HOLOCENE VEGETATION AND FIRE HISTORY OF PENDER ISLAND, BRITISH COLUMBIA, CANADA

by

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BSc, Ferrum College, 2010

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Supervisory Committee

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Abstract

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Pollen and charcoal analyses were used to reconstruct the Holocene vegetation and fire history of Pender Island (48°46’59” N, 123°18’11” W), located in the southern Gulf Islands on the south coast of British Columbia. A 9.03 m sediment core was retrieved from Roe Lake, a small, deep lake on Pender Island. Four AMS radiocarbon ages, the stratigraphic position of the Mazama tephra and a series of ^{210}Pb ages were used to produce an age-depth model that estimated the base of the sediment core to be 9880 ± 126 calendar years before present (cal yr BP).

The vegetation history from Roe Lake is similar to other paleoecological studies from the region. The early Holocene (10,000-7500 cal yr BP) was characterized by mixed woodlands with abundant *Pseudotsuga menziesii* and a diverse understory that included abundant *Salix* shrubs and *Pteridium aquilinum* ferns in these open canopy communities. An open *Quercus garryana*-dominated community with *Acer macrophyllum* and *Arbutus menziesii* in the canopy and xeric associations in the understory occurred from 7500-5500 cal yr BP. By 3500 cal yr BP, modern mixed *Pseudotsuga menziesii* forests with an increasingly closed canopy were established on Pender Island.

Charcoal analyses of the uppermost sediments revealed low charcoal accumulation in the Roe Lake sediment core over the last 1300 years with a mean fire return interval of 100 years for the period before modern fire suppression, suggesting that fire was not a major control on plant community composition on Pender Island on this timescale. Fires were more frequent (i.e., every 47 years on average) during the Medieval Climate Anomaly with warm, dry conditions facilitating a higher fire frequency. Few fires (i.e., every 141 years on average) occurred between 1200-1850 AD, coinciding with the Little Ice Age. As climate was cooler and wetter during the Little Ice Age, fires during this time may reflect intentional burning by First Nations.

In general, changes in vegetation and fire dynamics on Pender Island correlate well with changes in climate throughout the Holocene period, suggesting that climate change was likely the principal mechanism driving plant community composition and changes in the fire regime.

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Dedication

To my grandma, Betty Lucas,
who always encouraged me to follow my dreams,
and always asked
"Have you finished that paper yet?"
Yes, Maw Maw, I finally did!

Chapter 1: Introduction

Background

Fossil pollen and charcoal analyses can provide detailed records of vegetation and fire dynamics over long temporal scales (Iversen 1941, Birks and Birks 1980, Fægri and Iversen 1989, MacDonald et al. 1991, Bennett and Willis 2001, Whitlock and Larsen 2001). Pollen and charcoal are preserved in many depositional environments, including forest hollows, bogs, fens, lakes, and ocean floors, most commonly transported by wind or sediment erosion (Jacobson and Bradshaw 1981, Bradshaw and Webb 1985, Faegri and Iversen 1989, Bennett and Willis 2001, Whitlock and Larsen 2001). The catchment size for a depositional basin generally determines the type of signal shown in pollen and charcoal records: local (within the watershed), extra-local (nearby, but not necessarily within, the watershed), or regional (distant) (Bennett and Willis 2001, Whitlock and Larsen 2001). Sediments from small lakes are commonly used for pollen and charcoal analyses to document local changes in vegetation and fire history. When coupled with paleoclimatic data, these paleoecological records can indicate the role of climate change in altering species distributions and fire regimes.

The analysis of fossil pollen and spores preserved in sediments is the key technique in determining vegetation change on long ecological timescales (Bennett and Willis 2001). The dispersal of pollen and spores occurs annually, with plant communities producing a characteristic pollen rain based on species composition and abundance (Faegri and Iversen 1989). This pollen rain is deposited into lakes by wind, streams, and slope outwash, where it settles to the lake floor and is embedded in sediment (Faegri and

Iversen 1989, Bennett and Willis 2001). The outer walls of pollen grains, the exine, are made of cellulose and sporopollenin, a substance resistant to most physical conditions; oxidation does breakdown sporopollenin, which is why fossil pollen is typically well-preserved in anaerobic environments (Bennett and Willis 2001). These anaerobic sediments are less prone to bioturbation, promoting the production of a stratigraphic sequence of pollen preservation. Once pollen grains are extracted from sediment samples, morphological differences permit family, genus, or in some cases, species level identification using light microscopy (Birks and Birks 1980, Faegri and Iversen 1989, Bennett and Willis 2001). The proportion of pollen types found in a sample is representative of the surrounding vegetation (Jacobson and Bradshaw 1981, Bradshaw and Webb 1985); however, wind-pollinated taxa are more commonly present in the fossil pollen record as they produce a larger volume of pollen (Faegri and Iversen 1989). Models of pollen dispersal are useful in the interpretation of fossil pollen records, although most paleoecologists use basic knowledge of plant family and/or species pollen dispersal patterns in the interpretation of pollen diagrams.

Fossil charcoal is commonly used as a proxy for fire history reconstructions (Whitlock and Larsen 2001). Charcoal is produced when fire incompletely combusts plant material, and is commonly deposited in a basin by wind fall-out and sediment erosion (MacDonald et al. 1991, Whitlock and Larsen 2001). Charcoal assemblages, like pollen, require a basin with little to no bioturbidity to ensure that the charcoal sampled accurately represents its position in the stratigraphic sequence (Gavin et al. 2003a). Upon extraction from a sediment record, charcoal particles are tallied and reported with respect to the time sequence; particles >150 µm are generally counted to ensure a local charcoal source area for fire history reconstruction (MacDonald et al. 1991, Whitlock and Larsen 2001). Fires are then inferred from stratigraphic levels with abundant charcoal, called ‘charcoal peaks’. Recent advances in numerical analyses use a decomposition method for separating ‘background’ and ‘peak’ charcoal series (Gavin et al. 2006, Higuera et al. 2009). The terms ‘background’ and ‘peak’ charcoal were originally used by Clark and Royall (1995) to describe low-frequency trends in the abundance of small charcoal particles (<100 µm in size) and high-frequency trends in the abundance of large charcoal particles (>100 µm) that are likely indicative of fire episodes. These definitions were expanded by Long et al. (1998) for examining macroscopic (>100 µm) charcoal, with peak charcoal defined by local fire episodes, and background charcoal originating from extra-local sources. ‘Background’ charcoal has been used differently in the literature to account for ecological and physical processes that result in low-frequency charcoal variations (Higuera et al. 2007).

Fossil pollen and charcoal analyses are often conducted on the same sediment samples to link vegetation responses to fire activity (Whitlock and Larsen 2001, Conedera et al. 2009). A combination of study sites from a region can be used to track these changes more closely across the landscape and provide greater understanding of driving factors (Jacobson and Bradshaw 1981, Faegri and Iversen 1989, Bennett and Willis 2001). A multi-faceted interpretation of these paleoecological data is derived by examining other ecological and climatic changes. Paleoclimate proxies, such as ice cores, tree rings, and microorganism remains, are used to estimate climatic changes and can lend support for climate-induced vegetation and fire regime changes (Birks 1994, Bennett and Willis 2001, Birks 2003).

Research Objectives and Significance

The ultimate goals for this research were to document Holocene vegetation change and reconstruct fire dynamics over the last several millennia on Pender Island, located in the southern Gulf Islands between Vancouver Island and mainland British Columbia. Fossil pollen, spores, and charcoal were extracted from sediments collected from Roe Lake and compared to nearby sites to determine local and regional patterns in past vegetation dynamics and fire regimes. An analysis of regional studies was also conducted to examine the changing Holocene abundance of *Quercus garryana* throughout the Pacific Northwest.

This study adds to the body of paleoecological knowledge from the coastal forests of southern British Columbia. In an area with high human and agricultural development, this high resolution analysis can provide a greater understanding of long-term successional patterns. Improved charcoal methods used in this study can add to previous studies from Pender Island (McCoy 2006), as well as other nearby studies, and provide a more accurate range of pre- and post-European settlement fire return intervals that could be used to inform management and conservation efforts.

Study Site: Pender Island

Pender Island is located in the Strait of Georgia, 15 km northeast of the Saanich Peninsula on Vancouver Island (Fig. 1). Roe Lake (48°46’59” N, 123°18’11” W; 100 m asl) is a small lake (3 ha) located on the northwestern side of Pender Island within the Gulf Islands National Park Reserve. A hiking trail circles Roe Lake, and park visitors have boat access to the lake. It is bounded to the east by Cramer Hill, a rocky outcrop approximately 200 m asl. Roe Lake has a maximum water depth of 9.5 m (Masuda and Perrin 2005), and at present, there are no inflowing streams. The lake's catchment is approximately 100 ha (McCoy 2006). The forest surrounding the lake is dominated by *Pseudotsuga menziesii*, *Thuja plicata*, and *Abies grandis* in the canopy. A stand of *Alnus rubra* is located along the southeastern margin of the lake, with scattered *Acer macrophyllum*, *A. glabrum* and *Salix* present along the water's edge. Xeric taxa, including *Arbutus menziesii*, *Quercus garryana*, and *Arctostaphylos columbiana,* are scattered on the southwestern facing side of Cramer Hill. The understory is dominated by abundant *Gaultheria shallon, Holodiscus discolor, Symphoricarpos albus,* and *Rosa nutkana*. *Polystichum munitum* and *Pteridium aquilinum* ferns are also common in the understory.

Modern Vegetation and Climate

Present-day forests of the Gulf Islands are dominated by *Pseudotsuga menziesii*, *Thuja plicata*, and *Abies grandis*. These forests lie within the Coastal Douglas-Fir biogeoclimatic zone (CDF), confined to the southeastern coast of Vancouver Island, the southern Gulf Islands, and an adjacent strip on mainland British Columbia, generally below 150 m asl (Nuszdorfer et al. 1991, Mackinnon et al. 2005). The CDF zone lies within the rain shadow of the Olympic Mountains and the Vancouver Island Ranges, which results in dry summers. Mean annual precipitation in the CDF zone is 650-1260 mm/year, falling mostly as

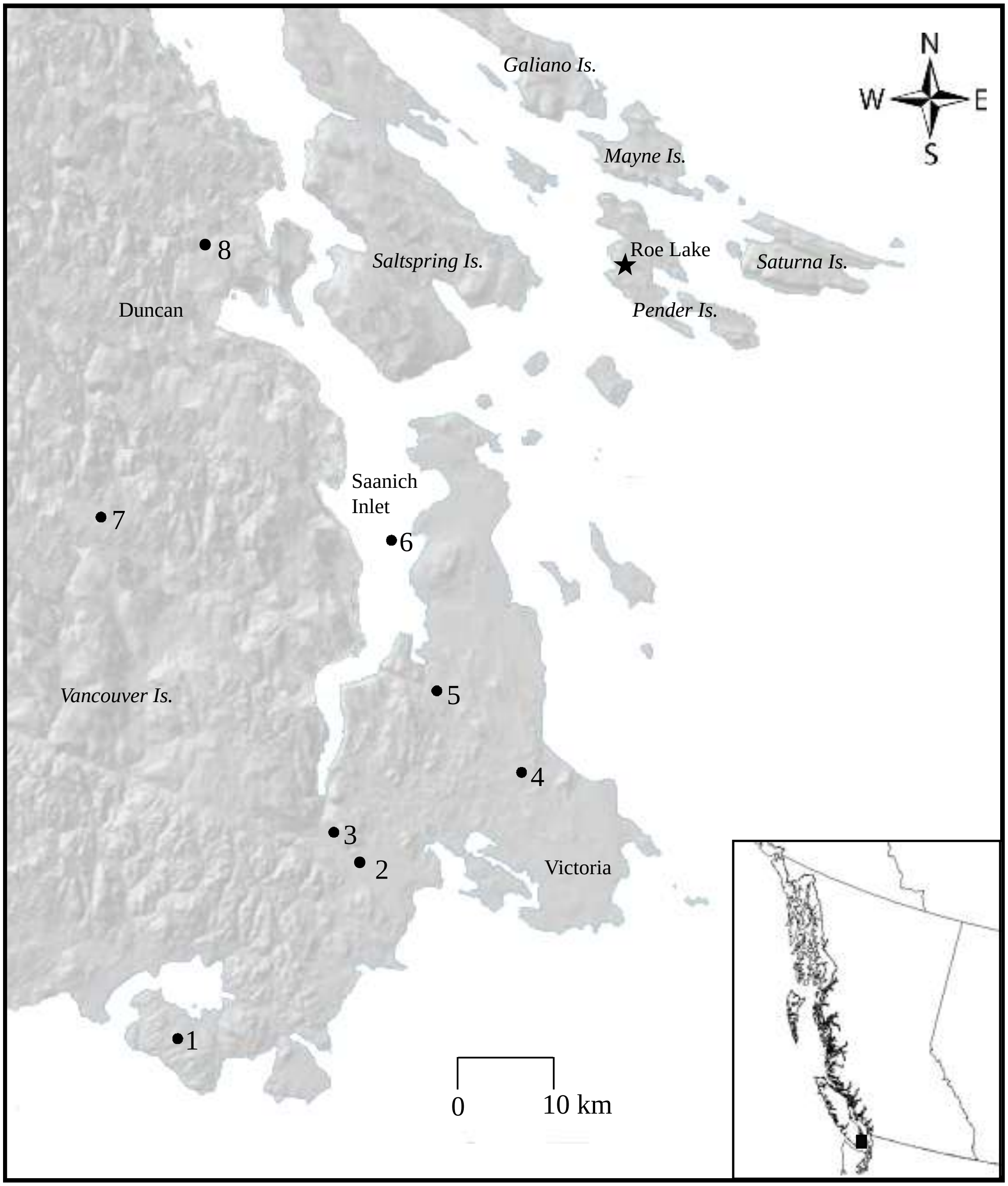

Figure 1. Map of the southern Vancouver Island and Gulf Islands region showing the location of Roe Lake (★) and nearby paleoecological study sites: 1. East Sooke Fen (Brown and Hebda 2002b); 2. Florence Lake (McCoy 2006); 3. Langford Lake (Hansen 1950); 4. Rithet's Bog (Zirul 1967); 5. Heal Lake (Allen 1995); 6. Saanich Inlet (Pellatt et al. 2001); 7. Rhamnus Lake (Allen 1995); 8. Quamichan Lake (McCoy 2006).

rain in the winter months (Nuszdorfer et al. 1991). Mean annual temperatures for the CDF range are 9.5-11°C, with warm summers and mild winters (Nuszdorfer et al. 1991, Environment Canada 2012).

