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Bachelor Thesis

Degree Project in
Geological Sciences, 15 hp

Evidence for Vegetation Change Associated with Fluctuating Seabird Colony Populations Over the Last 1000 Years from Eastern Canada

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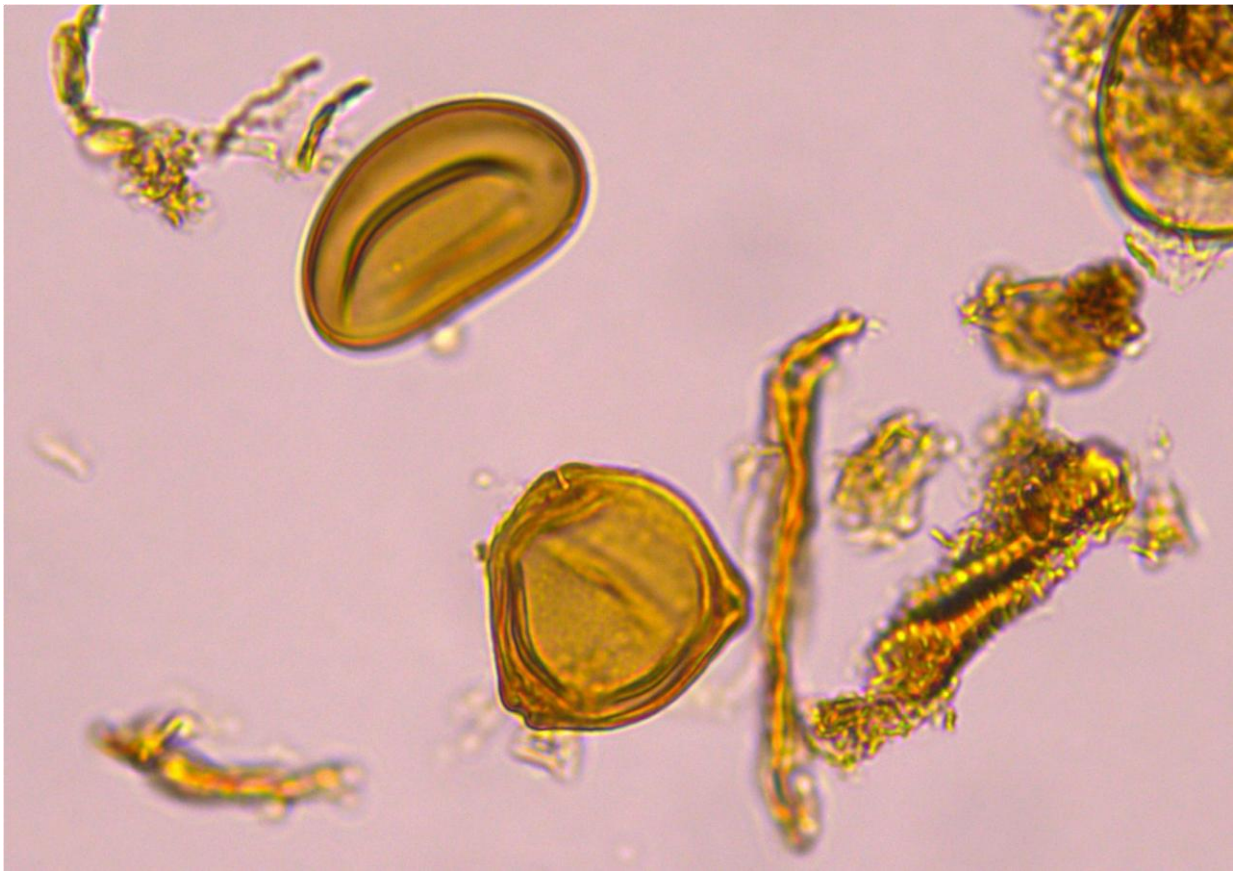

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Abstract

Grand Colombier Island, located within the Saint Pierre and Miquelon Archipelago off the coast of eastern Canada, supports the worlds third largest known colony of Leach's Storm Petrel (*Hydrobates leucorhous*) (Duda *et al*., 2020a). Leach's Storm Petrel are an ecologically important species due to their roles as both ecosystem engineers and as a sentinel species (Duda *et al*., 2020b). Through guano, feather, eggshell and carcass deposition, as well as their burrowing activity, Leach's Storm Perel engineer ecosystems by transferring marine-derived nutrients to terrestrial and lacustrine environments, thereby significantly affecting soil chemistry and subsequent plant assemblages (Duda *et al*., 2020a; Kane, Duda and Smol, 2026). Building on this work Kane, Duda and Smol (2026) examined changes in cladoceran assemblages preserved in lake sediments to understand the impact of the seabirds on aquatic communities. Previous studies conducted on Grand Colombier Island and nearby Baccalieu Island have demonstrated that population fluctuations are associated (Duda *et al*., 2020b) with changes in vegetation composition and geochemical proxies in lake sediments.

Substantial declines in Leach's Storm Petrels population on Grand Colombier Island have been documented, with an estimated 70% decline since 1950, along with longer term decline coinciding with the arrival of European settlers in the area (Duda *et al*., 2020a). Understanding the links between anthropogenic factors and their influence seabird populations will potentially guide future interactions with Leach's Storm Petrels (Kane, Duda and Smol, 2026).

The aim of the study is to investigate whether vegetation trends align with population fluctuations in Leach's Storm Petrels. Pollen and spores preserved within limnological sediments, retrieved from Grand Colombier Pond on the island will allow for the reconstruction of past vegetation assemblages and infer changes related to seabird influence. This sampling interval provides the required timescale to reconstruct seabird population fluctuations over the period spanning the arrival of European colonisers in the region (Duda *et al*., 2020a).

The results of the study do not demonstrate a strong correlation between seabird population fluctuations and changes in vegetation composition over the observed period. Fern spores remained the dominant component of the assemblage throughout the sequence and exhibited

a gradual increase relative to inferred Leach's Storm Petrel population decline, while grass, shrub, and arboreal taxa showed comparatively limited variation. This suggests that either vegetation assemblages on Grand Colombier Island are relatively resilient to seabird derived nutrient input or limitations in the study such as required meant that the pollen and spore record was insufficient to measure subtle ecological responses.

Acknowledgements

I would like to take this opportunity to thank everyone who has made it possible for me to achieve everything that I have accomplished throughout my time at Stockholm University and especially the work I have accomplished within this thesis.

Firstly, I would like to thank my supervisor, Scott Cocker, for his unrivalled knowledge, guidance, and understanding in introducing me to the fascinating field of pollen analysis. I genuinely would not have been able to achieve what I have without his support and feedback throughout this project.

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Finally, I would like to thank my amazing partner, Sandra Eriksson, for her unwavering support, patience and encouragement through this busy period, and for caring for our beautiful daughter, Freja. Your support made the completion of this thesis possible, and I will always be grateful.

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1 Introduction

1.1 Research Aims and Objectives

1.1.1 Research question

How have fluctuations in Leach's Storm-Petrel populations influenced vegetation assemblages on Grand Colombier Island over the last 1000 years?

1.1.2 Research aim and objectives

The aim of this thesis is to analyse long-term vegetation change on Grand Colombier Island and examine how vegetation assemblages responded to environmental changes associated with European arrival and settlement, a period known to have affected local populations of Leach's Storm Petrels (Duda *et al*., 2020a) This will be achieved through the analysis of pollen assemblages and abundances preserved in lake sediments spanning approximately the last 1,000 years, enabling the reconstruction of long-term vegetation trends on the island. Comparisons will be made with vegetation paleo reconstructions on nearby Baccalieu Island, researched by Duda *et al* (2020b).

