HOLOCENE FIRE FREQUENCY AND LINKS TO CLIMATE AND VEGETATION HISTORY ON PENDER ISLAND, BRITISH COLUMBIA, CANADA

By

Camille Giuliano

BSc, McMaster University, 2019

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

In the Department of Biology

HOLOCENE FIRE FREQUENCY AND LINKS TO CLIMATE AND VEGETATION HISTORY ON PENDER ISLAND, BRITISH COLUMBIA, CANADA

By

Camille Giuliano

BSc, McMaster University, 2019

Supervisory Committee

Dr. Terri Lacourse, Supervisor
Department of Biology

Dr. Barbara J. Hawkins, Committee Member
Department of Biology

Dr. Joseph A. Antos, Committee Member
Department of Biology

ABSTRACT

Contiguous macroscopic charcoal analyses were performed on a 9.03 m long lake sediment core from Roe Lake on Pender Island in the Gulf Islands National Park Reserve of British Columbia, Canada to reconstruct the island's fire history over the last 10,000 years. Charcoal particles >150μm were counted to quantify charcoal concentrations, charcoal accumulation rates and mean fire return intervals. Results show that the early Holocene was characterized by high charcoal accumulation rates and frequent low-severity fire with a mean fire return interval of 100 ± 29 years. Forests at the time were dominated by *Pseudotsuga menziesii* with an open canopy and fern taxa, particularly *Pteridium aquilinum*, being common in the understorey. This open vegetation, coupled with warm and dry summer climate, likely created conditions conducive to this fire regime. Charcoal accumulation rates decreased in the middle to late Holocene, and fire frequency decreased, resulting in a mean fire return interval of 167 ± 43 years. Climate cooled and moistened along with a decrease in seasonality during this time and the canopy closed, establishing closed-canopy *Pseudotsuga menziesii* forests. Climate appears to be the primary factor controlling fire regimes near Roe Lake for most of the Holocene.

At times, shifts in the fire regime cannot be explained by changes in climate. Fire frequency increased between 7000-5000 cal yr BP, coincident with a peak in *Quercus garryana* pollen, despite cooling and moistening climate. Fire likely maintained patches of *Q. garryana* savanna during this time. Fire again became more common contrary to trends in climate after ~2500 cal yr BP. This late Holocene increase in fire is also seen elsewhere in the Pacific Northwest and may be a reflection of increased climate variability due to more frequent El Niño events or an increase in human-lit fires. Indigenous populations on southern Vancouver Island

commonly used fire as a resource management tool and it is likely that people on Pender Island did as well.

As fire management practices shift from fire suppression to more sustainable practices, this study offers the Gulf Islands National Park Reserve important baseline information on the area's natural fire regime to help guide future conservation efforts.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

First, I want to thank my supervisor, Dr. Terri Lacourse. Your help and guidance over the last two and a half years have been invaluable. Despite the difficulties and isolation of the pandemic, you always made me feel confident in what I was doing and I am an infinitely better researcher as a result. Thank you.

Thank you to my committee members, Dr. Barbara Hawkins and Dr. Joe Antos. Your perspectives and feedback on my project have been nothing but helpful and insightful. Thank you to Dr. Dan Gavin for serving as External Examiner for my MSc thesis. Thank you to Jennifer Lucas who conducted the Roe Lake pollen analysis as well as J. Lucas, T. Lacourse, M. Pellatt, B. Hodgin, and T. Rodengen who collected the sediment core from Roe Lake.

I would also like to thank my parents and family. Your love and support mean the world even though you are not quite sure what exactly it is that I am doing across the country. I could not have done it without the daily phone calls from Mom and the cousins' group chat.

Finally. I would like to thank all the friends that kept me sane during the entirety of this Masters. From the pre-pandemic crochet club to the somewhat post-pandemic Friday beers, and all those long Discord calls in between, I cannot thank you all enough.

This research was supported through research grants to Terri Lacourse from the Natural Sciences and Engineering Research Council of Canada, Canada Foundation for Innovation, British Columbia Knowledge Development Fund and Pacific Institute for Climate Solutions.

INTRODUCTION

Wildfires are one of the most common forms of natural disturbances in many ecosystems. They serve many ecological purposes, such as maintaining open plant communities and increasing soil nutrient availability (MacDougall et al. 2004; Vellend et al. 2008). However, fire is also an important concern in terms of human community health and safety as well as posing a risk to infrastructure. In 2019 alone, British Columbia spent $172.5 million towards forest fire management (Province of British Columbia 2020). That cost can increase dramatically depending on the severity of the fire season, with the cost of management reaching as high as $565 million in 2021 and $615 million in 2018 (Province of British Columbia 2021; 2020). As climate continues to warm, wildfires are expected to steadily increase, with yearly area burned in Canada expected to increase anywhere between 74% and 118% by the end of the century (Flannigan et al. 2005). With that in mind, understanding the dynamics of wildfires is becoming increasingly important from both a societal and ecological perspective. Using modern observations or historical data to infer natural fire regimes, however, has limitations. Wildfire regimes in most ecosystems have been unsustainably modified for centuries by human activities including various forms of fire management, fire suppression or exclusion, and land clearing. Therefore, modern records of fire are not appropriate for assessing the natural fire frequencies of many environments.

Tree rings allow for annual-precision reconstructions of fire regimes but records generally only extend a few centuries at most (Conedera et al. 2009; Remy et al. 2019). Paleoecological studies of past fire regimes can be a powerful alternative as they allow us to look at changes in wildfire regimes on long timescales as both climate and vegetation have changed. Charcoal deposits in lake sediments or peatlands offer a lower temporal resolution than tree rings

but much longer records of fire history (Whitlock and Larsen 2001; Conedera et al. 2009; Remy et al. 2019).

Charcoal Production and Deposition in Lake Sediments

Charcoal is the result of the incomplete combustion of organic matter (Whitlock and Larsen 2001; Conedera et al. 2009) and is mainly produced as a result of wildfire (Scott 2010). Low-energy depositional environments, such as lakes, can offer a chronological record of past ecosystem conditions over long periods of time (Whitlock and Larsen 2001; Whitlock and Anderson 2003). The spatial scale represented in the sedimentary archives of these environments varies, largely based on the size of the lake and catchment, with smaller lakes providing more localized paleo-environmental information, often restricted to within the watershed (Whitlock and Larsen 2001). Small lakes are often used in paleoecological analyses to reconstruct past local environmental conditions. Charcoal particles in these lakes can be used as a paleoecological indicator of past local wildfires. Other organic material deposited alongside sediment can also be used as environmental proxies that allow us to infer long-term environmental change (Whitlock and Larsen 2001; Conedera et al. 2009) Pollen can be counted and identified to infer past vegetation composition and structure, and chironomid head capsules can be used to infer past average temperatures.

On long timescales, fire is primarily controlled by climate and vegetation. Climate is often the main factor responsible in controlling an environment's long term fire regime (e.g. Gavin et al. 2007; Walsh et al. 2008; Prichard et al. 2009). Warmer and drier climates will often be much more fire prone than climates with cooler conditions and higher moisture levels. Vegetation structure controls fuel availability which can sometimes override the effects of

climate (Gavin et al. 2007). Density, composition, and individual species' adaptability to fire all influence the probability of fire and its severity in a given ecosystem. However, changes in vegetation composition and structure are often largely climate-driven, indicating climate may still be the primary factor controlling fire regimes both directly and indirectly (e.g. Gavin et al. 2006; Long et al. 2007; Walsh et al. 2008; Higuera et al. 2009; Walsh et al. 2017; Hoecker et al. 2020). Fire also requires a source of ignition, usually lightning (Agee 1991; Flannigan et al. 2005; Scott 2010) but human-lit fires can sometimes be more common than lightning-initiated fires depending on environmental and historical contexts (e.g. Agee 1991; MacDougall et al. 2004). In British Columbia today, 58% of fires are caused by lightning on average (Province of British Columbia 2020).

When fire occurs, charcoal particles become airborne and can travel varying distances before being deposited on the landscape. If directly deposited in water, charcoal can float on the surface for long periods of time and be transported elsewhere before eventually becoming water-logged and sinking to the bottom (Nichols et al. 2000; Scott 2010). Smaller charcoal particles generally travel longer distances and represent charcoal from a regional spatial scale, whereas larger particles represent more localized fires (Whitlock and Larsen 2001; Conedera et al. 2009; Scott 2010; Remy et al. 2018). Particles <100 μm reach much greater heights and can readily fall over 100 m away from their source whereas particles >1000 μm remain relatively close to the ground and are deposited much nearer to the fire (Whitlock and Larsen 2001). This creates a size bias in the sediment record. Particles greater than 200 μm in size rarely travel over 6 km away from their source (Whitlock and Larsen 2001). However, fire intensity and severity also play an important role in charcoal dispersal, with particles travelling further under more extreme conditions (Whitlock and Larsen 2001; Whitlock and Anderson 2003; Conedera et al. 2009).

Studies in various ecosystems and vegetation types have found that particles >160 μm can originate from fires up to 30 km from the lake (Higuera et al. 2010; Oris et al. 2014; Remy et al. 2019).

