A middle to late Holocene paleo-environmental study of L'Anse aux Meadows National Historic Site, Newfoundland, Canada

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ABSTRACT

Paleoecological reconstructions offer insight into environmental and climatic conditions of the past, allowing us to understand how changing climate conditions have shaped Canada's landscapes over millennia. While instrumental data only reaches back a few centuries, paleo-reconstructions allow us to understand past environmental variability over much longer periods of time as well as predict future changes. They also contextualize archaeological sites within the broader context of ecological conditions of the period. Using high-resolution, multi-proxy analysis, this study reconstructs the past 6,000 years of vegetation and fire history around the UNESCO World Heritage archaeological site of L'Anse aux Meadows and provides new understanding into long-term ecological changes and their relationship with regional climate variations and human activity. While many previous analyses have studied samples from directly within the archaeological remains, my research offers the first regional combined charcoal and pollen record, with a well-dated chronology based on a larger suite of AMS radiocarbon dates than previously used, for the area directly downwind of the site. First, I situate this site within the human history of the North Atlantic as well as review previous paleo-ecological work done within the region, including the Northern Peninsula of Newfoundland and that of southern Labrador. Then, I present a reconstruction of pollen, macrocharcoal, and loss-on-ignition analysis based on a 2 m peat core located 300 m east of the archaeological site. The core sequence was dated using ^{14}C dating methods with the bottommost core-section dating to ~4055 BCE (6000 cal BP). The analysis shows transitions from fen- to bog-like environments, punctuated by fire events and shifts in vegetation composition. Early fen conditions (4055–1740

BCE) transitioned to a more bog-like environment, following a significant fire disturbance. The early fen conditions were followed by a prolonged period of low peat accumulation (1095 BCE–50 CE), potentially due drier conditions. Fire frequency increased during the first millennium CE, peaking during the Medieval Climate Anomaly (920–1280 CE), suggesting warmer conditions preceding the onset of the Little Ice Age. The long-term decline in pollen influx aligns with regional cooling trends documented in the other paleo-ecological studies in the North Atlantic, driven by decreasing solar radiation and sea-surface temperature changes. This research contributes to our understanding of Holocene environmental dynamics in northern Newfoundland, situating L'Anse aux Meadows within a broader climatic and ecological context, and explores potential anthropogenic impacts on fire regimes and landscape changes.

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Contributions of Authors

As first author, I was the main person responsible for data analysis and the writing of the manuscript related to this thesis. The manuscript was co-authored by George Drummond, who analyzed the charcoal record of the core, Dr. Jeannine-Marie St-Jacques and Dr. Matthew Peros, who advised on experimental design, statistics, editing, and revisions to the manuscript. Others have and will continue to play important roles in this work, including Paul Ledger, Emilie Gauthier, Elia Roulé, Cesar Arturo Vera, Nathasha Roy, and Paola Jirado. We also thank Parks Canada for permission to work at L’Anse aux Meadows National Historic Site and for logistical support while in the field.

Our bodies have formed themselves
in delicate reciprocity
with the manifold
textures, sounds and shapes
of an animate earth

David Abram

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CHAPTER 1: Introduction

Since the Last Glacial Maximum, some 21,000 years ago, North America has seen widescale changes to its terrestrial ecosystems. The northward melting of the Laurentide and Cordilleran icesheets led a major south-to-north plant migration that moved species into their modern ecological zones around 11,000 years ago (COHMAP members 1988; Muller and Richard, 2001; Ritchie, 2004; Ruddiman, 2013). Today, anthropogenic climate change has begun to affect broad-scale changes across North America, already influencing the distribution of arboreal species, pests, precipitation and temperature. These large-scale climate forcings have affected and will continue to affect the living conditions of the human and more-than-human world, particularly in Arctic regions where climate warming is predicted to have the strongest influence on ecosystems, resulting in a further northward progression of vegetation zones (Walther et al., 2002; IPCC, 2013; Natural Resources Canada, 2018). Paleo-ecological records of North American landscapes have played a vital role in contextualizing human history during and after the ecological changes of the Last Glacial Maximum on the North American continent, particularly the environmental effects of European Contact. In this study, these records serve a twofold purpose of contextualizing archaeology, while also documenting baseline ecological conditions which can be used to understand the oncoming changes to our landscapes.

The analysis of environmental proxies such as pollen, microcharcoal and macrofossils preserved in lake and peat sediments offer valuable ecological information to situate archaeological sites within the wider context of human adaptations and to contextualize diet, site function, site abandonment/demise, and broad anthropogenic disturbance within local vegetation patterns (Webb, 1980; Davis, 1984; D'Andrea et al., 2011; Perren et al., 2012; Ledger et al., 2019; Zhao, et al, 2022; Roulé et al., 2025). These palaeoecological records can thus aid us in understanding important long-term human adaptations and possible ecological disturbances of North American ecosystems throughout the Holocene, where the European colonialization of Turtle Island has had devastating effects on the populations and cultures of Indigenous nations. Long-term climate and ecological records are essential to establish these reference conditions from which to track climate and ecosystem changes. Paleo-ecological records from coring peatlands (bogs and fens) and lakes have been used across eastern Canada and the North Atlantic region to document changes in climate, precipitation, forest-cover, and fire regimes throughout the Holocene (Davis et al., 1988; Bergeron et al., 2006; Perren et al., 2012; Ledger et al., 2019; O'Neil Sanger et al., 2021; Finkenbinder et al., 2022). These long-term records serve as a valuable means to differentiate significant anthropogenic ecosystem changes from natural environmental variability.

The L'Anse aux Meadows archaeological UNESCO World Heritage Site on the northern tip of Newfoundland offers a fascinating place to employ these techniques. While known for being the only verified Norse settlement in North America, this site also shows evidence of over 5,000 years of intermittent Indigenous occupation, including the Maritime Archaic, Paleo-Inuit cultures (Groswater and Dorset), as well as those during the Recent Period (e.g. Cow Head and various other complexes) (Davis et al., 1988; Wallace, 2006; Kristensen and Curtis, 2012; Ledger et al. 2019; Betts and Gabriel, 2021). This site is one of the few places where we are able to study the impacts of First Nations groups, as well as pre-Columbian Europeans on the same landscape. It is therefore fascinating for the sheer amount of human history that has taken place there in the Holocene: from the long-term activity of Indigenous groups using the locale for warm weather bird hunting grounds to the relatively short but compelling long houses of the Norse, this site provides a unique opportunity to examine environmental-human interactions between two very different populations. It also offers the opportunity for us to gather more data on baseline pre-industrial ecological conditions in northern Newfoundland that will be important in coming decades as anthropogenic climate change continues to change our landscapes and ecologies in North America.

CHAPTER 2: Literature Review

This literature review seeks to situate the site of L'Anse aux Meadows in the human and ecological history of North Atlantic Canada. The first section provides a brief overview of pollen as a paleo-ecological proxy. I then explore the history of the Norse in the North Atlantic, followed by a detailed description of the archaeological site itself. Next, I examine the presence of the various Indigenous groups on Newfoundland over the past several thousand years, with a particular focus on occupation at L'Anse aux Meadows. Finally, I integrate a number of pollen records from Newfoundland and Labrador, as well as the past palaeoecological work done at the L'Anse aux Meadows.

2.1 Pollen as a paleo-ecological proxy

In the context of establishing past ecological datasets that serve to situate archaeological sites, as well as to create baseline environmental conditions from which to understand future changes, pollen records have been studied from both peat and lake cores across North America and the North Atlantic region (St Jacques et al., 2008; Gauthier et al., 2010; Munoz et al., 2010; Blundell et al., 2018). Because pollen grains are dispersed and can be preserved in anaerobic environments, specific species assemblages create an ecological snapshot of the vegetation conditions of that area. Often dispersed by wind and deposited in temperate latitudes where sediments are accumulating, pollen grains settle into the substrate's stratigraphic record where they are preserved (Bradley, 2015). These layered records can then be used to reconstruct past vegetation and, along with radiocarbon dating, can be used to glean something of the past environmental conditions, e.g., temperature and precipitation of the area. Palynology has often been used to understand the effects of various human groups on vegetation and can sometimes help infer specific subsistence and survival practices such as forestry, animal husbandry, and agricultural practices (Moore et al., 1991; Davis et al., 1998; Bell et al., 2005; Gauthier et al., 2010). It has also been used to understand the effect of large-scale environmental changes on cultural shifts, population fluctuations, migration patterns, and subsistence changes (Munoz et al., 2010).

2.2 Discovery of L'Anse aux Meadow Site

The discovery of the remains of several Norse longhouses propelled L'Anse aux Meadows onto the world stage in 1960 when two researchers, Anne and Helge Ingstad, succeeded in finding the Norse outpost in the hypothesized and somewhat fabled region of Vinland (Ingstad, 1977; Kunz and Sigurdsson, 2008; Wallace, 2006). This landing and small settlement on the shores of North Atlantic Canada has long stood as a defining feature of the Viking Age, and parts of it were poetically recorded in the tradition of the Norse Sagas (Sigurdsson and Kunz, 2008; D'Andrea et al., 2011; Ingstad, 1977; Perren et al., 2012; Ledger et al., 2019). In particular, the *Saga of the Greenlanders* and *Saga of Erik the Red* (together, known as the *Vinland Sagas*) which contain lyrical accounts of westward voyages from Iceland to Greenland, and then from Greenland to what has been assumed to be north-eastern Canada (based on geography and the descriptions of the lands) have been the subject of extensive multidisciplinary discussions (Kunz and Sigurdsson, 2008).

Eventually, the *Vinland Sagas* kindled enough curiosity in the academic world that in 1960 the Ingstads set out in search of *Straumfjord* Vinland (Ingstad, 1977; Wallace, 2003a). The Ingstads succeeded in discovering an archaeological site near the fishing village of L'Anse aux Meadows on the most northern tip of Newfoundland. The initial archaeological excavations on the site soon exposed clear signs of an 11th century Norse settlement (Ingstad, 1977). Further archaeological research then revealed thousands of years of intermittent human disturbance from

Indigenous groups in the area (Ingstad, 1977; Ingstad, 1985; Wallace, 2005; UNESCO World Heritage Centre, n.d.; Kay, 2016; Ledger, 2019). The verification of L'Anse aux Meadows as a Viking site was ultimately settled by a combination of the information from the *Vinland Sagas,* the layout and style of the houses, and distinguishing artifacts including a spindle whorl, a bone needle, a piece of gilded copper and a bronze ring pin (Ingstad, 1977, 1985, 2013; Petré, 1985; Wallace, 2006; Kay, 2016). The exact date of their arrival in North America remains uncertain. However, new research using dendrochronological methods indicates that the site was occupied by the Norse in the year 1021 CE (Kuitems et al., 2021). This date The Norse site at L'Anse aux Meadows rests within the wider context of the Norse colonization, or *landnám,* of Iceland and Greenland, and so far represents the most westerly-located Norse settlement in the North Atlantic.

2.3 Past Palynological Research at the L'Anse aux Meadows

Paleoecological investigations at L'Anse aux Meadows began in the 1970s and were followed by several studies (Henningsmoen, 1977; Davis et al., 1988; Wallace, 2006; Ledger et al., 2019; Forbes et al., 2020; Speller and Forbes, 2022). Some of the earliest work was undertaken by Henningsmoen (1977), whose research was driven by questions such as whether the Norse found a landscape similar to today, what impacts the Norse had on the local vegetation, and to what extent the shoreline was different from that of today. In this work, samples were collected from eight pond and bog locations, three of which were from within the archaeological site itself, and all within approximately a 10 km radius of the Norse remains. At each location, the sampling resolution of the pollen in the cores was approximately every 10 cm, and the longest sequence was collected from West Saddle Hill Pond, about 2 km east of the site, which consisted of a core that measured 370 cm long, with a basal date of 7500 ± 130 ^{14}C yr BP (uncalibrated). The longest (and oldest) bog record was from Palsa Bog, within 50 m of the archaeological site, covering a depth of 175 cm, and with a basal date of 5320 ± 60 ^{14}C yr BP (uncalibrated). Excepting Davis' work (1988), all of the records published in this work have only one or two radiocarbon dates, which is not uncommon for the time, and all these were made using the beta-counting method, which requires large samples of often heterogenous materials. In the case of this study, the materials that were used for the radiocarbon dating were not reported.

Overall, the results from all the sites reported by Henningsmoen (1977) show that the pollen spectra are dominated by both boreal and sub-arctic taxa, characteristic of the landscape today. Several diagrams, such as those from Mosquito Pond and "the Pond between Ship Cove and Raleigh," show large increases in *Sphagnum* spores at depths of between 140 to 200 cm in their respective cores, but it is difficult to ascertain when these changes occurred due to only single radiocarbon dates available for both cores. Skin Pond, about 1.5 km south of the archaeological site, also shows a large increase in *Sphagnum* (followed by its decline), suggesting a general shift to a more ombrotrophic peatland type environment during the last few thousand years. The pollen diagram from Palsa Bog, the closest location to our study site, was characterized by an abrupt increase in *Sanguisorba*, *Cornus*, *Potentilla*-type, and other taxa, for what was probably a short duration at around 120 cm depth, suggesting a sudden change in the environment, possibly related to disturbance (at this depth, likely occurring before the Norse period). However, this diagram is also notable by a long-term increase in *Rubus chamaemorus* beginning at about 100 cm depth and continuing to the surface. Overall, the study by Henningsmoen (1977) did not document any clear impact from the Norse settlement on the regional vegetation, although the sampling resolution may not have been sufficient to have done so. This work also accords to an earlier study by Mott (1975) who examined several peat monoliths from within the archaeological site itself, and found no substantial changes to the vegetation over the last 2000 years, with the only prominent changes coming in non-arboreal pollen, likely representing very local-scale habitat changes.

Later pollen work focused on higher-resolution sampling of bog environments from a number of sites within the vicinity of the L'Anse aux Meadows archaeological site. A pollen diagram published in Davis (1984) called the "Road Cut site", located several dozen meters south of the Norse settlement in a "basin bog" provides a ~6,500-year long record. The key feature of this diagram is a large expansion of Ericaceae at around ~3000 cal BP, likely representing a period of paludification due to "climate deterioration", which Davis (1984) interpreted as representing the onset of colder conditions in the late Holocene following a warmer middle Holocene period. In addition, MacPherson (1995) reports that John H. McAndrews undertook pollen work at Saddle Hill Pond, several kilometers west of L'Anse aux Meadows. It is unclear whether this represents the same site as "West Saddle Hill Pond", as reported by Henningsmoen (1977), but four radiocarbon dates are provided for a core at least 355 cm in length (the oldest date is 9430 ± 255 ^{14}C yr BP indicating a nearly complete Holocene sequence) but the only pollen data is a brief qualitative summary indicating a presence of *Salix* at the base of the core, with an increase in *Alnus* around ~6000 cal BP, consistent with many other pollen records from the region (MacPherson, 1995).

Finally, Davis et al.'s (1988) paleo-environmental study of the L'Anse aux Meadows site gives context for the last ~2,300 years of vegetation and allows us to hypothesize about what to expect in our own study during this time-period. The principal pollen results from Davis et al. (1988) are shown in Figure 1 provide an important base of knowledge for the flora of the area.

The pollen and spore data show large swings of *Sphagnum* and *Sanguisorba* spores over the last 2000 years as well as an increasing trend of *Alnus* and Cyperaceae. *Betula* also shows larger peaks near the top of the core. Davis et al., also noted the decreasing trend of conifers from the base to surface of the core as shown most prominently in *Picea* percentages, which they interpret to mean the region was more wooded in early years than in more recent years.

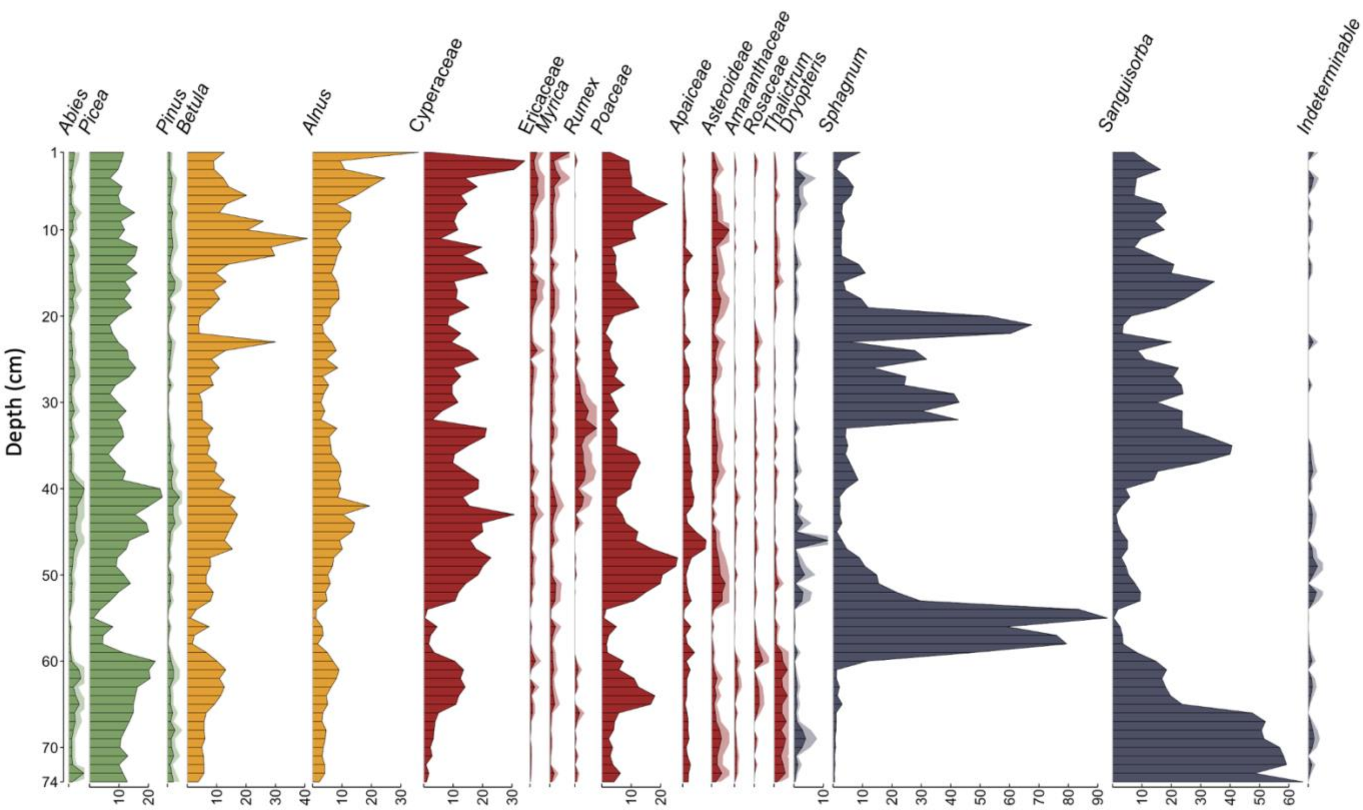


Figure 1. Pollen percentage diagram for the principal taxa from L'Anse aux Meadows, Newfoundland from Davis et al. (1988). Shown are pollen percentages of principle ecological taxa. Lighter areas show an exaggeration of 3×.