Vegetation in the CDF is dominated by *Pseudotsuga menziesii* var. *menziesii*, occurring in the canopy and regenerating in forests of both closed and open structure. The *Pseudotsuga-Gaultheria shallon* vegetation association is most common in the CDF, with mature forests containing scattered *A. grandis* and *T. plicata*, with *G. shallon* dominating the shrub layer (Nuszdorfer et al. 1991). *Pteridium aquilinum* is the most abundant species in the herb layer (Nuszdorfer et al. 1991), where it persists in canopy gaps. Dry associations include scattered *Pinus contorta* var. *contorta* and *Arbutus menziesii* within open canopy forests, and *Quercus garryana* savanna-parklands present as mosaics on the landscape (Nuszdorfer et al. 1991, Fuchs 2001, Pellatt et al. 2007). Wet and disturbed sites are typically associated with high *Alnus* spp. and *T. plicata* abundance, with occasional *Acer macrophyllum* and *Tsuga heterophylla* (Nuszdorfer et al. 1991, MacKinnon et al. 2005). A well-developed herb and fern layer is also found on wet sites, marked by the presence of *Athyrium filix-femina*, *Equisetum telmateia*, *Polystichum munitum,* and *Lysichiton americanus.*

Paleoenvironmental History of the Gulf Islands

The southern Gulf Islands are located in the Strait of Georgia, between Vancouver Island and mainland British Columbia (Fig. 1). A rugged topography characterizes these islands, modified extensively by the Cordilleran Ice Sheet during the Fraser Glaciation, approximately 30,000-10,000 calendar years before present (cal yr BP) (Clague 1981). The Juan de Fuca lobe of the Cordilleran Ice Sheet overtopped the Gulf Islands and adjacent Vancouver Island, with ice about 2 km thick on the Strait of Georgia (James et al. 2008) during its maximum extent approximately 17,500 cal yr BP, or 14,000 radiocarbon years before present (^{14}C yr BP) (Clague et al. 1982, Clague and James 2002). The retreat of the Cordilleran Ice Sheet left the Strait of Georgia ice-free sometime before 14,000 cal yr BP (12,000 ^{14}C yr BP) (Barrie and Conway 1999), with modern ice cover reached in British Columbia by 11,500 cal yr BP (10,000 ^{14}C yr BP) (Clague 1981, Clague and James 2002). The Gulf Islands show evidence of extensive marine inundation due to eustatic and isostatic changes in sea levels (Clague 1981, James et al. 2008), with a sea level high stand (75 m above current sea level) at 14,250 cal yr BP and a low stand (30 m below current sea level) at 11,200 cal yr BP (James et al. 2008). Sea levels reached near present conditions around 6000 cal yr BP (James et al. 2008).

Climate in the region was cold near the end of the glacial period, approximately 12,500 cal yr BP, with prevailing easterly winds produced by the glacial anticyclone causing relatively dry conditions in the Pacific Northwest (Mathewes and Heusser 1981, Heusser et al. 1985, COHMAP 1988, Mathewes 1993, Bartlein et al. 1998). A rise in temperatures and the persisting dry climate marks the beginning of the early Holocene around 10,000 cal yr BP (Mathewes and Heusser 1981, Heusser et al. 1985), both likely caused by high summer insolation and an increased effect of the strong subtropical high-pressure system (Berger and Loutre 1991, COHMAP 1988, Bartein et al. 1998). Low winter insolation also occurred in the early Holocene, resulting in increased seasonality (Berger and Loutre 1991, Bartlein et al. 1998). By the mid- to late Holocene, around

4000 cal yr BP, the decreased effect of the subtropical high increased the importance of westerly winds (COHMAP 1988, Bartlein et al. 1998), establishing the cool and moist climate that is present in the Pacific Northwest today.

Previous Paleoecological Studies in the Coastal Douglas-fir Forests of Vancouver Island

Previous paleoecological studies in the southern Vancouver Island region suggest that vegetation palynologically similar to modern CDF vegetation developed by 7500 cal yr BP on Vancouver Island (Hansen 1950, Zirul 1967, Heusser 1983, Allen 1995, Pellatt et al. 2001, Brown and Hebda 2002a, Brown and Hebda 2002b, Brown et al. 2008). Principal components analysis comparing fossil and modern pollen spectra from soil samples shows that broad vegetation types, including distinct xeric parklands and CDF forests, can be clearly distinguished on Vancouver Island during this early to mid-Holocene period (Allen 1995, Allen et al. 1999, Brown et al. 2008). These studies suggest that the xeric vegetation assemblages produce characteristic pollen rain (Brown et al. 2008), by having high and distinctive non-arboreal pollen signatures (Allen et al. 1999) that can be seen in the fossil record. A change in climate during the middle Holocene, between 8000 and 4000 cal yr BP, allowed an abundance of species that are associated with warmer and drier conditions, such as *Quercus garryana*, to thrive in the forests of Vancouver Island (Hebda 1995, Pellatt et al. 2001). Modern CDF forests developed in the southern Vancouver Island region around 4000 cal yr BP as climatic conditions became increasingly cool and moist. Pellatt et al. (2001) suggest that high pollen accumulation rates of xeric taxa around 3800 cal yr BP indicate local influences maintained *Quercus* meadow environments near Saanich Inlet on southern Vancouver Island, because regional climate was becoming cooler and wetter, allowing for the establishment of more mesic taxa to outcompete xeric taxa. At 2000 cal yr BP, several sites on southern Vancouver Island record an increase in charcoal accumulation and pollen indicative of xeric vegetation even as climate was continuing to cool and moisten (Heusser 1983, Allen 1995, Brown and Hebda 2002a, McCoy 2006, McDadi and Hebda 2008), which is in agreement with Pellatt et al. (2001) that non-climatic factors may have been responsible for the increase in fire activity, and maintenance of *Quercus* dominated communities in CDF forests.

These previous studies contributed to the body of knowledge on the development of modern CDF forests. However, many of these studies had poor chronological control and conducted pollen analysis at low temporal resolution (Hansen 1942, Zirul 1967, Brown and Hebda 2002a, 2002b, McCoy 2006, Brown et al. 2008). In addition, these studies examined sediments from Vancouver Island only, leaving the paleoecological history of the southern Gulf Islands largely unknown. This study improves upon these previous studies by conducting high-resolution pollen analyses on a well-dated lake sediment core from Pender Island in the southern Gulf Islands that spans the last 10,000 calendar years. In addition, these analyses are coupled with charcoal analyses to provide a 1300 calendar year record of past fire activity.

Chapter 2: Changes in vegetation and fire dynamics of Douglas-fir forests on Pender Island, southwestern British Columbia

Introduction

Paleoecology is an important tool for determining the natural variability of ecosystems and allows for an extension of knowledge about landscapes and climate change over millennia (Iversen 1941, Birks and Birks 1980, Fægri and Iversen 1989, Smol 1992). Fossil pollen data allow temporal examination of past distribution and abundance of plant species. Fire history reconstructions from fossil charcoal provide information on the importance of fire in shaping and maintaining plant communities. These data, coupled with paleoclimatic data, can show how fire regime and community-scale vegetation changes are influenced by changing climate.

The dry, coastal ecosystems of southern Vancouver Island and the southern Gulf Islands, British Columbia, are floristically unique, driven by a relatively dry, mild climate (Nuszdorfer et al. 1991, Environment Canada 2012). Species composition varies greatly throughout these ecosystems as a result of human disturbance and differences in soil, topography, and mesoscale climate (Nuszdorfer et al. 1991). *Pseudotsuga menziesii* dominates regional forests, with other taxa common depending on local nutrient and moisture regimes (Nuszdorfer et al. 1991, Pellatt et al. 2007). *Quercus garryana* is restricted to lower elevations and is associated with xeric taxa and herb-dominated grasslands (Fuchs 2001, Pellatt et al. 2007). Many rare species occur primarily in *Q. garryana* dominated communities (Nuszdorfer et al. 1991, Fuchs 2001), making these ecosystems an important area of research for decades, with paleoecological tools used to explore driving factors. Turner (1999) discusses First Nations use of fire in *Q. garryana* ecosystems to maintain availability of food resources prior to European settlement. After the initial use of fire for land clearing by European settlers in the late 19th century, fire suppression legislation removed fire from the landscape, promoting the conversion of open *Quercus* communities to conifer-dominated forests (Tveten and Fonda 1999, Pellatt et al. 2007).

Previous reconstructions of the vegetation history of the southern Vancouver Island region were conducted at low temporal resolution with low pollen counts, had poor chronological control, and/or only span the last 250 years (Hansen 1942, Zirul 1967, Allen 1995, Brown and Hebda 2002a, 2002b, McCoy 2006, Brown et al. 2008, McDadi and Hebda 2008). McCoy (2006) also conducted charcoal analysis on three sediment records from the region, spanning the last ~250 years, but these analyses did not use contiguous sampling, which is essential for accurate reconstruction of fire history and estimation of fire return intervals (Higuera et al. 2007). Pellatt et al. (2001) used a marine sediment core from Saanich Inlet, a large basin with substantial fluvial input, to document regional vegetation dynamics over the last 11,500 calendar years.

This study presents fossil pollen and charcoal analyses of a ^{210}Pb and AMS radiocarbon-dated sediment core from Roe Lake, a small lake on Pender Island on the south coast of British Columbia. The goals for this study were to reconstruct Holocene vegetation dynamics with high temporal resolution and to use improved charcoal methods and numerical analyses to examine fire regime changes over the last 1300 calendar years. The results of these analyses are discussed in the context of independent paleoclimate records to link vegetation and fire dynamics to long-term climatic controls.

This paper also provides an overview of the migration of *Quercus garryana* in the Pacific Northwest following the last glacial period.

Study Site

Roe Lake (48°46’59” N, 123°18’11” W; 100 m asl) is a small lake (3 ha) located on the western side of Pender Island within the Gulf Islands National Park Reserve. It is bounded to the east by Cramer Hill, a rocky outcrop approximately 200 m asl. Roe Lake has a maximum water depth of 9.5 m, and at present, there are no inflowing streams. The forest surrounding the lake is dominated by *Pseudotsuga menziesii*, *Thuja plicata*, and *Abies grandis* in the canopy, with *Gaultheria shallon*, *Symphoricarpos albus*, *Polystichum munitum*, and *Pteridium aquilinum* common in the understory. A stand of *Alnus rubra* is located along the southeastern margin of the lake, with scattered *Acer macrophyllum* and *A. glabrum* along the lake margin. Xeric taxa, including *Arbutus menziesii* and *Quercus garryana*, are scattered on the southwestern facing side of Cramer Hill.

Materials and Methods

Sediment Core Collection

In April 2011, a 9.03 m sediment core was collected from a platform secured to two inflatable boats from the deepest part of Roe Lake, in 9.14 m of water, using a 5 cm diameter Livingstone piston corer (Wright et al. 1984). The sediment-water interface was retrieved using a 6.25 cm diameter Glew gravity corer (Glew 2001). The 47.5 cm of sediment collected with the Glew corer were extruded in the lab in 0.5 cm sections.

^{210}Pb and AMS ^{14}C Analyses

Lead 210 (^{210}Pb) ages were obtained from 17 sediment samples in the upper 30.5 cm of the sediment core (Table 1). Dried sediment samples were analyzed at MyCore Scientific in Deep River, Ontario. ^{210}Pb age determinations are based on the constant rate of supply model (Appleby and Oldfield 1983). Accelerator mass spectrometry (AMS) radiocarbon ages (^{14}C yr BP) were obtained on plant macrofossils and organic-rich sediment (Table 2), from Rafter GNS Science in Lower Hutt, New Zealand and Beta Analytic Inc. in Miami, Florida. Radiocarbon ages were calibrated to calendar ages (cal yr BP) using CALIB 6.1.1 (Stuiver and Reimer 1993). Radiocarbon ages were assigned the calendar age using the weighted average of a probability distribution, as determined by CALIB 6.11. ^{210}Pb ages were paired with AMS radiocarbon ages to produce an age-depth model for the entire length of the sediment core.

Pollen Analysis

Sediment samples (1 cm^3) were taken at 6 cm intervals along the length of the sediment core, except immediately above the Mazama tephra where a finer resolution was used, and prepared for pollen analysis using standard techniques (Bennett and Willis

Table 1. ^{210}Pb age determinations and sediment accumulation rates (SAR) for Roe Lake, Pender Island, British Columbia.

Depth (cm)	**Year (AD)**	**Age (cal yr BP)**	**Precision in Age Estimate (± 1 SD in yr)**	**SAR (g/m²/yr)**
0.0	2011	-61	0.00	170
1.5	2010	-60	0.07	163
3.0	2007	-57	0.38	116
4.5	2003	-53	0.63	126
6.5	1996	-46	0.92	110
8.5	1988	-38	1.20	125
10.5	1981	-31	2.20	123
12.5	1973	-23	2.77	110
14.5	1965	-15	4.49	112
16.5	1955	-5	4.84	85
18.5	1944	6	5.99	93
20.5	1933	17	6.64	76
22.5	1921	29	8.44	62
24.5	1908	42	11.14	64
26.5	1894	56	21.05	62
28.5	1876	74	21.90	40
30.5	1851	99	42.43	43

Table 2. AMS radiocarbon and calibrated calendar ages of plant macrofossils and organic sediment from Roe Lake, Pender Island, British Columbia.

Lab Code[a]	**Depth (cm)**	**Material**	**Radiocarbon Age (^{14}C yr BP ± 1 σ)**	**Calendar Age (cal yr BP)**[b]	**1σ Calendar Age Range (cal yr BP)** [c]
NZA 37783	117.5	male *Thuja plicata* cone	1323 ± 15	1266	1270-1290
NZA 37784	385.0	twig	4411 ± 20	4980	4890-5040
	573.0-573.5	Mazama tephra	6730 ± 40[d]	7595	7570-7650
NZA 37785	614.5	wood	7125 ± 25	7952	7940-7970
BETA 313896	892.25-894.0	organic sediment	8780 ± 50	9809	9700-9900

[a] NZA = Rafter GNS Science, Lower Hutt, New Zealand; BETA = Beta Analytic Inc., Miami, Florida

[b] Based on the weighted average of the probability distribution from CALIB 6.1.1 (Stuiver and Reimer, 1993; Reimer et al., 2009)

[c] Rounded to the nearest 10 cal yr

[d] From Hallett et al. (1997)

2001), including 10% potassium hydroxide, 10% hydrochloric acid, concentrated hydrofluoric acid, and acetolysis solution. A known amount of *Lycopodium* spores (Batch #177745, 18584 ± 371 spores) was added to each sample prior to chemical processing (Stockmarr 1971) to calculate pollen concentrations (grains/cm^3) and pollen accumulation rates (grains/cm^2/yr). A minimum sum of 500 terrestrial pollen and spores was identified for each sample. Error associated with each pollen percentage depends on the pollen sum and the percentage of the sum for each pollen type (Mahr 1972); 95% confidence intervals range between ± 0.004% and 2.08% for this dataset, with outlying errors of 3.42% and 3.9% for *Pseudotsuga menziesii* and *Alnus rubra*, respectively. Pollen and spore identification was conducted using a Carl Zeiss compound microscope at 400× magnification, with critical identifications conducted at 630× and 1000× magnification. Pollen and spore identification to the lowest possible taxonomic level was achieved using published dichotomous keys (Helmich 1962, McAndrews et al. 1973, Hebda 1985, Warner and Chinnappa 1986, Heusser and Peteet 1988, Fægri and Iversen 1989, Moore et al. 1991, Punt et al. 2007) and a modern pollen and spore reference collection at the University of Victoria. Diploxylon *Pinus* pollen was assigned to *Pinus contorta* based on morphology and modern phytogeography. *Pseudotsuga menziesii* and *Picea sitchensis* were also identified based on pollen morphology and modern phytogeography. *Abies* pollen could be from *A. amabilis, A. grandis, or A. lasiocarpa*, but *A. grandis* is more common in Gulf Island forests today. *Alnus rubra* and *Alnus viridis* type pollen were differentiated following May and Lacourse (2012). *Arbutus menziesii* type and *Gaultheria shallon* type pollen were identified based on criteria from Sarwar et al. (2008)

and Lu et al. (2009). Botanical nomenclature follows the Flora of North America (1993+).