Sedimentary charcoal can also be divided into primary and secondary charcoal. Primary charcoal represents charcoal that is deposited during or immediately following a fire whereas secondary charcoal is deposited later through run-off and sediment mixing (Whitlock and Larsen 2001; Conedera et al. 2009). Secondary charcoal deposition can occur over several years following a fire (Whitlock and Larsen 2001). This creates a low level of background charcoal within charcoal accumulation rates throughout the sediment, even if there has not been a recent fire. Peaks among this background charcoal indicate periods with fire activity as the increase in particle accumulation rate cannot be explained solely by run-off or sediment mixing (Higuera et al. 2009).

Charcoal Analysis

Charcoal deposited in lake sediments can be used as a proxy for biomass burning and fire frequency (Whitlock and Larsen 2001; Conedera et al. 2009: Remy et al. 2019). Microscopic (<100 μm) or macroscopic (>100 μm) charcoal can be used with differing results. Microscopic charcoal was first used as a fire proxy in Iversen (1941) and is usually counted alongside pollen on the same microscope slides (Whitlock and Larsen 2001). However, it is not commonly used as it inflates charcoal abundance due to breaking during preparation and the charcoal source area largely represents regional scale fire activity. Contiguous sampling is also uncommon with this method due to cost effectiveness and time commitment (Whitlock and Larsen 2001; Conedera et al. 2009). A lack of contiguous sampling makes fire frequency impossible to calculate due to

time gaps in the data. Macroscopic charcoal (usually > 150 μm) is prepared separately from pollen, and provides a more localized spatial scale than microscopic charcoal. Sediment samples are usually taken at contiguous 1 cm intervals, which corresponds to a resolution of 5-20 years per sample in most North American lakes (Whitlock and Larsen 2001). Samples are usually sieved, and then charcoal particles can be counted for each sample.

Counts of charcoal particles can be used to calculate charcoal concentrations and accumulation rates over time within the sediment. These accumulation rates can be used to infer changes in biomass burning over time and to determine fire frequency. To identify fire events, background charcoal is estimated using statistical smoothing methods and is used to identify charcoal peaks in the record (Gavin et al. 2006; Higuera et al. 2009). These peaks represent past fire events and can be used to calculate fire frequency or the mean fire return interval (mFRI), which is the mean amount of time between two fire events. These FRIs are different from those that may be calculated from modern observational studies or tree-ring studies, as only fires large and/or intense enough to produce significant charcoal peaks in the sediment record will be recorded. They are also not relevant in the context of a single tree as in tree-ring analyses, but rather offer a record of larger scale fire within a study area as a whole. Specific software, such as CharAnalysis, is available to easily conduct these numerical analyses (Higuera et al. 2009; Conedera et al. 2009). However, these analyses are most suited to sites with high severity fire and will more accurately identify fires at these sites (Kelly et al. 2011).

Holocene Fire History in The Pacific Northwest

Macroscopic charcoal analysis is common in paleoecological studies in the Pacific Northwest (Figure 1, Table 1). Previous studies cover a variety of different timescales and forest

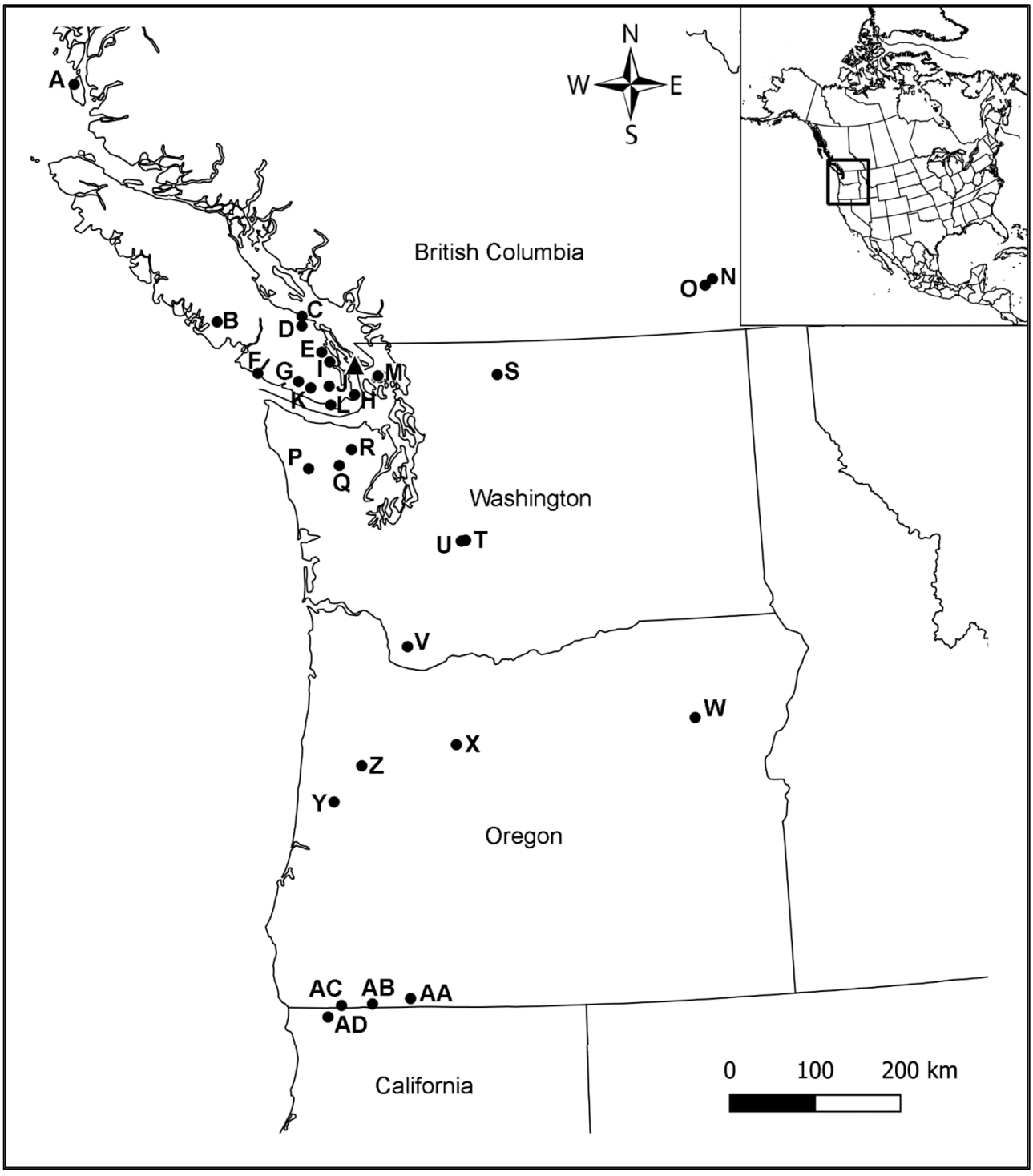

Figure 1: Map of the Pacific Northwest with other relevant sediment-based macroscopic charcoal studies (black circles). Roe Lake is noted as a triangle. See Table 1 for a list of sites.

Table 1: List of sites from other relevant sediment-based macroscopic charcoal studies in the Pacific Northwest. See Figure 1 for site locations.

Site	Site Name	Province/State	Latitude (°N)	Longitude (°W)	Source
A	Hakai Lúxvbálís Conservancy	British Columbia	51°38’	128°05’	Hoffman et al. 2016
B	Clayoquot Lake/Valley	British Columbia	49°12'01"	125°31'08"	Gavin et al. 2003a, 2003b
C	Enos Lake	British Columbia	49°16'53"	124°09'28"	Brown and Hebda 2002a
D	Boomerang Lake	British Columbia	49°10'48"	124°09'25"	Brown and Hebda 2002a
E	Somenos Lake	British Columbia	48°48'13.5"	123°42'12.8"	Murphy et al. 2019
F	Whyac Lake	British Columbia	48°40′20″	124°50′40″	Brown and Hebda 2002b
G	Pixie Lake	British Columbia	48°35'42"	124°11'49"	Brown and Hebda 2002b
H	Mystic Vale	British Columbia	48°27'38"	123°18'18"	McDadi and Hebda 2008
I	Porphyry Lake	British Columbia	48° 54' 20"	123° 50' 00"	Brown and Hebda 2003

Site	Site Name	Province/State	Latitude (°N)	Longitude (°W)	Source
J	Sooke Lake Reservoir	British Columbia	48° 32' 60"	123° 42' 36"	Brown et al. 2019
K	Walker Lake	British Columbia	48° 31' 45"	124° 00' 08"	Brown and Hebda 2003
L	East Sooke Fen	British Columbia	48° 21' 07"	123° 40' 54"	Brown and Hebda 2002b
M	Moran State Park	Washington	48°39'53.5"	122°49'29.2"	Sugimura et al. 2008
N	Rockslide Lake	British Columbia	49°33'03"	117°31'14"	Gavin et al. 2006
O	Cooley Lake	British Columbia	49°29'28"	117°38'43"	Gavin et al. 2006
P	Yahoo Lake	Washington	47° 40' 38"	124° 1' 8"	Gavin et al. 2013
Q	Moose Lake	Washington	47°53'00"	123°21'00"	Gavin et al. 2001
R	Martins Lake	Washington	47°42'50"	123°32'25"	Gavin et al. 2001
S	Panther Potholes	Washington	48° 39' 31"	121° 2' 23"	Prichard et al. 2009
T	Sunrise Lake	Washington	46°55'10"	121°35'22"	Walsh et al. 2017