Around the year 1000 cal BP (~30cm), around the time of Norse occupation of the region, there is a distinct rise in *Betula* pollen (Kuittems et al., 2021). This could be related to Norse forest-clearing activities, as arboreal *Betula* are primary successional species and do not tolerate shade and therefore may have been able to prosper with the clear-out of other arboreal species. This could also have been due to a warmer climate, as arboreal *Betula* prefer conditions around 18-22°C (Perala, 1990). However, other Norse archaeological sites exhibit an instantaneous decrease in *Betula* pollen due to Norse land-clearance (Fredskild, 1973, 1992; Ledger et al., 2013). This discrepancy among Norse sites may be explained by shrub and tree *Betula* exhibiting different responses to Norse occupation, but often remaining undifferentiated in palaeoecological studies. Splitting *Betula* pollen into shrub- versus tree-derived pollen may therefore provide further insight into its pollen fluctuations during the period of Norse occupation. The *Rumex* peak in the middle of the core underlies the Norse horizon of this core and is therefore not a consequence of their activity at the site. Either way, changes in this pollen taxon's abundance are important to watch for in our pollen counts from the site.

There is a second period of *Betula* increase between 300-600 cal BP (Figure 1; Davis et al., 1988). This could be due to a climate anomaly. This is also, around the time of permanent European arrival in Newfoundland; however, it is unlikely that the few fishermen that made their way to the northern-most part of the island would have had such a significant effect on *Betula* abundance. This second spike of *Betula* comes right at the transition of the Medieval Climate Anomaly, 950 – 1250 CE (MCA) to the Little Ice Age, 1300 – 1800 CE (LIA). Towards the end of the Medieval Climate Anomaly, tree *Betula* may have been taking advantage of the prolonged warmth, only to decrease again as the temperatures dropped at the beginning of the LIA. The end of the spike in *Betula* is almost exactly coincident with the Little Ice Age and thus it is possible that this decrease can be attributed to the cooling climate (Perala, 1990). In summary, this study by Davis et al. (1988), provides a useful, initial exploration of the site, which our own research will expand upon further, using the most-up-to-date dating techniques, taxonomy, and multiple proxies to more deeply understand the ecological and climatic context of the Indigenous occupation, as well as the Norse period.

2.4 Norse in the North Atlantic

Norse expansion across the North Atlantic began in the 9th century CE with voyagers establishing agropastoral communities and resource-trade routes in the Faroe Islands, Iceland, and Greenland. The Norse colonization (*landnám*) of the North Atlantic began in the 9th century CE with the settlement of Shetland, followed by the Faroes Islands, Iceland, Greenland and finally culminated on the shores of Newfoundland, with the small settlement built at L'Anse aux Meadows around 1000 CE (Dugmore et al., 2005; Schofield and Edwards, 2011).

The Norse *landnám* has been studied both archaeologically and paleo environmentally across the Faroe Islands, Iceland and Greenland (Arneborg et al., 2012; Fredskild, 1992; Gauthier et al., 2010; Ledger, 2013; Lynnerup 1996; Schofield et al., 2008; Schofield and Edwards, 2011). These Norse settled agricultural settlements were the first of their kind and had profound ecological impacts on the environment (Dugmore et al., 2005). These consequences are evident in the substantial and prompt decline of birch pollen (Dugmore et al., 2005), increased frequencies of introduced species and changing concentrations of coprophilous and *Sporormiella*-type fungi (Gauthier et al., 2010; Schofield and Edwards, 2011), elevated lacustrine sedimentation rates (Richter et al., 2021), presence of cereal-type pollen, increased grass-type pollen (Perren et al., 2012; Gauthier et al., 2023), as well as enhanced soil erosion due to cattle grazing (Thórarinsson, 1961; Fredskild, 1992), and peat stripping for the construction of houses (Dugmore et al., 2005).

In Iceland the predominate pollen indicators of Norse *landnám* is the decline of *Betula* pollen and a corresponding increase of Poaceae (grasses) and Cyperaceae (sedges) along with weeds like *Rumex* spp (Dugmore et al., 2005). Increased soil erosion was also a notable signature of *landnám* in Iceland (Dugmore et al., 2005). In practice this seems to have been the impact of clearing woodland for grazing, structural timber and fuel for burning which was then replaced by heath and grassland (Dugmore et al., 2005; Fredskild, 1992; Gauthier et al., 2023). In the Faroes, a common palynological signal of Norse settlement in the Faroes was the appearance of cereal-type pollen (Dugmore et al., 2005).

Norse settlement of Greenland began in 985 CE when Erik the Red, exiled from Iceland, arrived and set up the first Norse farming settlement there. Eventually two main settlements were established, which in the following centuries, expanded and developed to collectively sustain some 3,000 to 6,000 residents at their height (Lynnerup, 1998; McGovern, 1991). By the early 15th century CE, approximately 500 farms supported this population along with their sheep, cattle, horses, and dogs (Dugmore et al., 2005; Gauthier et al., 2010; Lynnerup, 1998). These Greenland farms seem to have been based on a mixture of agriculture and pastoralism, as well as communal seal hunting, caribou hunting and fishing (Arneborg et al., 1999, 2012). However, in later years it seems that the reliance on marine resources increased (Arneborg, 1999). The overarching *landnám* pattern that appears in Greenland is similar to that of Iceland, with the initial clearance of shrub and woodland vegetation by fire or manual labour, the subsequent expansion of grasslands, herbs, increased microscopic charcoalconcentrations, and the appearance of *Rumex acetosella* (Dugmore et al., 2005; Schofield and Edwards, 2011; Gauthier et al., 2010; Ledger et al, 2014, Fredskil, 1973). The Norse *landnám* is noticeable in pollen signal by a sustained increase in Poaceae, suggesting the expansion of grassland at the expense of woodland (Schofield and Edwards, 2011; Ledger et al., 2014). The Norse site at Ujaragssuit, Godthåbsfjord, show a layer of wooden chip and charcoal (Iversen, 1934; Fredskild 1973), while Lake Tugtuligssuag is marked by the appearance of docks and the decline of shrubs such as *Salix* and *Alnus* in the palynological data (Fredskild, 1973). There is also evidence of the use of fire for land clearance in the Western Settlement of Greenland found as a thin black line in the surrounding peat bogs (Schofield and Edwards, 2011). It was also noted that high levels of ascospores from coprophilous fungi, which occur due to the presence of grazing animals, can be indicators of animal husbandry as their fluctuations indicate changes in the number of herbivores on the landscapes (Gauthier et al., 2010). Soil erosion also intensified during this period, likely due to cattle grazing and peat stripping for construction (Dugmore et al., 2005).

Noticeably, the Norse *landnám* of Greenland took place during the Medieval Climate Anomaly (~950 CE to ~1250 CE), a period of relatively warmer temperatures in the North Atlantic (Lamb, 1965; D'Andrea et al., 2011; Finkenbinder et al., 2022). It was during this warmer climatic period that the houses were built at L'Anse aux Meadows, reinforcing the hypothesis that warmer environmental conditions at this time facilitated Norse expansion across the region (Kuitems et al., 2021, Roulé et al., 2025). Researchers have widely theorized that the warmer climatic conditions of the Medieval Climate Anomaly may have enabled agropastoral subsistence in the region (D'Andrea et al., 2011; Perren et al., 2012). However, despite its early success, the Greenland colony was abandoned in the mid-15th century CE.

It is likely that the onset of the Little Ice Age (~1450 to ~1850 CE) contributed to the decline Norse settlements in Greenland (Barlow et al., 1997; Roulé et al., 2025; Zhao et al., 2022). The precise causes for the abandonment of these farms remains the subject of much continued debate (Barlow et al., 1997; Grove, 1988). Increasing storm frequency (Dugmore et al., 2007a), the onset of drought (Zhao et al., 2022), sustained climatic cooling (D'Andrea et al., 2011), and changes in icefloes and animal migration (Dugmore et al., 2007b), all point to serious climatic changes that affected Greenland and Iceland in the 1300's. However, some speculate that the failure of the settlement had more to do with changes in European trade or governance structures (Dugmore et al., 2012). In reality, it is likely that it was neither just one nor the other, but a mix of climatic and political reasons that ultimately led to the failure of the Norse settlement in Greenland.

Together, these environmental indicators paint a clear picture of Norse land use and its lasting ecological imprint on Greenland's landscape. It seems likely that a combination of climate fluctuations, resource pressures, and sociopolitical changes ultimately shaped the trajectory of Norse settlement in the region, culminating in its abandonment by the 15th century CE (Barlow et al., 1997; Dugmore et al., 2012).

2.5 The Norse at L'Anse aux Meadows

Several factors confirm that L'Anse aux Meadows was a Norse settlement, including the design and construction of the remains of eight structures, the scant but compelling evidence from radiocarbon-dated artifacts and evidence of smelting (Ingstad, 1977, 1985; Ingstad and Ingstad, 2000; Wallace 2203a). Wallace (2003a) argues that the site is most likely to be *Straumfjord* from the Norse sagas, which is described as a large base set on fjord surrounded by strong currents and used year-round (Sigurdsson and Kunz, 2008; Wallace, 2003a)

The site consists of eight structures that are grouped together in clusters of twos and threes (Ingstad, 1977, 1985; Lindsay, 1975; Wallace 2005). With the exception of the smithy, these buildings all appear to have been dwellings although, some specialized crafts took place in them i.e., boat repair, storage, living, and smithing (Wallace, 2005 and 2012). They seem to have been built contemporaneously and due to the evidence of many *naust* (boatsheds) along the beach, suggest the presence of many boats stored there at once, implying that the buildings were occupied simultaneously (Wallace, 2003a). The construction techniques of the buildings at L'Anse aux Meadows match those of contemporary Scandinavian sites in Greenland and Iceland, which uses turf for the main building material and was prevalent in the Viking age (A.S.

Ingstad, 1985; Ingstad and Ingstad, 2001; Wallace, 2006). However, the layout of the buildings differs from these sites the Greenland or Iceland in its location on exposed headland as well as its clusters of buildings (Wallace, 2003a).

Wallace (2003a) contended that this was a short-term base camp used for only a few years, and Ledger et al. (2019) later suggested intermittent use by the Norse of up to a century but agreed that use was likely shorter term. Wallace (2005, 2012) interpreted this site as a waystation from which the Norse explored farther southwest into Vìnland (Wallace, 2005). This interpretation was based on the fact that the there was a distinct lack of byres, barns, or animal pens that would have been indicative of a more permanent settlement. Instead, the layout and artifact evidence suggest a site that was not built with the intention to be self-supporting i.e. capable of producing its own sustenance (Wallace, 2003a). The discovery of butternuts, which do not grow in Newfoundland but are native to areas further south such as New Brunswick, suggests that expeditions traveled beyond L'Anse aux Meadows, possibly reaching the temperate forests described as Vìnland in the Norse sagas (Ingstad, 1977; Wallace, 2003a, 2005, 2012).

The Norse settlement was large with capacity to sleep 70-90 individuals and from gendered archaeological evidence (a spindle whorl, a needle hone, and a bone pin) it seems that both men and women inhabited the site over its use (Wallace, 2003a). The sturdy nature of the buildings suggest that they were constructed to withstand winter and thus intended for year-round use (Wallace, 2003a). Its exposed location on the open water of the Straight of Belle Isle contrasts with the sheltered locales of other Norse sites in Iceland and Greenland and suggests that seafaring was the most important function of the settlement (Wallace, 2000, 2003a).

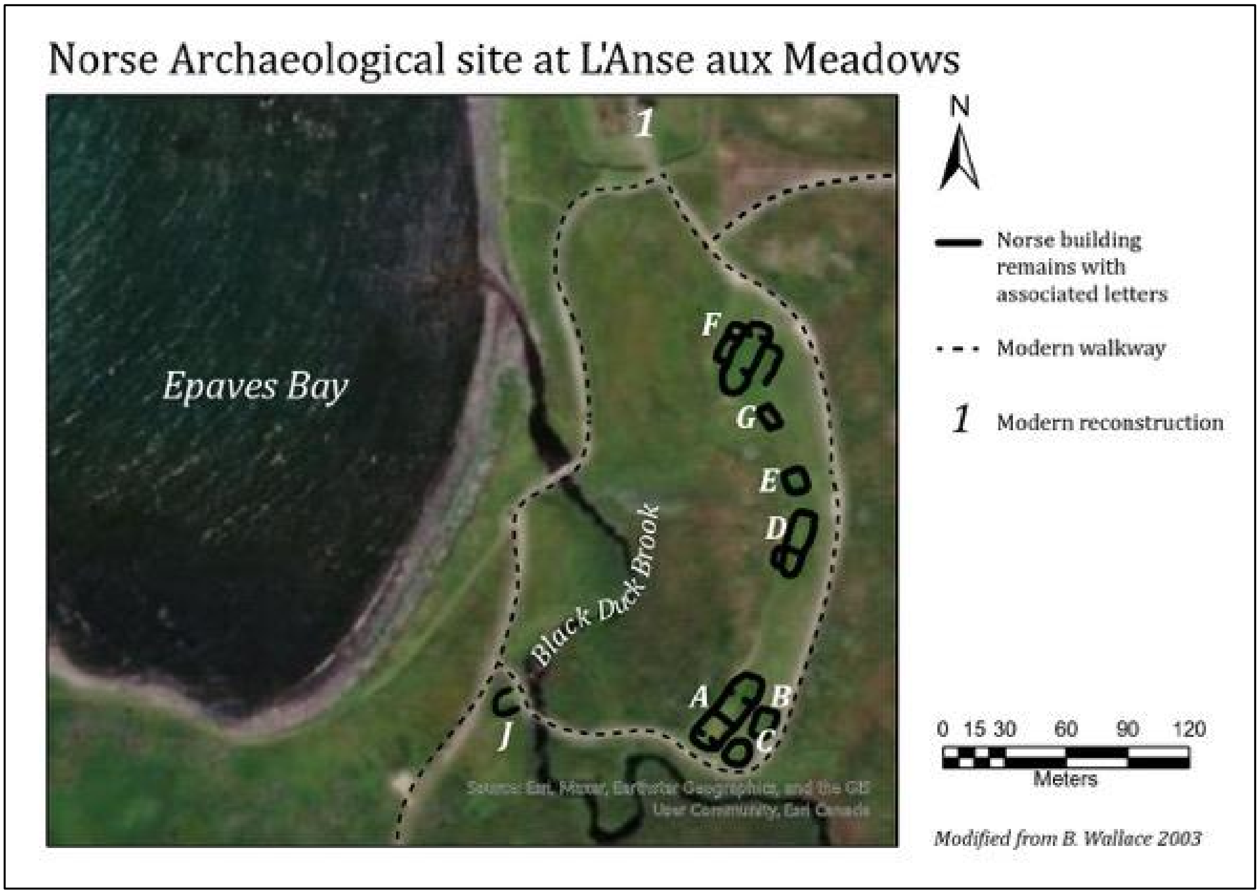


Figure 2. Map of Norse buildings ruins at L'Anse aux Meadows, showing all building complexes, A-G, as well as the smithy marked as J. Not pictured here are the depressions between the smithy and Épaves Bay which were identified as boat sheds.

Activities at the site support the idea that seafaring was important here, and boat repair, iron manufacturing, and wood working are evidenced by the presence of iron nails, which were primarily used in shipbuilding and wood shavings (Ingstad 1985; Wallace, 2003a, 2005, 2012). Building J, identified as a smithy, further supports this theory. Positioned apart from the other structures and near Black Duck Brook, its location aligns with Norse traditions of placing smithies near water sources to mitigate fire risks (Kay, 2016). Additional evidence of ironworking includes approximately 15 kg of recovered slag and remnants of furnaces, pits, and other smithing debris. Since iron smelting was not practiced by Indigenous groups in Newfoundland at the time, its presence further confirms Norse occupation. However, the relatively small amount of slag and limited nail debris suggest that iron manufacturing activities were not extensive.

Notably, there is a distinct lack of evidence for typical Norse agricultural practice found at other Norse agricultural sites in Greenland, Iceland and the Faroe Islands (Wallace 2003a, 2003b). Indicators of such activities such as animal parasites, feed crops, and specific outbuildings, such as barns and byres, for animals, are noticeably absent from the L'Anse aux Meadows record (Wallace, 2006; Kay, 2016; Ingstad, 1977, 1985). Despite initial identifications, no domesticated animal bones were found on site, which suggests that no livestock were butchered on site. While this does not rule out the presence of animals for dairy or wool production, the archaeological record lacks the usual signals of animal husbandry found in other Norse farming communities.

Diet in the Norse North Atlantic settlements was based on a combination of pastoralism and marine resources (Arneborg et al., 2012). As Épaves Bay sits on the shores of a rich cod fishery it is likely that fish was (Ledger et al., 2019). It follows that this settlement was predominantly reliant on marine resources for subsistence. Archaeological remains in Greenland show that the Norse also relied on caribou hunting for at least part of their subsistence there, thus it is plausible that they employed the same hunting skills at L'Anse aux Meadows for part of their diet (Perren et al., 2012). The Norse occupation L'Anse aux Meadows sits within the rich history of intermittent Indigenous activity at the site over the lasts 5000 years.

2.6 Indigenous activity L'Anse aux Meadows

Investigations into the Norse occupation of the site revealed evidence of intermittent Indigenous activity at a series of on-site coastal terraces for several thousand years (Kristensen and Curtis, 2012). Archaeological evidence links Indigenous occupation to both Late Maritime Archaic, Groswater, Paleo-Inuit, and the Recent Period. While archaeological findings confirm episodic Indigenous occupation for the past 5000 years, research has focused almost exclusively on the relatively short period of Norse occupation (Davis et al., 1988; Wallace, 2003a; Parks Canada Agency, 2019). In contrast, there is currently very little research on this much longer Indigenous occupation of the area. Kay (2016) notes that while there were several excavations of the site, they primarily focused on collecting evidence of Norse occupation, instead of collecting *all* evidence available at the site, a practice that may have prevented the identification of Indigenous artifacts. Similarly, Betts and Gabriel (2021) argue that the arrival of the Norse at L'Anse aux Meadows holds little contextual importance against the rich backdrop of the complex Indigenous archaeology of the late Holocene. Given these gaps, long-term, high-resolution, paleo-ecological research may provide insight into the site's ecological history before and after the Norse, to contextualize the use of the location during the last 6,000 years.

2.6.1 Maritime Archaic

Newfoundland was settled around 4050 BCE (6,000 cal BP) by the Late Maritime Archaic people, who practiced varied subsistence strategies. However, they were predominantly coastal-fisher hunters who relied on marine resources for subsistence (Renouf, 1999; Betts and Hrynick, 2021). At their peak population, they inhabited much of the coasts of Labrador and Newfoundland (Kristensen and Curtis, 2012). The evidence for the Maritime Archaic occupation of L'Anse aux Meadows is based on several disturbed hearths just below Norse building D (Figure 2), as well as diagnostic artefact evidence consisting of a ground stone adze made from green chert (Wallace, 2006). In Newfoundland overall, evidence for the Maritime Archaic period ceases around 1550 BCE (3,500 cal BP) when there seems to have been a hiatus before the Groswater culture arrived and appeared to have been the sole inhabitants of the island for about 1,000 years (Renouf, 1999; Kristensen and Curtis, 2012).

2.6.2 The Groswater Culture

The Groswater Culture seems to have developed from an earlier culture in Labrador that was coastally based and continued a similar maritime-based lifestyle when they inhabited Newfoundland from about 1000 BCE to 1000 CE. Evidence for this culture at L'Anse aux Meadows is based predominantly on radiocarbon dates on a few hearth and fireplace features instead of artefact evidence (Wallace, 1989). Their presence at this coastal site is not a surprise as they were residentially mobile and relied seasonally on harp seal hunting (Hrynick and Betts., 2021). It is unclear how the Paleo-Inuit culture interacted in later years with the rise of the Dorset culture, which also arrived from the north.