Pollen percentages were calculated based on the sum of all pollen and spores, excluding pollen from obligate aquatics i.e., *Nuphar*, *Typha latifolia* and *Potamogeton*. Sedimentation rates (cm/cal yr) and pollen concentrations (grains/cm^3) for each sample were used to calculate pollen and spore accumulation rates (PAR, grains/cm^2/cal yr). Pollen zones were determined based on samples with similar pollen and spore assemblages that are distinct from adjacent sections of samples (Gordon and Birks 1972). For zonation, the pollen percentage data were limited to taxa that exceeded 1% of the pollen sum and then recalculated based on those taxa. Pollen from obligate aquatics and the basal sample, containing 56% *Cicuta* pollen, were excluded from numerical zonation. Binary sum-of-squares was used to determine pollen zones (Bennett 1996), but optimal sum-of-squares and constrained cluster analysis (CONISS) provided identical results. Statistical significance of zones was determined by using a broken-stick model, with significant zones having a higher variance than values produced from the model (Bennett 1996).

Principal components analysis (PCA) was used to reduce the dimensionality of the large pollen dataset and display dominant trends. For PCA, taxa were limited to those greater than 1%, and a square-root transformation was conducted on the dataset to stabilize variance. The statistical significance of the eigenvalue of each PCA axis was tested using a broken-stick model (Jackson 1993, ter Braak and Verdonschot 1995). Rarefaction analysis was used to quantify the palynological richness of each sample, $E(T_n)$ i.e., the number of pollen and spore taxa in n pollen grains at each sample for *n*=500 (Birks and Line 1992, Bennett and Willis 2001). Palynological richness was used to document changes in floristic richness in the pollen source area through time (Birks and Line 1992).

Charcoal Analysis

For charcoal analysis, contiguous sediment samples (1 cm^3) were taken every 0.5 cm for the first 47.5 cm of the sediment core and then every 1 cm from 47.5 to 118 cm, resulting in 172 sediment samples. Chemical charcoal preparation methods were adapted from Whitlock and Larsen (2001): sediment samples were deflocculated with 10% sodium pyrophosphate, treated with 3% hydrogen peroxide for 24 hours, and sieved through 150 µm mesh with distilled water. The remainder of the sample was transferred to a Bogorov tray and charcoal (particles/cm^3) were identified and enumerated under a Wild Makroskop stereomicroscope at 14-35× magnification. Charcoal was identified as black, reflective angular particles, at times with cellular structure still visible (Whitlock and Larsen 2001).

Charcoal concentrations (particles/cm^3) were analyzed numerically using CharAnalysis 1.1 (Higuera et al. 2009). The data were interpolated to the median sampling resolution of 6 yr/sample before all analyses were conducted. Sedimentation rates were used to calculate charcoal accumulation rates (CHAR, pieces/cm^2/cal yr) from these interpolated data. Background charcoal was estimated using a 200 year smoothing window based on a locally weighted (LOWESS) regression robust to outliers. The dataset was detrended by subtracting background from interpolated CHAR to obtain ‘peak’

CHAR. A local threshold, or moving window, was determined using a Gaussian mixture model and used to identify non-fire, noise-related variations in charcoal peaks (Gavin et al. 2006). This threshold was defined by the 99th percentile of the Gaussian distribution, and used to delineate local fire episodes. Peaks identified with optimal threshold values were used to estimate a fire-return interval (FRI, years between fires) and fire episode magnitude (particles/cm^2).

Results

Sediment Stratigraphy

The 9.03 m Roe Lake sediment core consists of nearly uniform, dark brown (Munsell 2.5Y 3/2, 10YR 3/2) gyttja i.e., fine-grained organic-rich lake sediment. A tephra layer at a depth of 573.0-573.5 cm (Fig. 2) was identified as belonging to the 6730 ± 40 ^{14}C yr BP Mt. Mazama eruption (Hallett et al. 1997), based on major element chemistry of its glass shards (Lacourse, unpublished data). The 2.5 cm directly above the Mazama tephra is composed of olive-brown (Munsell 2.5Y 4/3) gyttja with fine laminations.

Chronology

An age-depth model was constructed, based on 17 ^{210}Pb age determinations (Table 1), and calibrated calendar ages of four AMS radiocarbon ages and the Mazama

Figure 2. Mazama tephra at 573.0 - 573.5 cm depth in the Roe Lake, Pender Island sediment core. The 5 cm diameter sediment core is shown split in half lengthwise.

tephra (Table 2), using linear interpolation (Figs. 3 and 4). This model predicted a basal age for the sediment core of 9880±126 cal yr BP. Polynomial line fitting and cubic spline models were also considered for these data; however, these models produced negative sedimentation rates for the Roe Lake data and were discarded for a simpler model based on linear interpolation.

Pollen Analysis

Pollen analysis was conducted on a total of 144 sediment samples with an average temporal resolution of 88 calandar years between samples. Numerical zonation of the Roe Lake pollen percentage data identified four pollen assemblage zones that were statistically significant (Figs. 5 and 6). Given the compositional similarity between the lowest two zones, these were deemed subzones R-1a and R-1b. For the same reason, the same approach was used in naming the upper two zones i.e., R-2a and R-2b.

Zone R-1a: 903-685 cm, 9880-8430 cal yr BP (8840-7540 ^{14}C yr BP)

This basal zone is dominated by *Alnus rubra*, with a maximum value of 39% at 8745 cal yr BP (Fig. 5). *Pinus contorta* reaches its highest percentage (17%) for the entire record during this zone. *Pseudotsuga menziesii* accounts for only 4% at the beginning of this zone, but then steadily increases to about 20%. Other common trees and shrubs include Cupressaceae, *Tsuga heterophylla, Alnus viridis*, Rosaceae, and *Salix*. *Abies,*

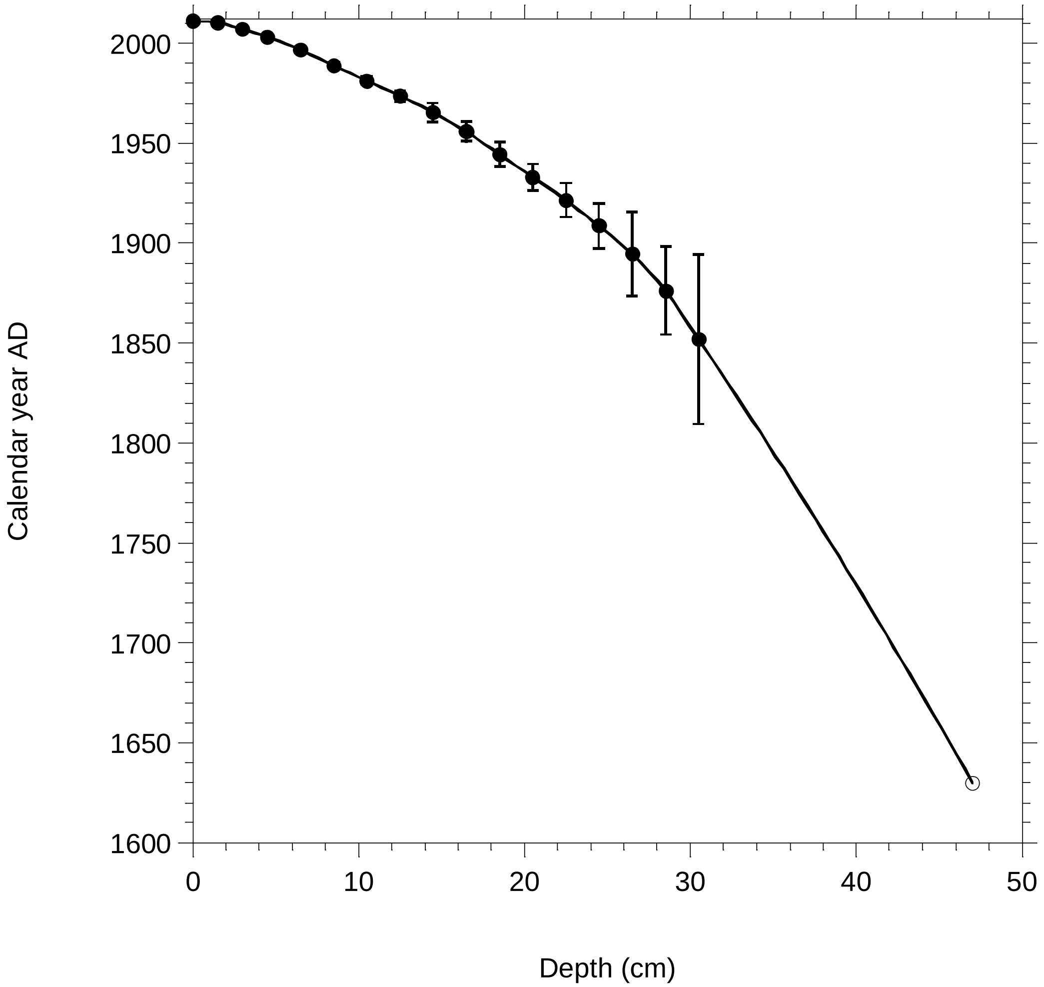

Figure 3. Age-depth model for the uppermost sediments from Roe Lake, Pender Island including error (Table 2). Open marker denotes extrapolated age at 47.5 cm derived via linear interpolation to the AMS radiocarbon age at 117 cm.

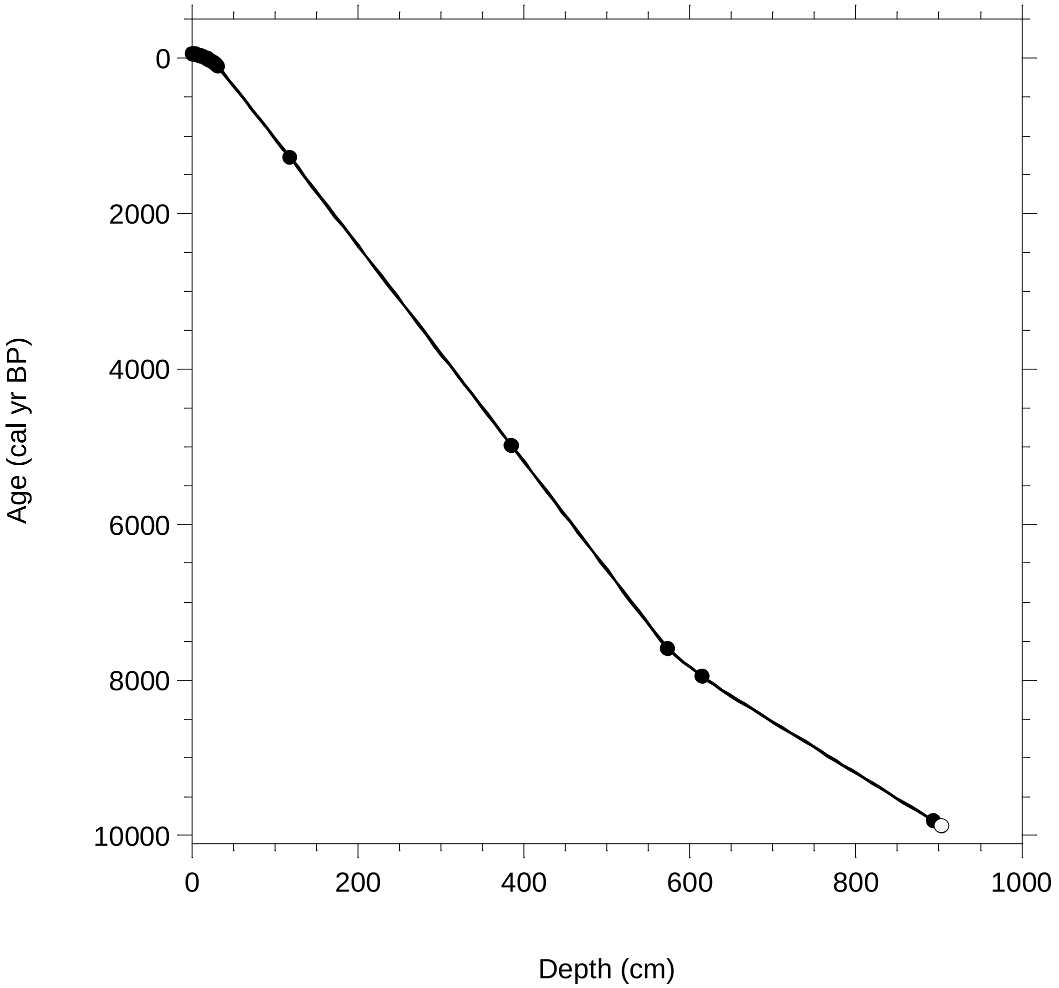

Figure 4. Age-depth model for the Roe Lake sediment core based on linear interpolation between calendar ages derived from AMS radiocarbon analyses (Table 21) and ^{210}Pb age determinations (Table 12). Open marker denotes extrapolated basal age of the sediment core.

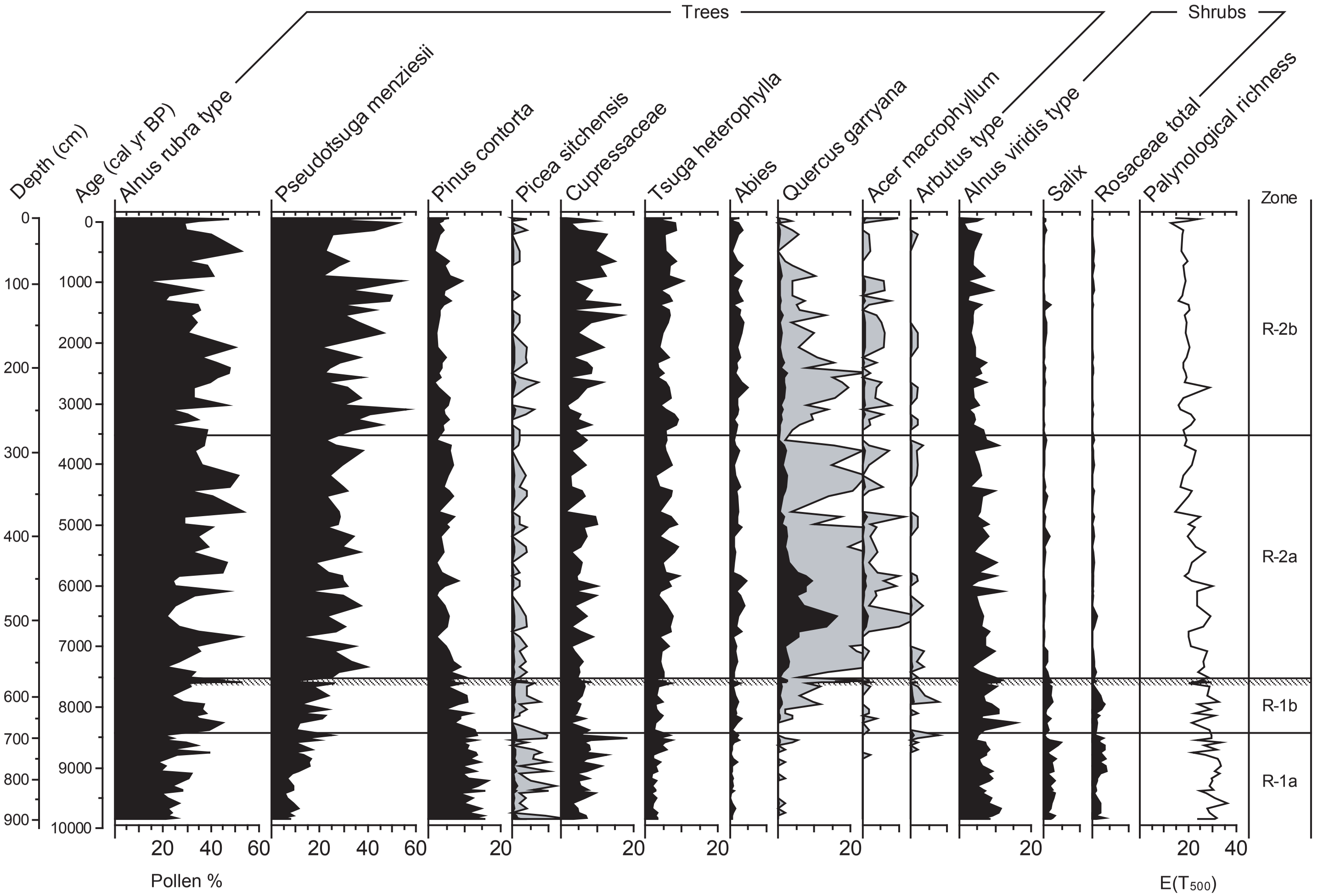

Figure 5. Pollen percentages of select tree and shrub taxa for Roe Lake, Pender Island with 10x exaggeration applied to infrequent taxa. Palynological richness and numerical zonation are also displayed. The hatched line across the diagram denotes the stratigraphic position of the Mazama tephra.