Site	Site Name	Province/State	Latitude (°N)	Longitude (°W)	Source
U	Shadow Lake	Washington	46°54'41"	121°39'25"	Walsh et al. 2017
V	Battle Ground Lake	Washington	45° 48' 20"	122° 29' 36"	Barnosky 1985; Walsh et al. 2008
W	Anthony Lake	Oregon	44°57′36.6"	118°13′53.6"	Long et al. 2019
X	Breitenbush Lake	Oregon	44°46'05.8"	121°46'48.9"	Minckley and Long 2016
Y	Little Lake	Oregon	44°09′56"	123°34′14"	Long et al. 2007
Z	Beaver Lake	Oregon	44° 55' 02"	123° 17' 46"	Walsh et al. 2010
AA	Hobart Lake	Oregon	41° 5' 58"	122° 28' 54"	White et al. 2015
AB	Upper Squaw Lake	Oregon	42°02'30"	123°01'11"	Colombaroli and Gavin 2010
AC	Bolen Lake	California	42° 01' 30"	123° 27' 30"	Brilles et al. 2005, 2008
AD	Sanger Lake	California	41° 54' 06"	123° 38' 49"	Brilles et al. 2008

types, but general trends in fire activity in the region can be established. Fire was uncommon throughout the Pacific Northwest at the start of the Holocene, around 12,000 cal yr BP, but increased over time as the Cordilleran Ice Sheet retreated and temperatures gradually increased (Walsh et al. 2015). By 10,000 cal yr BP, fire frequency was high at most sites in the Pacific Northwest (e.g. Walsh et al. 2008, 2010, 2015; White et al. 2015; Minckley and Long 2016; Long et al. 2019). The warmer and drier regional climate coupled with increased seasonality at the time likely contributed to this period of more frequent fire. The mid-Holocene was characterized as a period of decreased fire activity in most of the region as seasonality continued to decrease, reaching an overall low in biomass burning around 5500 cal yr BP (Walsh et al. 2015). After this point, biomass burning increased at many sites despite decreased temperatures, peaking around 900 cal yr BP (Walsh et al. 2015). This is often attributed to Indigenous burning practices (e.g. Brown and Hebda 2002; Walsh et al. 2015; Hoffman et al. 2016; Brown et al. 2019). Some sites in the Pacific Northwest again see increased burning ~150 cal yr BP, likely due to the use of fire for land clearing and development associated with the establishment of European settlements (e.g. McDadi and Hebda 2008; Walsh et al. 2015).

Anthropogenic Fire in the Late Holocene

Pre-contact Indigenous populations of northwestern North America are known to have used low severity fire as a form of resource management in a variety of different environments (Turner 1999; Lepofsky and Lertzman 2008), including on southern Vancouver Island (Turner 1999; Fuchs 2001; MacDougall et al. 2004; Vellend et al. 2008; McCune et al. 2013). Early European travelers and settlers noted that fire was frequently used to promote the growth of edible camas bulbs found within Garry oak savannas and woodlands (Turner 1999; MacDougall

et al. 2004; Lepofsky and Lertzman 2008) and archeological evidence suggests fire was actively used by Indigenous populations in the region as early as 2000 cal yr BP (McCune et al. 2013). According to Brown and Hebda (2002), population estimates for southwestern Vancouver Island before European contact range from anywhere between 360 people to 9000 people, with the higher number being far more likely. Inconsistencies in late Holocene charcoal records throughout southern Vancouver Island suggest the use of fire by Indigenous peoples is likely (Brown and Hebda 2002; Walsh et al. 2015; Brown et al. 2019).

Research Objectives and Significance

The primary goal of this study is to reconstruct the fire history on Pender Island over the last 10,000 years through lake sedimentary charcoal analysis conducted at high temporal resolution. Most other charcoal studies in the area cover much shorter timescales (e.g. McDadi and Hebda 2008; Murphy et al. 2019) or do not use contiguous sampling methods (e.g. Brown and Hebda 2002a; 2002b; 2003). Macroscopic charcoal analyses were used to quantify charcoal accumulation rates, fire return intervals, and charcoal peak magnitude, and the charcoal record was then compared to local vegetation and climate data from independent sources on the same timescale.

In particular, this study allows for further understanding of the role of climate in regulating fire regimes. Most of the changes in forest composition on Pender Island over the last 10,000 years revolve around the gradual closing of the canopy rather than drastic changes in the type of vegetation present. This provides an opportunity to focus on climate as a main driver of change in the fire regime as the vegetation shifts are relatively minor compared to many other sites in western North America.

This study expands our understanding of the importance of fire in maintaining these ecosystems by providing a long-term perspective and adds to the body of paleoecological studies in those environments. This study also provides important baseline information on natural fire frequencies, which can be used to develop prescribed burning strategies in the region.

Study Site

Pender Island is one of the Gulf Islands of southwest British Columbia in the Strait of Georgia. The climate on Pender Island is relatively dry compared to much of British Columbia's coast with a mean annual temperature of 9.9 °C and mean annual precipitation of 802 mm (Wang et al. 2016). The island is located within the Coastal Douglas-fir biogeoclimatic zone (Nuszdorfer et al. 1991). Forests are dominated by *Pseudotsuga mensiezii* with fragmented patches of *Quercus garryana* savanna throughout (Nuszdorfer et al. 1991; Vellend et al. 2008). These savannas are particularly important as they contain many endangered and threatened species (Nuszdorfer et al. 1991; Fuchs 2001; Pellatt et al. 2015) and require low severity fires to avoid encroachment (Fuchs 2001; MacDougall et al. 2004; Gedalof et al. 2006; Vellend et al. 2008).

Lucas and Lacourse (2013) provide a high temporal resolution record of vegetation composition on the Island over the last 10,000 years from the same sediment core used in this study. Pollen analyses indicate *Pseudotsuga menziesii* is the dominant conifer species throughout the record, although it was found at lower levels in the early Holocene. Shrub, herb, and fern taxa, notably *Pteridium aquilinum*, were common at this time indicating the presence of open canopy forest. *Pseudotsuga menziesii* becomes increasingly common in the middle to late Holocene, along with an increase in Cupressaceae after 3000 cal yr BP, suggestive of cooler and

wetter conditions. *Quercus garryana* also establishes in the middle Holocene, reaching its peak between 7000 and 6000 cal yr BP, but decreases significantly after that point and is uncommon on Pender Island today. Changes in vegetation structure and composition at Roe Lake over the course of the Holocene mainly consist of a shift from open-canopy mixed conifer forests towards closed-canopy *P. menziesii* dominated forests as climate cooled and moisture increased.

Roe Lake (48°46'59" N, 123°18'11" W) is a 3-hectare lake on northwestern Pender Island within the Gulf Islands National Park Reserve. The lake is found at 100 m asl and its maximum water depth is 9.5 m with no current inflowing streams (Lucas and Lacourse 2013). Its catchment is estimated to be around 105 ha (McCoy 2006). Modern vegetation around the lake is largely dominated by *Pseudotsuga menziesii* but *Thuja plicata* and *Abies grandis* are also common in the canopy (Lucas and Lacourse 2013). The understorey is mainly composed of *Gaultheria shallon, Symphoricarpos albus, Polystichum munitum*, and *Pteridium aquilinum*. *Quercus garryana* can be found scattered on nearby ridges on the east side of the lake (McCoy 2006; Lucas and Lacourse 2013) but no clearly defined patches of *Q. garryana* savanna are present in the catchment (Pellatt et al. 2015).

While the Gulf Islands National Park Reserve acknowledges that this ecosystem is dependent on fire, its fire management strategy has continued to be fire suppression over the last 100 years (Parks Canada 2010). As a result, no large fires seem to have occurred on the island since the early 1930s based on photographs and charcoal analysis (Lucas and Lacourse 2013).

MATERIALS AND METHODS

Sediment Collection and Chronology

In May 2011, a 903 cm long sediment core was collected near the centre of Roe Lake in 9.14 m of water. The sediment-water interface and the uppermost 47.5 cm of sediment were collected using a 6.25 cm diameter Glew gravity corer (Glew et al. 2001). The rest of the sediment core was collected using a 5 cm diameter Livingstone piston corer (Wright et al. 1984) in nine drives, each approximately 1 m in length. This core is nearly entirely composed of dark brown gyttja (organic-rich lake sediment) with a tephra layer at 573.0 to 573.5 cm from the Mt. Mazama eruption (Lucas and Lacourse 2013). This Roe Lake sediment core was used in Lucas and Lacourse (2013) for inferring forest history over the last 10,000 years and fire history over the last 1300 years. This fire history work corresponds to the first 118 cm of the 903 cm long core. The charcoal counts from the samples collected in Lucas and Lacourse (2013) were used in this study.

The Roe Lake sediment core was dated using a combination of ^{210}Pb dating, accelerator mass spectrometry radiocarbon (^{14}C) dating on plant macrofossils and bulk sediment (Appendix A), and the Mazama tephra (Egan et al. 2015). Lucas and Lacourse (2013) used IntCal09 (Reimer et al. 2009) and linear interpolation for the age-depth model. The age-depth model (Appendix A, Figure A) has since been re-built using IntCal20 (Reimer et al. 2020) and Bayesian approaches in Bacon 2.3 (Blaauw and Christen 2011) and rplum 0.1.4 (Aquino-Lopez et al. 2018).