1.1.3 Hypothesis

Increased numbers in the population of Leach's Storm Petrels have previously been shown to correspond with an increased abundance in plant taxa tolerant to disturbance and nutrient fluctuations. A previous studies conducted by Duda *et al* (2020b) from Baccalieu Island, demonstrated that fern and grass species respond positively to conditions of elevated seabird nutrient input. In contrast, less tolerant taxa such as Alder (*Alnus*) were negatively impacted relative to an increasing bird population.

Given the documented collapse of Leach's Storm Petrel populations on Grand Colombier Island following nineteenth century European settlement (Duda *et al*., 2020a), we hypothesise that a reduction in seabird derived nutrient inputs will be reflected in corresponding vegetation changes. Specifically, we predict declines in disturbance and nutrient tolerant taxa, including ferns and grasses, and increases in arboreal and shrub taxa as seabird influence on the island ecosystem diminishes.

1.2 Study Site

1.2.1 Geographic setting

The study site of Grand Colombier Island is located within the French overseas territory of Saint Pierre and Miquelon. Situated off the eastern coast of Canada, the island is in the northwest of the Atlantic Ocean, an area containing several major breeding sites for Leach's Storm Petrels, such as Baccalieu Island (Duda *et al*., 2020b).

Current vegetation on the island consists of high quantities of ferns (Lormée *et al*., 2012), the preferred habitat of Leach's Storm Petrel, clustered around Grand Colombier Pond. The pond is small, covering 1600m^2 and is relatively shallow, reaching a depth of 60cm (Duda *et al*., 2020a)

Grand Colombier Island coordinates: 46°49'21.5"N 56°09'59.7"W

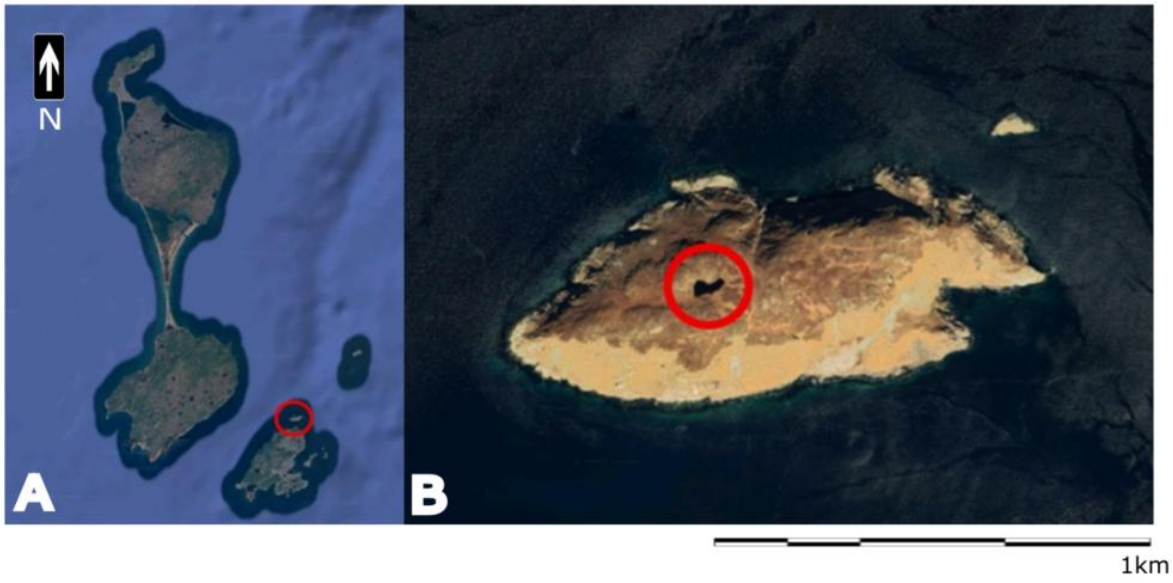


Figure 1. Map of the study site and surrounding region. **A**. Saint Pierre and Miquelon. Grand Colombier Island Circled in red. **B**. Map of Grand Colombier Island. Sediment samples collected from Grand Colombier Pond, circled in red. (Google Maps, 2026; Duda et al., 2020a). Figures compiled and edited using Inkscape.

1.2.2 Climate patterns

The climate for the study region is classified as cold oceanic, which is typical for subarctic marine regions. The island experiences frequent high winds, high precipitation rates and regular storms. Due to the island's geographic location, the climate is influenced by both the

cold Labrador Current from the north and the warmer Gulf Stream Current to the southwest. (Climates to Travel, n.d.)

Climate data for the region of nearby Baccalieu Island, was compiled by Duda *et al* (2020b) using past records from a weather station in the city of St. John's, Newfoundland. Their analysis of this data shows that the region between 1874 and 2018, the mean annual temperature was 4.9 ^{o}C ± 0.7 SD and mean annual precipitation was 1460 mm ± 199 SD.

1.2 Literature Review

1.3.1 Leach's Storm Petrels

Leach's Storm Petrels (*Hydrobates leucorhous*) play a pivotal role as ecosystem engineers by facilitating the transfer of marine derived nutrients into terrestrial ecosystems (Duda *et al*., 2020b). These transferred nutrients can substantially alter ecosystem processes through the introduction of nutrients, isotopes, and trace metals derived from guano, eggshells, feathers, and carcasses (Duda *et al*., 2020a). Due to the long-term occupation on islands as a breeding ground such as Grand Colombier Island, Leach's Storm Petrels provide sustained nutrient inputs that significantly influence both terrestrial and limnological environments (Duda *et al*., 2020a; 2020b; Kane, Duda and Smol, 2026).

Guano-derived nitrogen fertilisation has been shown to affect lake chemistry through eutrophication and acidification (Duda *et al*., 2020a). As guano decomposes, ammonia (NH_3) is released and may volatilise before redepositing as acidic compounds, thereby lowering pH and altering aquatic geochemistry (Duda *et al*., 2020a; Duda *et al*., 2020b). These nutrient inputs have been seen to both increase or decrease vegetation biomass and primary productivity depending on the initial environment, as well as the intensity and duration of nutrient input. Alterations in water chemistry can subsequently influence biotic assemblages. Lake sediments provide a sedimentary archive, preserving these ecological responses (Kane, Duda and Smol, 2026).

In addition to functioning as ecosystem engineers, seabirds possess the ability to provide an indication of overall ecosystem health as 'sentinel species' (Duda *et al*., 2020a). This is a result of seabirds representing the highest trophic level in their environment, therefore, changes in lower levels of the food chain and chemical changes in their habitat, strongly

affect the birds (Duda *et al*., 2020a). Anthropogenic factors such as pollution, habitat disturbance, climate change and over exploitation of food resource are reflected in overall seabird population abundance (Bost and Le Maho, 1993; Duda *et al*., 2020a). Considering breeding rates are more responsive to environmental factors than adult abundance, areas such as Grand Colombier Island are an important indicator of ecosystem health (Parsons *et al*., 2008) The current rapidly declining population trends of Leach's Storm Petrels on Grand Colombier Island can be seen as a potential indicator that the health of the Atlantic Ocean as a whole is in decline (Duda *et al*., 2020a).

In summary, Leach's Storm Petrels have been shown to be strong influencers of local ecosystems and population changes providing important indicators of marine ecosystem health.

1.3.2 Avian impact on Grand Columbier

Grand Colombier Island is a site of special significance to Leach's Storm Petrels, hosting the third largest breeding colony in the world (Kane, Duda and Smol, 2026). Grand Colombier Pond, located on the island, has been shown to contain five independent paleolimnological proxies by Duda *et al* (2020a), including δ15N, δ13C, diatom and chironomid assemblage, and cadmium/zinc metal inputs. This was then added to by Kane, Duda and Smol (2026) to also include Cladoceran assemblages as proxies. Together, they give a coherent record of nutrient and waste input from a fluctuating population of Leach's Storm Petrels over the last approximately 5800 years (Duda *et al*. 2020a; Kane, Duda and Smol, 2026).