2.6.3 The Dorset

The Dorset seem to have been on Newfoundland from the 1st to the 8th centuries CE with a subsistence strategy particularly focused on seal hunting, though walrus and sea bird hunting was also undertaken (Holly, 2019; Hrynick and Betts., 2021; Speller and Forbes 2022). Their material cultural remains varied substantially from that of the Groswater period in particular, as theirs was the first archaeological culture on Newfoundland where art appears in their artifact assemblages, in the form of seal, human and polar bear effigies (Hyrnick and Betts, 2021). Evidence for the Dorset at L'Anse aux Meadows come from radiocarbon dates linked to charcoal patches and circular stone patterns, as well two triangular end-blades of fine grain chert, characteristic of Dorset assemblages (Wallace, 1989; Hrynick and Betts, 2021). These artefacts were notably gathered from varied locations across the site, which complicates interpretations but implies the potential of wider site usage (Wallace, 2003b; Speller and Forbes, 2022).

Dorset archaeological evidence from Port aux Choix (to the south of L'Anse aux Meadows) suggests that Dorset subsistence was heavily reliant on harp seal hunting (Hodgetts et al., 2003). Due to the harp seal migration route passing close by to L'Anse aux Meadows, it is likely that the Dorset also used the location as a seal hunting camp.

2.6.4 The Recent Period and Cow Head Complexes

Around 160 BCE (2110 cal BP), the Recent Period began on Newfoundland, establishing a more interior-centered lifeway on the island (Renouf et al., 2011; Kristensen and Curtis, 2012). The resource separation of these marine- and terrestrial-based settlement patterns may have allowed for the co-habitation of Newfoundland for some years. The Recent Period cultures were likely to have frequented both Newfoundland and Labrador on either side of the strait (Kristensen and Curtis, 2012). The Cowhead Complex in particular on Newfoundland consists of several sites along the western coast of the island (e.g. Port au Choix) that exhibit repeated patterns of lithic workshops, comparable bifaces, and Cow Head chert (Renouf et al., 2011; Kristensen and Curtis, 2012).

The Recent Period artifact evidence at L'Anse aux Meadows points primarily to the Cow Head Complex (CHC) archaeological era between 260 BCE – 1020 CE (2210 – 930 cal BP). In general, this cultural complex is distinguished as being more sedentary, with larger storage habits (Hartery, 2007). A total of 25 Cow Head and Recent Period features have been found at L'Anse aux Meadows, including radiocarbon dates for two large hearths, fire-cracked rocks, and large, ovate bifaces, all of which indicate intense cooking events (Hartery, 2007; Kristensen and Curtis, 2012). These cooking events may have consisted of roasting meat on hot rocks, processing mammals/birds or lining the pits with hide and filling them with water and hot rocks for boiling. Apart from these cooking features, there are bi-faces and brown chert debitage (Wallace, 2006). The only sign of dwellings is the excavation of a pair of two small tent rings on a terrace west of Black Duck Brook (Kristenen and Curtis, 2012). Interestingly, the site lacks components characteristic of other CHC residential sites such as storage areas and substantial shelter structures with defined walls, further suggesting that L'Anse aux Meadows was used as a seasonal warm weather camp (Renouf et al., 2011; Kristenen and Curtis, 2012). This, along with ecological context, suggests that this site was used repeatedly as a summer camp to hunt birds, gather eggs, process food and prepare hunting tools for terrestrial hunting at other sites (Kristensen and Holly, 2013; Harris et al., 2019; Parks Canada Agency, 2019; Kristensen, 2022).

2.7 Pollen Records in Eastern Canada

To set the stage of our study period, I am briefly presenting the ecological history of Labrador and Québec from the Last Glacial Maximum. Because of the proximity of L'Anse aux Meadows to the North Shore of the Saint Lawrence Estuary, much of the paleo-ecological record of southern Labrador and parts of northeastern Québec is relevant to the site's ecological history. At the Last Glacial Maximum (21,000 cal years BP) much of North America was under ice, including Newfoundland which was almost entirely covered by the Laurentide Icesheet (LIS), other than a small portion of the southernmost Burin peninsula which is thought to have remained ice-free (Ritchie, 1987). During this time, northern Newfoundland was also underwater due to the depression of the land under the weight of ice. By 10,000 cal BP large parts of the island were ice-free, as well as a large tract of southeast Labrador up to 55°N (Ritchie, 1987).

The LIS lingered in northern Québec and Labrador until about 6800 cal BP and may have prolonged cooler temperatures in the east of Canada (Kaufman et al., 2004). Pollen analyses at Lake Hope Simpson (Engstrom and Hansen, 1985) in southeastern Labrador, and Whitney's Gulch (Lamb, 1980) in Blanc Sablon, Québec, both of which are relatively close to L'Anse aux Meadows, suggest that northern Newfoundland would have experienced its first consistent period of non-arboreal pollen (NAP) at ~10,500 cal BP, soon after the land was clear of ice. This period lasted until about ~8000 cal BP and was dominated by *Betula nana* (shrub birch), Ericaceae (heather family), *Alnus crispa* (green alder) and *Salix* (willow). After 8000 – 7000 cal BP, there was a sharp rise in *Picea glauca* (white spruce) which was followed by a rise in *Abies* (fir), coincident with a decrease in *Alnus.* Following this, in southern Labrador, there was a shift at 4050 BCE (6000 cal BP) when the boreal forest arrived at its modern-day position. This was dominated by predominantly *Picea mariana* (black spruce) with the presence of *Betula* and *Alnus crispa.* The *P. mariana*-dominated forest seemed to remain constant for the rest of the record and into the boreal forest of today (Ritchie, 2004).

2.8 Paleoclimate and Palynology in Newfoundland

Pollen records on Newfoundland are still relatively scarce and much of the post-glaical conditions remains to be studied on the island. However, the available paleoecologic studies agree on the Holocene Thermal Maximum occurring on the island between 4050 – 2050 BCE (6000 – 4000 cal BP) followed by a long-term neoglacial cooling trend over the subsequent 4000 years as confirmed in pollen, chironomid head capsules, and $\delta^{18}O$ values that are consistent with cooling sea surface temperatures and declining summer insolation values (MacPherson, 1982; MacPherson, 1995; Evans, 2002; Thompson et al., 2002; Levac, 2003; Bell et al., 2005; Rosenberg et al., 2005; Porter et al., 2019; Orme et al., 2021). MacPherson's (1995) comparative study synthesized twelves sites to reconstruct a temperature signal on the island and establishes that the period of the Holocene Thermal Maximum on the island began at 4050 BCE (6000 cal BP), slightly later than elsewhere in Canada (MacPherson, 1995; Kaufman et al., 2004; Porter et al., 2019; Thompson et al., 2022). Another study notes that maximum pollen accumulation rates occurred about 3350 BCE (5300 cal BP) (MacPherson, 1982); and a chironomid-based temperature reconstruction by Rosenberg et al. (2005) on Newfoundland also put the Holocene Thermal Maximum at around 3050 BCE (5,000 cal BP), with subsequent cooling. Notably, the coastal regions of Newfoundland lagged the warming of inland regions. After the Holocene Thermal Maximum, the climate followed a long-term cooling trend that was also noted in Orme et al.'s (2021) reconstruction of sea surface temperatures in Trinity Bay. The first signs of cooling began around 2550 – 2050 BCE (4500 – 4000 cal BP) (MacPherson, 1995). Coastal sites lead the cooling trend indicating that sea surface temperatures (SSTs) led terrestrial cooling.

Two paleoecological analyses from Port aux Choix (Bell et al., 2005) and the Grey Islands (Evans, 2002) provide the two closest palynological studies to L'Anse aux Meadows and cover more than 6000 years of history for northern Newfoundland. The pollen record at Stove Pond at Port au Choix, just 220 km southwest of L'Anse aux Meadows, exhibits high percentages of *Picea, Abies,* and tree *Betula* over the last 7,000 years, (Bell et al., 2005). Conifer pollen increased from 5050 BCE to 1850 BCE (7,000 – 3800 cal BP) with a peak at 1850 BCE (3800 BP) which was coincident with the maximum charcoal concentration (Bell et al., 2005). This large charcoal spike aligns with other datasets that illustrate that the Holocene Thermal

Maximum occurred on Newfoundland between 4050 and 2050 BCE (6000 and 4000 cal BP) and may have contributed to increased fuel availability for wildland fires. Pollen concentration increased between ~3050 – 50 BCE (5000 – 2000 cal BP) and noticeably dropped after 50 BCE (2000 cal BP).

The second pertinent paleoecological study by Evans' (2002) consists of the last 9000 years of pollen data from the Grey Islands, just off the east coast of Newfoundland. Her data noted that the boreal forest was established on the Grey Islands around 4750 BCE (6700 cal BP) and continued until it gave way to shrubland at 2550 BCE (4500 cal BP). This boreal period was coincident with increased tree *Betula* influx values until the same date. The boreal forest assemblage along with increase tree *Betula* was interpreted as the Holocene Thermal Maximum, and the return to shrubland and decreasing *Betula* pollen as signaling climate deterioration. Both of these signals are in agreement with both Davis et al. (1988)'s work at L'Anse aux Meadows and MacPherson (1995)'s comparative study. The period around 2500 cal BP exhibited the onset of paludification on the Grey Islands as total pollen influx declined dramatically.

2.9 Conclusion

The site of L'Anse aux Meadows is fascinating due to the variety of human cultures that have lived there over the middle to late Holocene, as well as its interesting ecological location in the subarctic region of the North Atlantic. From the long-term activity of Indigenous groups using the locale for warm weather bird hunting grounds to the short but compelling longhouses of the Norse, it offers the possibility to understand the ecological effect of various human groups on Newfoundland before permanent European contact. While there has been extensive paleoecological and archaeological research done on the site since its discovery in the

1960s, there remains a lack of high-resolution, long-term regional fire and vegetation history records for the site and for northern Newfoundland more generally. This site offers the opportunity to study local fen-bog dynamics, the potential impacts of human groups on vegetation and fire histories, and to establish long-term ecological trends in northern Newfoundland over the late Holocene. These reconstructions will be important in the coming decades as anthropogenic climate change continues to change our landscapes and ecologies in North America.

While this section provides a review of past work, it is also critical to highlight the research being undertaken at present. For example, ongoing palynological research from next to the archaeological site is in progress and is expected to shed important new light on the nature of the cultural deposits at L'Anse aux Meadows (Ledger et al., 2019; Forbes et al., 2020), while palynological work is also currently being undertaken on the development of a new lake-sediment record from Black Duck Pond, about 1.5 km south of the site (Roulé, work in progress). My thesis is different from and adds to previous and ongoing paleo-environmental research at L'Anse aux Meadows in a number of keyways: 1) my work provides a long-term pollen record with higher taxonomic resolution and better dating control; 2) this work represents the first long-term (millennial-scale) record of charcoal and LOI from a site outside the immediate archaeological remains with which the pollen data can be directly compared and interpreted; 3) the coring location we selected does not appear to have been previously studied, and provides a new record of local and extra-local vegetation and fire history for the Park in close proximity to, but not within, the archaeological site itself; and 4), most previous work at L'Anse aux Meadows has focused on the relationship between environment and the Norse settlement, whereas my work examines both the Norse and Indigenous periods, and in so doing provides both a cross-cultural and longer time-depth perspective for the study of environmental-human interactions during the middle to late Holocene in northeastern North America.

CHAPTER 3: Research Questions

As mentioned in the previous section, there remains a need for a long-term, high-resolution paleo-ecological study that incorporates up-to-date techniques to situate L'Anse aux Meadows within the broader climatic and ecological context of northern Newfoundland, southern Labrador, and the North Atlantic during the Holocene. My research addresses this gap by producing a continuous high-resolution pollen, macrocharcoal, and loss-on-ignition analysis for the last 6000 years. In doing so, my research is guided by the following research questions:

1) *What were the major patterns of vegetation and fire history in the L'Anse aux Meadows region over the last 6,000 years?*

2) *How do changes in species composition, pollen, and charcoal accumulation reflect the influence of major Holocene climate events, including Holocene Thermal Maximum, neoglacial cooling, the Medieval Climate Anomaly, and the Little Ice Age?*

To capture a more regional picture, this research is based on peat samples collected from a fen 300 m east of the Norse remains. By expanding the spatial scope of previous work, this study offers new analysis that contextualizes the site within the regional ecological changes of northern Newfoundland during a much longer period of time, as well as providing the first regional fire reconstruction of the area. This research may thus reveal otherwise hidden changes in the vegetation and fire history that may be related to the activities of Norse or Indigenous groups in the area.

CHAPTER 4: Manuscript

Not just Norse America: A late Holocene paleo-environmental study of L'Anse aux Meadows, Newfoundland Canada

4.1 Introduction

Palynological analyses, alongside other palaeoecological studies, are valuable tools for understanding long-term environmental variability. They have been widely applied to archaeological sites to reconstruct past environments and further contextualize cultural site dimensions such as subsistence practices, land and plant use, agricultural practices, site function, and fire use (Davis, 1984; Bell et al., 2005; Perren et al., 2012; Ledger et al., 2014; Zhao et al., 2022; Gauthier et al., 2023). One such opportunity presents itself at the site of L'Anse aux Meadows, Newfoundland. While predominantly known for being the only verified Norse site in continental North America, L'Anse aux Meadows also is a complex site with evidence of over 5,000 years of intermittent Indigenous occupation (Davis et al., 1988; Kristensen and Curtis, 2012; Ledger et al. 2019; Betts and Gabriel, 2021). This site provides a unique opportunity to examine the effects of climatic and environmental changes on human populations, as well as the possible human impacts of both Indigenous groups and Norse resource-seeking voyages on the local environment. Archaeological and paleoecological work has been ongoing at the site since the 1960s, shedding light on nature of the Norse settlement around in the early 11th century and exploring Indigenous use of the area (Mott, 1975; McAndrews and Davis, 1978; Davis, 1985; Davis et al., 1988; Ledger et al., 2019; Speller and Forbes, 2022). As such, most work has focused on samples either directly within or immediately adjacent to the Norse archaeological site, emphasizing this localized human history.

To build a broader, more regional record of the vegetation shifts and peatland processes, this study aims to reconstruct a high-resolution, long-term record from a peat-core 300 m east of the archaeological site. It will also offer new macrocharcoal analysis to analyze the regional fire history and its impact on vegetation. Davis et al. (1988) examined the last 2300 years of vegetation history in their pollen study, but their work was limited to samples taken within the archaeological site and did not analyze macrocharcoal for regional fire history. Similarly, Henningsmoen's study (1977), though on samples taken from multiple locations within the vicinity of the site, was at lower temporal resolution (~10 cm per sample), making it difficult to detect abrupt environmental signals potentially linked to human groups. Expanding the temporal and spatial scope of paleoecological research in this region allows for a more comprehensive reconstruction of past environmental conditions and their relationship to the major climate forcings of the late Holocene.

By examining vegetation shifts and fire disturbance over the last 6000 years, this study assesses how Holocene climate shifts, such as the Holocene Thermal Maximum's warmer temperatures, subsequent neoglacial cooling, the mild conditions of the Medieval Climate Anomaly (MCA, 800-1250 CE), and the cooling trend of the Little Ice Age (LIA, 1300-1850), influenced regional ecology. This study aims to reconstruct a long-term climate and ecological history of northern Newfoundland to better contextualize human occupation over the last 6000 years. Additionally, it seeks to establish how late Holocene climate forcings have affected the environmental conditions on the Northern Peninsula prior to the effects of anthropogenic climate change.

4.2 Study Area

Our coring site (51.595451 N, -55.533226 W) was a fen located in a mixed peat- and fen-dominated plain directly east of L'Anse aux Meadows, on the northern tip of the Great Northern Peninsula, Newfoundland, Canada (Figure 3). The plain has standing water layer of about 20 cm covered in a *Sphagnum* peat mat (Figure 4A). The wetland is for the most part submerged in water without a raised portion characteristic of an ombrotrophic bog (Figure 4). The elevation around the fen is relatively low, with rolling exposed bedrock visible in some areas. These hillocks support the trees, predominantly low *Betula, Picea,* and *Alnus,* the height of which greatly depends on the available shelter (Ingstad, 1977). Our coring location was ~300 m inland from the archaeological site and 13 m above sea level. The archaeological site is directly upwind of the coring location, meaning that the dominant westerly winds sweep directly over the Norse site towards the peat lands we cored directly to the east. The downwind location of our coring location in relation to the archaeological site is important due to the fact that airborne charcoal from human fires as well as pollen and spores would have travelled downwind to our site with the potential to show up in the record.

The site sits on the Strait of Belle Isle, just across from the coast of southern Labrador. The landscape surrounding the fen consists of mostly flat, exposed headlands, dominated by bogs, fens and low rocky outcrops of Paleozoic volcanics and sediments that rarely exceed 60 m in elevation (Davis et al., 1988). The area contains many lakes and peatlands, both ombotrophic and minerotrophic. This landscape is also subject to discontinuous permafrost which keeps the mean annual soil temperatures between 2°C to 8°C (Davis et al., 1988; Kristensen and Curtis, 2012).

The study site sits in the transition zone between the boreal forest and the subarctic tundra. In a survey of the modern pollen spectra, Davis (2008) denoted the area as shrub-tundra, dominated by a mosaic of fen, bog heath, coastal and fluvial vegetation. The local ecoregion is characterized by dwarf *Picea glauca* (Moench) Voss (white spruce) krummholz along the coast, which is tolerant of salt-spray off the ocean, while the inland vegetation is predominantly *Picea mariana* (Mill) Britton, Sterns and Poggenburg (black spruce) and *Larix laricina* (Du Roi) K. Koch (larch) (Davis et al., 1988; Kristensen and Curtis, 2012). While arboreal *Betula cordifolia* Regel (eastern paper birch), *Populus balsamifera* L. (eastern balsam poplar), both species of

Picea, and *Alnus alnobetula* ssp. *crispa* (Aiton) Turrill (green alder), are all present on the landscape, these trees do not usually exceed 3 m in height, with *Betula* and *Alnus* appearing today predominantly as species: *Betula michauxii* Spach. (Newfoundland dwarf birch) and *Betula pumila* L. (dwarf birch) (Davis et al., 1988). This leaves the local region mainly open with small but dense thickets of stunted trees in sheltered areas. The understory is made up of a variety of herbs, mosses, and lichens. More than a quarter of this region is covered by wetlands (which is apparent in the area directly surrounding our coring location) which are dominated by *Sphagnum* spp. L. (peatmoss), *Rubus chamaemorus* L. 1753 not Fisch. Ex Ser 1825 (cloudberry), Cyperaceae Juss (sedges), and *Myrica gale* L. (sweetgale). The boreal forest proper begins just 10 km to the south of the site where *Abies balsamea* (L.) Mill. (balsam fir), *P. mariana*, and *L. laricina* dominate (Davis et al., 1988).

Climatically, the region is classified as a subarctic climate characterized by long, cold winters and cool summers. The coastal area is usually locked in ice in the winter, while summers are short, cool and foggy (Kristensen and Curtis, 2012). The L'Anse aux Meadows climate is recorded at the St Anthony Environment Canada and Natural Resources station just 40 km to the south, with an average annual temperature at around 1.8°C, a winter mean temperature of -5.5°C, and a mean summer temperature of 10°C (*St. Anthony Climate: Average Temperature by Month, St. Anthony Water Temperature*, n.d.). The annual mean precipitation ranges anywhere from 830 to 1200 mm (*St. Anthony Climate: Average Temperature by Month, St. Anthony Water Temperature*, n.d.). Fog is common year-round and is particularly prevalent in summer and autumn months. The ice floes that block the strait in the spring often keep the temperatures cold and delay the warmth of the growing season, which usually only lasts for 100 days, with considerable inter-annual variation (Davis et al., 1988).