Charcoal Analysis

The lake sediment core was contiguously sampled by collecting 1 or 2 cm^3 of sediment every centimetre of the length of the core except for the upper 47.5 cm and 3 cm at and around the Mazama tephra where resolution was increased, and 1 cm^3 samples were taken every 0.5 cm. In total, 960 sediment samples were collected for charcoal analysis, 784 of which were prepared in this study. Samples were prepared for macroscopic charcoal analysis according to an adapted protocol from Higuera et al. (2005), Schlachter and Horn (2010), and Whitlock and Anderson (2003). Each sample was treated with 3% H_2O_2 for 24 hours and then gently rinsed through a 150-µm sieve with distilled water. The portion with particles larger than 150 µm was poured into a Bogorov counting tray with particles suspended in water. Charcoal particles were identified and counted at 15-40× magnification using a ZEISS Axio Zoom V16. Particles that were black, opaque, angular, and relatively shiny were identified as charcoal (Whitlock and Larsen 2001). Charcoal particles were assigned to one of three size classes: 150-250 µm, 250-500 µm, and >500 µm.

Statistical Analysis

CharAnalysis 1.0 was used to statistically interpret the charcoal concentration data (Higuera et al. 2009). The data were interpolated to a median sample resolution of 13 years and charcoal accumulation rates (CHAR) were calculated using charcoal concentrations and sedimentation rates. Background CHAR was estimated using a 900-year LOWESS smoothing window robust to outliers (Appendix B) and was used to identify peaks in CHAR. A Gaussian mixture model was used to determine a local threshold to differentiate peaks in CHAR associated with fire events from peaks caused by noise-related variation in CHAR (Gavin et al. 2006). The

Gaussian mixture model assumes non-fire peaks follow Gaussian distributions with changing means and variance throughout the record (Gavin et al. 2006). Any CHAR peaks above the 99% percentile of this Gaussian distribution were used to identify fire episodes (i.e. one or more fires occurring within the time period of a sample). These peaks were then used to calculate various parameters. The fire return interval (FRI) is measured in years and represents the number of years between two identified fire events. Peak magnitude, measured in particles/cm^2/peak, represents the amount of charcoal particles per peak and can be used to infer fire severity. Fire frequency, similar to the FRI, is a metric of fire activity, but is measured by the average number of fire events over a 1000-year period.

The charcoal record was divided into two zones using change point analysis based on changes in mean and variances of CHAR (Killick and Eckley 2014; Rius et al. 2014). The R package 'changepoint' (Killick and Eckley 2014) was used to identify significant change points in the dataset to facilitate discussion of the results and identify periods with distinct CHAR and fire regimes.

Vegetation History and Paleoclimate Estimates

Various vegetation and climate proxies were used to compare to the charcoal data. These proxies were collected from several relevant studies. Pollen data (Appendix C) were taken mostly from Lucas and Lacourse (2013) and pollen types were classified into five categories based on their fire survival strategies according to Rowe (1983) to compare with the charcoal data: endurer, invader, evader, resister, and avoider (see Appendix D for information on this classification). Holocene mean July air temperature anomalies from nearby Saltspring Island were taken from Lemmen and Lacourse (2018) and are based on chironomid assemblages from

Lake Stowell. Inferred mean annual precipitation rates were taken from Marion Lake in the UBC Research Forest (Mathewes and Heusser 1981). Insolation anomalies for 50°N were taken from Berger and Loutre (1991). Finally, the NGRIP record of δO^{18} (NGRIP 2004) and warm ENSO events over 100-year windows (Moy et al. 2002) were also plotted to compare to the fire record at Roe Lake and help shape a more complete record of Holocene climate in the region.

RESULTS

Charcoal Concentrations and Accumulation Rates

Change point analysis identified one change point in charcoal accumulation rates at 7190 cal yr BP. To simplify discussion, the Roe Lake fire history is described below according to the two zones created by this change point: Zone 1 - 10,140 to 7190 cal yr BP, and Zone 2 - 7190 cal yr BP to present. These zones are used throughout the discussion of the results, including climate and vegetation comparisons.

Overall, mean charcoal concentration in the Roe Lake sediment record is 39.5 particles/cm^3 (Figure 2b). Concentrations are higher early in the record, reaching a maximum of 182 particles/cm^3 around 8260 cal yr BP with a mean of 55.6 particles/cm^3 in Zone 1 (i.e., 10,140 – 7190 cal yr BP). Afterwards, concentrations begin to drop, and mean concentration after 7190 cal yr BP is 28.9 particles/cm^3 with a maximum of 143 particles/cm^3 at about 3550 cal yr BP. Charcoal concentrations follow a similar pattern within the three charcoal size classes (150-250 μm, 250-500 μm, and >500 μm). Mean concentrations in Zone 1 are 15.2 particles/cm^3, 19.6 particles/cm^3, and 20.8 particles/cm^3, for each size class, respectively. In turn, means are much lower following 7190 cal yr BP at 6.8 particles/cm^3, 9.8 particles/cm^3, and 13.2 particles/cm^3, respectively (Figure 2c-e).

Charcoal accumulation rates (CHAR) follow a similar trend. Mean CHAR for the entire record is 3.6 particles/cm^2/yr, but is much higher in Zone 1 with a mean of 6.7 particles/cm^2/yr and a maximum of 18.1 particles/cm^2/yr. After 7190 cal yr BP, mean CHAR is much lower at 2.3 particles/cm^2/yr with a maximum of 9.7 particles/cm^2/yr (Figure 2a).

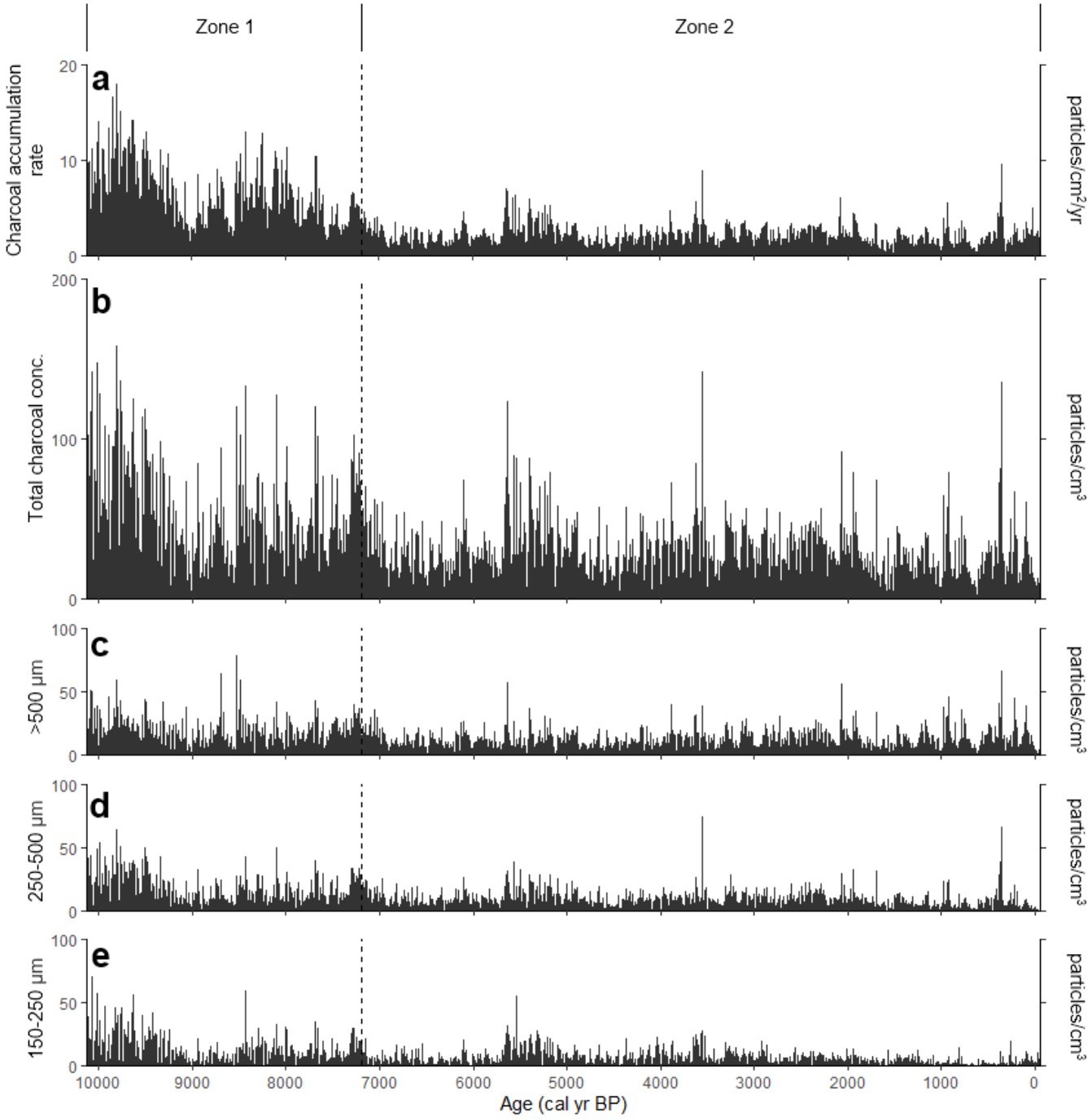

Figure 2: (a) Charcoal accumulation rates (CHAR) at Roe Lake over the last 10,000 years. (b) Total charcoal concentrations at Roe Lake. (c-e) Charcoal concentrations by size class at Roe Lake.