Stable nitrogen and carbon isotopes allow for the tracking of marine derived nutrients entering the pond, whereas diatoms, chironomids and metals allow for the changes in pond acidity and eutrophication to be tracked (Kane, Duda and Smol, 2026). In particular, chironomid taxa have been seen to shift after 3500 years before present to taxa that thrive in acidic conditions, this corresponds to an increasing population of Leach's Storm Petrels, before diminishing again 170 years ago. This decline corresponds with the arrival of European settlers in the area (Duda *et al*. 2020a).

An additional study conducted by Kane, Duda and Smol, (2026) further provides evidence that changes in Leach's Storm Petrels coincided with the arrival of European settlers in the early 1800s by looking at small pelagic cladocerans (mainly *Bosmina* spp.) as an indicator of increased nutrient loading and the related changes in pond environments.

Overall, the sediment record in Grand Colombier Pond provides a multi proxied record of fluctuations in Leach's Storm Petrel populations, which all align to record a relatively stable population throughout the past 5800 years until the arrival of humans.

1.3.3 Vegetation changes on Baccalieu Island

Baccalieu Island provides another important site for understanding vegetation responses to Leach's storm Petrel driven ecosystem dynamics. Located approximately 300 km northeast of Grand Colombier Island, on the eastern side of Newfoundland, the island shares a similar environmental and climatic area of the North Atlantic and hosts the worlds largest breeding population of Leach's Storm Petrels. As a result, Baccalieu Island, provides another valuable site for the study of vegetation response to Leach's Storm Petrels (Duda *et al*., 2020b).

Paleoecological investigation into past vegetation on the island were conducted by examining fossil pollen assemblages from interior ponds and demonstrate a clear link between periods of increased Leach's Storm Petrel with an expansion in fern, grass and moss taxa on the island. A corresponding decline in arboreal taxa, such as *Alnus*, was observed during peak colony size, possibly resulting from its poorer competitive potential under intensified guano-derived nitrogen fertilization (Duda *et al*., 2020b).

These findings were supported by aerial photography of the site, showing an increase in vegetation cover form 23% in 1940 to 58% in 2017. This corresponds with a confirmed population increase of Leach's Storm Petrels in 1980, reconstructed by Duda *et al* (2020a) using paleolimnological proxies from Grand Colombier Pond.

Overall, vegetation assemblages on islands supporting large breeding populations of Leach's Storm Petrels provide an important indicator of long-term ecosystem changes (Duda *et al*., 2020b). In particular, characterised by the increase fern and grass expansion alongside the decline in shrub taxa. Baccalieu Island, therefore, provides a useful comparative model for interpreting vegetation changes on other seabird impacts islands such as Grand Colombier Island.

2 Methodology

2.1 Sample collection

Our sediment cores were collected from Grand Colombier Pond, the only body of freshwater situated on Grand Colombier Island and within close proximity to the breeding population of Leach's Storm Petrels. Further details about sample collection are outlined in Duda *et al*. (2020a).

At Stockholm University, we received dried sediments collected at 0.5 cm intervals and chose to process samples at 2cm intervals between depths 1.5–30 cm for further processing. According to Duda *et al*. (2020a), these sediments represent approximately the last 1000 years of sediment accumulation.

2.2 Palynological processing, counting and identification

We processed a total of 12 sediment samples for palynological analysis at Stockholm University (See Table.2). Two *Lycopodium clavatum* tablets (Batch no. 140119321; 19,855 spores per tablet) were added to each sample to allow calculation of pollen concentrations. We then processed the sediment with 10% hydrochloric acid (HCl), 10% sodium hydroxide (NaOH), 50% hydrofluoric acid (HF), and finally subjected the samples to acetolysis (10:1 acetic anhydride: concentrated sulphuric acid). Residues were then stored in a 1:1 glycerin:water solution.

We used a LEICA DM200 LED light microscope to count our palynological slides and took photomicrographs with the LEICA FLEXACAM C1 with a reference scale of 25um. All routine counts were taken at 40x magnification, however 100x magnification was available when necessary to aid identification of abnormal or poorly preserved grains.

For each sample, we counted a minimum of 300 grains, from which we excluded indeterminate grains, non-Pollen Palynomorphs (NPPs) and *Lycopodium* exotic marker spores from the total count. Some pollen grains are susceptible to breakage and so we adjusted counts to include half grains where necessary. This is common with bisaccate pollen grains in the family Pinaceae, whereby one or both air sacs frequently became separated from the main body.

We used a combination of published reference material and online databases to identify pollen and spore taxa. Online resources used included The Flora of Newfoundland and Labrador (n.d.), VASCAN (2010–) and PalDat (n.d.). Additional printed literature provided identification keys and reference photographs of pollen and spores (McAndrews, 2004; Bassett, Crompton and Parmelee, 1978).

Species level identification was carried out using relevant studies when possible. Warner and Chinnappa (1990) supported the likely identification of Ericaceae grains as crowberry pollen (*Empetrum nigrum*), See figure.4g. Additionally, Lormée *et al*. (2012) confirmed that *Dryopteris spinulosa* was present on the island, allowing for probable identification of similar fern spores to the species level, see figure. 5a.

2.3 Data analysis

The raw grain counts were converted to relative abundance (%) to standardise counts between samples. The resulting data was exported as a .csv file to Rstudio for plotting relative to collection depth and corresponding age markers.

Analysis of the pollen and spore data was conducted using Rstudio and the “rioja” package, specifically created for the Analysis of Quaternary Science Data (Juggins, 2024). To improve readability of the dataset, several pollen taxa were combined into broader taxonomic categories. For example, *Abies*, *Pinus* and *Picea* were combined into the family Pinaceae, whilst multiple different morphologies of Asteraceae were combined into a single category. For photomicrographs of example grains, see Figure. 4,5,6.

For Rstudio code used, see Appendix.

3 Results

3.1 Overview

This section presents the results of pollen counting and identification for the 12 samples analysed from Grand Colombier Pond. The results are presented as raw number of counts for each identified taxa (Table. 2), a table of relative abundance of taxa (Table.3) and as a several figures displaying relative abundance for each depth and corresponding time period. A visual key, showing photomicrographs of relevant pollen and spore taxa as well as non-pollen palynomorphs (NPPs) taken during the counting process is included for reference.

3.2 Chronology and palynology

Twelve sediment samples were analysed for pollen and spores. The samples were obtained from the sediment core retrieved from Grand Colombier Pond by Duda *et al* (2020a. The samples ranged between 1.5 cm – 29.5 cm deep corresponding to approximately within the past 1000 years. The age-depth relationship of samples can be seen in Table. 1, complied by Duda *et al* (2020a). The shallowest sample analysed during the study was taken from 1.5 cm depth, corresponding to approximately 2013 CE, while the deepest sample from the core used was 29.5 cm (sample 15) corresponding to approximately to 1300 CE.

A total of 4114 grains were counted, representing 16 pollen taxa and 3 spore taxa. Several NPPs where also encountered, however not included in the count due to not being relevant to the interpretation of vegetation assemblage changes and were outside the scope of this study.

Raw counts for all identified taxa and are shown in Table. 2 and relative abundance of the taxa is shown in Table. 3. Relative abundance data for individual taxa are plotted in a visual graph in Figure.2, illustrating vegetation trends throughout the sequence. To allow for broader changes in the vegetation assemblages, Figure.3 presents the same data grouped into major ecological categories of plants, including trees, shrubs, ferns, grasses and flowers.