L'Anse aux Meadows National Historic Site lies about 60 m inland from the shore of Épaves Bay on a low ridge about 4-6 m above sea-level (Kay, 2016; UNESCO World Heritage Centre, n.d.).

Figure 3. Upper left insert: location of Newfoundland in the context of the North Atlantic Ocean. Middle left insert: location of L'Anse aux Meadows on the island of Newfoundland. Main map: White star shows location of FEN4 core sequence, white triangle shows the archaeological site of L'Anse aux Meadows within the National Historic Site.

4.3 Methods

Field methods

A sequence of four core drives and one surface monolith (FEN4) was extracted from the fen in August 2022 with a Russian peat corer with a diameter of 5 cm (Figure 3). We selected the site location based on its proximity to the archaeological site (Figure 3). Coring was not possible past 210 cm below the surface due either to the presence of glacial sediment or discontinuous permafrost, which has been noted for the region. We transferred the cores to PVC split tubes and wrapped them in saran wrap (Figure 4C) for transportation back to the *Climate and Environmental Change Research Laboratory* at Bishop's University in Sherbrooke, Québec, where they are stored in a walk-in fridge at 4°C.

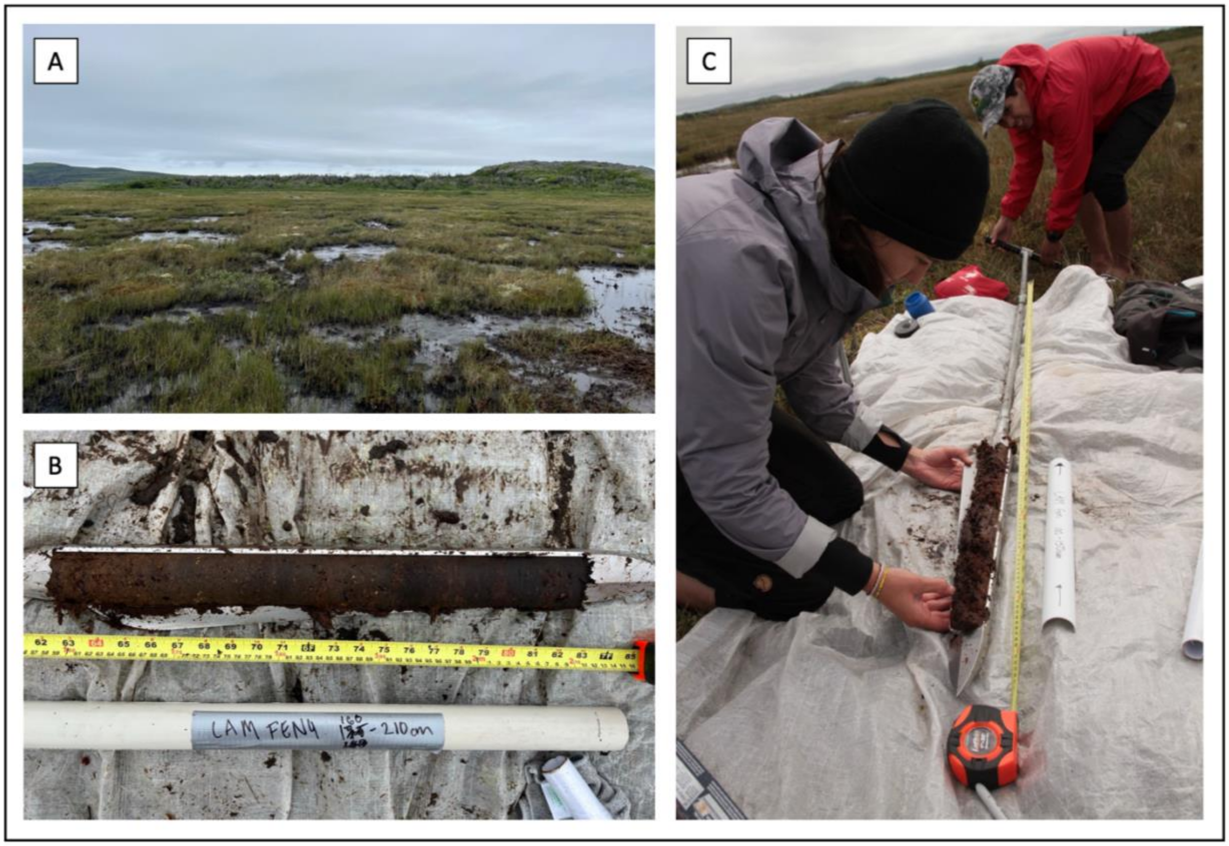


Figure 4. Coring on the fen. A) Looking east towards the interpretive centre, showing the fen that we cored. B) The section from 160-210 cm from Fen4, the deepest section of the core. C) A newly cored section of core, still in the Russian peat-corer, about to be transferred to the split PVC tubes and wrapped in saran wrap.

<u>Chronology methods</u>

Nine plant macrofossils were sampled in the lab throughout the peat core for AMS radiocarbon dating. The dating was done at the A.E. Lalonde AMS Laboratory at the University of Ottawa. The dates were calibrated using OxCal v4.4 and the IntCal20 calibration curve for northern hemisphere terrestrial samples (Ramsey, 2009; Reimer et al., 2020). The nine ^{14}C dates, along with the 2022 coretop, were used to calculate an age-depth model and peat accumulation rates using the Bayesian R package *rbacon* using default priors (Blaauw and Christen, 2011).

Pollen analysis methods

Ninety-five samples of either 0.62 cm^3 or 1.25 cm^3 were sampled for pollen analysis from the FEN4 core, which refers to the combined sequence of individual core drives. The samples were 1 cm thick and were taken from the entire length of the core and were spaced every 2 to 4 centimeters. The samples were processed using a modified LacCore (University of Minnesota) Pollen Preparation Procedure, a standardized preparation procedure that allows for the removal of most of the non-pollen sediments, while leaving the pollen grains themselves intact (this consisted of a KOH wash, HCL wash, and acetolysis) (Moore et al., 1991; LacCore, 2016). HF was not used in the preparation procedure given the low presence of mineral matter. Samples were stained with 1% safranin, stored in silicone oil and mounted on microscope slides for pollen counting. One *Lycopodium* tablet (Lund University, batch 208521, 13761 grains per tablet ± 448) was added to each sample prior to processing to allow the calculation of pollen concentrations and influx using the exotic marker grain method (Benninghoff, 1962; Bonny, 1972; Moore et al., 1991).

Using a Leica DM 2500 LED microscope, pollen grains and spores were counted and identified at 400x-800x at the *Climatology, Hydrology and Paleo-Environmental Laboratory* at Concordia University with the goal of counting 400 non-*Sphagnum* pollen grains per sample when possible. Counts ranged from 302 to 508 grains, with a median of 402 grains per sample. Pollen grains were identified using regional vegetation and pollen guides, as well as reference slides from our lab (Richard, 1970; McAndrews et al., 1973; Basset et al., 1978; Gajewski and Vetter, n.d.). Hansen and Engstrom (1985) and Lindbladh et al. (2002) were used to differentiate

P. glauca from *P. mariana*. The method outlined by Lindbladh (2002) demonstrated that *Picea* can be segregated by size, with anything under 88.5 µm being *P. mariana,* and any grain exceeding 88.5 µm being *P. glauca.* While this method does not result in perfect segregation of species, in combination with Hansen and Engstrom's method, it allowed for separation at the species level (Richard, 1970; Basset et al., 1978; Hansen and Engstrom, 1985; Lindbladh et al., 2002; Bell et al., 2005). *Pinus* pollen grains were distinguished as *Pinus* section Haploxylon and *Pinus* section Diploxylon types. The only Haploxylon pine species present was *P. strobus* L. (eastern white pine) and the two Diploxylon *Pinus* species present were *Pinus resinosa* Sol. Ex Aiton (red pine) and *Pinus banksiana* (jack pine) (Barton et al., 2010). *Alnus* grains were split between *Alnus crispa* (green alder) and *Alnus incana* subsp. *rugosa* (L.) Moench. (speckled alder) according to Leopold et al. (2012) and May and Lacourse (2012).

Constrained Clustering with Incremental Sum of Squares (CONISS), together with the broken stick test with a 95% significance level, was used for zonation of the relative abundance pollen stratigraphy using the R package *rioja* (Juggins, 2023). Pollen influx values or pollen accumulation rate (PAR) were also calculated using the sedimentation rate and exotic marker method and plotted by taxa. Principal components analysis (PCA) was done on the percentage data to explore the main variability in the pollen relative abundance data using the R package *FactoMineR* (Lê S, et al., 2008). The broken stick test was used to assess the PCA axes for significance at the 95% level.

Pollen concentration=((13761 / sample *Lycopodium* count) × total pollen count) / cc per sample

Pollen influx = pollen concentration × sedimentation rate

Charcoal analysis methods

Fire events were reconstructed using sedimentary charcoal analysis. A total of 184 samples were analyzed for charcoal in the FEN4 core sequence. For each depth, 1.2 cm^3 of peat was sampled from contiguous 1-cm thick intervals. Each sample was soaked in an aqueous solution of 8% sodium hypochlorite and 5% sodium hexametaphosphate solution overnight, in order to bleach and deflocculate the sediments. The subsamples were then sieved through a 150 µm Nytex mesh, and the course fractions were retained for analysis. Charcoal particles greater than 150 µm were identified visually under a Leica M80 stereo-microscope and a Flexacam C3 12 MP microscope camera was used to take their digital image. The digital images of the charcoal were analyzed using Winseedle© image analysis software to calculate the total surface area of charcoal for each sample.

The charcoal surface area time series was then analyzed using the Matlab version of CharAnalysis to detect significant peaks from local fires (Higuera et al., 2009). Charcoal area accumulation rates were interpolated using the Bayesian age-depth model and a proportional interpolation approach to a fixed time interval bin size of 23 years (the median resolution of the record), producing an interpolated series of samples of equal duration ($\mu m^2 \cdot cm^{-2} \cdot yr^{-1}$) (Higuera et al. 2009b; Remy et al., 2018). The background charcoal (BCHAR) of non-local and secondary charcoal was calculated using a moving window of 900 years and a robust lowess smoother to ensure that the signal-to-noise index (SNI) of the charcoal peaks was as high as possible and always above 3.0 as recommended by Kelly et al. (2011). The BCHAR series represents distant fires, long-term shifts in fire regimes and secondary taphonomic processes not related to local fire occurrences (e.g. particles shifting in loose peat, overland wash). Then CHAR was calculated as the residual of the interpolated charcoal series minus BCHAR. Peaks in charcoal, interpreted as local fire events, were identified as CHAR values exceeding the 95th percentile of the CHAR noise distribution modelled using Gaussian mixture models with a locally set threshold (Higuera et al. 2009b).

Loss-on-ignition analysis methods

The loss-on-ignition (LOI) analysis was done to evaluate the ratio of organic to carbonate and noncarbonate content in the peat core sediments, using the standardized LOI procedure of Heiri et al. (2001). Along the core, 1.2 cm^3 samples were taken every 1 cm starting at 0.5 cm and ending at 210 cm, heated successively to different temperatures and weighed before and after each step. LOI data was also collected for the overlapping portions of the core drives and monolith. In the overlap between drive 3 and 4, the LOI results from drive 3 were used. In the overlap between the monolith and drive 1, the LOI results from drive 1 were used.

Each sample was first heated to 105°C over 12-24 hours in a VWR Symphony convection oven to extract the water content and to determine the constant dry weight (DW). Following this, the samples were heated to 550°C for four hours to determine the organic content, and the carbonate and silicate residue in each sample. The following equations were used:

% organic content = $((DW_{105}-DW_{550})/DW_{105})*100$

% silicate and carbonate content = $((DW_{550})/DW_{105})*100$

4.4 Results

Core chronology and core log

The final FEN4 sequence consisted of one surface monolith of 33 cm and four 50 cm successive drives from the fen just 300 m east of the archaeological site (Figures 3, 4 and 5). The total length of the FEN4 sequence was 210 cm. There was a 15 cm overlap between the third and fourth drives. However, our analysis only used counts from the third drive for the overlapping section. These four Russian peat drives, along with the surface monolith formed a combined core that will be referred to as “the core” or “FEN4” hereafter.

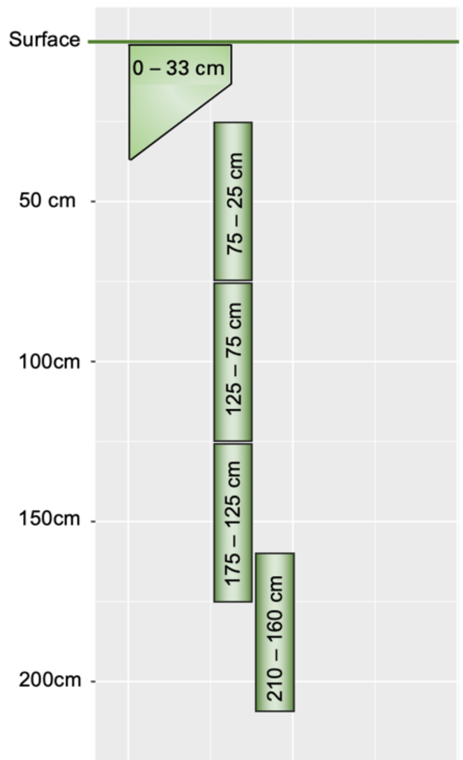


Figure 5. Core drives of FEN4, spanning from core top at 0 cm to 210 cm below the surface/air transition.

The age-depth model (Figure 6) was developed using the nine radiocarbon dates, as well as the core top, using the R package *rbacon* with default priors (Table 1) (Blaauw and Christen, 2011). Our chronology was developed by ^{14}C dating four twigs, one piece of wood, three peat samples, and one bulk sediment sample. The core top was dated at -72 cal BP (2022 CE). The deepest date was done at 199 cm on bulk sediments and dated to 5820 cal BP (3870 BCE). The last 8 cm were extrapolated using the BACON age-depth model. The core spanned -72 cal BP to 6020 cal BP (2022 CE – 4070 BCE). All nine radiocarbon dates fell in chronological order and suggested a relatively consistent accumulation rate throughout the core, excepting a notable period of low accumulation between 75 cm and 100 cm. Excluding this period, the relationship between depth and calibrated year was predominantly linear. The average deposition time for the core was 1 cm for every 28.7 years.

A core consisted of very dark brown peat in the bottommost section, which then transitioned to a more woody section between ~185 and ~95 cm. This woody section was then interrupted by a dark brown layer which was followed by a more spongy peat section with increase fibre. The top most layers were denoted by a woodier section with a defined caatotelm transition and then a living sedge layer at the surface.

Table 1. The radiocarbon results from the Lalonde AMS Laboratory. Errors for conventional radiocarbon Ages (^{14}C yr BP) are 1σ. The calibration was performed using OxCal v4.4 (Bronk Ramsey, 2009) and the IntCal20 calibration curve (Reimer et al., 2020).

Sample ID	Depth (cm)	Macro-fossil description	14C Date (BP) ± 1σ	Cal BP (median)	cal BP
Core top	0	core top	N/A	-73	n/a
UOC-21074	29-30	twig	722 ± 20	669	684 - 651 (95.4%)
UOC-25199	37-38	peat	860 ± 20	756	789-726 (95.4%)
UOC-25200	73-74	twig	1810 ± 20	1710	1741-1695 (64.7%) 1665-1626 (30.8%)
UOC-21026	88-89	twig	2921 ± 13	3065	3155 - 3089 (32.6%) 3083 - 2997 (62.9%)
UOC-21075	127-128	twig	3412 ± 21	3651	3811 - 3805 (1.0%) 3715 - 3709 (1.2%) 3700 - 3574 (93.3%)
UOC-21076	163-164	twig	3922 ± 21	4360	4420 - 4290 (92.8%) 4269 - 4254 (2.7%)
UOC-25201	173-174	peat	4170 ± 25	4714	4829-4786 (19.6%) 4767-4616 (74.4%) 4596-4586 (1.4%)
UOC-25202	185-186	peat	4660 ± 25	5402	5464-5371 (76.8%) 5363-5342 (6.2%) 5335-5316 (12.4%)
UOC-21077	199-200	bulk sediment	5062 ± 22	5820	5899 - 5745 (95.4%)

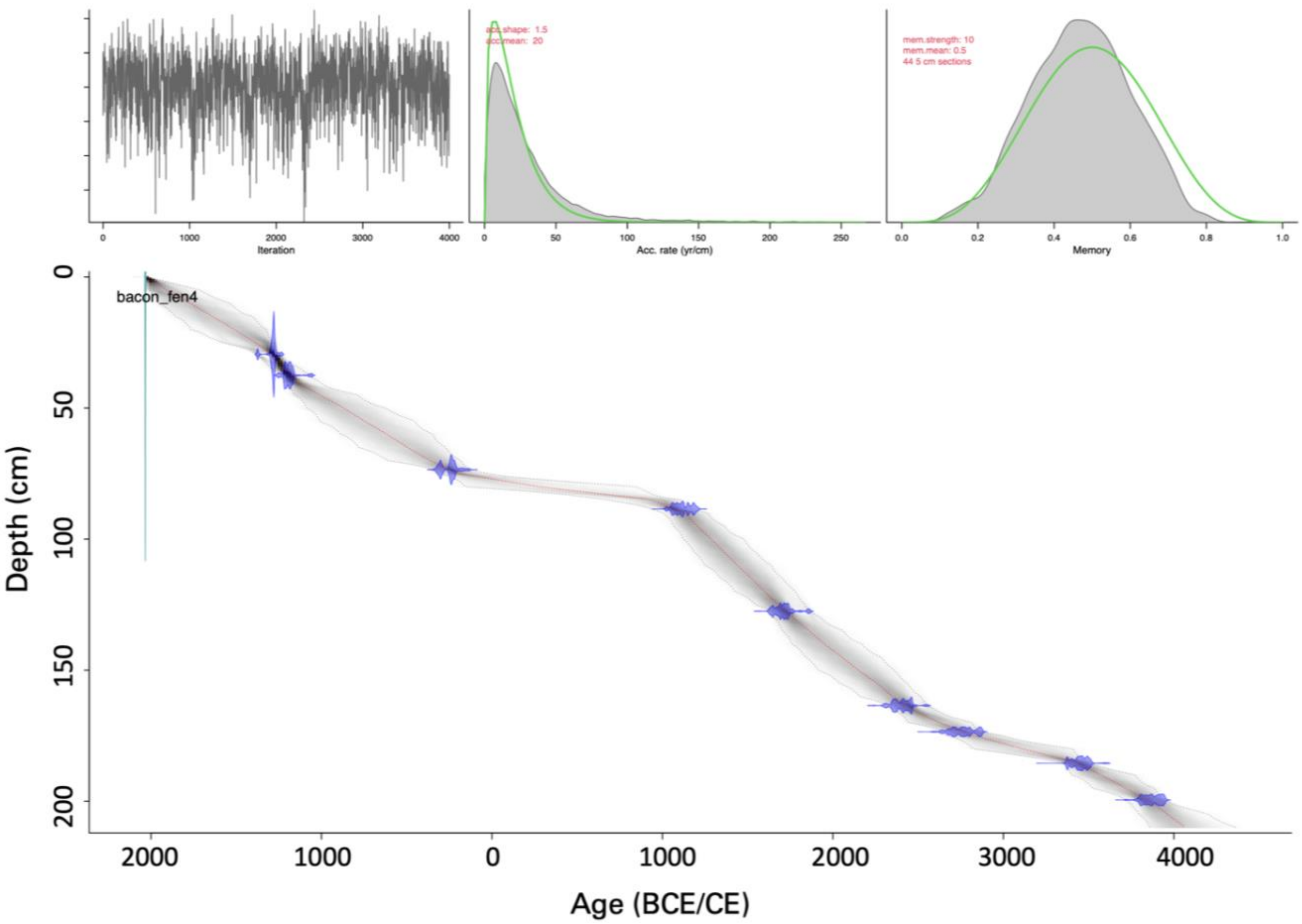


Figure 6. Age-depth model for the Fen4 core. Top left panel: Markov Chain Monte Carlo (MCMC) model iterations. Top middle panel: prior (green line) and posterior (solid gray) distribution of deposition time. Top right panel: prior (green line) and posterior (solid gray) distribution of the model memory. Bottom panel: the age-depth model spanning 4055 BCE to 2022 CE was obtained using the *rbacon* package in R. Probability distributions of the radiocarbon dates are shown in purple. The central red dashed lines show the 'best" model based on the weighted mean age. The outer grey dashed lines denote 95% confidence levels.