Fire History and Regimes

A total of 71 charcoal peaks were identified as statistically significant over the last 10,000 years (Figure 3), resulting in a mean fire return interval (mFRI) of 142 ± 28 years for the duration of the record. However, mFRI varies considerably during the record, from a minimum of 71 years to a maximum of 352 years (Figure 4b).

Zone 1: 10,140 to 7190 cal yr BP. This zone is characterized by high CHAR and frequent charcoal peaks of low magnitude. Within this 2950-yr period, 28 charcoal peaks were identified with a mFRI of 100 ± 29 years. This means that 39% of all significant charcoal peaks occur within the first 29% of the record. Peak magnitude remained low throughout this zone, with a mean peak magnitude of 38.0 particles/cm^2/peak. The highest charcoal peak reached a maximum of 120 particles/cm^2 and occurred near the end of the zone around 7690 cal yr BP. The second largest peak in this zone occurred about 8260 cal yr BP and had a magnitude of 100 particles/cm^2 (Figure 4a). Fire frequency decreased over time, starting at nearly 12 peaks/1000 yr and dropping to around 6 peaks/1000 yr by the end of Zone 1 (Figure 4c).

Zone 2: 7190 cal yr BP to present. This zone is defined by having lower CHAR and less frequent fire. CHAR never exceeds 10 particles/cm^2/yr throughout Zone 2 (Figure 3). Over this 7190-yr period, 43 fires were identified resulting in a mFRI of 167 ± 43 years, although this varies considerably over the course of the zone. mFRI reached a maximum of 352 years at about 2540 cal yr BP and a minimum of 75 years at about 5330 cal yr BP (Figure 4b). Mean peak magnitude was 23.4 particles/cm^2/peak in this zone. The highest magnitude peak was 204 particles/cm^2 and occurred at ~390 cal yr BP. No fires had occurred for over 300 years prior to

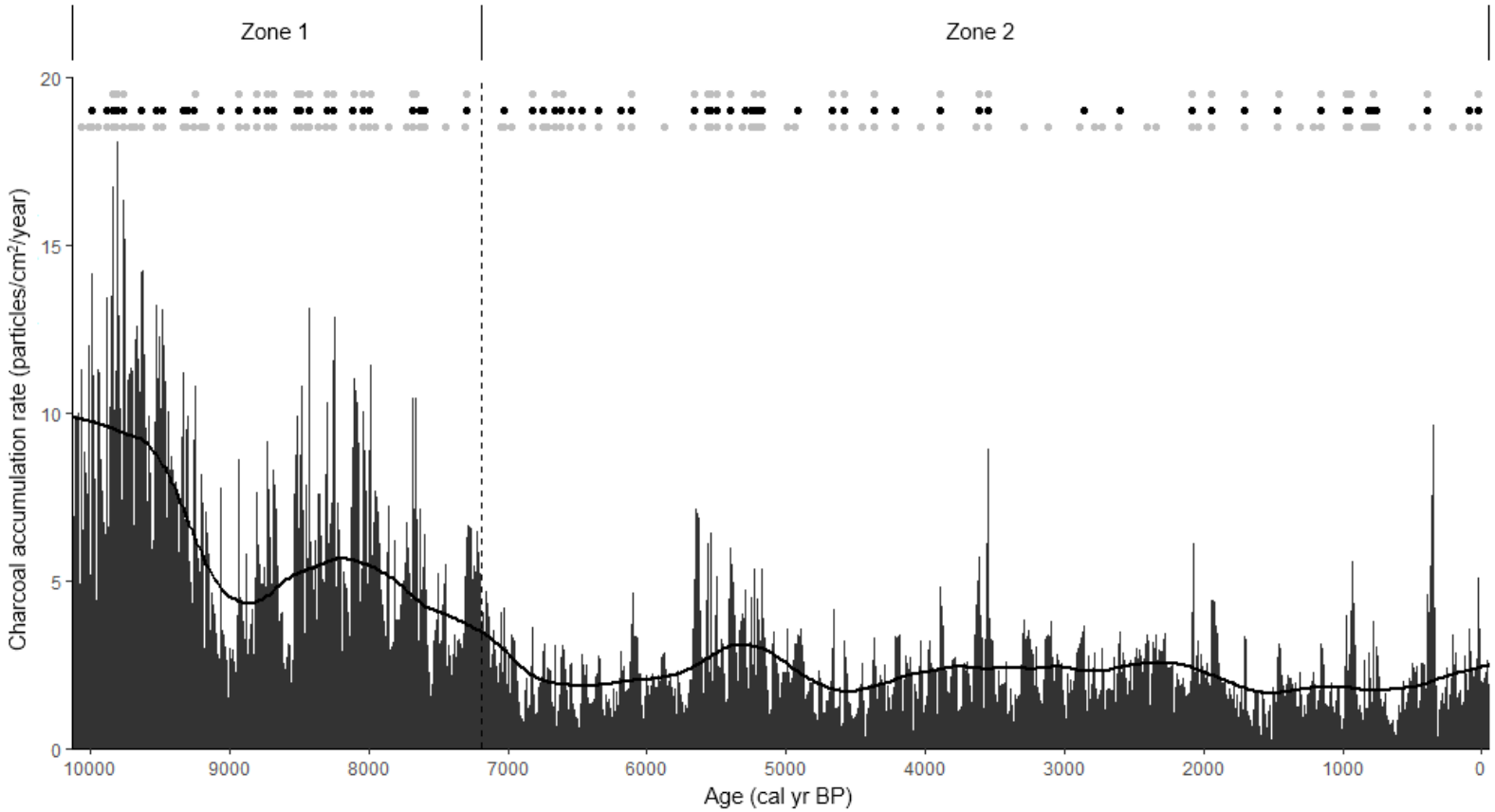

Figure 3: Charcoal accumulation rate, background charcoal accumulation rate (black line), and identified charcoal peaks at the 99th percentile (black circles) over the last 10,000 years at Roe Lake. Light grey circles represent peaks identified at the 95th (bottom) and 99.9th (top) percentile.

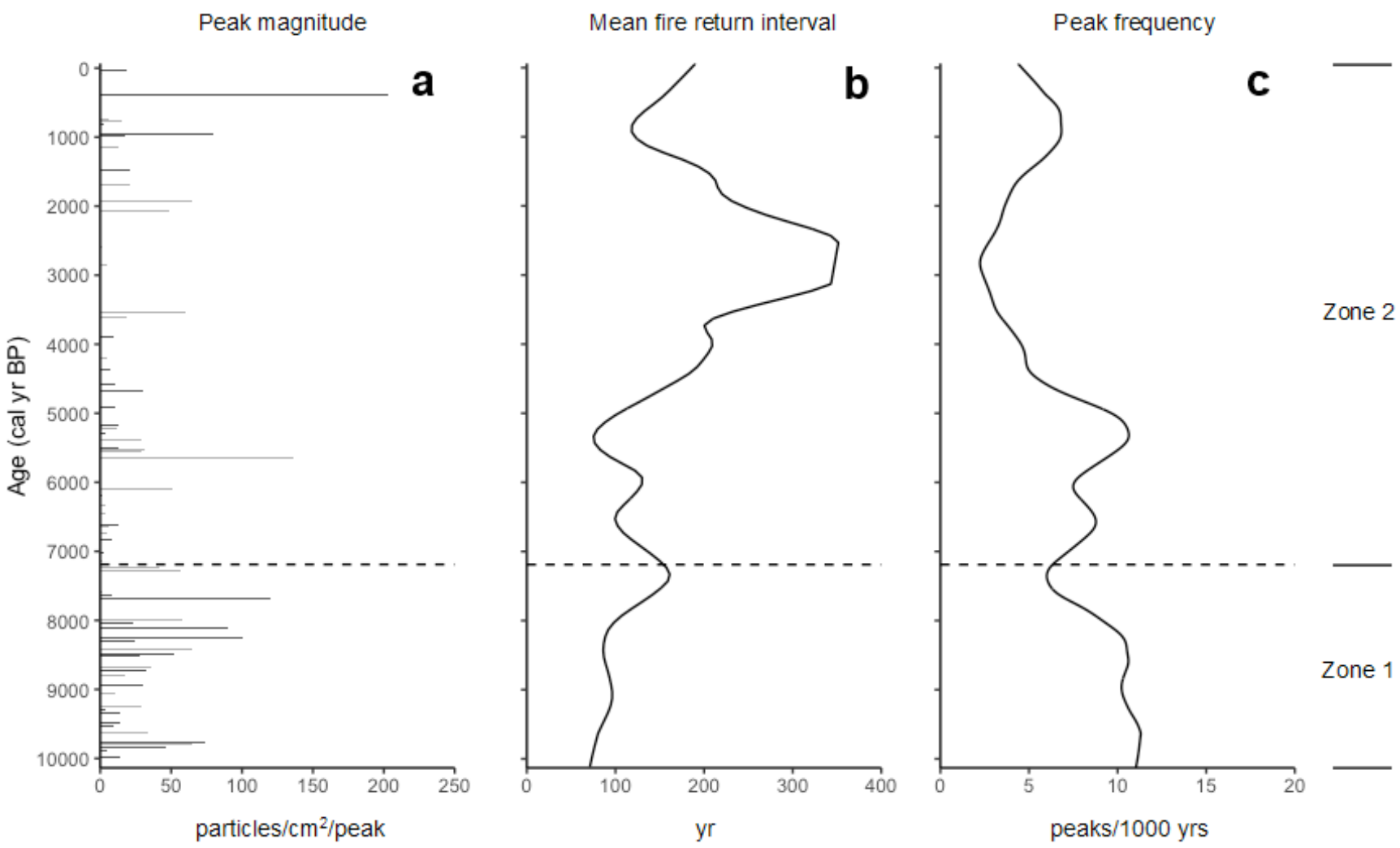

Figure 4: (a) Charcoal peak magnitudes at Roe Lake. (b) Mean fire return interval (mFRI) at Roe Lake. (c) Peak frequency over a 1000-year moving window at Roe Lake.

that peak. Another large charcoal peak occurred at ~5680 cal yr BP with a magnitude of 136 particles/cm^2 (Figure 4a). Fire frequency fluctuates much more in this longer zone than in Zone 1, reaching nearly 12 peaks/1000 yr around 5300 cal yr BP and dropping to about 2 peaks/1000 yr at around 2800 cal yr BP (Figure 4c).