Depth (cm)	Year BP	Year (CE)	Depth (cm)	Year BP	Year (CE)
0.25	-68	2018	**15.25**	102	1848
0.75	-66.5	2016.5	**15.75**	119.5	1830.5
1.25	-65	2015	**16.25**	137	1813
1.75	-63.5	2013.5	**16.75**	154.5	1795.5
2.25	-62	2012	**17.25**	172	1778
2.75	-60.5	2010.5	**17.75**	189.5	1760.5
3.25	-59	2009	**18.25**	207	1743
3.75	-57.5	2007.5	**18.75**	224.5	1725.5
4.25	-56	2006	**19.25**	242	1708
4.75	-55	2005	**19.75**	259.5	1690.5
5.25	-54	2004	**20.25**	277	1673
5.75	-52	2002	**20.75**	296	1654
6.25	-50	2000	**21.25**	315	1635
6.75	-48	1998	**21.75**	334	1616
7.25	-46	1996	**22.25**	353	1597
7.75	-44.5	1994.5	**22.75**	372	1578
8.25	-43	1993	**23.25**	391	1559
8.75	-41	1991	**23.75**	410	1540
9.25	-39	1989	**24.25**	429	1521
9.75	-37	1987	**24.75**	448	1502
10.25	-35	1985	**25.25**	467	1483
10.75	-21.5	1971.5	**25.75**	485.5	1464.5
11.25	-8	1958	**26.25**	504	1446
11.75	6	1944	**26.75**	522.5	1427.5
12.25	20	1930	**27.25**	541	1409
12.75	33.5	1916.5	**27.75**	559.5	1390.5
13.25	47	1903	**28.25**	578	1372
13.75	60.5	1889.5	**28.75**	596.5	1353.5
14.25	74	1876	**29.25**	615	1335
14.75	88	1862	**29.75**	633.5	1316.5

Table 1. The age-depth relationship of the sediment core from Duda (2020a). Purple indicates approximate depth of the 12 analysed samples. The core continued below 30cm but was omitted as it is outside the scope of this study. 1950 is chosen as the reference year for Before Present (BP) due to between 1955 and 1963 nuclear weapon testing resulted in a large increase in the concentration of ^{14}C in the atmosphere leading to imprecise radiocarbon dating (Hua, 2009).

Sample	1	2	3	4	5	6	7	8	9	11	13	15
Depth (cm)	1.5	3,5	5,5	7,5	9,5	11,5	13,5	15,5	17,5	21,5	25,5	29,5
Poaceae	47	68	46	72	42	45	71	90	62	101	79	105
Apiaceae	3	8	2	6	5	9	6	5	11	13	12	3
Pinaceae - Pinus	3	2	2	0	0	0	0	0	2	0	0	0
Pinaceae - Picea	2	3	3	2	2	0	0	0	0	1	1	0
Pinaceae - Abies	0	0	0	0	0	0	1	0	0	0	0	0
Pinaceae - Indet	10	10	5	5	8	6	4	8	2	2	6	5
Asteraceae	29	60	44	27	48	41	48	48	49	65	59	45
Asteraceae - L	2	3	1	4	2	2	1	4	5	4	1	1
Ericaceae	9	25	16	3	6	3	6	1	4	7	3	3
Alnus	3	2	0	0	0	1	1	0	0	1	2	1
Betula	12	18	11	6	10	4	2	4	6	4	5	3
Myricaceae	0	2	0	0	0	0	0	0	0	0	0	1
cf . Corylus	0	1	0	0	0	0	0	0	0	0	0	0
Caryophylaceae	0	0	1	1	1	1	0	0	0	0	0	0
Typha	0	0	0	0	0	1	0	0	0	0	0	0
Polygonaceae	0	0	0	0	0	0	0	0	0	1	0	0
Indet. pollen	5	4	1	1	2	4	1	2	5	2	7	5
Dryopteridaceae	160	320	162	174	151	171	139	131	204	107	117	102
Polypodiaceae	0	1	0	0	0	0	0	1	1	1	1	1
Osmundaceae	30	70	45	32	25	19	20	10	12	23	21	33
Total pollen and ferns	315	597	339	333	302	307	300	304	363	332	314	308
Lycopodiaceae	13	12	22	27	25	34	15	22	12	8	12	24

Table 2. Raw counts for grains recorded during the analysis of the sediment samples. Pollen taxa are shown in light green; spore taxa in blue, and total counts in orange. The exotic spore marker *Lycopodium* is shown in purple but was not included in the total count. Note that several taxa where subdivided based on morphological differences (e.g. subfamily Cichorioideae listed as Asteraceae – L).

Sample	1	2	3	4	5	6	7	8	9	11	13	15
Depth (cm)	1.5	3,5	5,5	7,5	9,5	11,5	13,5	15,5	17,5	21,5	25,5	29,5
Poaceae	14,9	11,4	13,6	21,6	13,9	14,7	23,7	29,6	17,1	30,4	25,2	34,1
Apiaceae	1,0	1,3	0,6	1,8	1,7	2,9	2,0	1,6	3,0	3,9	3,8	1,0
Pinaceae - Pinus	1,0	0,3	0,6	0,0	0,0	0,0	0,0	0,0	0,6	0,0	0,0	0,0
Pinaceae - Picea	0,6	0,5	0,9	0,6	0,7	0,0	0,0	0,0	0,0	0,3	0,3	0,0
Pinaceae - Abies	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0
Pinaceae - Indet	3,2	1,7	1,5	1,5	2,6	2,0	1,3	2,6	0,6	0,6	1,9	1,6
Asteraceae - M	9,2	10,1	13,0	8,1	15,9	13,4	16,0	15,8	13,5	19,6	18,8	14,6
Asteraceae - L	0,6	0,5	0,3	1,2	0,7	0,7	0,3	1,3	1,4	1,2	0,3	0,3
Ericaceae	2,9	4,2	4,7	0,9	2,0	1,0	2,0	0,3	1,1	2,1	1,0	1,0
Betulaceaea alder	1,0	0,3	0,0	0,0	0,0	0,3	0,3	0,0	0,0	0,3	0,6	0,3
Betulaceaea birch	3,8	3,0	3,2	1,8	3,3	1,3	0,7	1,3	1,7	1,2	1,6	1,0
Myricaceae	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3
cf . Corylus	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Carophylaceae	0,0	0,0	0,3	0,3	0,3	0,3	0,0	0,0	0,0	0,0	0,0	0,0
Typha part	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0
Polygonacea	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0
Indet pollen	1,6	0,7	0,3	0,3	0,7	1,3	0,3	0,7	1,4	0,6	2,2	1,6
Dryopteridaceae	50,8	53,6	47,8	52,3	50,0	55,7	46,3	43,1	56,2	32,2	37,3	33,1
Polypodiaceae	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,3	0,3	0,3	0,3	0,3
Osmundaceae	9,5	11,7	13,3	9,6	8,3	6,2	6,7	3,3	3,3	6,9	6,7	10,7
Total pollen and ferns	100	100	100	100	100	100	100	100	100	100	100	100

Table 3. Relative abundance (%) of all counted taxa with corresponding depth the sample was retrieved from. *Lycopodium* spores are omitted from the total counts.