Loss-on-ignition Results

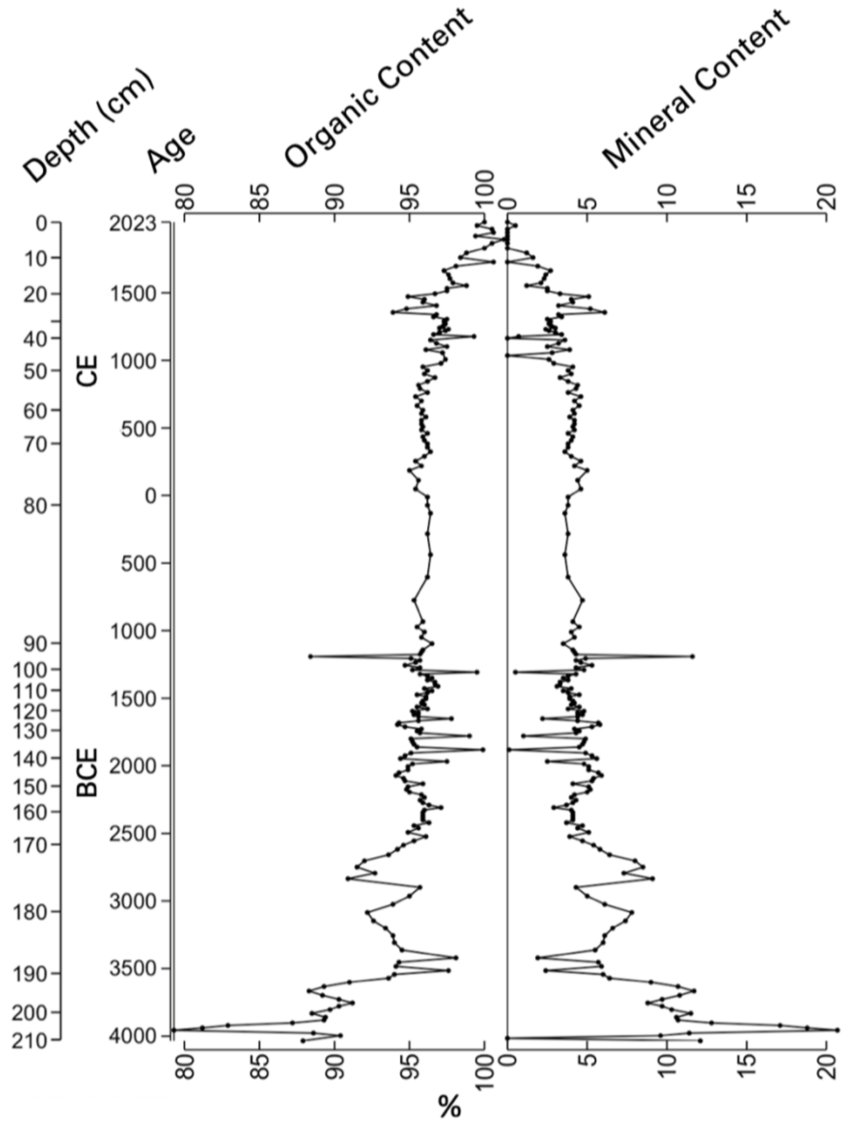


Figure 7. LOI data from FEN4 with percent organic material and percent silicate and carbonate minerals in the dry sediments.

On average, the organic content of the FEN4 core sequence was 94.7%, meaning the mineral content was low (Figure 7). Water also remained between 80 and 90% for most of the core, excepting a period between 1030 to 1260 CE (46 – 30 cm) where it dipped to 30.8 % and 39.8 %. Organic content remained between 80 to 100% in the core, excepting one dip at 4015 BCE (209.5 cm) where it dropped to 12.5%. Organic content also increased in more recent years, going from 80-90% at the core bottom to 95-100% at the top of the core. There was a noticeable dip at 1190 BCE (94.5 cm) to 86.7 %. Mineral content formed an average of just 4.6 % of the core, with the bottom of the core containing slightly more mineral content than the upper sections of the core. There was decreasing trend in mineral content in the most recent years. There was a spike of mineral content in the early section of the core, occurring at 3955 BCE (206.5 cm) with a content of 20.7 %. This was the highest value of mineral content in the core apart from 209 cm and was followed by two more relatively high values of 18.8 % and 17.1 %. There was another spike at 1190 BCE (94.5 cm) with a content of 11.6 %.

Pollen results

In total, 95 samples were counted for pollen analysis. This was an average of one pollen count every 63 years, however this varied due to sedimentation rate changes in the core. The arboreal and shrub taxa dominating L'Anse aux Meadows over the last 6,000 years were *Betula*, *Picea mariana*, *P. glauca*, and *Alnus* (Figures 8 and 9). The non-arboreal pollen was dominated by Cyperaceae, Ericaceae and *Myrica,* although their relative abundances fluctuated greatly throughout the core. CONISS and the broken stick test separated the pollen stratigraphy into six significant zones (Figure 8 and 9), the uppermost of which was sub-divided into two sub-zones (6a and 6b) based on a barely insignificant broken stick test and human interest. Each zone was named after the dominant terrestrial taxa or taxon.

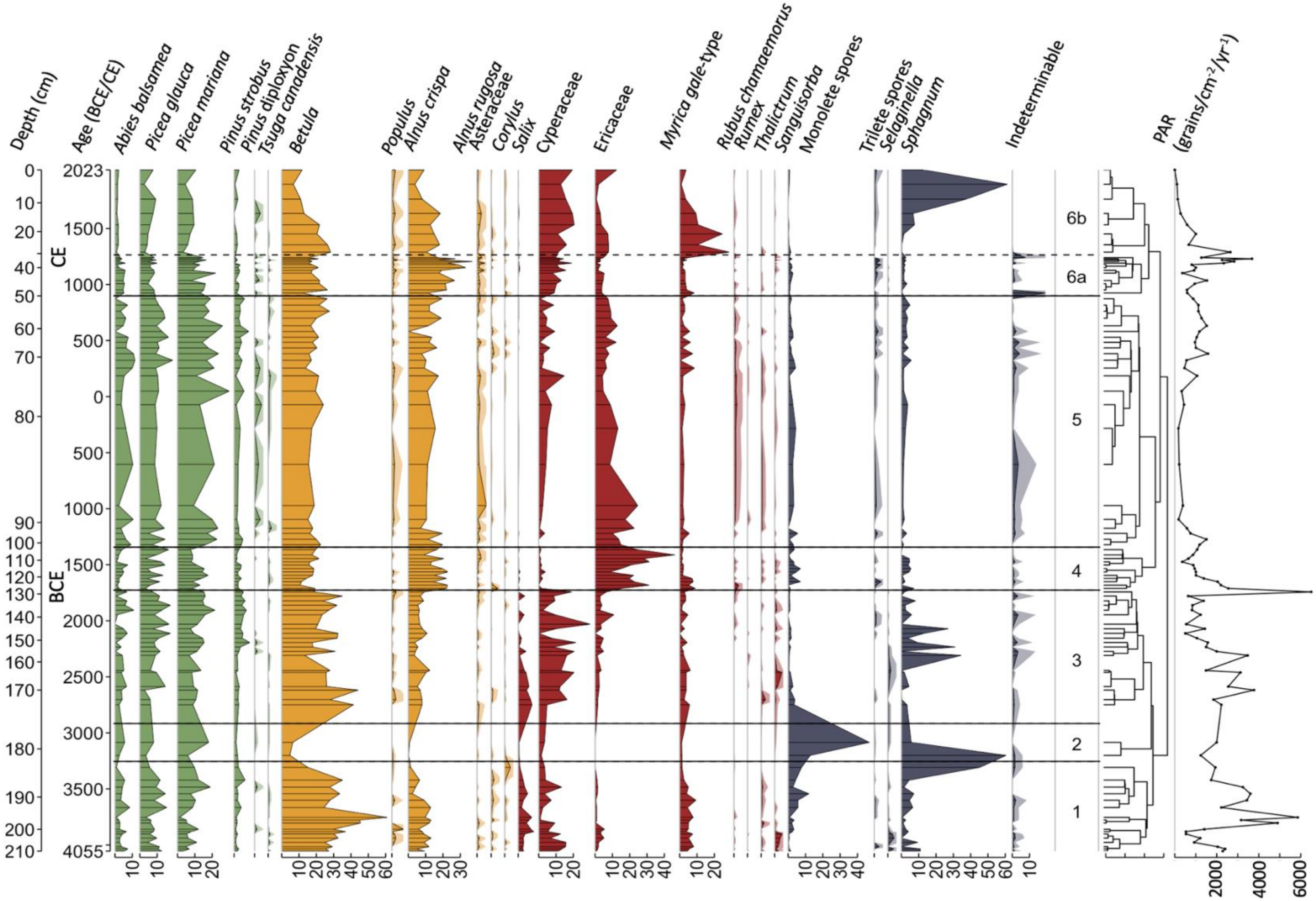


Figure 8. Terrestrial pollen and spore percentages diagram for principal taxa from the Fen4 core taken near the L'Anse aux Meadows, Newfoundland, archaeological site. Conifers are in green, deciduous species in gold, herbs in red, and spores in purple. Shown are pollen percentages of main taxa (total terrestrial pollen sum >15% from the entire core). Lighter areas show an exaggeration of 4x. Solid black horizontal zone lines from CONISS were significant at the 95% level as assessed by broken stick test. The dashed black horizontal zone line was barely insignificant. Also shown is the total pollen influx or accumulation rate (PAR) (grains/cm^2/yr). Also shown is the interpolated charcoal accumulation rate (CHAR) (µm^2/cm^{-2}/yr^{-1}).

Zone 1 Betula (4055 – 3200 BCE, 210 - 182 cm)

This zone began at 4055 BCE at the bottom of the core and continued to 3200 BCE (Figure 8). Zone 1 was characterized by a high relative abundance of *Betula*, with a mean of 34%, with a peak of 61% at 3755 BCE. In this zone, *P. glauca* and *P. mariana* had mean abundances of 9.5% and 8.7%, respectively, percentages of which increased toward the top of the zone. Both *P. strobus* and *A. balsamea* were present but had relative abundances generally less than 5%. Other abundant taxa in this zone included *Alnus crispa*, which was 8.7% at the beginning of zone 1, but decreased to almost zero by the zone 5-6 boundary, and Cyperaceae had an average of 8.2%. Asteraceae, *Myrica gale* and Ericaceae were important. *Rubus chamaemorus* and *Sanguisorba* appeared sporadically throughout zone 1. The total pollen influx started with a dip and quickly increased to the highest sustained values in the core (Figures 8 and 9). The mean pollen accumulation in this zone was 2399 grains/cm^2/yr. Zone 1 also included the second highest total pollen influx values in the core. With an average of 2436 grains/cm^2/yr, *Betula* was the most numerous taxon in this zone and was the predominant contributor to the total influx spike in 3755 BCE. There was an initial dip in the influx values at the very bottom of the core that rapidly changed to two high spikes. *Betula* itself had influx values reaching 3174 grains/cm^2·yr at its highest point in the entire core at 3755 BCE. *Picea glauca* and *P. mariana* had some of their highest influx values during this zone, with averages of 222 and 195 grains/cm^2/yr, respectively. *Abies balsamea* also established itself in this zone with a steady presence of 90 grains/cm^2/yr. *Alnus crispa*, followed a similar influx pattern as *Betula*, though at much lower values, with a peak of 586 grains/cm^2/yr in 3805 BCE. Asteraceae, Cyperaceae and *M. gale* also had relatively high influx values within this assemblage, with averages of 109, 176 and 140 grains/cm^2/yr respectively.

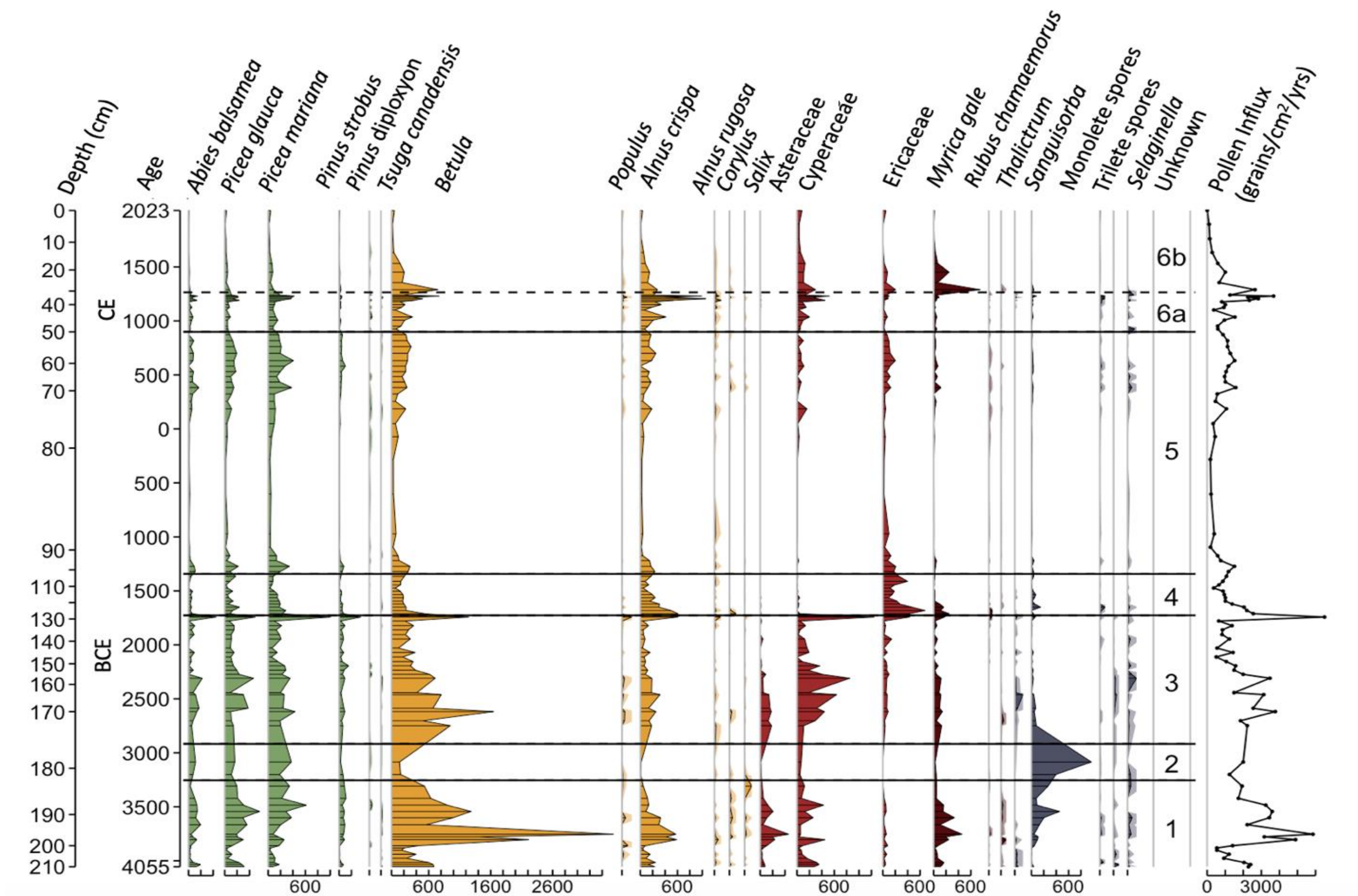


Figure 9. Terrestrial pollen and spore pollen accumulation rates for principal taxa from the Fen4 core taken near to the L'Anse aux Meadows, Newfoundland, archaeological site. Conifers are in green, deciduous species in gold, herbs in red, and spores in purple. Solid black horizontal zone lines from CONISS were significant as assessed at the 95% significance level using the broken stick test on percentage data. The dashed black horizontal zone line was barely insignificant. Also shown is the total pollen influx or accumulation rate (PAR) (grains/cm^2/yr).

Zone 2 Monolete spores (3200 – 2750 BCE, 181 - 174 cm)

Zone 2 consisted of only two samples and was dominated by a high peak of monolete spores without exospores, reaching 48% at 3085 BCE (179 cm), which otherwise rarely appeared at consistently low levels throughout the core (Figure 8). Zone 2 was also characterized by relatively high percentages of *P. mariana* (16.8%) and *P. glauca* (8.4%), and *A. balsamea* (5.8%). Low values of *Betula*, *Alnus crispa,* and Asteraceae were also apparent. There was a decline in total influx values (also apparent in *Betula* and *A. crispa*) in this zone (Figures 8 and 9). There is also a large spike of *Sphagnum* during this zone.

Zone 3 Cyperaceae-Betula (2750 – 1740 BCE, 173 – 128 cm)

Zone 3 spanned ~1000 years (from 2750 to 1740 BCE) and was dominated by high percentages of *Betula* (between 20% and 40%) (Figure 8). Cyperaceae became more pronounced in this zone with a mean of 13.3%. The relatively high percentages of *P. glauca, P. mariana* and *A. balsamea* continued from zone 2, while *Alnus crispa* and Asteraceae returned to the previous levels they had in zone 1, with means of 7.7% and 2.6% respectively.

The total pollen influx started at levels similar to those of zones 1 and 2, but declined towards the end of zone 3, excepting the final sample, the highest spike in the core (Figures 8 and 9). The total pollen influx remained relatively high at an average of 1956 grains/cm^2·yr. *Betula* returned to higher levels with an average of 533 grains/cm^2·yr, though it had lower influx values towards the top of zone 3 that were not apparent in the percentage data. *Abies balsamea, P. glauca,* and *P. mariana* maintained steady values in the influx values, as well as the percentage data, with averages of 92, 185 and 246 grains/cm^2/yr, respectively. The monolete spores all but disappeared in this zone. There was also a notable spike in the accumulation values of many taxa in the topmost sample of this zone (1740 BCE, 129 cm) that is hidden in the percentage data. *Abies balsamea, P. glauca, P. mariana, Betula, A. crispa,* and Cyperaceae, and Ericaceae all exhibited this peak, which was also notable in the total pollen accumulation rate which spiked to 6496 grains/cm^2/yr.

Zone 4 Ericaceae-*Alnus crispa (1740 – 1325 BCE, 127 – 102 cm)*

Zone 4 was characterized by its sudden change from high percentages of Cyperaceae to high percentages of Ericaceae*,* that occurred at ~1710 BCE (Figure 8). Where zone 3 was dominated by high percentages of Cyperaceae (~13%) and relatively low percentages of Ericaceae (3.6%), Zone 4 was the opposite, with Ericaceae ranging from 16 – 40% with a mean of 24.4%. It is possible that this represents a transition from a fen to a more bog-like environment. Ericaceae reached its peak of 46% in this zone at 1410 BCE (107 cm). Cyperaceae fell in this zone, reaching a mean of 1.37%. *Picea glauca* and *P. mariana* both dropped slightly, while *Betula* showed a more pronounced drop. At 1710 BCE, *A. crispa* increased, from 7.7% in Zone 3, to an average of 18.1% in zone 4. The pollen accumulation rate declined from its peak at the end of zone 3 (Figures 8 and 9). The mean accumulation rate for this zone was 1246 grains/cm^2·yr. Almost all the taxa followed this downward trend, excepting Ericaceae which had high influx rates as well as high pollen percentages throughout this zone. *Alnus crispa* also had higher pollen influx rates then the rest of the taxa.