Comparison to Vegetation History and Environmental Change

Vegetation data. Although CHAR zones identified by changepoint analysis are used here in comparison to the vegetation history, the delimitation of these zones is similar to those determined through independent cluster analysis of the pollen data, which showed a significant change in pollen assemblages at 7510 cal yr BP (Appendix C). This is similar in timing to the significant change in charcoal accumulation rates at 7190 cal yr BP (Figure 2).

Arboreal pollen is high throughout the Holocene, but is lower in Zone 1 when fire is more frequent, with a mean of 78.4% and reaching a maximum of 90.6% of the assemblages at ~7600 cal yr BP. In Zone 2, the mean increases to 96.1% arboreal pollen and reaches a maximum of 99.0%, which reflects closure of the canopy as fire frequency decreases (Figure 5b). As a result, the arboreal to non-arboreal pollen ratio (AP/NAP) steadily increases over time, from a mean of 11.7 in Zone 1 to 63.3 in Zone 2 (Figure 5d). Palynological richness, a measure of plant diversity based on rarefaction, is higher in Zone 1, when herbs and ferns were more common with a mean of 26.4 E(T_{500}) early in the record and eventually dropping to a mean of 19.1 E(T_{500}) in Zone 2, when disturbance by fire becomes less common (Figure 5e). Pollen accumulation rates (PAR) are lower in the early Holocene and increase over time, as arboreal pollen becomes more common (Figure 5f). Rates of change in the pollen assemblages are low

throughout the record, but peak around 7550 cal yr BP, near the delineation of the two charcoal zones (Figure 5g).

Pseudotsuga menziesii is relatively uncommon in Zone 1, when fire is most common, never exceeding 40% of the pollen record with a mean of 14.1%. However, as fire decreases in frequency, *P. menziesii* quickly dominates the record during Zone 2 reaching a maximum of 56.0% and a mean of 32.2% (Figure 6b). The increase in *P. menziesii* is the main factor in the closure of the canopy seen over the course of the record. *Pteridium aquilinum,* a fire promoting fern (USDA 2021), follows an opposite trend. *Pteridium aquilinum* levels are high in Zone 1, when fire is frequent, with a maximum of 20.2% and a mean of 8.6% but becomes infrequent in Zone 2 with a maximum of 7.2% and a mean of only 1.3% (Figure 6c). *Quercus garryana* is rare in Zone 1 and is often not present in the assemblages at all. Its frequency increases slightly near the end of the zone reaching a maximum of 3.1% ~7240 cal yr BP. It peaks early in Zone 2, maintaining a mean of 5% between 6820 and 5770 cal yr BP, but decreases after that point and never exceeds 5% again. At its peak, around 6490 cal yr BP, *Q. garryana* reached 16.3% of the assemblage. This peak occurs during a period of increased fire frequency in Zone 2.

Of the five different fire survival strategies, endurers and resisters changed the most over time. In Zone 1, prior to 7510 cal yr BP, resisters make up 14.1% of the pollen record and endurers represent 16.1% on average. However, after 7510 cal yr BP in Zone 2, once fire frequency decreased, resisters increased to a mean of 32.2% while endurers decreased to a mean of only 4.9% (Figure 6f, 6g). The trend among endurers is mainly controlled by *P. aquilinum, Polypodium,* and *Cicuta* type, whereas *P. menziesii* is the only resister present in the Roe Lake pollen record (Appendix D). Invaders and avoiders vary much less over the course of the record with invaders shifting from a mean of 51.9% to 46.1% between Zones 1 and 2, and avoiders

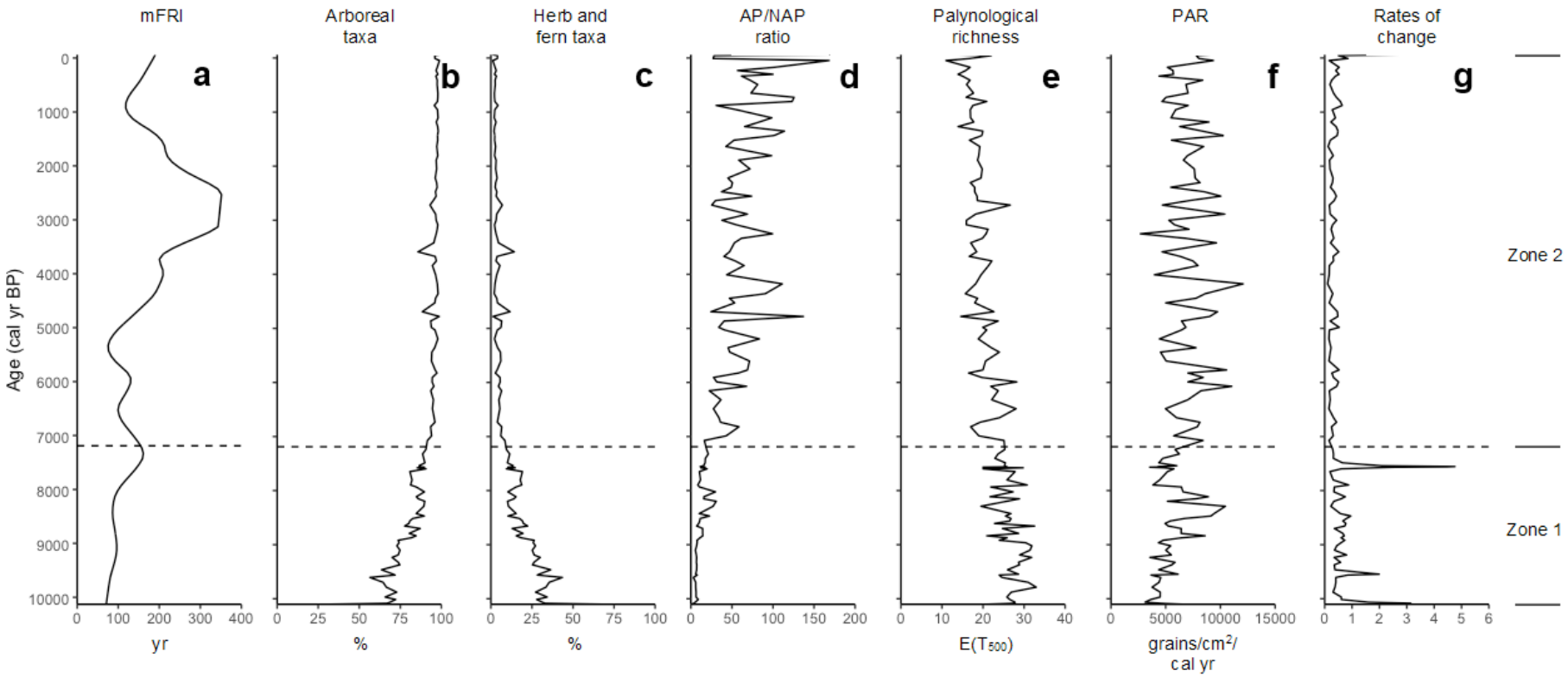

Figure 5: (a) Mean fire return interval (mFRI) at Roe Lake. (b) Total arboreal (AP) pollen percentages at Roe Lake. (c) Total herb pollen and fern spore percentages at Roe Lake. (d) Ratio of arboreal to non-arboreal (AP/NAP) pollen. (e) Palynological richness based on rarefaction sum of 500. (f) Total pollen and spore accumulation rates (PAR). (g) Rates of change in Roe Lake pollen assemblages based on chord distances. The pollen data include those in Lucas and Lacourse (2013) as well as additional samples.