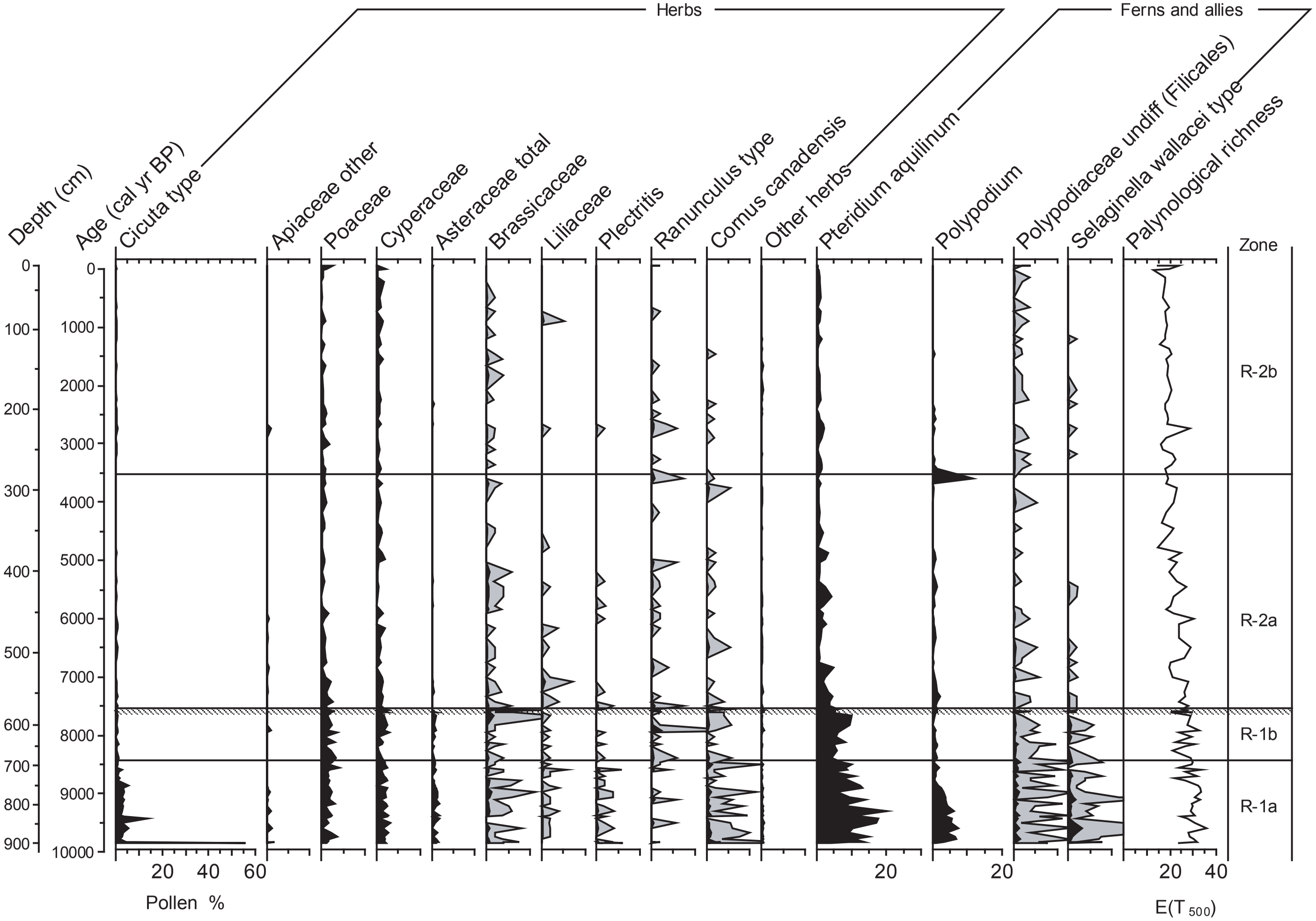

Figure 6. Pollen percentages of select herb and fern taxa for Roe Lake, Pender Island with 10x exaggeration applied to infrequent taxa. Palynological richness and numerical zonation are also displayed. The hatched line across the diagram denotes the stratigraphic position of the Mazama tephra.

Picea sitchensis, and *Quercus garryana* are present in trace amounts and *Acer macrophyllum* and *Arbutus menziesii* first appear near the top of this zone. This basal zone contains a diverse assemblage of herbs, including Poaceae, Cyperaceae, Asteraceae, Apiaceae and many other species (Fig. 6). *Cicuta* accounts for 56% of total pollen sum in the basal sample at 9850 cal yr BP, but then decreases to about 5% for the remainder of this zone. Total herbs reach their maximum value of 61% for the entire record in this zone. *Pteridium aquilinum* accounts for as much as 20%. Other common pteridophyte spores include *Polypodium*, *Athyrium filix-femina* and Polypodiaceae (Filicales). *Selaginella wallacei* is also present in this zone, with a maximum value of 3%. *Nuphar* and *Typha latifolia* pollen are present in trace amounts. Total pollen accumulation rates (PAR) range from 4800 to 9850 grains/cm^2/cal yr, with a trend of increasing PAR for all tree, shrub, and herb taxa later in the zone (Fig. 7 and 8). Palynological richness shows that the highest diversity of taxa is within this zone, with a maximum of 36 taxa present at 9584 cal yr BP (Fig. 5).

Zone R-1b: 685-568 cm, 8430-7530 cal yr BP (7540-6670 ^{14}C yr BP)

Pollen assemblages from this zone closely resemble Zone R-1a, with a defining factor of decreased shrub, herb and fern input (Figs. 6 and 8). *Alnus rubra* continues to dominate the pollen record, reaching a maximum of 53% near the top of the zone, ~7 cal yr after deposition of the Mazama tephra. *Alnus rubra* PAR are highest at 8250 cal yr BP. *Pseudotsuga menziesii* continues to increase in this zone but has its lowest value of 6%, correlating with the *A. rubra* maximum and the Mazama tephra. *Quercus garryana*

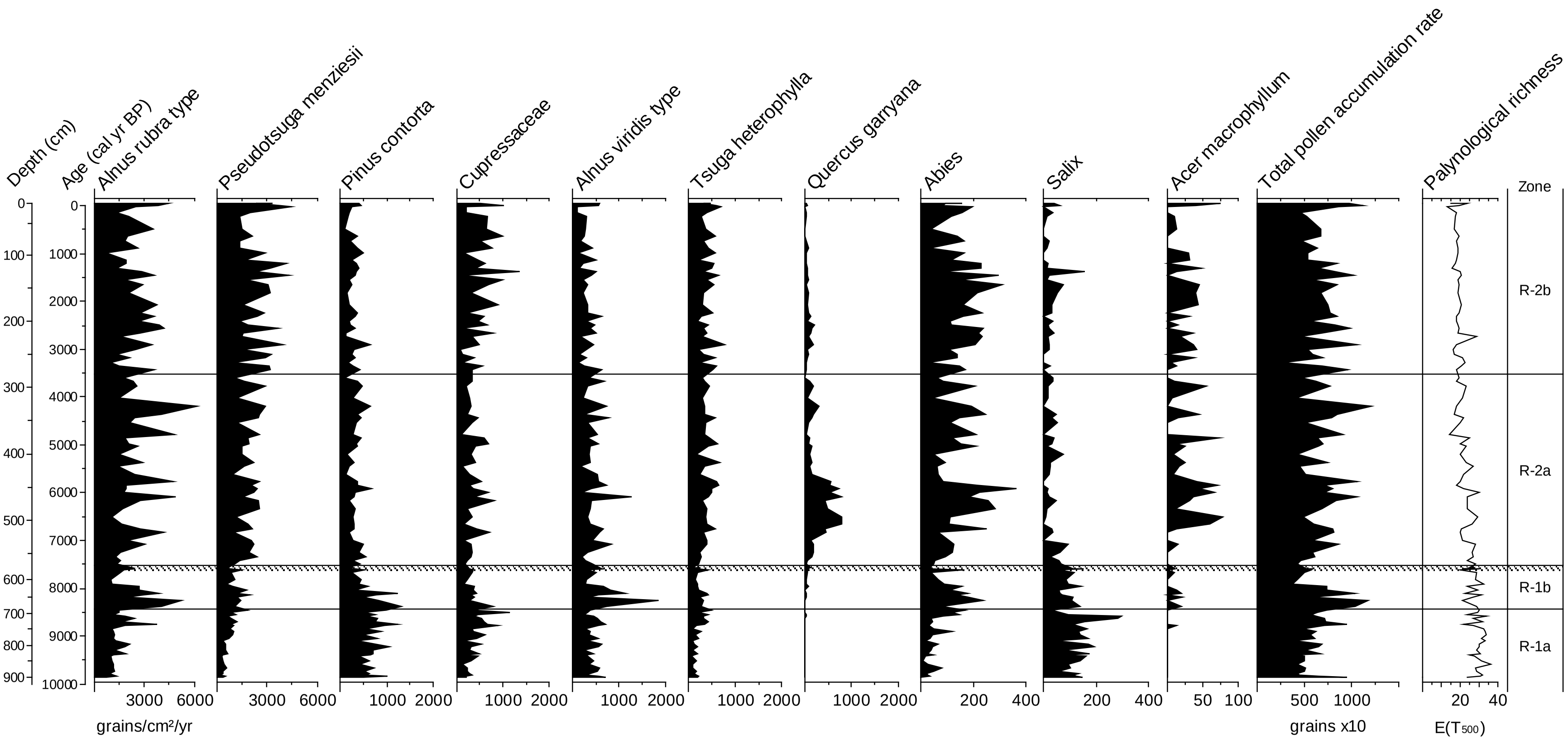

Figure 7. Pollen accumulation rates for select tree and shrub taxa from Roe Lake, Pender Island. Note changes in scale. The hatched line across the diagram denotes the stratigraphic position of the Mazama tephra.

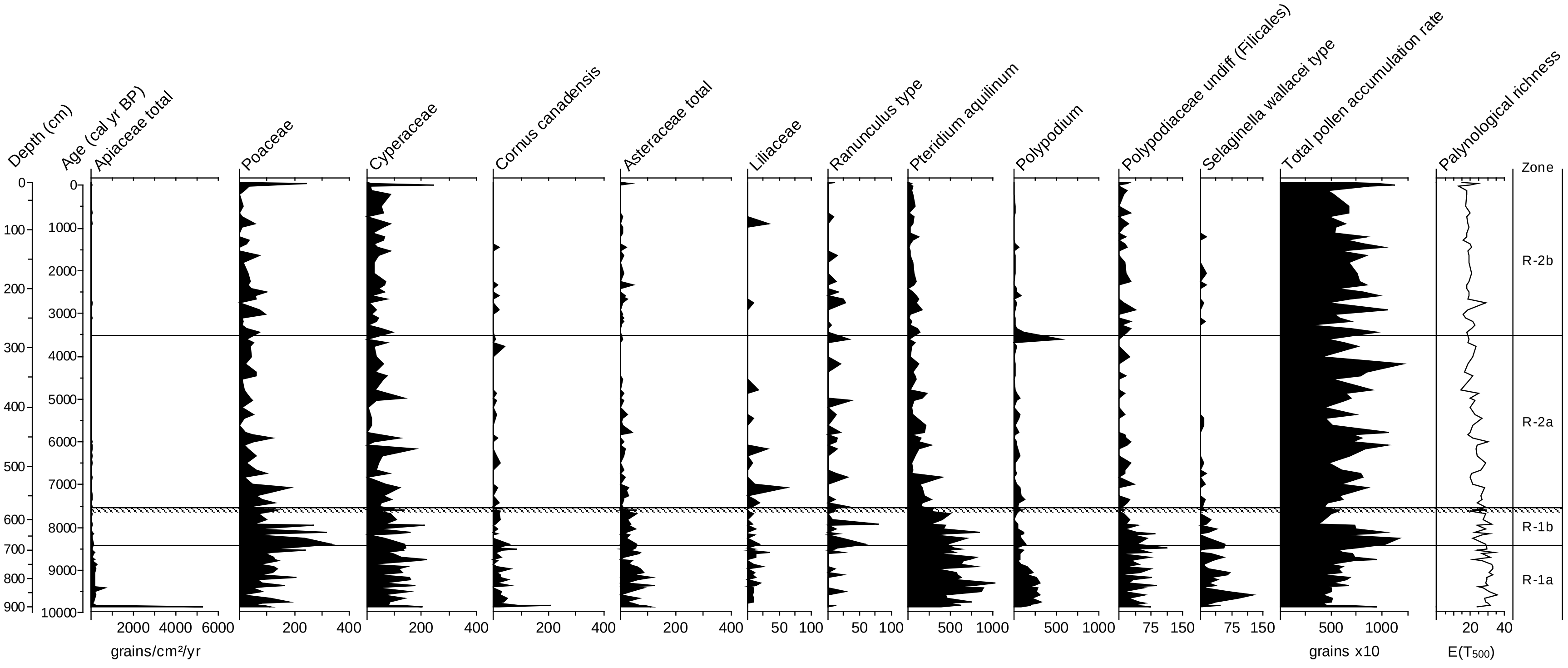

Figure 8. Pollen and spore accumulation rates for select herb and fern taxa from Roe Lake, Pender Island. Note changes in scale. The hatched line across the diagram denotes the stratigraphic position of the Mazama tephra.

begins to increase about 8000 cal yr BP. Substantial decreases in *Cicuta* and *Polypodium,* and to a lesser extent in *Pteridium aquilinum*, characterize the non-arboreal pollen (NAP) signature of this zone. *Tsuga heterophylla*, Cupressaceae, *Abies*, *Alnus viridis*, *Salix*, Poaceae, and Cyperaceae are all present at percentages similar to the previous zone, although Poaceae and *Salix* PAR are higher and lower, respectively. An increase in total PAR to 12,000 grains/cm^2/cal yr at 8200 cal yr BP correlates with an increase in *A. rubra* PAR to 5300 grains/cm^2/cal yr, as well as increases in *Alnus viridis* and *Pinus contorta*, at the beginning of this zone (Fig. 7). Total PAR for most other tree, shrub, herb and fern taxa decrease throughout the remainder of this zone. Palynological richness decreases through this zone, with an average of 26 taxa present.