Zone 5 Ericaceae-*Picea mariana (1325 BCE – 920 CE, 101 – 50 cm)*

This zone spanned 2000 years (Figure 8). Zone 5 was distinguished by its relatively high values of Ericaceae (10-20%) with an average of 11%. *Abies balsamea, P. glauca* and *P. mariana* increased in abundance relative to zone 4. *Betula* had a mean of 20% for this zone. *Alnus crispa* decreased from Zone 4. Cyperaceae slowly increased from 0% to ~9%. *Rubus* *chamaemorus* had a mean of 0.7%, with higher values than anywhere else in the core, reaching 1.7%. Monolete spores also ranged from 3-5%.

Zone 5 was characterized by generally low total pollen accumulation rates as well as low pollen concentrations, with a slight increase in the last 700 years (Figures 8 and 9). The pollen accumulation rate was notably low for the middle section of this zone. The average total accumulation rate was 849 grains/cm^2/yr. This period was distinguished by low influx values, which might have been due in part to the low accumulation rate also ocurring during this time. All the taxa declined around 1200 BCE and reappeared ~1 CE, with *Betula* being the first. *Betula, A. crispa,* and the three main conifer species influx rates increased by the end of the zone. Cyperaceae reappeared, but at much lower levels than in the previous three zones. Ericaceae also increased again.

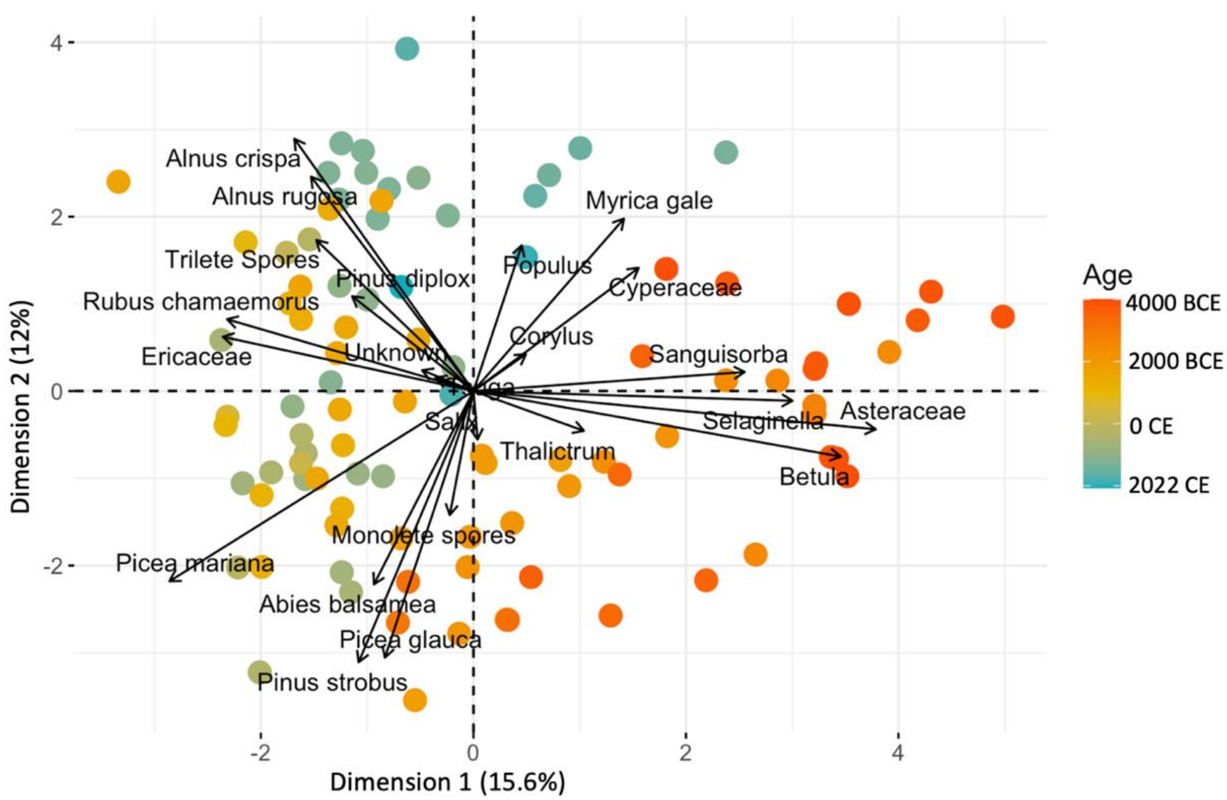
Zone 6A Alnus crispa-Cyperaceae (920 – 1280 CE, 49 – 30 cm)

This zone spanned over 300 years from 920 – 1290 CE and included the period of Norse settlement in the early 11th century (CE, Kuitems et al., 2021). *Alnus crispa* percentages increased (with a zonal average of 23.5%), reaching its highest point in the core at 33%. Cyperaceae increases in zone 6A, from a mean of 4% in zone 5 to a mean of 12% in zone 6A, whereas Ericaceae declined from an average of 10% in zone 5 to 3% in zone 6A. There were small declines in both *Picea* species, as well as *A. balsamea* and *P. strobus*. *Betula* had a mean of 18.7%. *Myrica gale* remained at low percentages during this zone. The mean total accumulation rate in this zone was 1471 grains/cm^2/yr. There was a noticeable spike in *A. balsamea*, both *Picea* species, *Betula*, *A. crispa* and Cyperaceae nearing the top of this zone. *A. cripsa,* a possible disturbance indicator, reached its highest accumulation rate in the core at a peak of 1060 grains/cm^2/yr in 1205 CE.

Zone 6B Cyperaceae-Myrica gale (1280 - 2022 CE, 0 - 29 cm)

This zone spanned over 700 years, from 1290 – 2022 CE (Figure 8). This zone was defined by an initial spike in *Myrica gale* that reached a peak of 28%; Cyperaceae continued its upward trend, increasing to a peak of ~25%; together with sharp decreases in both *Picea* species and *Alnus crispa* at its beginning. *Betula* slightly increased at zone 6B's beginning but declined slightly to ~18% for the most recent period. The mean influx during this topmost zone was 676 grains/cm^2/yr, which was the lowest mean of all the zones. This zone had a noticeable drop in the influx of all taxa towards its top. *Betula* and *Myrica gale* were the most prominent influxes in this zone (Figure 8 and 9). It seems likely that at this time the wetland returned to a fen environment.

A)



B)

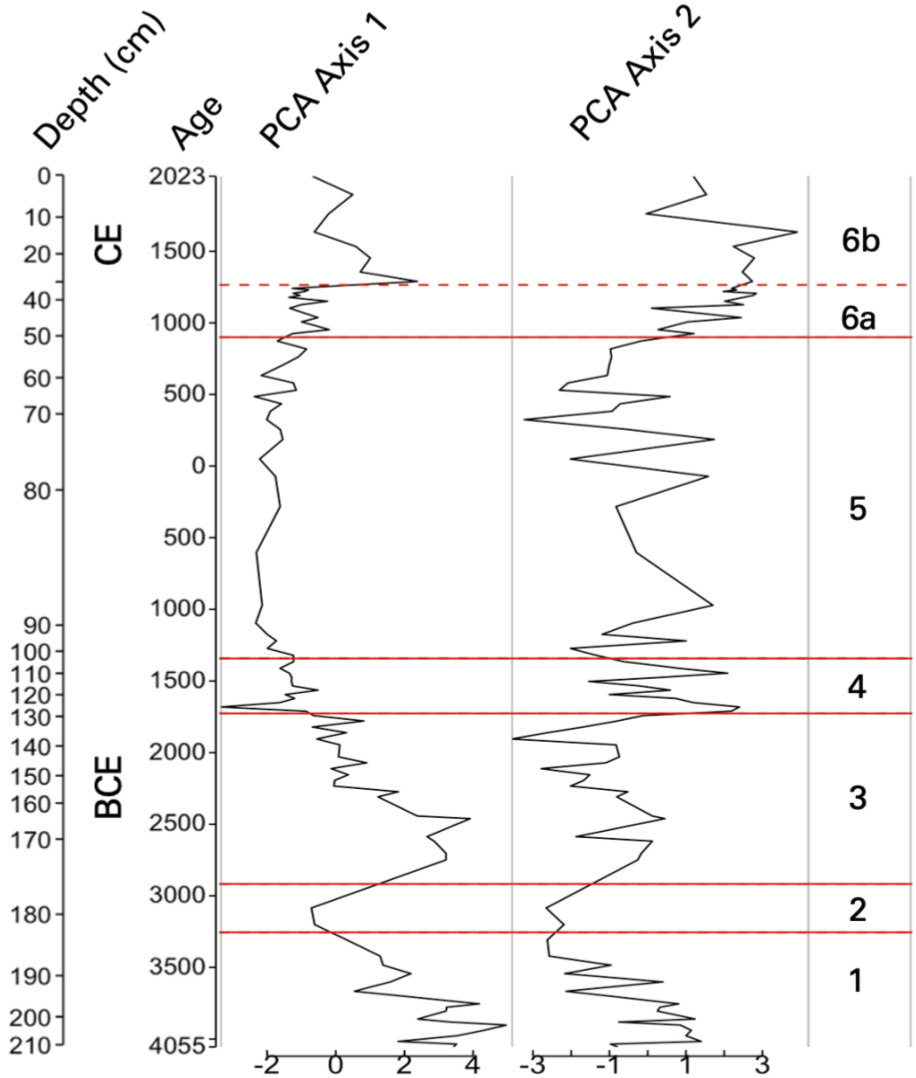


Figure 10. A) PCA biplot the first two principal components of FEN4 pollen percentages (*Sphagnum* spp not included in analysis) with colours denoting dates of the samples. B) L'Anse aux Meadows PCA sample scores (unsmoothed) for the first two principal components (4055 BCE – 2022 CE). Pollen zones and subzones shown with red and hatched lines.

The PCA analysis from the FEN4 pollen percentages was used to determine the main patterns of ecological variation within the pollen data (Figure 10). The PCA illuminated changes in local vegetation conditions at L'Anse aux Meadows. The significant two initial PCA axes explained 27.6% of the pollen variation in the core while this is only about a quarter of the variation in the core, there are still pertinent patterns that make this analysis relevant. PCA axis 1 explained 15.6% and was defined by high positive PCA axis 1 scores for Asteraceae, *Betula*, *Selaginella*, and *Sanguisorba*; together with low negative PCA axis 1 scores for Ericaceae, *R. chamaemorus* and *P. mariana* (Figure 10A). PCA axis 1 captured the gradient conditions between Cyperaceae-dominated fen (high positive scores) and Ericaceae-dominated *Sphagnum* bog (low negative scores). PCA axis 2 explained 12.0% of the pollen variation and was defined by high positive PCA axis 1 scores for *A. crispa, A. rugosa, Populus* and *M. gale*; together with low negative PCA axis scores for *P. strobus* and *P.glauca.* PCA axis 2 captured the successional gradient between early pioneers after disturbance, i.e. *Alnus* ssp., and *Populus* (high positive scores) versus later successional trees, i.e. *Picea* spp., *A balsamea,* and *P. strobus* (low negative values).

PCA 1 scores were generally positive in pollen zones 1, 3, and 6b; negative in zones 2, 4, 5 and 6a (Figure 10B). PCA 2 scores showed higher-frequency variability, varying between positive and negative values in all zones, except for zone 2 (where it was positive for the two samples) and zone 6 (where it was negative for the last millennium except for one sample).

Charcoal Results

In total, 208 charcoal samples were counted from the Fen4 peat core. Charcoal contents varied from 0 (139 samples) to 51 pieces per sample, with a mean of 1.6 and a median of 0 pieces per sample (Figure 11A). The SNI was ≥ 3 for the entire Fen4 record, with a median of 19.1 (Figure 11B). The mean and median interpolated charcoal accumulation rates were 9.6×10^3 $\mu m^2/cm^2 \cdot yr$ and 0 $\mu m^2/cm^2 \cdot yr$, respectively (including zeroes), with mean and median of 2.1×10^4 $\mu m^2/cm^2 \cdot yr$ and 1.0×10^4 $\mu m^2/cm^2 \cdot yr$, respectively (excluding zeroes) (Figure 11C). CharAnalysis identified 17 local significant fire peaks in the Fen4 core over the last 6000 years. Local fires are unevenly distributed with 8 fires between 4025-1750 BCE, no fires between 1749-323 BCE, and then 9 fires between 324 BCE - 1493 CE, with none subsequently. The dates of the four fires with the highest peak charcoal accumulation rates were: 3820 BCE, 3176 BCE, 1750 BCE, and 757 CE. Local fires at our site doubled in the two millennia of the Common Era (8 fires) compared to the four millennia preceding it (9 fires). Background charcoal increased over the Common Era relative to the earlier four most recent millennia BCE (Figure 10C).

There was a local fire approximately during the Norse settlement period that occurred at 1035 CE (Figure 11C). Local fires occurred more frequently in the warmer MCA (800 - 1300 CE) than in the colder LIA (1400 - 1850 CE), as there were 4 fires in the MCA with a mean FRI (fire return interval) of 153 years versus 0 fires in the LIA. Overall, the mean FRI between 2022 CE and 4025 BCE was 336 years (Figure 11D), equivalent to 3 fires per millennium. However, there was great variability in this over the 6000-year record: with a mFRI of 305 years between 4025 - 1750 BCE, a mFRI of 1426 years for 1749-323 BCE, and then a mFRI of 227 years between 324 BCE – 1493 CE. (Note that because CharAnalysis uses median-interpolated dates, the dates are slightly different from those in the other analyses.)

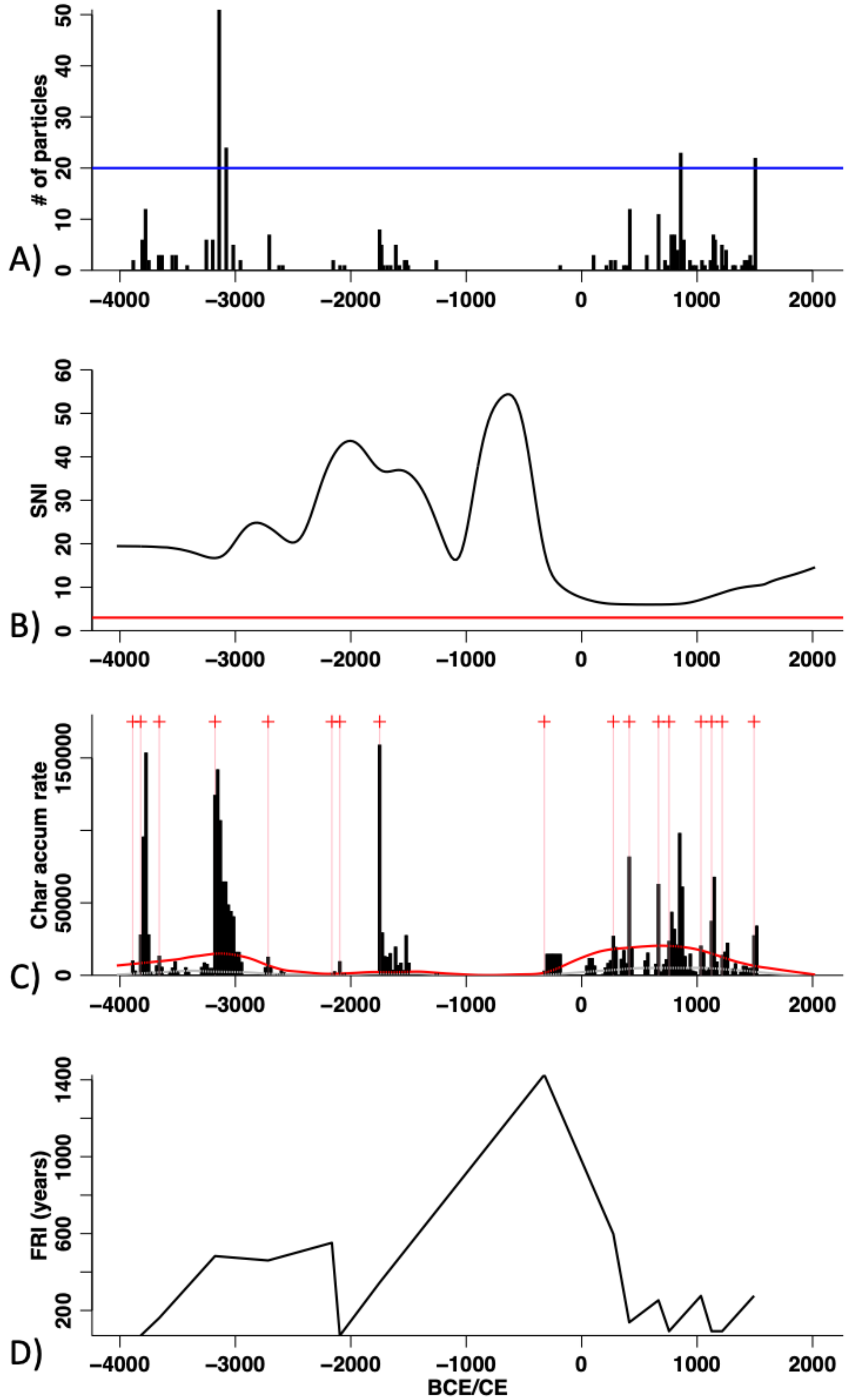


Figure 11. Charcoal results over 4055 BCE – 2022 CE. A) Number of particles recorded in each sample. Blue line denoting the mean number of particles per sample. B) Signal-to-noise index (SNI) and the red line with at SNI = 3). C) Charcoal accumulation rate (CHAR) ($\mu m^2/cm^{-2}/yr^{-1}$). Red crosses and pink lines denote significant charcoal peaks of local fires. D) Fire return interval.

4.5 Discussion

Synopsis

The multiple proxies revealed the vegetation and landscape history of L'Anse aux Meadows over the past six millennia, which collectively documented the imprint of wide-scale North Atlantic climate changes, acting together with small-scale local landform changes and fire processes (Figures 7-11). Arboreal pollen presented a more regional forest history, whereas herbaceous pollen presented a more localized vegetation history. Initially, from 4055 – 3200 BCE (pollen zone 1), the site is best characterized as a minerotrophic fen, as shown by higher mineral content, higher relative abundances of Cyperaceae and Asteraceae (plants that are abundant in such settings), and positive PCA axis 1 scores (Figures 7-10). This vegetation pattern was disrupted by a fire that occurred sometime within the period 3200 – 2750 BCE (pollen zone 2) in which the initial recovery was characterized by high amounts of monolete fern spores (Figures 8, 9, and 11). The fire was probably somewhat localized and unlikely to have been widespread in the region as the regional influx of *P. mariana* pollen remained unchanged. By 2750 – 1740 BCE (pollen zone 3), the local fen vegetation had re-established itself to be similar to that of zone 1, with *Betula* and Cyperaceae as dominant taxa, and Asteraceae and *Sanguisorba* as important herbaceous constituents (Figure 8).