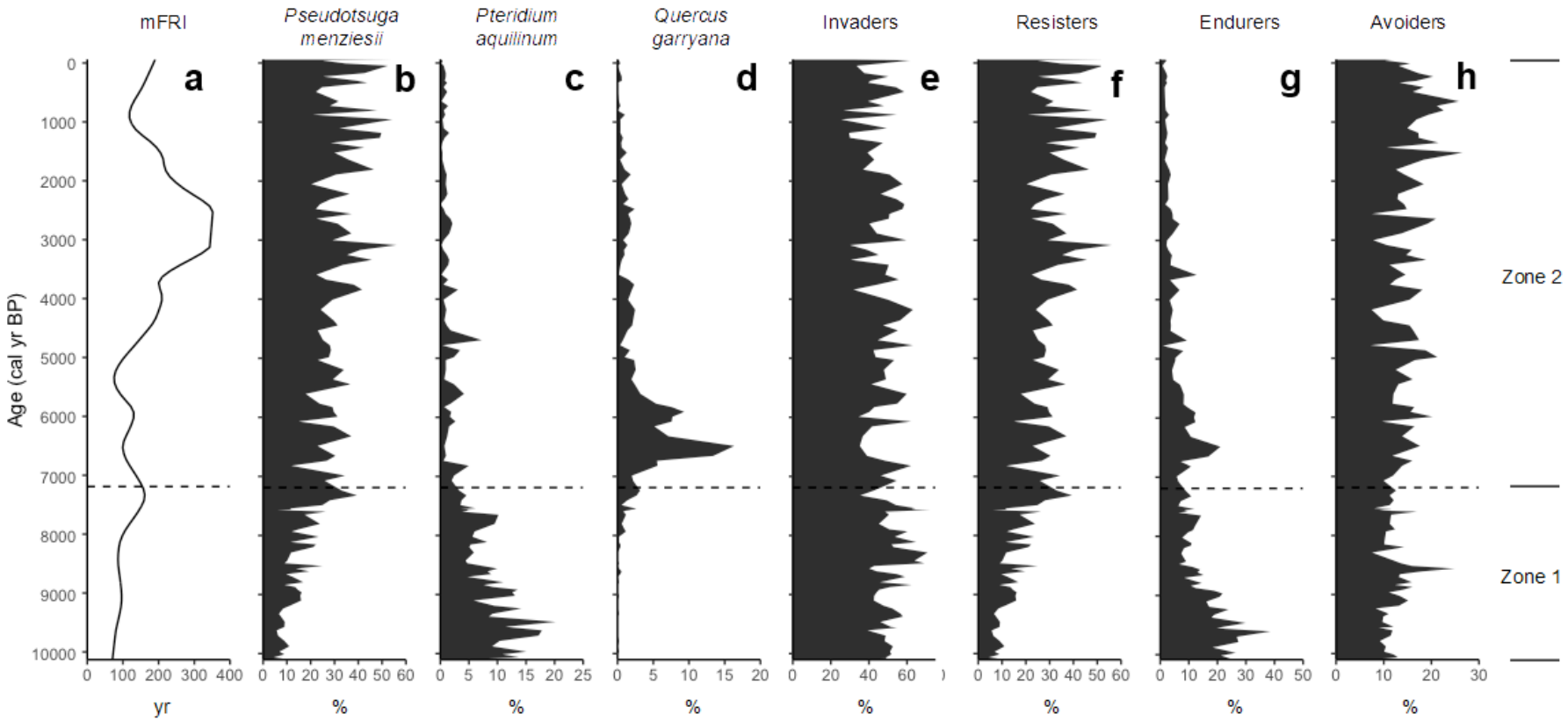

Figure 6: (a) Mean fire return interval (mFRI) at Roe Lake. Pollen and spore percentages of (b) *Pseudotsuga menziesii*, (c) *Pteridium aquilinum* and (d) *Quercus garryana*. Total pollen/spore percentages for (e) invader taxa, (f) resister taxa, (g) endurer taxa, and (h) avoider taxa. The pollen data include those in Lucas and Lacourse (2013) as well as additional samples. See Appendix D for classification of pollen taxa by fire survival strategy.

representing 12.0% of the early record and 15.2% in Zone 2 (Figure 6e, 6h). Common invaders include *Pinus contorta*, *Alnus viridis* and *Alnus rubra*, and common avoiders include *Tsuga heterophylla* and Cupressaceae (Appendix D). Evaders make up <1% of the pollen assemblages throughout the record and are therefore not plotted in Figure 6. In all, species that endure fire and those that invade following a fire are more common during the more frequent fire regime of Zone 1 and avoiders and resisters become more common in Zone 2, when fire is less frequent.

Climate data. In Zone 1, mean July air temperatures (MJAT) (Lemmen and Lacourse 2018) were generally higher than in Zone 2 with a mean of 1.4 °C warmer than present (Figure 7b). Inferred mean annual precipitation (Mathewes and Heusser 1981) was lower than present, with a mean of 1615 mm/yr in Zone 1 (Figure 7c). NGRIP (2004) oxygen isotope records indicate $\delta^{18}O‰$ is low at the start of Zone 1, reaching a low of −43.6 $\delta^{18}O‰$. However, this increases quickly and reaches an equilibrium by the start of Zone 2, staying between −34 and −36 $\delta^{18}O‰$ for the remainder of the record (Figure 7d). These climate reconstructions indicate a warmer and drier early Holocene, consistent with the more frequent fire during this time (Figure 7). Summer and winter insolation (Berger and Loutre 1991) are also much different in the early Holocene, with higher seasonality in Zone 1 compared to Zone 2. Zone 1 sees July insolation values of up to 39.2 W/m^2 higher than present, whereas January insolation anomalies reach a low of −12.1 W/m^2 at the start of the record (Figure 7e). Warm ENSO events (Moy et al. 2002) are rare early in the record, never exceeding 2 events/100 years in Zone 1 and likely not playing much of a role in controlling the local fire regime during this period (Figure 7f).

In Zone 2, MJAT are much more variable, reaching a minimum anomaly of −1.3 °C around 7060 cal yr BP and a maximum of 4.2 °C at 2020 cal yr BP. MJAT also slightly

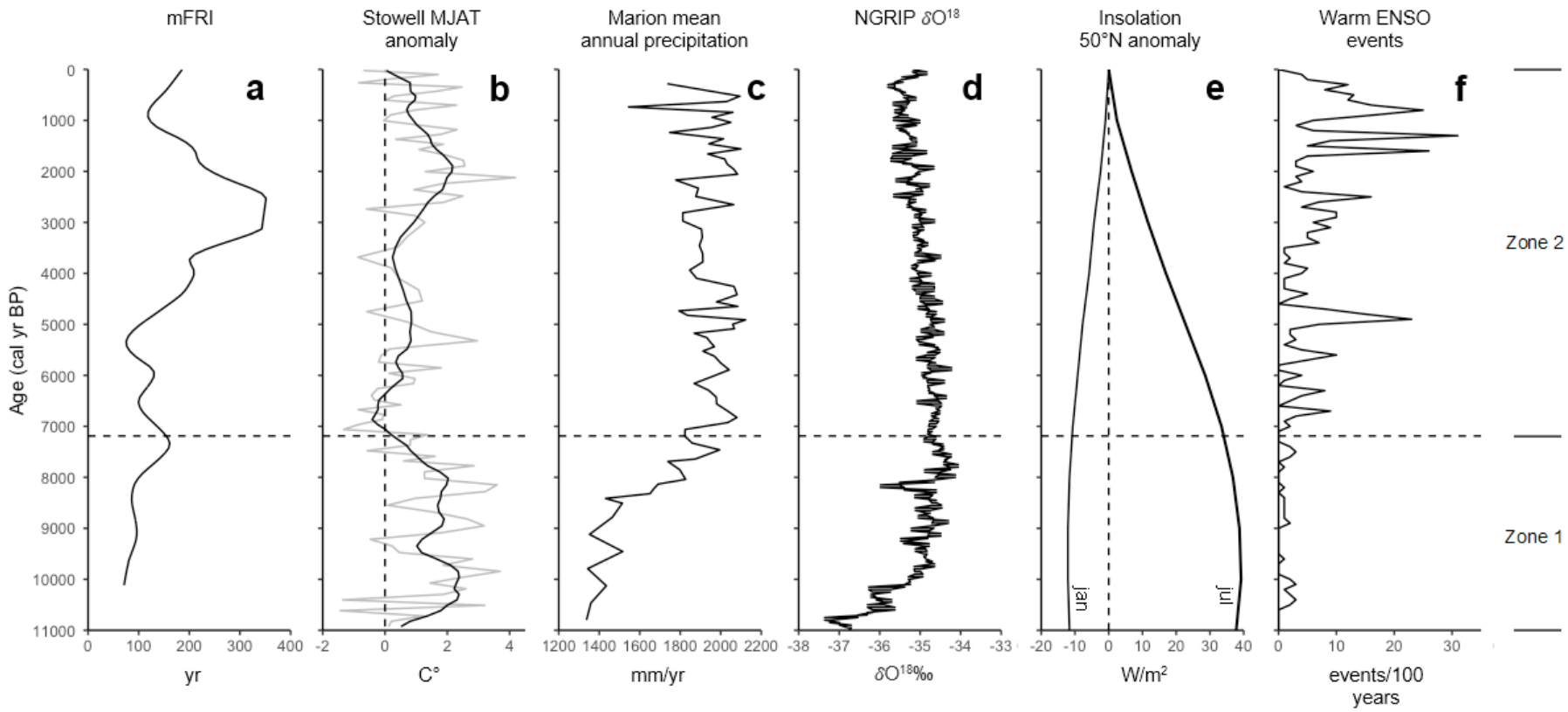

Figure 7: (a) Mean fire return interval (mFRI) at Roe Lake. (b) Mean July air temperature (MJAT) anomalies and Lowess smoothing from Lake Stowell on Saltspring Island, BC (Lemmen and Lacourse 2018). (c) Estimated mean annual precipitation at Marion Lake in the UBC Research Forest (Mathewes and Heusser 1981). (d) NGRIP record of δO^{18} (NGRIP 2004). (e) January and July insolation anomalies for 50°N (Berger and Loutre 1991). (f) Warm ENSO events in 100-yr non-overlapping windows (Moy et al. 2002).

increased around 5000 cal yr BP, coinciding with the increase in fire frequency around the same time (Figure 7b). Inferred annual precipitation also changes significantly later in the record. Between 8500 and 7000 cal yr BP, as fire becomes less frequent, mean annual precipitation increases rapidly, eventually reaching a mean of 1952 mm/yr in Zone 2 (Figure 7c). In terms of seasonality, both January and July insolation anomalies gradually shift towards modern conditions indicating decreased seasonality over time (Figure 7e). Warm ENSO events, however, become more frequent in Zone 2, peaking at 31 events/100 years around 1300 cal yr BP. ENSO events are also more frequent around 5000 and after 2000 cal yr BP, more or less in line with periods of more frequent fire in this zone (Figure 7f).