Zone R-2a: 568-279 cm, 7530-3520 cal yr BP (6670-3190 ^{14}C yr BP)

The pollen assemblages in this zone continue to be dominated by *Alnus rubra* with an increasing amount of *Pseudotsuga menziesii*, but is marked by a substantial increase in *Quercus garryana* pollen percentages and PARs, reaching maximum values for the entire record around 6500 cal yr BP (Figs. 5 and 7). *Pinus contorta* percentages and PAR decrease in this zone, as do most herbs, shrubs and ferns, most notably *Pteridium aquilinum*, *Salix* and Rosaceae. *Tsuga heterophylla*, Cupressaceae, and *Alnus viridis* are present at levels similar to the previous zone, whereas most herbaceous species that were prevalent in both subzones of R-1 are only present in trace amounts (<1%). There is an isolated peak in *Polypodium* at 3600 cal yr BP (Fig. 6). Total PAR range between 4500 to 12,500 grains/cm^2/cal yr with *P. menziesii* and *Tsuga heterophylla* PAR increasing during this zone (Fig. 7). *Quercus garryana* PAR sustains a maximum rate of about 800 grains/cm^2/cal yr from 6800 to 5800 cal yr BP. Peak PAR for *Abies*, *Acer macrophyllum*, and *Betula* occur during this *Q. garryana* peak. Rarefaction analysis shows a decreasing trend in palynological richness during this zone with the maximum number of taxa [$E(T_{500})$=30] at 6000 cal yr BP, near the end of the peak in *Q. garryana* (Fig. 5).

Zone R-2b: 279-0 cm, 3520-0 cal yr BP (3190-0 ^{14}C yr BP)

This zone is characterized by high frequency changes in *Pseudotsuga menziesii* and *Alnus rubra*, accounting for a combined value of 60-81% of the total pollen sum (Fig. 5). *Pinus contorta*, *Tsuga heterophylla*, Cupressaceae and *Alnus viridis* persist at values similar to the previous zone, with some higher frequency changes in Cupressaceae from 2000 cal yr BP to the present. *Quercus garryana* values decrease to trace amounts in this zone. *Abies, Acer macrophyllum,* and *Pteridium aquilinum* values are similar to the previous zone, usually less than 5%. Other shrub, herb and fern taxa (including *Salix*, Poaceae, Cyperaceae, and *Polypodium*) are only present in trace amounts (Figs. 5 and 6). Total PAR in this zone are similar to previous zones, ranging from 3750 to 11,100 grains/cm^2/cal yr (Figs. 7 and 8). The highest *Pseudotsuga menziesii* PAR for the period of record occurs in this zone, reaching a maximum value of 4440 grains/cm^2/cal yr at 27 cal yr BP. Cupressaceae PAR increase in this zone, with a maximum value for the period of record of 1400 grains/cm^2/cal yr. Total tree PAR remain high (>4500 grains/cm^2/cal yr) throughout this zone. Total shrub, herb, and fern PAR are on average less than 300 grains/cm^2/cal yr (Figs. 7 and 8). Palynological richness is lowest for the period of record during this zone, with an average of 19 taxa.

Principal Components Analysis

The broken-stick model identified PCA axes 1 and 2 as significant, and these axes represent 52.6 and 12.1% of the total variation, respectively. PCA axis 1 separates *Pseudotsuga menziesii*, *Tsuga heterophylla* and *Abies* from *Pteridium aquilinum*, *Pinus contorta,* and many other shrub, herb, and fern taxa, which have high negative and positive values, respectively (Fig. 9). This axis also highlights the correlation between *Quercus garryana* and *Acer macrophyllum*. Species values on axis 1 correspond closely with the change in the abundance of shrub, herb and fern taxa in the early Holocene to arboreal pollen dominance from the middle Holocene to the present. On this axis, early Holocene samples (Zones R-1a and R-1b) are separated from mid- to late Holocene samples (Zones R-2a and R-2b): early Holocene samples with abundant herb and fern taxa have positive loadings, while mid- to late Holocene samples are more tightly clustered on the negative side of this axis, dominated by *P. menziesii* and *A. rubra*. This separation of taxa and samples may reflect the increasingly closed canopy over the course of the Holocene, as demonstrated by increases in pollen accumulation rates (Figs. 7 and 8).

PCA axis 2 most notably separates *Alnus rubra* and *Alnus viridis* from *P. menziesii* and other taxa with similar values and possibly reflects changes in disturbance

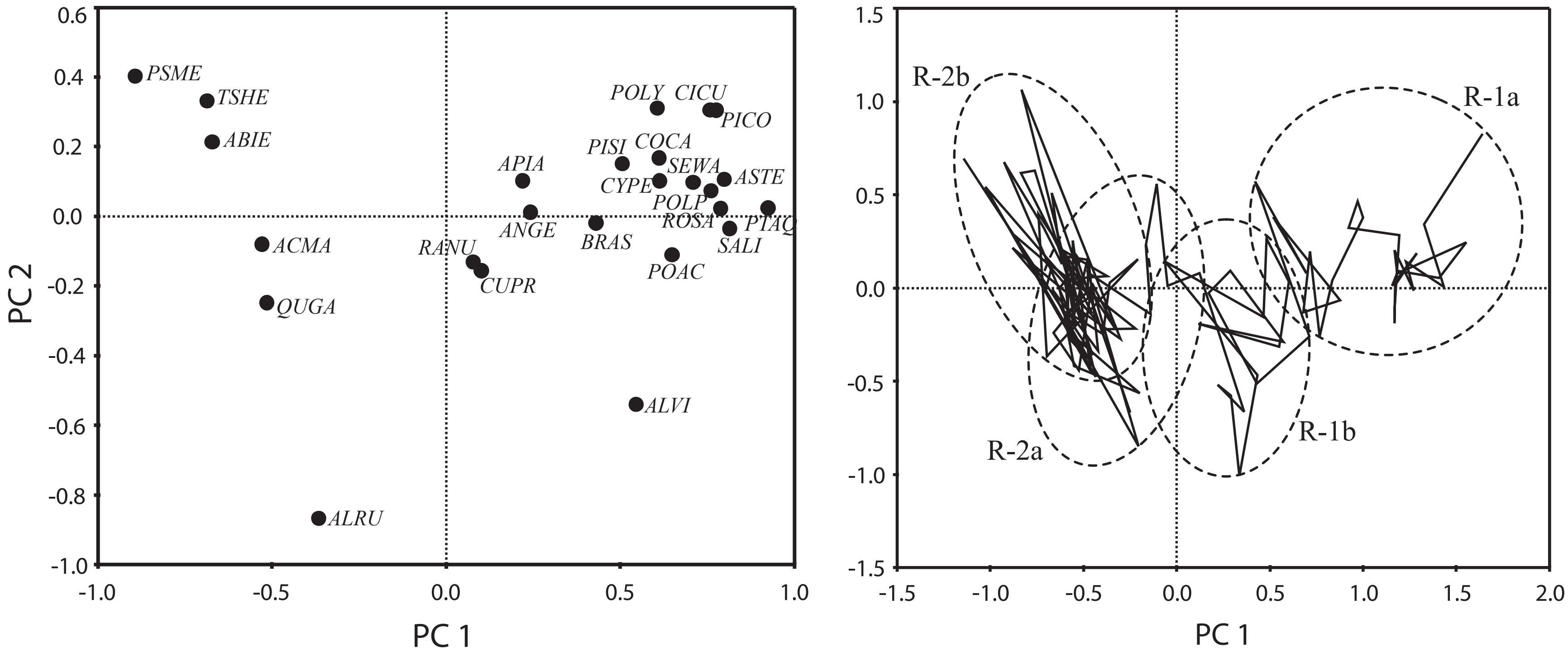

Figure 9. Principle components biplots of taxa (left) and sample scores in stratigraphic order (right) plotted on first and second axes, representing 52.6% and 12.1% of the total variation, respectively. Taxa abbreviations are as follows: ABIE= *Abies*, ACMA= *Acer macrophyllum*, ALRU= *Alnus rubra*, ALVI= *Alnus viridis*, ANGE= *Angelica*, APIA= Apiaceae other, ASTE= Asteraceae total, BRAS= Brassicaceae, CICU= *Cicuta* type, COCA= *Cornus canadensis*, CUPR= Cupressaceae, CYPE= Cyperaceae, PICO= *Pinus contorta*, PISI= *Picea sitchensis*, POLP= *Polypodium*, POLY= Polypodiaceae, PSME= *Pseudotsuga menziesii*, PTAQ= *Pteridium aquilinum*, QUGA= *Quercus garryana*, RANU= *Ranunculus* type, SALI= *Salix*, SEWA= *Selaginella wallacei* type, and TSHE= *Tsuga heterophylla*.

response and succession. This axis separates the early Holocene subzone R-1a from R-1b, with positive values correlated to higher values of NAP and negative values correlated with increases in *Alnus* spp. pollen. Axis 2 also highlights similarities in mid- to late Holocene samples (R-2a and R-2b), with samples from these subzones very closely clustered. Samples with abundant *Q. garryana* are clustered together near the center of the PCA biplot (Fig. 9), with the beginning of zone R-2a more negative, correlating to higher *A. rubra* values. Late Holocene (R-2b) samples with higher *P. menziesii* values are more positive.

Charcoal Analysis

Total charcoal concentrations were low (<150 particles/cm^3) over the last 1300 cal yr, resulting in low ‘peak’ CHAR and low background CHAR (<3 particles/cm^2/year) (Fig. 10). Using a 200-year threshold, 14 local fire episodes were identified over this period, with the largest magnitude fire episode occurring in 1555 AD (Fig. 11). Fire return intervals range from 18 to 198 years over the last 1300 years (Fig. 12), with a mean fire return interval (mFRI) of 91 years between fires. For the period prior to European settlement i.e., before 1850 AD, the mFRI is 100 years between fires. To aid in the discussion of fire activity, the record was divided into three time periods: 680-1200 AD, 1200-1850 AD, and 1850 to the present.

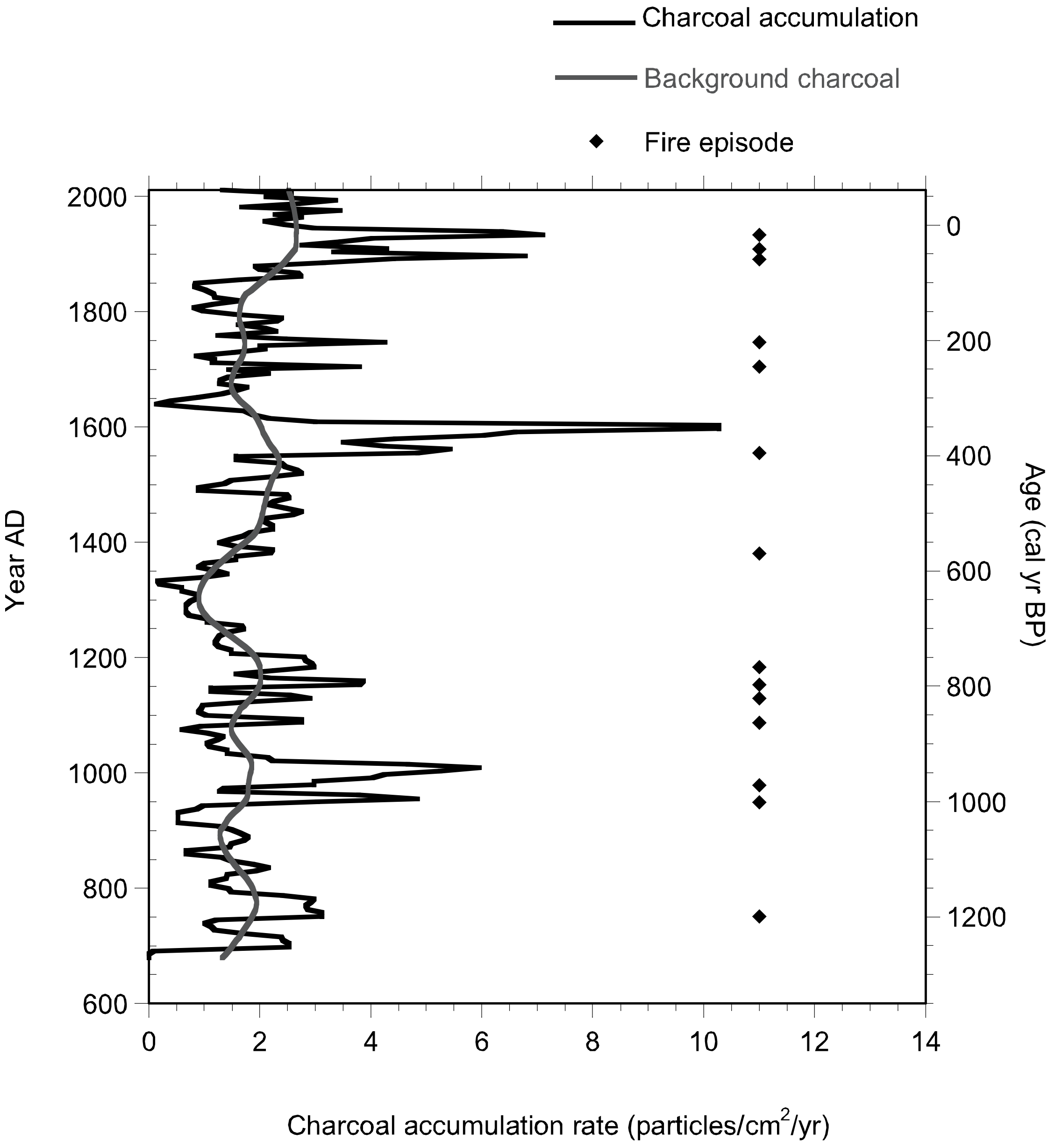

Figure 10. Roe Lake charcoal accumulation rates (CHAR), background charcoal accumulation rates, and inferred fire episodes.

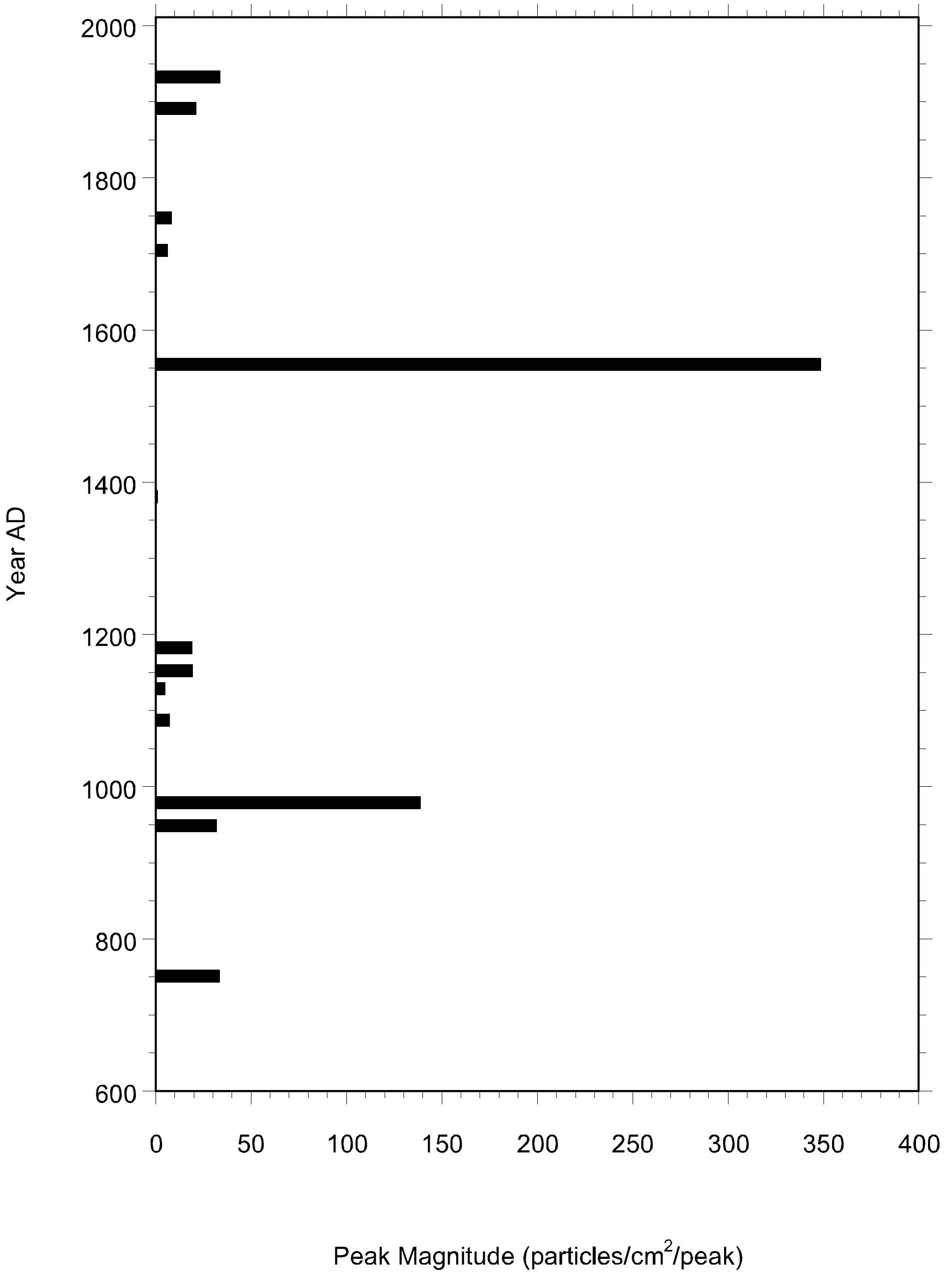

Figure 11. Peak magnitude of charcoal influx of inferred fire episodes at Roe Lake, Pender Island. Note: There are two small magnitude peaks, at 1910 and 1380 AD, that are not discernible on this scale.