A large change in environment and local vegetation occurred at the beginning of pollen zone 4 (1740-1325 BCE). At the beginning of this zone, another fire occurred, coinciding with the change of the local pH, this is possibly the change from a fen to a *Sphagnum* bog or perhaps from a rich fen to a poor fen (Figures 8 and 9). Nevertheless, this pH shift changed the local assemblage of herbs on the landscape. This landscape and vegetation transition is evident in the change from a Cyperaceae- to an Ericaceae-dominated bog. This switch to Ericaceae was apparent in both the percentage data as well as the accumulation rates of the pollen taxa (Figures

8 and 9). At this point there was also an increase in *Alnus crispa* pollen which may have been part of the early regeneration of the heterogenous area after the burn. This zone shifted to a 1200-year period of very low peat accumulation (pollen zone 5) with little pollen from any taxa (with likewise limited charcoal accumulation), from about 1095 BCE to 50 CE. This period of low pollen and charcoal accumulation may reflect a hiatus in the core, where the peat layer was eroded by higher rates of decomposition or a reduction of the *Sphagnum* growth. A shift to drier conditions would have increased peat decomposition and reduced the amount of peat we see in the core during this period. Alternatively, colder and drier conditions would and reduced the producitivty which in turn may have led to lower peat accumulation here. Comparable charcoal and pollen accumulation rates resume to background levels after 1 CE, coincident with decreasing Ericaceae influx and increasing Cyperaceae influx. Fire frequency also increased in the first millennium CE, at a higher frequency than prior intervals.

By pollen zone 6a (beginning at 920 CE) Cyperaceae regained dominance over Ericaceae, suggesting a reversion to a more fen-like environment, perhaps due to evapotranspiration. Early pioneering *Alnus crispa* perhaps took advantage of the high fire activity during zone 6a. This higher fire frequency continued until the mid-1500s CE and mirrored the increased pollen accumulation rates, pointing to potentially warmer climate conditions before the onset of colder temperature characterizing the Little Ice Age on the Northern Peninsula. Pollen zone 6a (920 – 1280 CE) also coincided with the Medieval Climate Anomaly (MCA) (900 – 1300 CE). In pollen zone 6b (1280 – 2022 CE) the pollen influx declined again, as did the frequency of fires. Cyperaceae increased in relative abundance, and *Myrica gale* and *Sphagnum* increased in relative and absolute abundance (Figures 8 and 9, SI Figure 1) suggesting even more expanding fen-like conditions.

Fire return interval and charcoal accumulation varied throughout the last 6000 years at L'Anse aux Meadows. Fire initiates three of the seven pollen zones with an event at the beginning of zone 2, zone 4, and zone 6a. It is difficult to assess the spatial scale or magnitude of fire events based on the available charcoal data, but the fact that pollen zone change often coincides with these events indicates that these fires were probably large enough to disturb the ecology surrounding L'Anse aux Meadows and shift the composition of species in the aftermath of the burn in a way that was long-lasting. This suggests that while this site looks to have been dominated by cold-tolerant taxa for the last 6000 years, fire activity in the surrounding landscape played a major role in the ecological changes during this timeframe.

The LOI results from our core showed the mineral content decreasing over time. This trend is consistent with the overall transition from a fen to a bog at the site, perhaps due to paludification, as fens have higher mineral content which is carried by groundwater transport and surface runoff. Conversely, bogs have lower mineral content as they are not part of the groundwater flow and only receive mineral input from aeolian sources (Mitsch et al., 2023). The mineral-rich bottom section of the core also coincides with higher abundances of Cyperaceae which are more often related to fen environments. The decreasing mineral content also coincides with an increase in Ericaceae which is tied to less acidic, bog-like environments.

Response to broader North Atlantic climate changes

The widespread cooling in the northeastern Atlantic over the last seven millennia (Orme et al., 2021) also occurred at L'Anse aux Meadows and is reflected in the gradual decline in total pollen productivity at our site (Figures 8, 9, 12, 13). Orme et al. (2021) used marine diatoms to reconstruct sea-surface temperatures in Trinity Bay, southeastern Newfoundland. They found a general declining trend in SST temperatures over this time-period, mirroring the decline in June solar radiation at 48° N. Given that the Inner Labrador Current influences the coast of the Northern Peninsula where L'Anse aux Meadows is located, it is reasonable to assume that the SST trends translate directly to terrestrial temperature trends at this coastal location. This interpretation is in agreement with other pollen and climate records that record the Holocene Thermal Maximum on the island as being between 4000 – 2500 BCE (6000 – 4500 cal BP) followed by a long-term cooling trend in the later Holocene (Figure 13) (MacPherson, 1996; Evans, 2002).

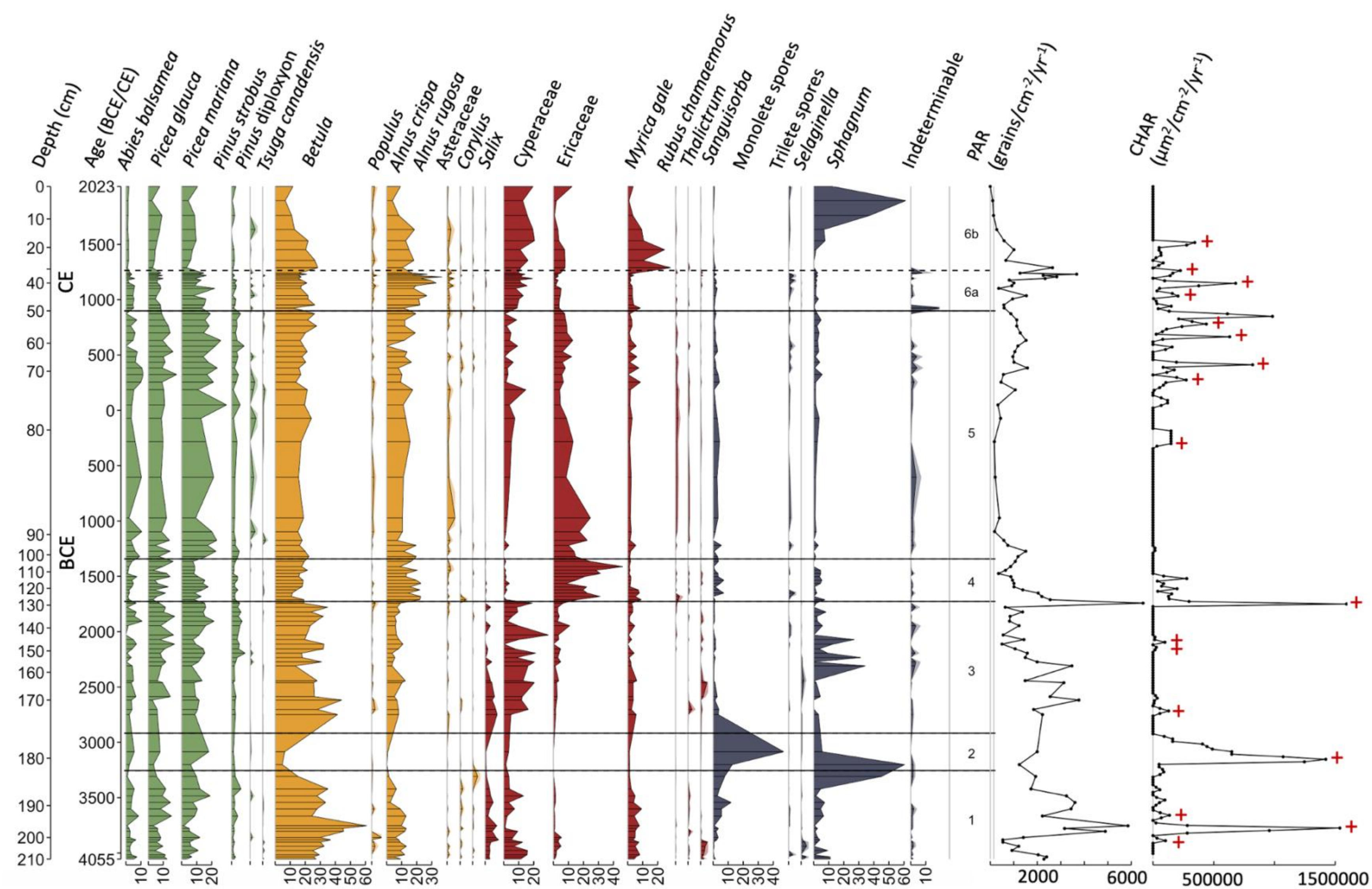


Figure 12. Terrestrial pollen and spore percentages diagram for principal taxa from the Fen4 core taken near the L'Anse aux Meadows, Newfoundland, archaeological site. Shown are pollen percentages of main taxa (total terrestrial pollen sum >15% in the core) and the interpolated charcoal accumulation rate (CHAR) ($\mu m^2/cm^{-2}/yr^{-1}$). Lighter areas show an exaggeration of 1.4x. Solid black horizontal zone lines from CONISS were significant at the 95% level as assessed by broken stick test. The dashed black horizontal zone line was barely insignificant. Also shown is the total pollen influx or accumulation rate (PAR) (grains/cm2×yr).

Zones 1, 2 and 3: Holocene Thermal Maximum (4055 – 1740 BCE, 6000 – 3690 cal BP)

The earliest three pollen zones of the core have a similar pollen assemblage (interrupted by only two samples dominated by monolete spores) and take place during what is known as the Holocene Thermal Maximum (Sawada et al., 1999; Kaufman et al., 2004). These three zones are therefore described together due to their similar taxa makeup. With regards to the local ecology during this period, the three bottommost zones illustrate the predominance of a fen-like environment, as mentioned above. The high occurrence of Cyperaceae (sedges), obvious in both the percentage and influx data (Figures 8 and 9), is indicative of a fen environment while Ericaceae is associated with ombrotrophic bog-like environments as they out-compete other species in the low-nutrient environment. This is further supported by the LOI results which showed a general trend of higher mineral content in the earlier period that slowly declined over time. Due to both these factors it is therefore likely that this site originated was a minerotropic fen by the (6000 cal BP) (connected to a groundwater source).

The total pollen influx reflects the occurrence of the Holocene Thermal Maximum warm period from the beginning of the core at 4055 (6005 cal BP) until ~1700 BCE (3690 cal BP). This period of late Holocene warmth has been documented in other studies across Newfoundland and Labrador. For example, in a comparative study of pollen stratigraphies from Newfoundland, MacPherson (1995) showed that sites from the Avalon Peninsula to the Northern Peninsula also record a Holocene Thermal Maximum between 4050 and 2050 BCE (6000 – 4000 cal BP). This is illustrated through various signals, including increased levels of arboreal *Betula* pollen in the Avalon Peninsula, increased *Fraxinus nigra* (black ash) pollen accumulation on the North Shore, and increased macrocharcoal from fire activity from multiple sites. These combined factors led MacPherson (1995) to conclude that the period 4000 – 2000 BCE (6500-4000 cal BP) was one of greater warmth on the island. While our site does not exhibit increases in *Fraxinus nigra* pollen in particular, the total pollen accumulation rates are higher at this time, until they drop around 2000 BCE (4000 BP), suggesting higher plant productivity of biomass due to more favorable growing conditions.

Similarly to these Newfoundland sites, a palynological study covering three sites from southeastern Labrador noted that pollen influx decreased significantly after reached its maximum around 4000 BP (Lamb, 1980), coinciding with the pollen influx levels from our core. One of these studies, just across the Strait of Belle Isle, near Blanc Sablon, recorded a period of greater warmth in increased pollen influx levels until 4050 BCE (4000 cal BP), which further suggests that the Holocene Thermal Maximum continued until *c.* 4050 BCE (6000 cal BP) in this region (Lamb, 1980). Elsewhere, a $\delta^{18}O$ record from Cheeseman Lake, 400 km south of L'Anse aux Meadows indicates that the warmest conditions of the Holocene occurred between 6050 – 4350 BCE (8000 – 6300 cal BP) and were followed by a long-term cooling trend which is associated with declining summer insolation (Finkenbender et al., 2016). While this puts the Holocene Thermal Maximum slightly earlier than other reconstructions on Newfoundland, it is likely that climate deterioration did not immediately cool the region at 4350 BCE and that Newfoundland was still relatively warm at the time our core began at 4050 BCE (6000 cal BP). This difference in timing is also possibly due to dating error in our core. Lamb (1980) interpret this to mean that the period of greatest Holocene warmth in Labrador lasted from 6000 to 4000 cal BP and then deteriorated in the later Holocene. Thus, the overall trend of high pollen influx between 4050 – 2050 BCE indicates that the period of greatest warmth on the island is associated with higher productivity at L'Anse aux Meadows.

This period of zones 1, 2, and 3, contains eight significant fire events, of unknown ignition type (Figures 12 and 13), putting the fire return interval at around 400 years. This period also contains the three charcoal peaks with the highest accumulations at 3820 BCE (5770 cal BP), 3176 BCE (5125 cal BP), and 1750 BCE (3700 cal BP). Two of these events (those of 3820 and 3176 BCE) initiate pollen zones 2 and 4, respectively. This indicates that these fires were significant enough to cause ecological disturbance in the area that initiated changes in the pollen assemblages. These eight peaks of charcoal occur during the era of greatest Holocene warmth recorded in our core. The warmth is likely to have made more available fuel during this period.

The largest charcoal spike around 1750 BCE (3700 cal BP) (Figures 11, 12, and 13) roughly coincides with a charcoal spike that Bell et al. (2005) found in Stove Pond near Port aux Choix, 200 km south of L'Anse aux Meadows (MacPherson, 2007). This study provides one of the two closest pollen reconstructions spanning a similar period to our study. While the major fire event *c.* 2050 BCE (4000 cal BP) at Stove Pond is slightly earlier than our biggest event, recorded at 1850 BCE (3800 cal BP), it is within a similar enough range (including dating error) to be of interest and suggest the possibility of a widespread event that effected both sites. Charcoal spikes at this time were also identified at Bishop's Falls in north central Newfoundland, as well as in Hawke Hills and Kennys Pond on the Avalon Peninsula (MacPherson, 2007). While the charcoal spikes on the Avalon Peninsula may be coincidence, the presence of a charcoal spike around 1850 BCE (3800 cal BP) at L'Anse aux Meadows, Port aux Choix, and Bishop's Falls suggests the possibility of a large regional fire on the Northern Peninsula. Given that this occurred during the period of maximum Holocene warmth, it is also possible that there was greater fuel ability for wildland fires which would have made the site more prone to fire activity.

In other records across Newfoundland, Labrador and Québec, *Pinus* pollen accumulation has been associated with increased fire activity and the Holocene Thermal Maximum. While *Pinus* appeared at L'Anse aux Meadows during the Holocene Thermal Maximum which included the three largest charcoal peaks in our core, its pollen accumulation was negligible enough that it does not seem to be the main reason for fire on this landscape (MacPherson, 1998). Together, these findings contextualize the period of increased pollen influx and more intense fire activity during the warmest period of the Holocene in Newfoundland.

<u>Zone 4: Fen-Bog Transition</u> (1740 – 1325 BCE, 3690 – 3275 cal BP)

Pollen zone 4 (Figures 8, 9 and 11) denotes the most significant ecological shift in our reconstruction with Cyperaceae giving way to Ericaceae, and *Betula* being replaced by *Alnus crispa* at 1740 BCE (3690 cal BP) (Figure 12). This switch in wetland species is usually indicative of a change in the mire, from a nutrient rich environment to a nutrient poor environment (Laine et al., 2011; van Breeman 1995). It is possible that this change picked up a either a rich fen to poor change or a fen to bog transition, as Cyperaceae are associated with nutrient rich, fen-like environments and Ericaceae with nutrient poor, bog-like environments (Heinselman, 1970). This is due to the fact that unlike Cyperaceae, Ericaceae can tolerate the nutrient-poor and acidic conditions characteristic of an ombrotrophic bog. Fens are often more nutrient-rich environments and therefore able to support more species of Cyperaceae (Davis, 2008; van Breeman, 1995). The transformation from a minerotrophic to ombrotrophic environment is caused by the accumulation of peat which can isolate the surface from the water table (Laine et al., 2011). This process also transform rich fens to poor fens and eventually to ombrotrophic bogs and is usually controlled by *Sphagnum.* Therefore, it is likely that the growth of *Spahgnum* at our coring location had an effect on the species change but counter to this process, the pollen and spore assemblage shows higher levels of *Sphagnum* in the bottom core when we suspect this wetland is a fen. The greater presence of *Myrica gale* in the first three zones (Figure 9) is also characteristic of fen environment. The decrease in influx further denotes a shift to a bog-like environment (Davis, 2008). This suggests that the shift at 1740 BCE was a local wetland shift from a minerotrophic fen to an ombrotrophic bog.

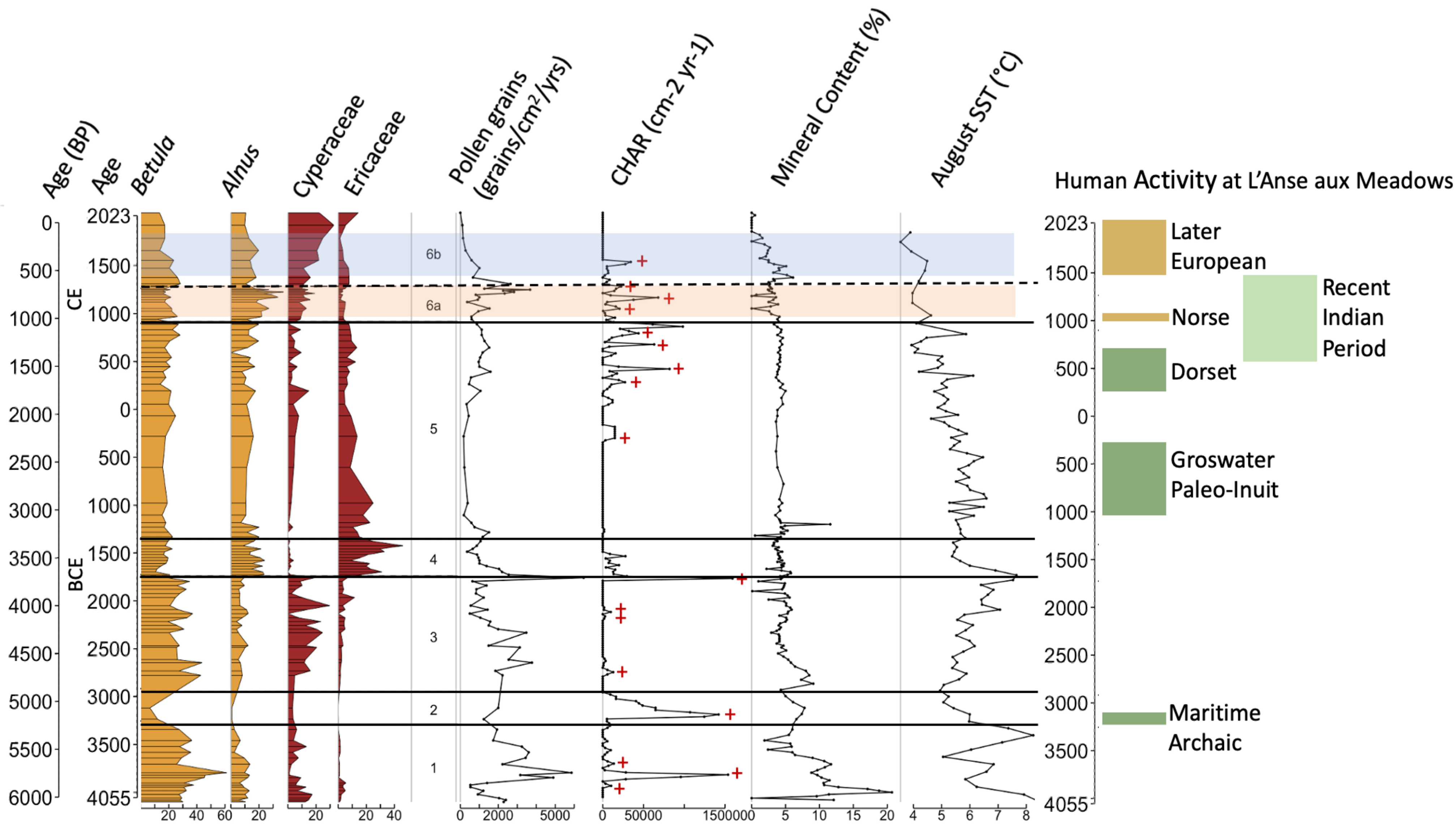


Figure 13. Terrestrial pollen percentages for four principal taxa from the Fen4. Also shown are total pollen influx/accumulation rate (PAR) (grains/cm^{-2}/yr^{-1}), the interpolated charcoal accumulation rate (CHAR) (μm^2/cm^{-2}/yr^{-1}), and mineral content (%) from Fen4. Solid and dashed black horizontal zone lines show zonal divides from pollen percentage data. August SST (C°) reconstructed by Orme et al. (2021) from Trinity Bay, Newfoundland. Red highlighted area shows the Medieval Climate Anomaly and blue highlighted area shows the Little Ice Age. Human activity periods are adapted from Kristensen and Curtis (2012) and Wallace (2006).