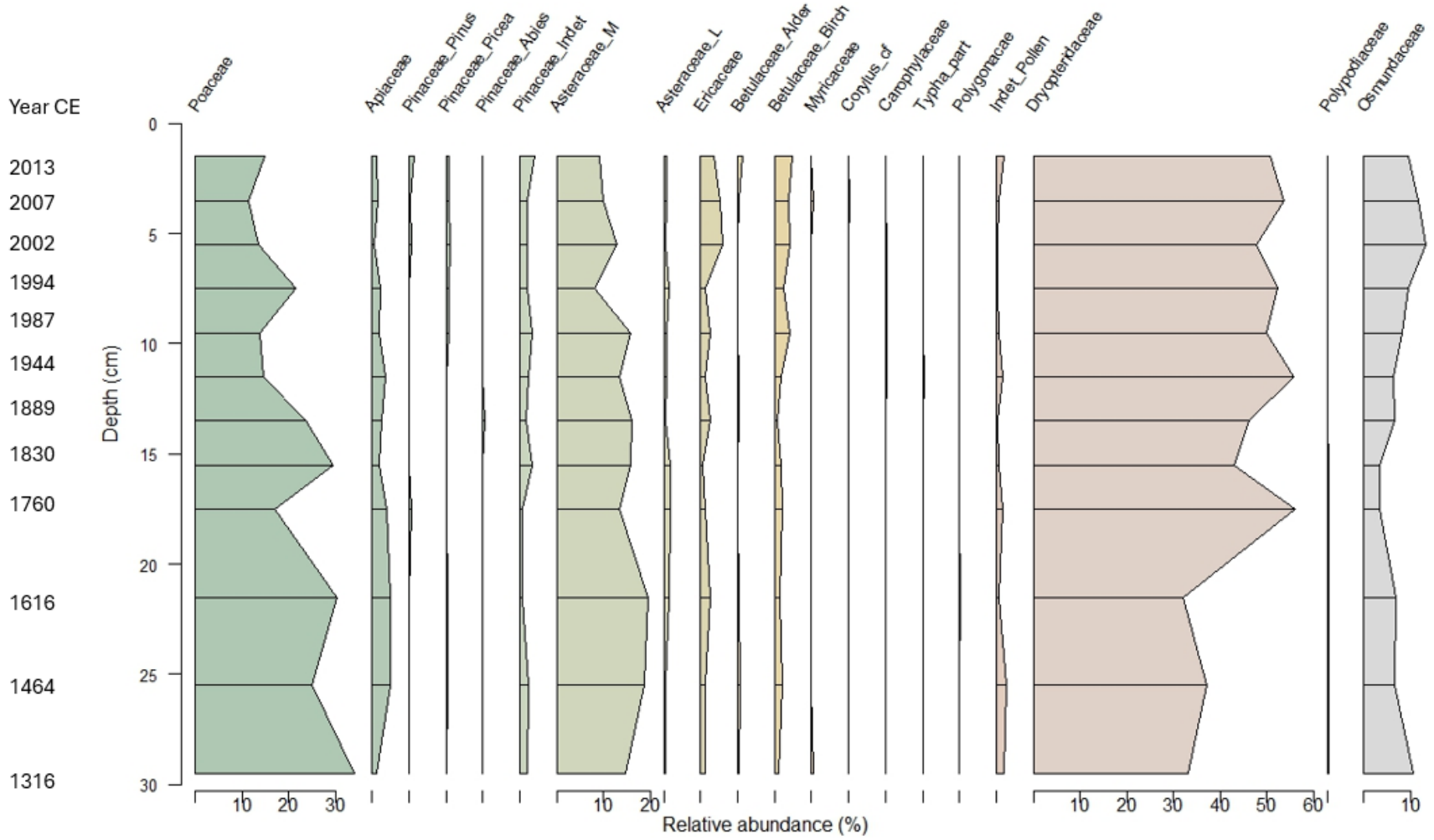


Figure 2 Relative abundance of all counted taxa throughout the sediment sequence. The diagram was plotted with the 'rioja' package (Juggins, 2024) in Rstudio.

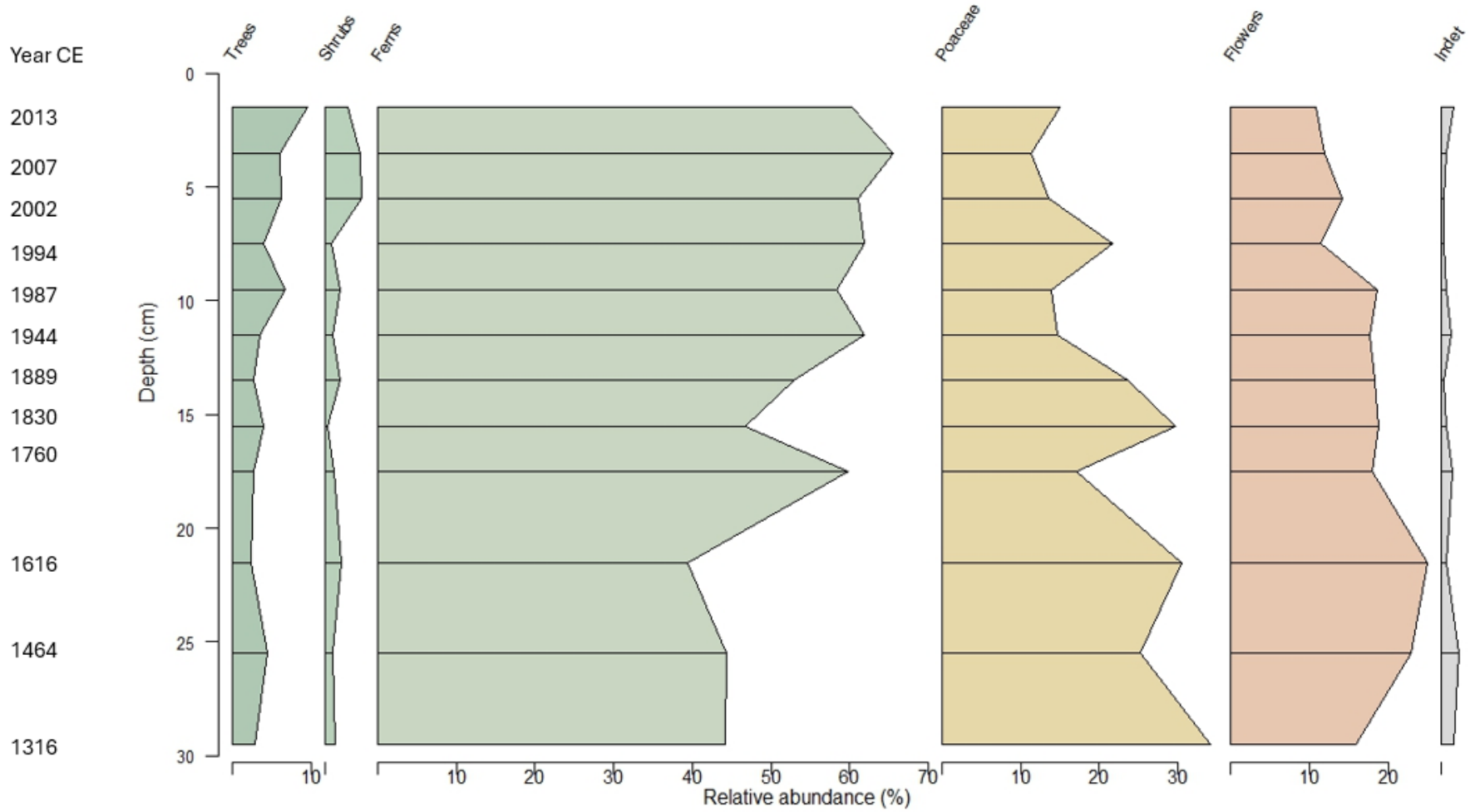
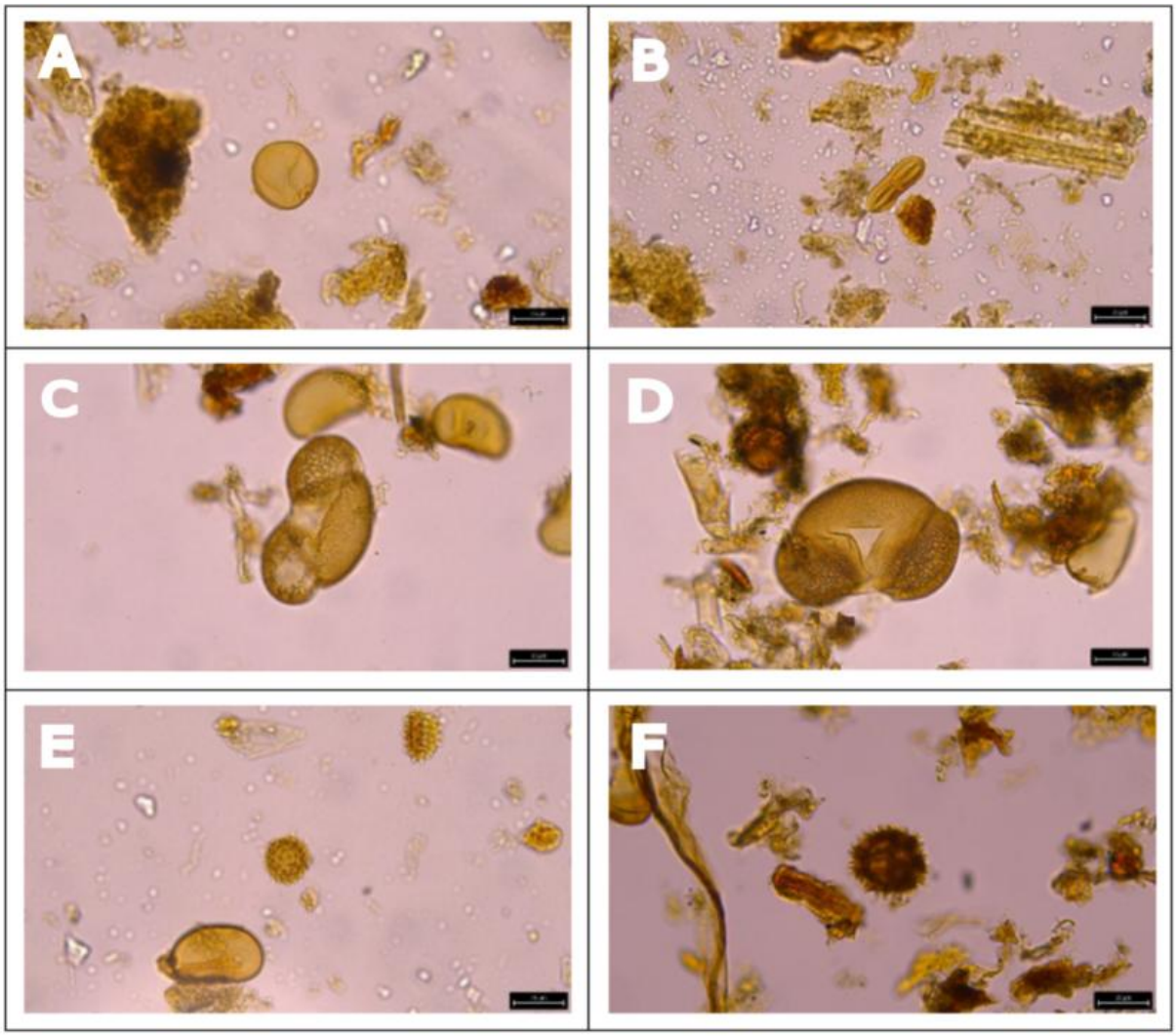


