215-246

- Patterson III, W.A., Edwards, K.J., Maguire, D.J. (1987). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews*, 6: 3-23
- Payette, S., Pilon, V., Couillard, P.-L., Laflamme, J. (2017). Fire history of Appalachian forests of the lower St-Lawrence Region (Southern Québec). *Forests*, 8: 120
- Peros, M.C., Gajewski, K. & Viau, A.E. (2008). Continental-scale tree population response to rapid climate change, competition and disturbance. *Global Ecology and Biogeography*, 17: 658-669
- Péwé, T.L. (1983). The periglacial environment in North America during Wisconsin Time. In S.C. Porter (ed.), *Late Quaternary Environments of the United States*, vol 1, The Late Pleistocene, 157-189. University of Minnesota Press, Minneapolis
- Pisaric, M.F.J. (2002). Long-distance transport of terrestrial plant material by convection resulting from forest fires. *Journal of Paleolimnology*, 28: 349-354
- Power, M.J, et al (2008). Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data, *Climate Dynamics*, 30: 887-907
- Prentice, I.C., Bartlein, P.J., Webb III, T. (1991). Vegetation and climate change in Eastern North America since the Last Glacial Maximum. *Ecology*, 72: 2038-2056
- R Core Team (2014). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.
- Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, ...& van der Plicht J.

- (2013). IntCal13 and MARINE13 radiocarbon age calibration curves 0-50000 years cal BP. *Radiocarbon* 55: 1869–1887
- Richard, P.J.H. (1994). Postglacial palaeophytogeography of the eastern St. Lawrence River watershed and the climatic signal of the pollen record. *Palaeogeog Palaeoclimatol Palaeocol* 109: 137–163
- Richard, P.J.H. (1978). Histoire tardiglaciaire et postglaciaire de la végétation au mont Shefford, Québec. *Géographie physique et Quaternaire*, 32: 81-93.
- Ritchie, J. C. (1995). Tansley review No. 83: Current trends in studies of long-term plant community dynamics. *New Phytologist*, 130: 469-494
- Ritchie, J.C. (1987). *Postglacial vegetation of Canada*. New York, NY: Cambridge University Press.
- Rodrigues, C.G. (1992). Successions of invertebrate microfossils and the late Quaternary deglaciation of the central St. Lawrence Lowland, Canada and United States. *Quaternary Science Reviews*, 11: 503-534
- Rogers, B., Soja, A.J., Goulden, M.L., Randerson, J.T. (2015). Influence of tree species on continental differences in boreal fires and climate feedback. *Nature Geoscience*, 8: 228-234
- Rowe, J.S. (1971). *Forest Regions of Canada*. Ottawa, Canada: Canadian Forestry Service, Department of the Environment
- Rummery, T. A. (1983). The use of magnetic measurements in interpreting the fire histories of lake drainage basins. *Hydrobiologia* 103, 53–58.

- Rummary, T. A., Bloemendal, J., Dearing, J., Oldfield, F., and Thompson, R. (1979). Persistence of fire-induced magnetic oxides in soils and lake-sediments. *Annal. Géophys.* 35, 103–107
- Rust, B. R., & Romanelli, R. (1975). Late Quaternary subaqueous outwash deposits near Ottawa, Canada.
- Sandgren, P., Snowball, I. (2001). Application of mineral magnetic techniques to paleolimnology. In Smol, J., Birks, H. J.B., Last, W.M. (Eds) *Tracking Environmental Change using Lake Sediments, Volume 2*. Dordrecht, Netherlands: Kluwer Academic Publishers
- Scott, A.C. (2000). The Pre-Quaternary history of fire. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 164: 281-329.
- Shuman, B. N., & Burrell, S. A. (2017). Centennial to millennial hydroclimatic fluctuations in the humid northeast United States during the Holocene. *Quaternary Research*, 88: 514-524
- Shuman, B. N., & Marsicek, J. (2016). The structure of Holocene climate change in mid-latitude North America. *Quaternary Science Reviews*, 141: 38-51
- Shuman, B., P. Newby, Y. Huang, and T. Webb^{3rd}. (2004). Evidence for the close climate control of New England vegetation history. *Ecology* 85: 1297–1310
- Stockmarr, J., (1971). Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13: 615-621