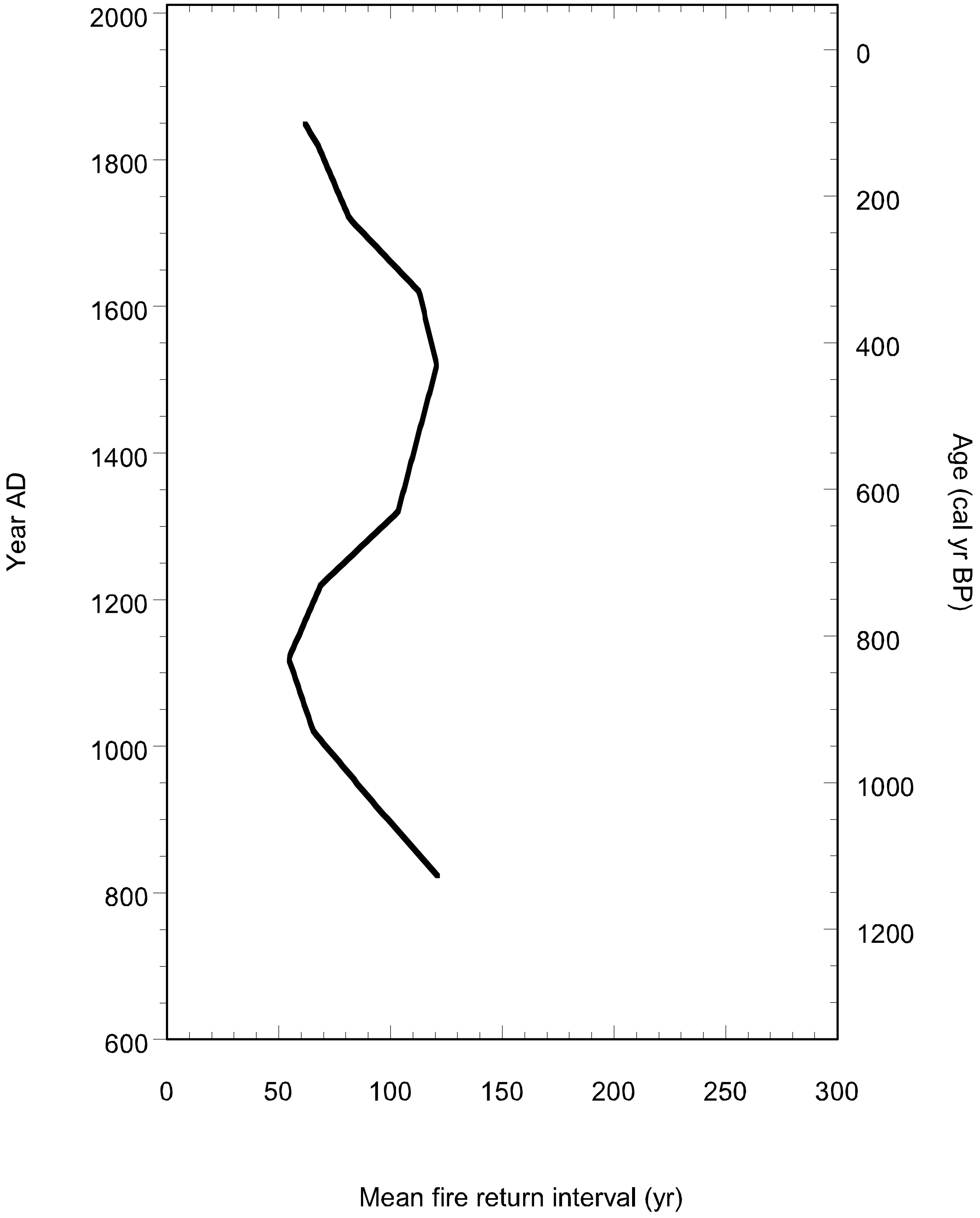

Figure 12. Mean fire return interval through time in the Roe Lake fire record.

680-1200 AD

This period is characterized by seven fire episodes. Fire return intervals range from 24 to 198 years between fires, with a mFRI of 72 years between fires. All fire episodes were moderate to low severity (<140 particles/cm^2/peak) (Fig. 11), with the largest fire episode occurring in 979 AD. Two fire episodes of similar magnitude (31 particles/cm^2) occurred in 751 and 949 AD.

1200-1850 AD

Four fire episodes occurred during this interval, with fire return intervals ranging from 42-198 years between fires. The mFRI for this period is 141 years. Low severity (<10 particles/cm^2/peak) fire episodes characterize this period; however, the largest fire episode for the period of record occurred in 1555 AD, with 349 particles/cm^2 (Fig. 11).

1850 AD to present

This period is characterized by three fire episodes, with the lowest magnitude episode (0.239 particles/cm^2) recorded in 1909 (Fig. 11). The other two fires were of low to moderate severity (20-35 particles/cm^2/peak).

Discussion

Holocene Vegetation History on Pender Island

Early Holocene Forests

The pollen record from Roe Lake begins at 10,000 cal yr BP with a herb dominated assemblage: *Cicuta* pollen alone accounts for 56% of the total pollen sum and collectively herbs and ferns account for 85%. Following this single basal sample, pollen assemblages in the early Holocene (Zone R-1: 10,000-7530 cal yr BP) reveal a landscape characterized by mixed forests with abundant *Pseudotsuga menziesii*. *Pinus contorta* and Cupressaceae were also present along with *Alnus rubra*, *A. viridis* and other shrubs, and an extensive herbaceous layer. Total pollen accumulation rates (PAR) are relatively high in the early Holocene interval, suggesting forests were well established on Pender Island by 10,000 cal yr BP if not before. An abundance of *Pteridium aquilinum*, a heliotropic fern, suggests that the forest canopy was open, allowing this species to flourish. A number of other shrubs, herbs and ferns (e.g., *Salix, Polypodium, Selaginella wallacei*, and members of the Apiaceae, Asteraceae, Cyperaceae, Poaceae, and Rosaceae families) were also common. Rarefaction analysis shows a decreasing trend in palynological richness throughout the entire Holocene.

Pseudotsuga menziesii pollen was present in low amounts at 10,000 cal yr BP i.e., less than 4% and 700 grains/cm^2/cal yr. However, given the limited pollen dispersal of this species (Prentice 1988, Sugita 1993), these low values indicate this species was likely the most abundant conifer on Pender Island in the early Holocene. Other paleoecological studies in southwestern British Columbia and western Washington

(Mathewes 1973, Heusser 1978, Mathewes and Heusser 1981, Allen 1995, Pellatt et al. 2001, Brown and Hebda 2002a, 2002b) also interpret an abundance of *P. menziesii*, coupled with *Alnus* and *Pteridium aquilinum*, as open forest with a high disturbance frequency, most likely fire. *Alnus rubra* pollen percentages and accumulation rates suggest this species was dominant across the landscape; however, because *A. rubra* is a prolific pollen producer, its abundance on Pender Island is likely overrepresented throughout the entire Roe Lake pollen sequence. Allen et al. (1999) demonstrate that high *Alnus* values, i.e., > 40% of the total pollen sum, can occur in modern pollen samples when the closest trees are 2 km away. *Alnus rubra* was likely more common on moist and/or disturbed sites near Roe Lake, with the majority of the *Alnus* input from regional pollen rain.

Pinus contorta PAR in the early Holocene suggests that this species was present on Pender Island, but decreased in abundance after 8000 cal yr BP. *Pinus contorta* was an early colonizer following deglaciation and remained abundant in the region until about 10,000 cal yr BP (Zirul 1967, Allen 1995, Pellatt 2001, Brown and Hebda 2002a, 2002b, 2003). At Roe Lake, *Pinus* has strong associations with early Holocene shrub, herb, and fern taxa in the PCA biplot (Fig. 9), reflecting the relatively open vegetation of this time.

Cupressaceae abundance increased until ~8500 cal yr BP, although it is unclear exactly which species were present on Pender Island, because *Thuja plicata*, *Chamaecyparis nootkatensis* [syn. *Callitropsis nootkatensis* (Little 2006)] and *Juniperus* spp. have indistinguishable pollen morphologies. Hebda (1995) suggests that Cupressaceae pollen at this time was likely from *Juniperus*. However, local presence of *Thuja plicata* was recorded across British Columbia by this time (Mathewes 1973, Hebda and Haggerty 1997, Lacourse et al. in press), suggesting that Cupressaceae pollen input to this low elevation lake at this time was most likely from *Thuja plicata.*

The vegetation on Pender Island was a conifer forest of relatively open structure with abundant *Pseudotsuga menziesii*, shrubs, herbs, and ferns. Similar forests occurred at other sites in southwestern British Columbia (Zirul 1967, Mathewes 1973, Allen 1995, Pellatt et al. 2001, Brown and Hebda 2002a, 2002b, 2003) during the warm, relatively dry early Holocene. Mathewes and Heusser (1981) described this period as a xerothermic interval, with a mean July temperature in southern British Columbia that was 3°C higher than present (Palmer et al. 2002) due to peak summer solar insolation at 10,000 cal yr BP (Berger and Loutre 1991), which would have decreased available moisture. Low winter insolation also occurred at this time, resulting in increased seasonality (Berger and Loutre 1991, Bartlein et al. 1998).

Middle Holocene Forests

Forests on Pender Island continued to be dominated by *P. menziesii* in the mid-Holocene with *Alnus* spp., Cupressaceae (*Thuja plicata*) and a variety of other species as minor constituents. In general, total PAR remain high, but decrease around 8000 cal yr BP until deposition of the Mazama tephra at 7600 cal yr BP, which suggests decreased forest density at this time when precipitation in the region was lower than present (Mathewes and Heusser 1981, Heusser et al. 1985). After 7600 cal yr BP, there is a noticeable decrease in shrubs, herbs and ferns, including *Salix*, Rosaceae, Poaceae, and

Pteridium aquilinum, suggesting that the forest canopy became increasingly closed through the mid-Holocene.

Pseudotsuga menziesii PAR increased during the mid-Holocene to greater than 2500 grains/cm^2/cal yr. However, the most striking feature of the pollen diagram from Roe Lake is the increase in *Quercus garryana* percentages (Fig. 5) and pollen accumulation rates (Fig. 7) following deposition of the Mazama tephra until 5500 cal yr BP. Local presence of *Quercus* in modern pollen assemblages is reflected by greater than 5% *Quercus* pollen (Allen et al. 1999), indicating that *Quercus* was a local species near Roe Lake around 8000 cal yr BP prior to deposition of the Mazama tephra, but did not reach maximum abundance until 7500 to 5500 cal yr BP, despite warm summer temperatures in the earlier Holocene. This later maximum abundance was possibly related to increased seasonality in the early Holocene with cold winter temperatures that limited *Quercus* establishment in the region (Walker and Pellatt 2003). It is also likely that this delay was related to inefficient seed dispersal of this species (Marsico et. al. 2009).

During maximum *Quercus* abundance, *Acer macrophyllum* and *Arbutus menziesii* populations also expanded. The oak-dominated woodland vegetation in the dry valleys of western Oregon (Franklin and Dryness 1973), often with *P. menziesii* as a co-dominant, is a reasonable analogue for this paleo-vegetation community. This type of vegetation community likely occurred on Pender Island between 7000 and 5800 cal yr BP, defined by increasing *P. menziesii* PAR simultaneous with *Quercus* abundance. *Acer* spp. and *Alnus* spp. likely occurred in seral communities and in disturbed areas, controlled by changing moisture and/or fire regimes (Franklin and Dryness 1973, Heusser 1978). Fuchs

(2001) describes *Quercus* communities on southern Vancouver Island as having an extensive herbaceous layer with abundant Poaceae and Liliaceae. At Roe Lake, total herbaceous abundance decreases significantly after deposition of the Mazama tephra (~7600 cal yr BP); however, Poaceae, Cyperaceae, and Liliaceae PAR suggest that these taxa were common in the mixed *Quercus*-conifer woodlands, and that conditions were sufficiently warm and dry to sustain canopy gaps for these taxa to commonly occur in the middle Holocene.

Late Holocene Forests

The demise of the *Quercus*-conifer woodland after 5800 cal yr BP marks the transition from a warmer and drier than present climate to the cool/moist neoglacial period that is present today. By 6000 cal yr BP, regional temperatures had decreased by ~2°C and average annual precipitation had increased by 600 mm/yr (Heusser et al. 1985). A decreased effect of the subtropical high-pressure system in the Pacific Northwest (COHMAP 1988, Bartlein et al. 1998) during this period increased the importance of moisture-carrying westerly winds. This cooler, moister climate is best shown at Roe Lake by an increase in Cupressaceae populations, likely *Thuja plicata* after 3000 cal yr BP, as this shade-tolerant species requires abundant soil moisture for regeneration under the forest canopy (Burns and Honkala 1990). This marks the establishment of the modern coastal *Pseudotsuga menziesii* forest on Pender Island and elsewhere in the region (Hansen 1950, Zirul 1967, Allen 1995, Pellatt et al. 2001).

Pseudotsuga menziesii reaches its maximum abundance during the late Holocene before 10,000 cal yr BP, showing the increased importance of this species as modern forests and climate developed in this region (Meidinger and Pojar 1991). PAR suggest that *Quercus garryana* continued to be present near Roe Lake until at least 2500 cal yr BP, although it is uncommon on Pender Island today. Most likely, *Quercus* was out-competed on deep soil sites as canopy density increased, but was able to persist on thin-soiled rocky outcrops across Pender Island.

Alnus spp. and *Salix* likely occurred at sites around Roe Lake with increased soil moisture, with *Acer macrophyllum* in areas immediately surrounding the lake and/or beneath *Pseudotsuga menziesii*. These species may have also persisted in seral communities maintained by fire (Hebda 1983). Brown and Hebda (2002b) suggest that increases in *Alnus* pollen and charcoal accumulation are indicative of frequent fire disturbance along the west coast of Vancouver Island. First Nations burning practices and tree harvesting (Turner 1999) are also thought to have contributed to the continued presence of early successional taxa. Herbaceous taxa continue to be present in the pollen record from Roe Lake throughout the late Holocene; however, the increase in Poaceae pollen near the top of the record likely represents the introduction of exotic grasses. High total tree PAR shows the development of the modern forest, with a well-developed canopy dominated by conifer species. Hebda and Mathewes (1984) suggest decreases in Cupressaceae pollen during the late Holocene throughout the region (Mathewes 1973, Mathewes and Rouse 1975, Barnosky 1981, Allen 1995, Brown 2000, Brown and Hebda 2002b, Lacourse 2005) are related to First Nations activities; this decline in

Cupressaceae, however, is not represented at Roe Lake or in a nearby regional study (Pellatt et al. 2001).