Figure 3 Relative abundance of all counted taxa throughout the sediment sequence, grouped into major vegetation categories. The diagram was plotted with the 'rioja' package (Juggins, 2024) in Rstudio.

3.3 Photomicrographs of pollen, spore and non-pollen palynomorph

Representative photomicrographs of selected pollen, spores and non-pollen palynomorphs (NPPs) identified during the analysis are presented in Figure. 4, 5, and 6 respectively. All images were captured during the counting process and were used to facilitate grain identification, particularly for morphologically similar grains (e.g. members of Pinaceae).

3.3.1 Pollen Photomicrographs



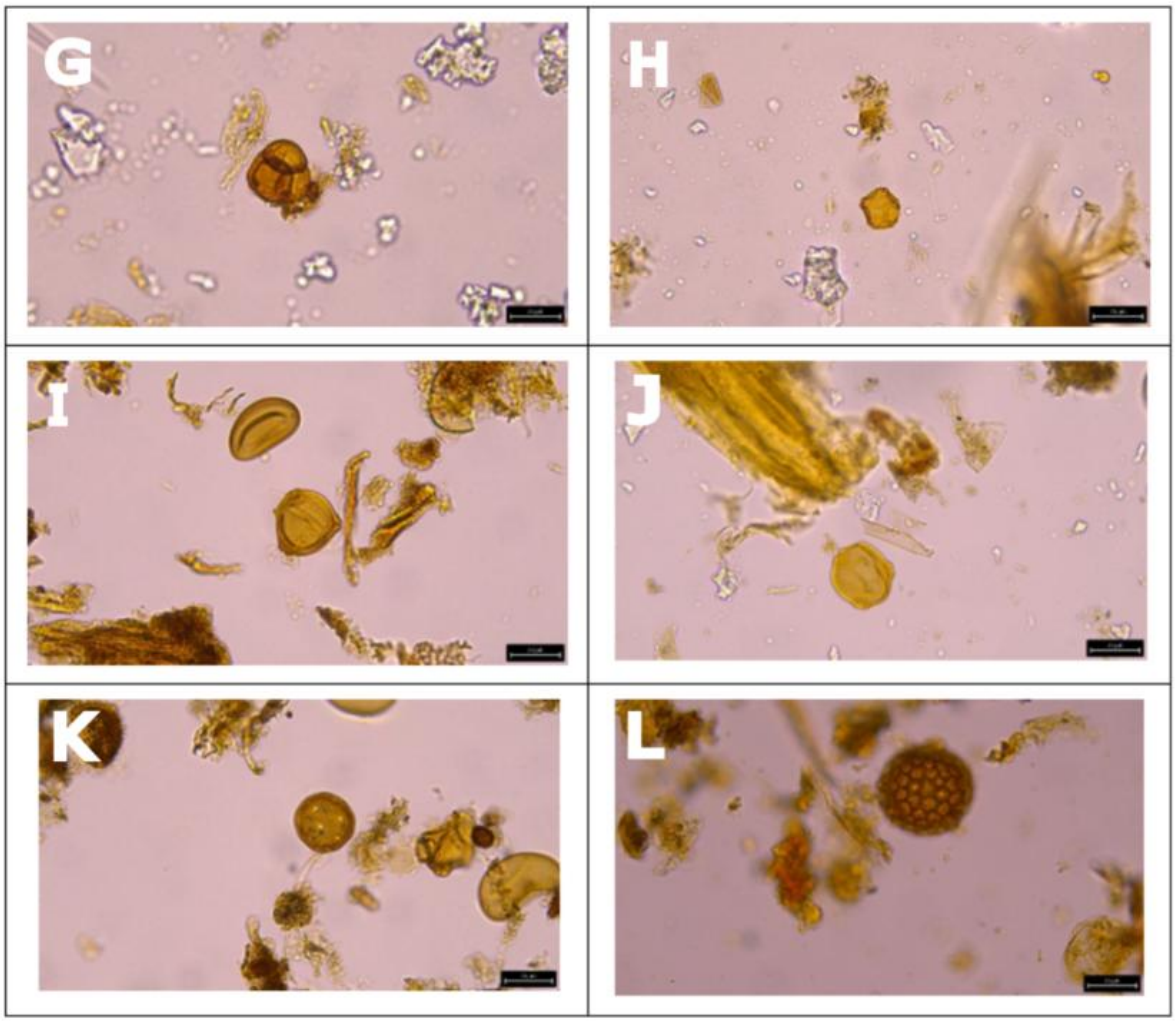


Figure 4 Photomicrographs of representative Pollen taxa identified from Grand Colombier Pond. Scale bar = 25 µm. (**A**) Poaceae; (**B**) Apiaceae; (**C**) *Pinus*; (**D**) *Picea*; (**E**) Asteraceae; (**F**) Asteraceae (subfamily Cichirioideae); (**G**) Ericaceae (cf *Empetrum nigrum*); (**H**) *Alnus*; (**I**) *Betula*; (**J**) cf. *Corylus*; (**k**) Caryophyllaceae; (**l**) *Polygonum* cf. *lapathifolia*