The shift is almost immediate and coincides with 1) a change in tree pollen, as *Betula* dips and *Alnus* rises and 2) another fire event, coincident with a period of high SSTs recorded in the reconstruction by Orme et al. (2021). The shift from *Betula* to *Alnus crispa* around 1740 BCE coincides with a similar switch in species in north and western Newfoundland, and is recorded in several other studies (MacPherson,1995). MacPherson (1995) infers that this transition denotes a change to wetter conditions on the island as *Alnus* shrubs increase as a result of enhanced moisture, which may be reflected in Newfoundland's overall climate deterioration after this time, as detailed by Orme et al. (2021) and Finkenbender et al. (2016). Indeed, the $\delta^{18}O$ values from Cheesemen Lake, 200 km south of L'Anse aux Meadows, indicate the onset of wetter conditions around 2350 BCE (4300 BP) (Finkenbender et al., 2016) which is also confirmed by a multi-proxy analysis from Bonavista Bay (Blundell et al., 2018). It seems likely that our record has demonstrated this regional climatic shift and though these studies record an earlier increase in *Alnus* than occurs at our site, it is possible that this shift in precipitation was time transgressive, in other words occurring at different times in different locations. For example, a study from Grey Islands (Evans, 2002) picks up the increase in *Alnus* at 3500 BP, which Davis (1984) interpreted as the end of the Holocene Thermal Maximum as the climate cooled. Similarly, across the Atlantic, a shift to a wetter climate was identified in northern Scotland (Anderson et al., 1998), Norway (Nilssen and Vorren, 1991), and Denmark (Aaby, 1976). All of these studies offer significant evidence that there was a time transgressive climatic shift around ~1740 BCE (~3700 BP) in the Labrador Sea region.

Elsewhere, Sillasoo et al. (2011)'s peatland study in Estonia records the effect of fire events on bog ecology, noting that charcoal peaks, denoting fire events, were followed by wet shifts in the bog. Plant communities also respond to fire in different ways, altering species composition. Ericales generally increase in the years following a fire event, a process that has been documented by a number of pollen studies (e.g., Damman 1978; Yeloff et al., 2006; Boiffin et al., 2015). It is possible this same response is recorded at L'Anse aux Meadows, as Ericaceae increased directly after this fire event, suggesting this fire event affected the species composition of the fen. It is also possible that this fire event created the right successional conditions for *Alnus crispa* to colonize the surrounding landscape, as Lamb (1980) notes that increases in *Alnus* pollen have been associated with disturbances. Though this pollen zone only represents a duration of ~1000 years, the shift at 1740 BCE marks a striking change in the wider climatic and environmental conditions around L'Anse aux Meadows.

<u>Zone 5: Low accumulation period</u> (1325 BCE – 920 CE, 3275 – 1030 BP)

This zone is denoted by low accumulation rates in both total pollen grains and charcoal, indicating 1) low productivity on the landscape 2) or declining accumulation rate (Figures 12 and 13). Other temperature and precipitation reconstructions from the North Atlantic give substantial evidence of climate change between 850 and 650 BCE (2800 and 2600 BP). A study from the Grey Islands (Evans, 2002) also notes a drastic decrease in pollen accumulation in the same period just after 1000 BCE, which signifies a regional shift around the northern peninsula. Elsewhere, a decline in pollen influx at Whitney's Gulch near Blanc Sablon is recorded after 2000 BP, which Lamb (1980) interprets as a decline in productivity. Other studies note that glaciers on Greenland and Baffin Island advanced during this time, while peatland records from Bonavista Bay, Newfoundland (Hughes et al., 2006), and mainland Canada (Bilali et al., 2013) record increased atmospheric moisture along the eastern seaboard *c.* 850 – 650 BCE (2800 – 2600 BP) (Nichols and Huang, 2012; Finkenbender 2016; Blundell et al,. 2018). This would suggest that the Northern Peninsula and broader North Atlantic Canada experienced a similar period of cooling. This period is also characterized by almost 1000 years of limited to no fire activity. While this could be due to climate, it could also be due to the period of low peat accumulation at this time which is evident in the pollen accumulation and the age-depth model of our core, rendering such events less detectable.

However, following these 1000 years of low pollen and charcoal accumulation, both charcoal and pollen accumulation increased again just after 1 CE (2000 BP). Davis et al. (1988) interprets the higher values of *Abies* and *Betula* around (3000 – 2400 BP) in their study, to mean that the area was more wooded than today. In comparison, arboreal pollen did not significantly increase in our core during this period, particularly with the low *Betula* percentages. The following zone in Davis et al. (1988)'s study is marked by high Cyperaceae values, in contrast to our own lower values for Cyperaceae at this time. The five significant fire events all take place within the top section of the zone, with four out of five occurring after 1 CE. Total pollen influx also increased in the upper section of this zone, suggesting an increase in peat accumulation or landscape productivity.

<u>Zone 6A: Medieval Climate Anomaly</u> (920 – 1280 CE, 1030 – 670 BP)

This zone spans the dates of the Medieval Climate Anomaly and also contains the period the Norse would have been at L'Anse aux Meadows (Ledger et al., 2019; Kuitems et al., 2021) (Figure 12). While the Medieval Climate Anomaly is subject to spatial variability, it is noteworthy that the pollen composition and fire activity reflected warmer temperatures at L'Anse Aux Meadows through increased pollen influx and fire events. The last high peaks of pollen accumulation, around 950 – 1150 CE (1000 – 800 BP), showed a similar pattern to that of the pollen concentration of Stove Pond, suggesting that there was a recent spike in productivity on the landscape of the Northern Peninsula followed by a decreasing over the last 500 years (Bell., 2005). This zone contained three fire events and had the lowest FRI in the core, perhaps suggesting warmer temperatures conducive to more frequent burns (Figures 11, 12, and 13). While at least one of these fire events is within the Norse period at the site, it is difficult to attribute this to human activity, and could be due to the warmer temperatures of the time. The low FRI during this period is also in agreement with a $\delta^{18}O$ study that suggested warmer temperatures in Newfoundland during the MCA around the time the Norse settlement at L'Anse aux Meadows (Finkenbender et al., 2022).

This period does not exhibit any dramatic vegetation changes in terms of species composition, with no introduction of exotic species to mark foreign species arriving from Europe detectable. However, there was a reversion of the fen-bog species as Cyperaceae pollen increased while Ericaceae returned to lower levels again. This suggests a return to a more fen-like environment, which continued until the top of the core.

<u>Zone 6B: Little Ice Age to present</u> (1280 - 2022 CE, 670 – -72 BP)

This zone begins almost exactly when the MCA shifts to the LIA around 1300 CE, a period of cooling in the Northern Hemisphere. This period is marked by a noticeable increase in Cyperaceae, as Ericaceae percentages remained low, indicating the continuation of a more fen-like environment that began in the previous zone (6a). This agrees with the presence of a fen environment which we observed when we cored the site in 2022, one that was for the most part submerged in water without a raised portion characteristic of an ombrotrophic bog (Figure 4). This indicates that this wetland site transitioned from a fen to a bog around ~1740 BCE (3725) and then transitioned back to a fen around 920 BCE. This significant drop in all taxa except *Betula, Myrica gale,* and Cyperaceae, suggests that Little Ice Age conditions were cold enough in northern Newfoundland to affect landscape productivity. Davis et al. (1988) denotes paludification in the past 600 years at the site which is consistent with our results as seen by the high presence of *Sphagnum* (Figure S2). The one significant fire during this zone seems to be indicative of colder temperatures compared to those of zone 6b, suggesting fire activity was dampened by cooler and wetter conditions.

Conclusion

This study presents a new pollen and charcoal reconstruction near the L'Anse aux Meadows UNESCO World Heritage Site. The findings illustrate key environmental transitions, including fen-bog transitions, in the local area, as well as the presence of the Holocene Thermal Maximum (~4000 BCE), which was marked by high vegetation productivity, and a large-scale environmental change around 1740 BCE. For the last 6000 years, L'Anse aux Meadows remained an important site for Indigenous groups likely due less to its terrestrial productivity, and more to its abundant marine and avian resources. During the Medieval Climate Anomaly, coincident with the period of Norse occupation, fire activity increased alongside the productivity around the site. There were no signs of European flora, further confirming that this site was used as an exploration base. Following this period, the Little Ice Age brought lower vegetation productivity, reduced fire activity and a change to a fen environment. This research provides further understanding of middle to late Holocene climate variability and its impacts on northern Newfoundland, as well as providing valuable ecological context for the last 6000 years of Indigenous occupation.

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CHAPTER 5: Conclusions

This study provides one of the longest fossil pollen analyses and first charcoal reconstruction near the L'Anse aux Meadows archaeological site in Newfoundland. The resulting species composition and fire histories are the results of complex interactions between climatic, oceanic and localized ecological dynamics. Notably, our record captured the Holocene Thermal Maximum period around 6000 BP, and subsequent climate deterioration, matching several other temperature and pollen records from the island. The Holocene Thermal Maximum in our core took place between period 4055–1740 BCE and was characterized by increased vegetation productivity, high percentages and influx rates of *Betula*, as well as eight fire events.

The study reveals that the site has undergone significant environmental transitions, including shifts from a minerotrophic fen to a Sphagnum bog, influenced by climatic variations, fire events, and regional cooling trends. Our record illustrates a significant ecological shift around 1740 BCE, marked by a major fire event, which transformed the landscape from a fen to a bog, as shown in the switch from Cyperaceae to Ericaceae. Following this shift, the site experienced a prolonged period of low peat and pollen accumulation (1095 BCE–50 CE), possibly reflecting colder and drier conditions that inhibited vegetation growth. Following this period of low accumulation, Zone 6A coincided with the Medieval Climate Anomaly period of Norse occupation, and was marked by increased fire activity and higher productivity in the landscape, which would have made the region more hospitable for habitation and resource gathering. There was also a return to a fen-environment at this time. The lack of exotic European taxa or significant changes in species composition in our core at this time supports the idea that the site was primarily used as a base for exploration and resource gathering instead of a full agricultural site.

In contrast, the subsequent Little Ice Age (Zone 6B) featured a cooling trend, with lower fire activity and continued wetland conditions and occurred during a climatic window that offered relatively warmer temperatures. The subsequent cooling may have dampened vegetation productivity, aligning with broader research that indicates a colder Little Ice Age in the North Atlantic.

The absence of significant shifts in the vegetation composition suggests that for Indigenous groups, L'Anse aux Meadows remained an important site due to its marine and avian resources, which were accessible even during times of low terrestrial productivity. The presence of bird species and marine resources would have been crucial to both Indigenous groups and the Norse in this relatively cold environment. This ecological stability supports the idea that the site was primarily used for seasonal hunting, particularly of migratory birds, which were abundant in the summer and early autumn months.

This research contributes to a broader understanding of middle to late Holocene climate variability and its ecological impacts on the Northern Peninsula. It provides valuable insights into how past climate forcings, and environmental changes influenced the site's suitability for human occupation, who have utilized this site for thousands of years due to the availability of marine and avian resources.

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Appendix

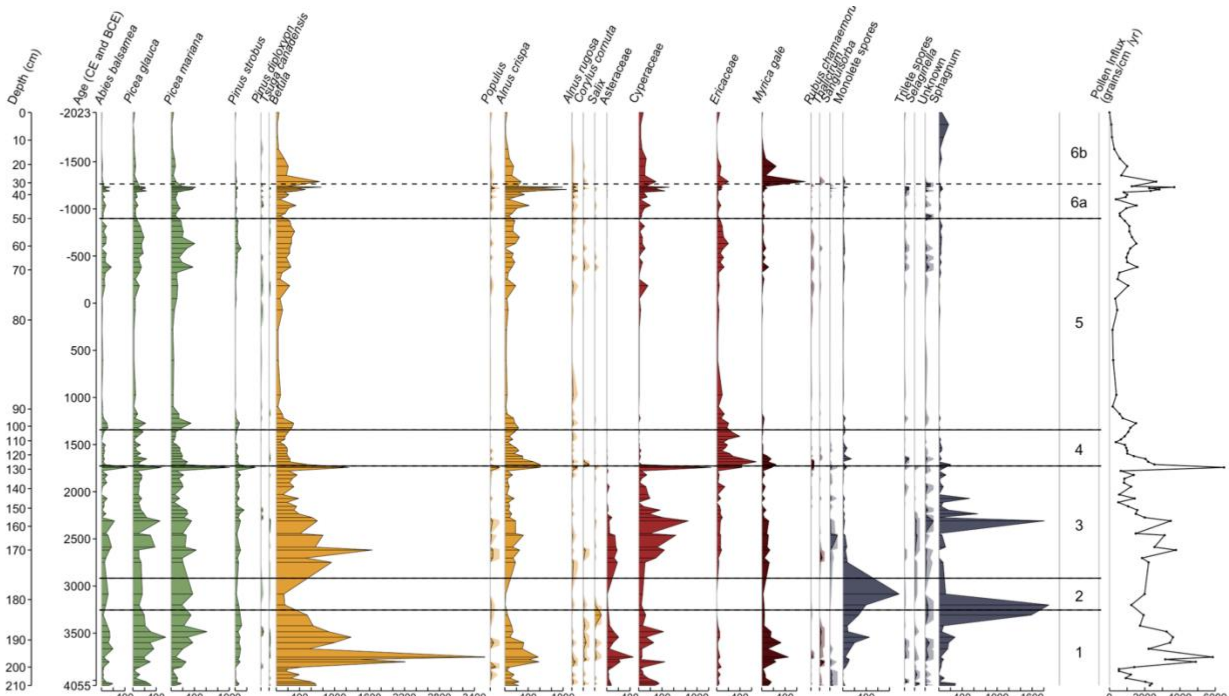

Figure S1. Terrestrial pollen and spore accumulation diagram for principal taxa, including *Sphagnum*, from the Fen4. Shown are pollen influx of main taxa with *Sphagnum.* Lighter areas show an exaggeration of 1.4. Solid black horizontal zone lines from CONISS were significant at the 95% level as assessed by broken stick test. The dashed black horizontal zone line was barely insignificant. Also shown is the pollen influx or accumulation rate (PAR) (grains·cm^{-2}/yr^{-1}).

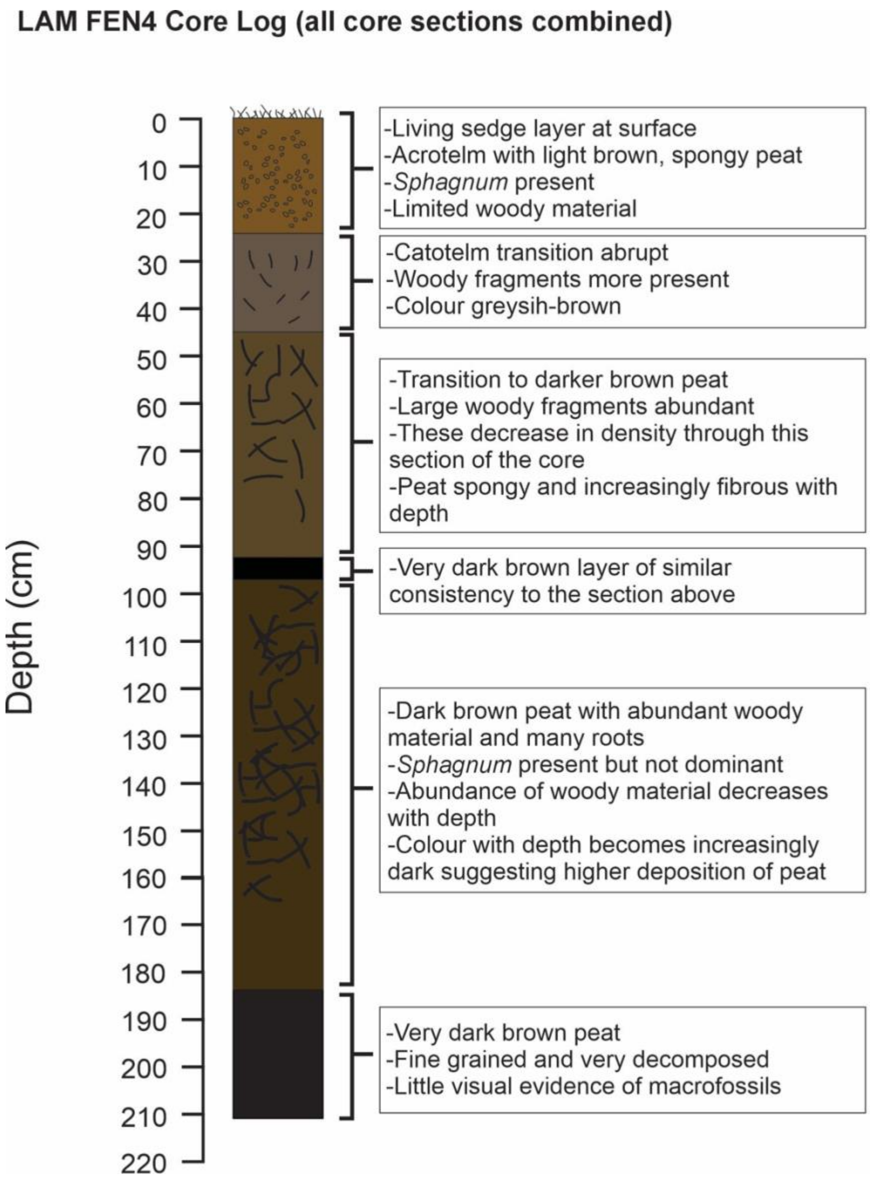
LAM FEN4 Core Log (all core sections combined)
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
-Living sedge layer at surface
-Acrotelm with light brown, spongy peat
-*Sphagnum* present
-Limited woody material
-Catotelm transition abrupt
-Woody fragments more present
-Colour greysih-brown
-Transition to darker brown peat
-Large woody fragments abundant
-These decrease in density through this section of the core
-Peat spongy and increasingly fibrous with depth
-Very dark brown layer of similar consistency to the section above
-Dark brown peat with abundant woody material and many roots
-*Sphagnum* present but not dominant
-Abundance of woody material decreases with depth
-Colour with depth becomes increasingly dark suggesting higher deposition of peat
-Very dark brown peat
-Fine grained and very decomposed
-Little visual evidence of macrofossils

Figure S2.