Postglacial Abundance of Garry Oak in the Pacific Northwest

The most noticeable change in the vegetation around Roe Lake during this Holocene sequence is the rise and decline of a *Quercus garryana*-dominated community. This dominance is referred to here as an 'oak peak', based on the shape of the oak curve on the percentage pollen diagram (Fig. 5). This peak presented a unique opportunity to examine spatio-temporal changes in Garry oak abundance in the Pacific Northwest following the last glacial period. Figure 13 maps 37 palynological sites (Table 3) in the Pacific Northwest with most of these pollen records spanning the entire Holocene. In these pollen records, oak abundance was determined by pollen percentage data, where >1% was used to indicate the local presence of oak and >5% was indicative of locally abundant oak, as per Allen et al. (1999). Other oak species are present at the southern end of Garry oak's range, making differentiating these pollen types critical for understanding patterns of abundance; only three of these southern-most records (Sea and Whitlock 1995, Worona and Whitlock 1995, Grigg and Whitlock 1998) did not distinguish between *Quercus* species.

The majority of Garry oak's modern range was not glaciated during the last glacial maximum, highlighted by presence of oak pollen in Oregon and southern Washington during this time (Barnosky 1985a, 1985b, Worona and Whitlock 1995, Hakala and Adam 2004). These dry valley sites from the eastern slope of the Coast and

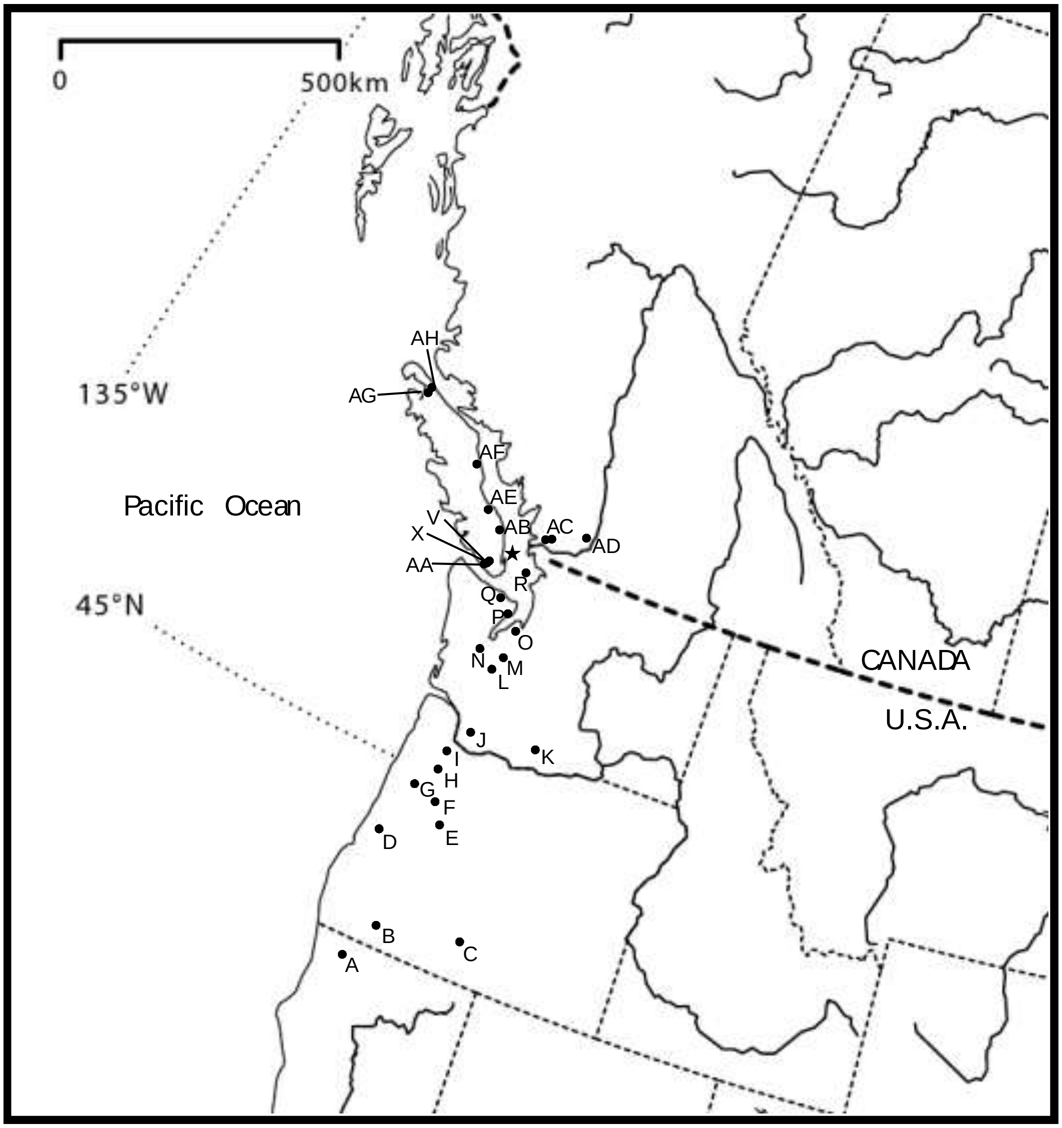

Figure 13. Map of the Pacific Northwest region, showing the location of Roe Lake, Pender Island (★) and other paleoecological studies mentioned in the text. See Table 3 for a list of sites and their map codes.

Table 3. Studies relevant to the paleoecological history of *Quercus* and their map codes for Figure 11. See Figure 1 the location of sites: S, T, U, Y and Z.

Code	**Site**	**Source**	**Latitude (°N)**	**Longitude (°W)**	**Elevation (m asl)**
California					
A	Sanger Lake	Briles et al. 2008	41° 54' 06"	123° 38' 49"	1550
Oregon					
B	Bolen Lake	Briles et al. 2005	42° 01' 30"	123° 27' 30"	1638
C	Caledonia Marsh	Hakala and Adam 2004	42° 18' 03"	121° 54' 04"	1262
D	Little Lake	Worona and Whitlock 1995	44° 10'	123° 35'	217
E	Gordon Lake	Grigg and Whitlock 1998	44° 21' 27"	122° 15' 47"	1067
F	Indian prairie fen	Sea and Whitlock 1995	44° 38'	122° 34' 30"	988
G	Beaver Lake	Walsh et al. 2010	44° 55' 02"	123° 17' 46"	69
H	Lake Labish 2	Hansen 1942	44° 56'	123° 02'	43
H	Lake Labish 1	Hansen 1942	44° 56'	123° 02'	43
I	Onion Flats	Hansen 1942	45° 21'	122° 50'	37
Washington					
J	Battle Ground Lake	Barnosky 1985a	45° 48' 20"	122° 29' 36"	155
K	Carp Lake	Barnosky 1985b	45° 55' 05"	120° 53'	714
L	Davis Lake	Barnosky 1981	46° 35' 30"	122° 15'	282
M	Mineral Lake	Tsukada and Sugita 1982	46° 43' 33"	122° 10' 32"	436
N	Zenkner Valley	Heusser 1977	46° 45' 20"	122° 57' 10"	63
O	Lake Washington	Leopold et al. 1982	47° 36'	122° 15'	10
P	Cedar Swamp	MacLachlan and Brubaker 1995	47° 54' 45"	122° 52' 30"	98
Q	Manis Mastodon Site	Petersen et al. 1983	48° 00'	123° 05'	165
R	Mt. Constitution, Orca Island	Sugimura et al. 2008	48° 40'	122° 49'	650

Table 3 continued.

Code	**Site**	**Source**	**Latitude (°N)**	**Longitude (°W)**	**Elevation (m asl)**
British Columbia					
S	East Sooke Fen	Brown and Hebda 2002b	48° 21' 07"	123° 40' 54"	155
T	Langford Lake	Hansen 1950	48° 27' 12"	123° 32' 05"	90
U	Rithet's Bog	Zirul 1967	48° 29' 20"	123° 22' 53"	60
V	Walker Lake	Brown and Hebda 2003	48° 31' 45"	124° 00' 08"	950
W	Heal Lake	Allen 1995	48° 32'	123° 28' 50"	369
X	Pixie Lake	Brown and Hebda 2002b	48° 35' 47"	124° 11' 48"	70
Y	Saanich Inlet	Pellatt et al. 2001	48° 37' 59"	123° 29' 59"	0
Z	Rhamnus Lake	Allen 1995	48° 38' 34"	123° 43' 17"	152
AA	Whyac Lake	Brown and Hebda 2002b	48° 40' 20"	124° 50' 40"	15
	Roe Lake	this study	48° 46' 59"	123° 18' 11"	117
AB	Porphyry Lake	Brown and Hebda 2003	48° 54' 20"	123° 50'	1100
AC	Marion Lake	Mathewes 1973	49° 18' 38"	122° 32' 53"	305
AC	Surprise Lake	Mathewes 1973	49° 19' 10"	122° 33' 34"	540
AE	Qualicum Beach	Hansen 1950	49° 21'	124° 25' 59"	60
AF	Pinecrest Lake	Mathewes and Rouse 1975	49° 29' 34"	121° 25' 54"	75
AG	Black Creek	Hansen 1950	49° 49' 52"	125° 07' 39"	320
AH	Misty Lake	Lacourse 2005	50° 36' 30"	127° 15' 48"	70
AI	Bear Cove Bog	Hebda 1983	50° 43'	127° 29'	30

Cascade Mountains show local oak presence, in low abundance, during the Fraser Glaciation. These are the only records with oak pollen that pre-date deglaciation but it is possible, based on these records, that oak persisted near other southern sites during this time.

In southern Oregon at high elevation sites (Hakala and Adam 2004, Briles et al. 2005), oak is an important component of the vegetation in the early Holocene. A mixed-conifer dominated forest was present at these sites when oak abundance was at its maximum. At an elevation of 1550 m in northern California, oak becomes the most abundant tree on the landscape during the early-mid Holocene, 9500-5000 cal yr BP (Briles et al. 2008); this highlights the warm, dry climate at this time, allowing oak to migrate to higher elevations, where today oak mainly persists in lower lying areas of the Klamath Mountains (Griffin 1977). Between 10,000 and 7600 cal yr BP, a *Pseudotsuga*-dominated forest with abundant *Alnus* was the setting for highest oak abundance at lower elevation sites in southern Oregon (Sea and Whitlock 1995, Worona and Whitlock 1995, Grigg and Whitlock 1998).

The vegetation of the Willamette Valley in Oregon has been of ecological interest for many years because today it supports widespread Garry oak savannas. Garry oak abundance in this area began early in the Holocene (10,900 cal yr BP) (Hansen 1942, Walsh et al. 2010) and this species remains dominant on the landscape today. At Beaver Lake in the southern Willamette Valley, a xeric oak woodland/savanna with scattered trees across the landscape and abundant herbs in the understory was present in the early Holocene (Walsh et al. 2010). Further north in the valley, Hansen (1942) describes highest oak abundance in the context of open *Pseudotsuga*-*Q.garryana* dominated communities; however, more detail about the composition of these communities is difficult to infer as only tree species were included in Hansen's (1942) pollen percentage diagram. Battle Ground Lake, located at the northern tip of the valley in southern Washington, exhibits lower oak abundance than southern sites in the Willamette Valley, with *Pseudotsuga*, Garry oak, and other deciduous trees scattered across the woodland landscape from 10,600-6000 cal yr BP (Barnosky 1985a).

Xeric communities similar to those found in the Willamette Valley today were present on the eastern slope of the Cascade Mountains in southern Washington by 8900 cal yr BP (Barnosky 1985b). Because these communities are located along the present day prairie margin, they were likely open in structure. *Q.garryana-Pseudotsuga* woodlands were likely confined to the forest/steppe border, with *Pinus* dominated forests present further west. Several dry valleys on the western slope of the Cascades exhibit little Garry oak pollen input during the early to mid-Holocene (Barnosky 1981, Tsukada and Sugita 1982), indicating that oak was present, but not a dominant component of the mixed conifer forests at this time. Around the same time period in the xeric Zenkner Valley, also west of the Cascades, a *Pseudotsuga-Alnus-Q.garryana* woodland mosaic was present with very little oak pollen input (Heusser 1977). Little to no oak pollen was present at sites east of the Puget Sound (Hansen and Easterbrook 1974, Leopold et al. 1982), indicating that oak may have been present in the area, but never gained abundance in these moist lowlands. Garry oak never became a dominant tree on the Olympic Peninsula; rather, a mosaic of coniferous forests with *Alnus* were present when oak was locally present (Petersen et al. 1983, MacLachlan and Brubaker 1995).

Western Vancouver Island shows little to no Garry oak presence throughout the Holocene (Brown and Hebda 2002b, Brown and Hebda 2003); scattered oaks were present in dry rocky areas but likely excluded by *Pseudotsuga menziesii*, *Tsuga heterophylla*, and *Thuja plicata* on deep soil sites. Sites surrounding the Victoria area on southeastern Vancouver Island exhibit an abundance of Garry oak beginning prior to deposition of Mazama tephra and extending into the mid-Holocene (Hansen 1950, Zirul 1967). Heal Lake, located on the Saanich Peninsula, shows oak abundance in forests from 7900-6700 cal yr BP, with *Pseudotsuga* co-dominant in the xeric woodlands, conifers present on deep and shallow soils, and abundant herbs and ferns in canopy gaps (Allen 1995). This is likely the scenario for the other sites surrounding Victoria, despite a lack of data on understory species and well-defined chronologies for these paleovegetation records (Hansen 1950, Zirul 1967). On Pender Island from 7500-5000 cal yr BP, highest Garry oak abundance occurs within an open *Pseudotsuga* woodland, with canopy gaps populated by more shade-intolerant taxa. Along the eastern coast of Vancouver Island, north of Victoria, oak is locally abundant in the mid- to late Holocene, but never gains dominance in the mixed coniferous forests (Hansen 1950, Allen 1995). Oak did not migrate to northern Vancouver Island (Hebda 1983, Lacourse 2005). On mainland British Columbia, oak reaches the Fraser River Valley in the mid-Holocene but never gains abundance in the mixed Cupressaceae-*Pseudotsuga* forests (Mathewes 1973, Mathewes and Rouse 1975).

Garry oak was present during the last glacial period at low and high elevation sites in Oregon and southern Washington but was not abundant in these forests until the early Holocene. Warm and dry climate during the early to mid-Holocene allowed for the establishment of oak dominated woodlands/savannas in southern California and Oregon by 10,000 cal yr BP. At its northernmost position, oak reached its greatest abundance between 8200 cal yr BP (Pellatt et al. 2001) and 5500 cal yr BP (this study). Since the mid-Holocene, as climate has cooled and available moisture increased, Garry oak populations appear to have declined throughout its range, although this species remains abundant in some areas such as the Willamette Valley, Oregon. Garry oak migrated from southern populations, reaching maximum Holocene abundance on landscapes during their warmest and driest periods. Patterns of genetic diversity within Garry oak populations from California to British Columbia reflect this postglacial migration, with higher genetic divergence among populations with increasing latitude (Ritland et al. 2005, Marsico et al. 2009). Populations from Vancouver Island and the Gulf Islands show high genetic similarity, suggesting that Garry oak migrated to the Gulf Islands from Vancouver Island, not from the San Juan Islands or mainland British Columbia populations (Ritland et al. 2005).