3.3.2 Spore Photomicrographs

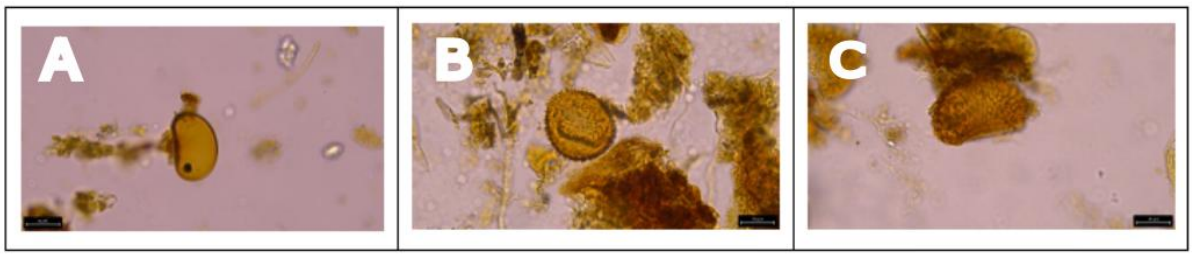


Figure 5. Photomicrographs of representative Spore taxa identified from Grand Colombier Pond. Scale bar = 25 µm. (**A**) Dryopteridaceae (cf. *Dryopteris spinulosa*); (**B**) Osmundaceae; (**C**) Polypodiaceae

3.2.3 Non-Pollen Palynomorph Photomicrographs

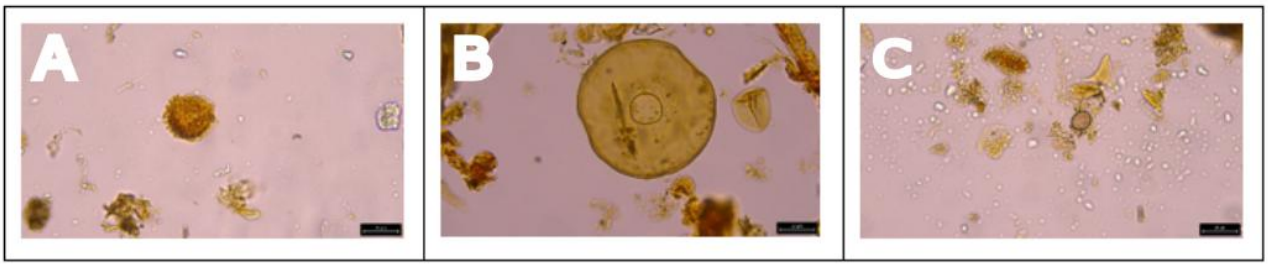


Figure 6. Photomicrographs of non-pollen palynomorphs identified from Grand Colombier Pond. Scale bar = 25 µm. (**A**) *Lycopodium* (exotic species control); (**B**) Testate amoebae (cf. *Arcella* sp.); (**C**) Unknown fungal spore

3.4 Distribution trends of Pollen and Spore taxa

Pollen and spore assemblages from Grand Colombier Pond show variation between samples, with some broad trends evident throughout the sequence.

Fern spores represent the dominant component of the assemblage throughout the core, collectively accounting for approximately 40-60% of the total count. Dryopteridaceae is the most abundant fern taxon, ranging between 47.8% - 55.7% until 11.5 cm depth, before dropping to 33.1% by the base of the sequence. Osmundaceae spores form a secondary component of the fern assemblage, although at lower concentrations, ranging between 3.3 - 13.3%. Polypodiaceae remained present at trace levels, below 0.5%, in all samples.

The arboreal pollen, containing Pinaceae*, Betula* and *Alnus* remained comparatively low throughout the sequence, ranging between approximately 0.1-3.5%, with *Betula* counts reaching a maximum of 3.8% for in the uppermost samples. Overall, combined arboreal pollen remained below 10% relative abundance throughout the sequence.

The shrub pollen grouping is primarily represented by Ericaceae and Myricaeae, which is present throughout sequence below 5% relative abundance. Shrub pollen counts are generally higher in the uppermost samples with a maximum value of 4.7% at 5.5cm depth.

Poaceae remained consistently present throughout the core ranging between 11.4 -34.4% and is the most abundant pollen taxa overall.

Flowering taxa were represented in the counts by Asteraceae and Apiaceae. Asteraceae pollen occurred as at least 2 different morphologies, however when combined ranged between 8.4 –21.0%, whilst Apiaceae ranged between 0.6 – 3.9%.

4 Discussion

4.1 Overview

The aim of this study was to analyse long-term vegetation change on Grand Colombier Island and examine how vegetation assemblages responded to environmental changes associated with European arrival and settlement, a period known to have affected local populations of Leach's Storm Petrels (Duda *et al*., 2020a).

The results of the study do not demonstrate a strong correlation between seabird population fluctuations and changes in vegetation composition. This suggests that there is either ecological stability on Grand Colombier Island or limitations in the study meant that the pollen and spore record was insufficient to measure subtle ecological responses.

4.2 Evaluation of the Hypothesis based on Interpretation of Vegetation Changes

4.2.1 Vegetation Trends

Fern spores accounted for between approximately 40-60% of the total count (Table. 3; Figure. 3), increasing towards the maximum count in younger sediments. The persistence in the abundance of fern spores, even during seabird population changes, suggest that a stable fern rich vegetation has been a long term characteristic of Grand Colombier Island. Seabird colonies have been proven to transfer substantial quantities of marine derived nutrients to terrestrial ecosystems through guano deposition, feathers, eggshells and carcasses (Duda *et al.,* 2020a; 2020b; 2021; Kane, Duda and Smol., 2026). Large nutrient inputs under these conditions have been shown to favour fast growing vegetations that are often associated with disturbed, nutrient rich environments (Azevedo-Schmidt *et al.,* 2024). Similar patterns, observed by Duda *et al* (2020b) on Baccalieu Island, where fern abundance remained consistently a stable part of the vegetation assemblage with a peak following the 1980 seabird population spike, which the authors describe as continued greening from inertia in plant communities. However, unlike Baccalieu Island, fern abundance on Grand Colombier Island remained consistently high through the record, suggesting that fern dominance may reflect long term nutrient enrichment as apposed to short term fluctuations in seabirds caused by human arrival.

In contrast to the dominant fern taxa, other vegetation such as trees, shrubs and flowers exhibited relatively little variation through the study period. Poaceae pollen remained abundant throughout the samples and showed a slight increase in relative abundance towards the uppermost part of the sequence. Similar to ferns, grasses are quick to colonise disturbed environments and are highly resilient as shown by its strategy as an r-selected species in the r/K selection theory (Gadgil, and Solbrig., 1972). Arboreal and shrub taxa included Ericaceae, Pinaceae, Betulaceae (*Betula* and *Alnus*), showed only minor fluctuations in relative abundance, indicating that they did not contribute significantly to change in the vegetation assemblage during the last 700 years BC. This contrasts to Baccalieu Island, where these taxa formed a larger percentage of the assemblage and showed greater variations (Duda *et al.*, 2020b). This could be due to ferns and grasses not dominating the vegetation assemblage on the island, thereby giving other taxa a chance to increase.

4.2.2 Potential causes of weak correlation

The relatively weak correlation observed between inferred Leach's Storm Petrel population changes and the vegetation assemblage on Grand Colombier Island could be the result of either ecological or methodological factors. Although seabird derived nutrients have been shown in multiple studies to influence comparable environments (Duda *et al.*, 2020b), the vegetation of Grand Colombier Island does not appear to have been strongly affected and has instead remained relatively stable.