- Sandgren P, Snowball I (2001). Application of mineral magnetic techniques to paleolimnology. In Last M, Smol JP (eds). *Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Geochemical Methods*. Dordrecht: Kluwer, 217-229
- Spurr, S.H., Barnes, B.V. (1980). *Forest Ecology*. New York, USA: John Wiley and Sons
- Swain, A.M. (1980). Landscape patterns and forest history in the Boundary Waters Canoe area, Minnesota: a pollen study from Hug Lake. *Ecology*, 61, 747—754
- Swain, A.M., (1978). *Quaternary Research* 3, 383—396. —, 1978. Environmental changes during the past 2000 years in north-central Wisconsin: analysis of pollen, charcoal, and seeds from varved lake sediments. *Quaternary Research* 10, 55—68.
- Swain, A.M. (1973). A history of fire and vegetation in northeastern Minnesota as recorded in lake sediment. *Quaternary Research*, 3: 383-396
- Sugita, S. (1994). Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. *Journal of Ecology*, 82: 881-897
- Talon, B., Payette, S., Filion, L., & Delwaide, A. (2005). Reconstruction of the long-term fire history of an old-growth deciduous forest in southern Québec, Canada, from charred wood in mineral soils. *Quaternary Research*, 64: 36-43
- Thomson, R., Battarbee, R.W., O’Sullivan P.E., Oldfield, F. (1975). Magnetic Susceptibility of Lake Sediments. *Limnology and Oceanography*, 20: 687-698
- Thompson, R., (1973). Palaeolimnology and palaeomagnetism. *Nature* 242: 182-184

- J.L. Toney, D.T. Rodbell, N.G. Miller (2003). Sedimentologic and palynologic records of the last deglaciation and Holocene from Ballston Lake, New York *Quaternary Research*, 60: 189-199
- Traverse, A. (2007). Holocene Palynology. In N.H. Landman, D.S. Jones (Eds) *Paleopalynology*. Dordrecht, Netherlands: Springer
- Trouet, V., Diaz, H. F., Wahl, E. R., Vial, A. E., Graham, R., Graham, N., & Cook, E. R. (2013). A 1500-year reconstruction of annual mean temperature for temperate North America on decadal-to-multidecadal time scales. *Environmental Research Letters*, 8: 024008
- Van Wagner, C.E. (1978) Age-class distribution and the forest fire cycle. *Canadian Journal of Forest Research*, 8, 220– 227
- Vial, A.E., Gajewski, K., Sawada, M.C., Fines, P. (2006). Millennial-scale temperature variations in North America during the Holocene. *Journal of Geophysical Research*, 111(D9)
- Walker, D., Wilson, S.R. (1978). A Statistical Alternative to the Zoning of Pollen Diagrams. *Journal of Biogeography*, 5: 1-21
- Waddington, J.C.B. (1969). A stratigraphic record of the pollen influx to a lake in the Big Woods of Minnesota. *Geological Society of America, Special Paper 123*, 263—282
- Webb, T. III, Bartlein, P.J., Harrison, S.P. & Anderson, K.H. (1993). Vegetation, lake levels, and climate in eastern North America for the past 18 000 years. *Global Climates Since the Last Glacial Maximum*. (eds H. E. Wright Jr, J. E. Kutzbach, T. Webb, III, W. F. Ruddiman, F. A. Street-Perrott & P. J. Bartlein), pp. 415–467. University of Minnesota Press, Minneapolis

- Webb, T. III, Richard, P.J.H., Mott, R.J. (1983). A mapped history of Holocene vegetation in southern Québec. *Syllogeus* 49: 273-336
- Weir, J.M.H., Johnson, E.A. & Miyanishi, K. (2000) Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. *Ecological Applications*, 10, 1162– 1177
- Whitlock, C., Millspaugh, S.H., (1996). Testing the assumptions of fire history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6: 7 – 15
- Whitlock, C., Shafer, S.L. & Marlon, J. (2003). The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest Ecology and Management*, 178(1-2): 5-21.
- Whitlock, C., Larsen, C. (2001). Charcoal as a fire proxy. In Smol, J., Birks, H. J.B., Last, W.M. (Eds) *Tracking Environmental Change using Lake Sediments, Volume 3*. Dordrecht, Netherlands: Kluwer Academic Publishers
- Whitmore J, Gajewski K, Sawada M et al. (2005). A North American Modern Pollen Database for Multi-scale Paleoecological and Paleoclimatic Applications. *Quaternary Science Reviews*, 24: 1828-1848
- Williams J.W., Shuman, B. (2008). Obtaining accurate and precise environmental reconstructions from the modern analog technique and North American surface pollen dataset. *Quaternary Science Reviews* 27: 669-687
- Wright, H.A., Bailey, A.W. (1982). *Fire Ecology: United States and Southern Canada*. New York, USA: John Wiley and Sons

Zhao, Y., Z. C. Yu, and C. Zhao. (2010). Hemlock (*Tsuga canadensis*) declines at 9800 and 5300 cal yr BP caused by Holocene climatic shifts in northeastern North America. *Holocene* 20: 877–886

Yu, Z., McAndrews, J.H. & Eicher, U. (1997). Middle Holocene dry climate caused by change in atmospheric circulation patterns: evidence from lake levels and stable isotopes. *Geology*, 25, 251–254

Ziegler, S.S. (2000). A comparison of structural characteristics between old-growth and postfire second-growth hemlock hardwood forests in Adirondack Park, New York, U.S.A. *Global Ecology and Biogeography* 9: 373–389