Late Holocene Fire History at Pender Island

680-1200 AD

This period is characterized by a relatively high fire frequency, with seven fire episodes occurring in a 520-year period. Most of these fires were moderate to low intensity based on peak magnitude data. Two fire episodes of similar magnitude (31 particles/cm^2) occurred at about 750 and 950 AD. The second most severe episode for the period of record occurred 30 years later (~980 AD). An episode of this magnitude, 138 particles/cm^2, may have been stand replacing, followed by a 100-year period with no fire activity. Four low to moderate intensity fire episodes occurred following the period of inactivity with 20-40 years between fires, which likely explains the lower magnitude of these episodes.

The latter half of this interval encompasses the Medieval Climate Anomaly (MCA), characterized by generally warm and dry conditions in the Pacific Northwest from approximately 950-1250 AD (Stine 1994, Broecker 2001, Mann 2002, Moberg et al. 2005, Mann et al. 2009), corresponding to when fires were most frequent at Pender Island i.e., on average 47 years between local fire episodes. During this time, widespread drought and relatively high fire frequency are apparent at other locations in the Pacific Northwest (Stine 1994, Broecker 2001, Gavin et al. 2003, Hallett et al. 2003, Long et al. 2007, Sugimara et al. 2008, Walsh et al. 2010b) with ignition mostly attributed to lightning strikes. Today, lightning strikes rarely occur in the southern Vancouver Island and Gulf Islands region; however, frequent lightning strikes coupled with dry conditions could produce the moderate to low intensity fires found at Roe Lake during this time period.

1200-1850 AD

Low fire frequency is exhibited during this interval, with only four fire episodes occurring during this 650-year period. A very low severity fire (1.21 particles/cm^2) occurred about 1380 AD after 200 years without fire activity. The most severe fire episode (349 particles/cm^2) occurred about 1555 AD, after a 175-year period of no fire activity. This episode was likely stand replacing, displacing fire activity for 150 years. Low magnitude fires occurred from 1705 to 1750 AD.

This period of low intensity, infrequent fire corresponds with the Little Ice Age (LIA) (Grove 2001). The LIA brought cooler, wetter conditions to the Pacific Northwest, marked by glacial advances in much of the Coast Mountains (Smith 1996, Luckman 2000, Larocque and Smith 2003, Lewis and Smith 2004). These conditions may have resulted in increased forest density with a decrease in fire occurrence. Based on these conditions, these fire episodes near Roe Lake may have been caused by local, non-climatic drivers, mirroring other studies in the area that show a decrease in fire activity (Brown and Hebda 2002a, Gavin et al. 2003, Hallett et al. 2003, McCoy 2006, McDadi and Hebda 2008, Walsh et al. 2010b). Cultural records suggest that the population of the Coastal Salish First Nations that inhabited the southern Gulf Islands was upwards of 30,000 (Turner 1999). These peoples, prior to European settlement, frequently used low intensity ground fires to increase the availability of food resources (Suttles 2005). This anthropogenic burning is a likely explanation for the low to moderate intensity fire episodes in the Roe Lake record prior to European settlement. However, other high severity and/or stand-replacing fire episodes were recorded in the region during the early to mid-1500s (Daniels et al. 1995, Weisberg 2003), so it is likely that the high severity fire event near Roe Lake in 1555 AD was caused by lightning, as opposed to prescribed burning by First Nations.

1850 AD - present

There were three fire episodes at or near Roe Lake after European settlement. Two of these episodes (~1890 and ~1930 AD) were of moderate severity (21 and 34 particles/cm^2, respectively) and the 1909 AD fire event was the lowest intensity (0.239 particles/cm^2) for the period of record. Aerial photographs from the 1920-30s confirm that there was a fire on Pender Island immediately north of Roe Lake (John Mackenzie, personal comm.) that likely corresponds to the peak in charcoal accumulation at 1933 AD. These fires may reflect the use of fire by European settlers for land clearing purposes, although this is uncertain because the early history of Pender Island is not well-documented. The lack of charcoal in the youngest sediments at Roe Lake reflects subsequent fire suppression imposed post-settlement.

Similar studies conducted near Roe Lake (Heusser 1983, Brown and Hebda 2002b, McCoy 2006, McDadi and Hebda 2008) record higher charcoal influx following European settlement. Heusser (1983) analyzed marine sediments from the Saanich Inlet, which provides a more regional charcoal signal that incorporates fires ascribed to the mining, logging, and road building activities of early settlers on southern Vancouver Island (Pyne 1982, Whitlock and Knox 2002). Fort Victoria was established in 1843 AD (Whitlock and Knox 2002) and increased influx of charcoal to many sites close to Victoria has been attributed to the fire activity from this period (Pyne 1982, Heusser 1983, Brown and Hebda 2002b, McCoy 2006, McDadi and Hebda 2008).

It appears, based on historical records and by inference from this study, that the area surrounding Roe Lake was not as heavily cleared and burned as the more populated

Victoria area, despite permanent settlers living on Pender Island by 1880 AD (Eis and Craigdale 1980). However, a previous record of charcoal analysis of Roe Lake sediments differs from this study, with eleven fire episodes identified in sediments estimated to span the last ~250 years and an inferred fire frequency of 27 years between fires (McCoy 2006; Pellatt et al. 2007). While these two records from Roe Lake are similar in terms of consistently low charcoal accumulation, there are some notable differences that affect their interpretation and comparison. McCoy's (2006) study reconstructed the fire history of the region for the last 250 years from three lakes. Two of these lake sediment records, from Roe Lake and Quamichan Lake, only used ^{210}Pb age determinations for chronological control (McCoy 2006). This poses a problem as the error with ^{210}Pb determinations increases with depth and there is no ^{14}C age to anchor the base of these records. which compromises the accuracy of the inferred fire frequency from these records. Furthermore, based on the ^{210}Pb and ^{14}C data presented here, it appears that the inferred age of ~1750 AD for the base of McCoy's (2006) Roe Lake record, which was based on extrapolation from the lowest ^{210}Pb age determination, underestimates the true age of these sediments by ~100-150 years i.e., a more likely basal age for McCoy's (2006) Roe Lake record is 1600-1650 AD. This underestimation for the age of these sediments would effectively decrease the inferred mean fire return interval, making the time between fires appear much shorter. Perhaps most importantly, McCoy (2006) did not use contiguous sampling in calculating charcoal accumulation for any of the lakes, which makes inferring fire frequency prone to error. Sampling gaps in the charcoal record can potentially miss large charcoal peaks or lower the effect of background charcoal, giving identified peaks more significance, whereas these peaks may have been smoothed over if contiguous sampling had been conducted (Higuera et al. 2007). In summary, McCoy’s (2006) inferred fire frequencies were lower (26-41 years) than those inferred by this study as well as other research that addresses fire regimes in the *Pseudotsuga menziesii*-dominated forests of the region (Agee 1991, Spies and Franklin 1991, Spies 1991, Agee 1993), and this discrepancy can be explained by poor chronological control and inconsistent sampling of the sediment cores.

Based on the charcoal record from Roe Lake presented here, the mean fire frequency is 100 years between fire episodes before European settlement, which represents the natural variability for the forests of Pender Island over the last 1300 years. This fire frequency should be considered by land managers attempting to reintroduce fire to these ecosystems. According to this study, the forests on Pender Island have not burned over the last 80 years and because this lies within the natural range of variability, prescribed burns may not be the best course of action at this time, particularly given the cost and risk associated with prescribed burns. Managers concerned about the future fire regime of these forests should consider using the mean fire return interval of 47 years for the Medieval Climate Anomaly as a reference period for prescribed burning, as climatic conditions during this period were similar to those projected for the Pacific Northwest in the next 50-100 years.

Conclusion

Pollen analysis of lake sediments from Pender Island indicated that by 10,000 cal yr BP, a mixed forest dominated by *Pseudotsuga menziesii* was established with a well-developed shrub, herb and fern layer. High *Pteridium aquilinum* input is indicative of an open canopy, persisting from 10,000 to 8000 cal yr BP. Low winter insolation during the early Holocene period and inefficient seed dispersal likely limited *Quercus* abundance prior to 7500 cal yr BP. As winter insolation increased in the mid-Holocene, *Quercus*-*Pseudotsuga* woodlands established on Pender Island. This type of community is seen at other paleoecological studies in the surrounding region with maximum oak abundance occurring earlier in the Holocene at lower latitudes. Cooler and wetter climatic conditions beginning 4000-3000 cal yr BP mark the establishment of modern coastal *Pseudotsuga menziesii* forests on Pender Island.

The Pender Island fire history reconstruction records frequent (mFRI 47 years) fire episodes between 950 and 1200 AD, suggesting that the warm and relatively dry conditions of the Medieval Climate Anomaly were conducive to fire activity. A decrease in fire frequency from 1200-1850 AD correlates with the cooler and wetter climatic conditions of the Little Ice Age. Based on historical records (Suttles 2005), some fire episodes during this period may be the result of First Nations management of food resources; however, there is regional evidence for large fires during this time that suggests that climate also played an important role in driving fire activity in the recent past. Low intensity fire episodes were recorded following European settlement (after 1850 AD) and were likely set for land clearing purposes.

Large scale changes in vegetation and fire dynamics from Pender Island are similar to those of the surrounding region and correlate well with climatic changes during the Holocene period, indicating that climate was likely the principal driving mechanism in community composition and fire regime changes. Other factors, such as competition and disturbance were likely more important in determining small scale changes in species abundance and vegetation dynamics.

Chapter 3: Conclusion

Summary

The vegetation reconstruction from Roe Lake begins 10,000 cal yr BP with a mixed forest with abundant *Pseudotsuga menziesii*. The presence of *Pteridium aquilinum* and a diverse assemblage of shrubs and herbs are indicative of an open forest canopy persisting from 10,000 cal yr BP to 7500 cal yr BP. The onset of warm and dry conditions is evident by the establishment of a *Quercus garryana-Pseudotsuga menziesii* dominated woodland by 7000 cal yr BP. This community consisted of abundant shade-intolerant taxa, such as *Arbutus menziesii,* persisting in this open woodland. Similar *Quercus garryana*-dominated communities occur earlier in the Holocene at lower latitudes, highlighting the necessity of warm and dry conditions for *Quercus garryana* establishment. This *Quercus*-dominated community persisted until 5800 cal yr BP when the development of modern climate increased shade-tolerant taxa and forest density, developing the coastal *Pseudotsuga mensiesii* forests of today.

The record of fire history from Roe Lake begins at 680 AD, with moderate severity fire episodes occurring frequently during the Medieval Climate Anomaly. The decreased frequency of fire episodes marks the Little Ice Age period. The low intensity fire episodes that did occur may be associated with local non-climatic factors as documented conditions were cooler and wetter during this period. Use of fire by First Nations for land clearing and food production have been attributed to fire episodes prior to European settlement. Use of fire by European settlers and subsequent fire suppression is evident in the Roe Lake record (1850 AD-present), with only three fire episodes occurring immediately following European settlement on Pender Island and no recorded fires after 1933 AD.

Significance

There are currently no other local vegetation records from the Gulf Islands that span the entire Holocene period. Long-term paleoecological records for these islands are useful for determining patterns of species migration following the last glaciation. Records in the southern Vancouver Island-Gulf Islands region are particularly useful for indicating the timing and development of *Quercus*-dominated communities that have been associated with human interaction and disturbance. Reconstructions of climate-vegetation interactions are important not only for the local setting, but of great use for regional comparisons as well.

The Roe Lake record of fire history pre-dates European settlement, which adds to the growing body of knowledge of how climatic and human influences have changed fire regimes across broad timescales, although these factors are difficult to disentangle. This record can be useful to land managers considering the reintroduction of fire in similar communities as a management tool. The range of fire return intervals provided by this study can be used for the maintenance of specific ecosystem types or desired seral communities. Given the natural range of variability, about 100 years between fire episodes, the best management plan should include the possibility of foregoing the reintroduction of fire in the immediate future. The project as a whole provides further insight to how coastal *Pseudotsuga menziesii*-dominated forests have responded to shifts in climate and fire patterns.

Study Limitations

Roe Lake has a water depth of over 9 m and it became increasingly difficult to collect sediments from this lake. Although 9.03 m of sediment was collected, it is likely that additional basal sediments remain below this depth. Obtaining the late-glacial sediments from Roe Lake would provide a record of early plant colonization to Pender Island and add more context to community-scale patterns of succession in the early Holocene.

Conifer stomata were scattered throughout the Roe Lake sediment core, but currently no stomata identification key exists for all of the conifers in British Columbia. Identification of these, in addition to plant macrofossils, could help determine the arrival of major plant taxa and would confirm local species presence.

Recommendations for Future Research

The Coastal Douglas-Fir (CDF) biogeoclimatic zone has been extensively studied because it contains unique vegetation communities. High resolution paleoecological records, spanning the late-glacial and Holocene period, of coupled vegetation and fire history reconstructions are necessary to further examine the role of fire in possibly modifying these communities. Long-term ecological experiments examining safe and effective burning strategies are necessary before a management plan with prescribed fire can be implemented. Diatom (Henrichs et al. 1997, Bennett et al. 2001) and chironomid (Walker and Mathewes 1989, Smith et al. 1998, Henrichs et al. 2001) records from mainland British Columbia have been helpful for determining past changes in climate. Paleoclimate estimates for the southern Vancouver Island region would be useful for determining local differences in climate and their possible impact on CDF forests. This and other studies from the CDF report little change in vegetation communities throughout the Holocene, warranting both modern and paleoecological studies of community resilience in this region.

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Appendix A

Latin and common names for all plant taxa mentioned in the text.

Latin name	**Common name**
Abies amabilis	Pacific silver fir
Abies grandis	grand fir
Abies lasiocarpa	subalpine fir
Acer glabrum	Douglas maple
Acer macrophyllum	big leaf maple
Alnus rubra	red alder
Alnus viridis	green alder
Angelica	angelica
Apiaceae	carrot family
Arbutus menziesii	Pacific madrone
Arctostaphylos columbiana	hairy manzanita
Asteraceae	aster family
Athyrium filix-femina	lady fern
Betula	birch
Brassicaceae	mustard family
Callitropis nootkatensis	yellow cypress
Chamaecyparis nootkatensis	yellow-cedar
Cicuta	water hemlock
Cornus canadensis	Canadian bunchberry
Cupressaceae	cypress family
Cyperaceae	sedge family
Equisetum telmateia	giant horsetail
Gaultheria shallon	salal
Holodiscus discolor	oceanspray
Juniperus	juniper

Latin name	**Common name**
Liliaceae	lilie family
Lycopodium	club moss
Lysichiton americanus	skunk cabbage
Nuphar	water lily
Picea sitchensis	sitka spruce
Pinus contorta	lodgepole pine, shore pine
Plectritis	sea blush
Poaceae	grass family
Polypodiaceae	polypod family
Polypodium	polypody fern
Polystichum munitum	sword fern
Potamogeton	pondweed
Pseudotsuga menziesii	Douglas-fir
Pteridium aquilinum	bracken fern
Quercus garryana	Garry oak
Ranunculus	buttercup
Rosaceae	rose family
Rosa nutkana	Nootka rose
Salix	willow
Selaginella wallacei	Wallace’s spikemoss
Symphoricarpos albus	snowberry
Thuja plicata	western redcedar
Tsuga heterophylla	western hemlock
Typha latifolia	common cattail