This does not necessarily indicate that seabird populations had no ecological impact. Instead, any response may have been too gradual or insufficiently different to be clearly expressed in the data. Furthermore, the dominance of the fern spores throughout the sequence may have obscured the change in the less abundant pollen taxa, such as shrubs, trees or flowers. Consequently, while nutrients derived from seabirds may have influenced the vegetation, the effects may be too subtle or have occurred over longer time than explored in this study.

4.2.3 Evaluation of the Hypothesis

Overall, the hypothesis was partially supported. Minor trends in fern and grass abundance were observed, suggesting that nutrients derived from seabirds have affected vegetation assemblages on Grand Colombier Island. However, the absence of substantial changes in arboreal, shrub and flower taxa indicate that population fluctuations were not strongly reflected in the pollen and spore record in the last 700 years BP. Consequently, the expected

relationship between Leach's Storm Petrel populations and vegetation response was weaker than expected.

4.3 Study Limitations and Method Analysis

Several limitations of the study and of the methodology can now be considered when interpreting the results.

Firstly, the sampling resolution was initially chosen because, according to Duda et al (2020a), the chosen samples span the time from before, during and after the arrival of European settlers in the area. The first permanent settlement was established on St Pierre and Miquelon in 1816 CE settlers (Livingston and Losier, 2021), this allowed for 4 samples pre settlement for population reference and 8 additional samples ranging form approximately 14 years to 197 years after settlement to observe effects. This means that for almost 700 years, only 12 samples were analysed, consequently, short term vegetation changes may have not been detected. Furthermore, each of the analysed samples represents a 0.5 cm interval of the sediment core. As shown in Table 1, the upper portion of the core indicates that this covers up to 3 years of deposition, consequently short term ecological changes may not have been detected.

A further limitation of the data relates to the representation of pollen vs spore taxa in the data counts. The fern spores consistently accounted for more than 40% of the total count within the vegetation assemblages and in some samples, exceeded 50%. While the dominance of ferns spores provided important ecological information, it may have reduced the visibility of pollen shifts in less abundant taxa, therefore obscuring subtle shifts. However, as the ferns have been shown to align with seabird nutrient input, (Duda., 2020b; Kane, Duda and Smol , 2026) could result in valuable information being missed.

Uncertainty in the identification of pollen and spores during the counting process represents another source of potential limitation in data. Several more ambiguous pollen grains could only be identified at the family level, and whilst this was sufficient for the study, others were unable to be positively identified and were recorded as indeterminate. Other pollen grains were particularly similar to each other, for example *Myrica* and *Betula* pollen, commonly shown in palynological studies as being problematic (McAndrews, 2004; Bassett, Crompton and Parmelee, 1978). The grouping of multiple taxa under a family heading instead of identifying to the genus level had the potential to miss interpretative information (Birks *et al*.,

2023). For example, multiple Asteraceae species were observed during counting but were grouped together in Figure. 3

The pollen and spore content of the samples has been assumed to represent the vegetation assemblage of the local environment surrounding Grand Colombier Pond on Grand Colombier Island. However, pollen studies have shown that pollen may originate from both local and regional sources (Okubo and Levin, 1989). Consequently, this means that changes of the seabird colony population might not be accurately reflected in the pollen record.

Despite these limitations, the methodology produced a well preserved pollen and spore record containing valuable insights into the vegetation dynamics of Grand Colombier Island.

4.4 Implications of Study and Further Research

The findings of this study provide an important foundation for further studies on the relationship between Leach's Storm Petrels and the vegetation on Grand Colombier Island. Although no strong correlation between the seabirds and the response in vegetation were seen, several minor signals were observed, including the gradual decrease in ferns and increase in grass. These findings contribute to the understanding vegetation change, seabird derived nutrient input and the environmental history, whilst highlighting areas that require further research.

One potential direction for further research would be reanalysing the existing samples but using different counting parameters. The pollen and spore count for this study was a minimum of 300 and was selected based on time limitations. However, an increased count would likely provide a more accurate reflection of the relative abundance of taxa and reduce the effects of anomalies thereby improving reliability in the reconstructed vegetation assemblage.

A further avenue for study would be to have an additional 'pollen only' count whereby all spores were eliminated from the total sum. Fern spores consistently dominate Grand Colombier Island (Duda *et* al., 2020a; Kane, Duda and Smol, 2026) so by focusing on pollen, this would have had the effect of allowing for more subtle changes in pollen taxa, that were not apparent in the study, to be observed.

Future study could also extend the observed duration back further into the past. The analysed sequence dated back to approximately 700 years BP (Table. 1), ending before several known periods of high Leach's Storm Petrel abundance (Duda *et al*., 2020a) allowing for earlier

comparisons to be made. Alternatively, increasing the sampling resolution by analysing additional sediment between the existing samples would provide a more detailed reconstruction of vegetation changes through time.

Finally, although *lycopodium* marker spores were added to each of the samples prior to counting, they were not utilised in this study. The inclusion of *lycopodium* spores could have allowed concentrations of pollen and spores to be calculated in addition to relative abundance to be seen. This happens because each *lycopodium* tablet contains as known number of spores, variations between pollen and spore to lycopodium ratios can be used to estimate concentration (Mertens *et al*., 2009). This could show variations in vegetation productivity through time that are not evident from the relative abundance data alone.

Overall, the study demonstrated the value of relative abundance data for pollen and spores over the studied time period, however, higher resolution sampling, larger pollen counts and concentration analysis would likely provide a more detailed representation of the changing ecological impacts of Leach's Storm Petrel populations.

5 Conclusion

The aim of this project was to investigate the long term vegetation changes on Grand Colombier Island using the pollen and spores preserved in Grand Colombier Pond from the last 700 years BP. A secondary aim was to determine whether changes in Leach's Storm Petrel populations, attributed to European settlement on Saint Pierre and Miquelon, were reflected in the vegetation assemblages.

The results demonstrated that fern and grass have been a consistent portion of the vegetation record, while grass, tree and shrub taxa contributed to a much lower portion of the vegetation. Although slight trends were observed, including a gradual decrease in ferns and a gradual increase in grass, no major shifts in overall vegetation composition were identified.

In summary, the hypothesis was only partially supported. The observed trends suggest that seabird derived nutrients have influence vegetation assemblages on Grand Colombier Island., however, the effects are not pronounced enough to produce substantial changes. This could be explained due to limitations in the study such as the possibility that due to the ecological resilience to change, the time frame of the study was too short, required more samples or increased sample size to observe more subtle shifts. Despite these limitations, future research using higher sampling resolution, larger pollen counts, concentration analysis or deeper sediment samples may provide more detailed information regarding connections between seabird derived nutrient inputs and vegetation dynamics on Grand Colombier Island through time.

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7 Appendix

7.1 Rstudio Code

```
library(readr)

library(rioja)

Pollen_Count <- read_delim(  "Earth Science/Thesis/Pollen Count.csv",
delim = ";")

depth <- Pollen_Count$Depth_cm

taxa_matrix <- Pollen_Count[, -1]

taxa_matrix <- as.data.frame(lapply(taxa_matrix, as.numeric))

cols <- rainbow(ncol(taxa_matrix))

windows(width = 12, height = 8)

par(mar = c(4.5, 4.5, 2, 2))

strat.plot(

  taxa_matrix,

  yvar = depth,

  y.rev = TRUE,

  ylim = c(0, 30),

  scale.percent = TRUE,

  plot.poly = TRUE,

  plot.bar = TRUE,

  plot.line = FALSE,

  col.poly = cols,

  col.poly.line = "black",

  lwd.poly = 1,

  col.bar = "black",


  srt.xlabel = 55,

  x.pc.inc = 10,

  cex.xlabel = 0.8,
```

```
  cex.axis = 0.9
mtext("Relative abundance (%)", side = 1, line = 3)
mtext("Depth (cm)", side = 2, line = 3)
```