DISCUSSION

Holocene Fire Regimes on Pender Island

The fire record from Roe Lake spans approximately the last 10,000 years. The first ~2800 years of the record is characterized by high charcoal accumulation rates (CHAR) as well as frequent low-severity fire with a mean fire return interval (mFRI) of 100 ± 29 years (Figure 3). Low severity fire in the context of this study can represent either a low-intensity fire or a geographically small fire as both events would appear as relatively small charcoal peaks within the record. A total of 28 fire episodes was identified between 10,140 and 7190 cal yr BP. However, the first ~1000 years of the record has a signal-to-noise index (SNI) below 3 (Appendix 3), which is below the threshold for accurate peak detection. Thus, it is possible that fire episodes are somewhat under or over-represented in this early period, although high CHAR are consistent with the inferred frequent fire episodes. Based on peak magnitude (Figure 4a), most fires in the early record appear to be of low severity but some higher severity fire events did occur. Fire episodes with high peak magnitude generally occurred after long periods without fire. For example, the largest peak in the early record, at ~7610 cal yr BP, had a magnitude of 120 particles/cm^2 and occurred after nearly 300 years without fire. These fires are likely more intense due to fuel buildup over time.

This early period of more frequent fire is common among paleoecological studies of varying forest types in the Pacific Northwest (e.g., Walsh et al. 2008, 2010, 2015; Prichard et al. 2009; Gavin et al. 2013; White et al. 2015; Minckley and Long 2016; Long et al. 2019). Roe Lake's mean fire frequency of 9.6 peaks/1000 years during Zone 1 is consistent with other nearby studies with forests similar to the open canopy *Pseudotsuga menziesii* forests present at the time (e.g. Walsh et al. 2008; Brown et al. 2019). Long et al. (2007) note that fire-adapted taxa

were more common in the early Holocene in the Coast Range in western Oregon when conditions were drier and fire was more frequent and fire-sensitive taxa became progressively more common over time. A similar vegetation shift occurs at Roe Lake, where endurer and invader taxa such as *Pteridium aquilinum* and *Alnus* respectively, both fire-adapted survival strategies, are more common in the early record when fire is most frequent, with avoiders following an opposite trend (Figure 6; Appendix D).

After ~7190 cal yr BP, CHAR and fire frequency both decrease at Roe Lake, with mFRI increasing to 167 ± 43 years with a total of 43 fire episodes occurring during this time (Figures 3, 4). CHAR remains low for the rest of the record, but fire frequency varies considerably over the last 7190 years, with mFRI fluctuating between 75 and 352 years. Fire severity does not vary much compared to earlier in the record despite the lower frequency, and low severity fire continues to be the norm, with larger severity fire occurring after long periods without identified fire episodes. The largest charcoal peak in the record, with a magnitude of 204 particles/cm^2, occurred ~390 cal yr BP, 300 years after the previous charcoal peak. The next largest fire episode was around 5660 cal yr BP and had a magnitude of ~136 particles/cm^2. Nearly 480 years had elapsed since the previous identified fire episode (Figure 4a).

This shift towards less frequent fire in the middle Holocene is typical for the Pacific Northwest, with decreased fire frequencies and biomass burning between 8000 and 4000 cal yr BP (Walsh et al. 2015). As forests surrounding Roe Lake become increasingly dominated by *Pseudotsuga menziesii* and the canopy closes, fire becomes less frequent and the regime begins to look similar to other Douglas-fir dominated forests (Long et al. 2007; Walsh et al. 2008; Brown et al. 2019). For example, consistent low severity fire is also seen at Battle Ground Lake, where forests are largely dominated by *P. menziesii* and are comparable to those at Roe Lake in

the middle to late-Holocene (Barnosky 1985; Walsh et al. 2008). Fire-sensitive avoider taxa, such as *Tsuga heterophylla* and Cupressaceae, become more common as fire decreases, a trend also seen in the Coast Range in Oregon with many of the same fire-sensitive taxa (Figure 6; Appendix D; Long et al. 2007).

Despite the general trend towards less frequent fire in the middle to late-Holocene at Roe Lake, the fire regime was highly variable. Fire increases in frequency between 7000 and 5000 cal yr BP. During this time, the mFRI shortens to as little as 75 years, the shortest return interval since ~9850 cal yr BP. Frequency drops quickly after this period and fire becomes especially infrequent between ~3500 and 2500 cal yr BP, with the mFRI well above 300 years (Figure 4b). In fact, only two low-magnitude fire episodes are identified during this time with peaks never exceeding 6 particles/cm^2 (Figure 4a). However, the latter half of this period of infrequent fire corresponds with a dip in SNI below 3 (Appendix 3). Therefore, it is possible fires are underrepresented around this time and are not actually as infrequent as they appear here. After 2500 cal yr BP, fire frequency gradually begins to increase again, reaching an mFRI of 118 years at its shortest around 940 cal yr BP (Figure 4b).

Other methods of past fire regime reconstruction are possible in the late Holocene. On a shorter timescale and higher time resolution, tree ring records in Washington indicate that individual trees scarred in a *P. menziesii* and *Q. garryana* woodland as frequently as every 18.4 years between 1700 and 1879, with the majority of fires being attributed to intentional Indigenous burning (Sprenger and Dunwiddie 2011). On nearby southern Vancouver Island, people likely burned *Q. garryana* savanna annually (Geladof et al. 2006). However, despite a clear increase in fire frequency around this time at Roe Lake as the mFRI shortened to about 118 years, these very frequent burns are not seen in the charcoal record at Roe Lake. This is likely

because these fires are too small to appear as distinct peaks in the charcoal record (McCune et al. 2013). After European settlement, between 1880 and 2004, the tree ring-inferred mFRI lengthens to over 100 years, reflecting a reduction in Indigenous burning practices and the introduction of modern fire suppression (Sprenger and Dunwiddie 2011). This is also seen on southern Vancouver Island, as European settlers were generally averse to Indigenous burning, and woody taxa, particularly *P. menziesii*, became progressively more common after European arrival (Geladof et al. 2006). A similar sharp decrease in fire frequency is not visible with the 1000 year smoothing window used in this study. However, the last identified fire episode in the Roe Lake record occurs over 90 years ago, ~30 cal yr BP (Figure 3), which is corroborated with photographs from the 1920s and 1930s when a fire occurred on Pender Island northeast of Roe Lake (Lucas and Lacourse 2013).

The Role of Climate in Regulating Fire Regimes

Climate appears to be the main factor controlling fire regimes on Pender Island for most of the last 10,000 years. The warm and dry climate (Lemmen and Lacourse 2018; Mathewes and Heusser 1981) in the early Holocene created conditions conducive to the more frequent fire in Zone 1 of the Roe Lake charcoal record (Figure 6c-d). Seasonality was also at its highest in the early Holocene (Berger and Loutre 1991) and precipitation was at its lowest (Figure 7c, 7e). In fact, climate was consistently warmer and drier throughout northwest North America and many other studies in the Pacific Northwest also show more frequent fire in the first half of the Holocene (e.g., Walsh et al. 2008, 2010; White et al. 2015; Minckley and Long 2016; Long et al. 2019). The mFRI from Roe Lake is at its shortest in the warm and dry early record with a mFRI of 100 ± 29 years, reaching a minimum of only 71 years between fire episodes at ~10,100 cal yr

BP (Figure 4b). After 7190 cal yr BP, as climate begins to cool and precipitation increases (Lemmen and Lacourse 2018; Mathewes and Heusser 1981), fire became less common and reached a mFRI of 167 ± 43 years. Relatively short-lived variations in climate, such as the Medieval Climate Anomaly and the Little Ice Age, are not visible in the Roe Lake mFRI and fire frequency curves due to the 1000-yr smoothing window, which smooths out short variations at this scale. However, Lucas and Lacourse (2013) found that these two climate anomalies did have an impact on the Pender Island fire regime when using a 200-yr long smoothing window for a charcoal record spanning only the last 1300 years. During the warm and dry Medieval Climate Anomaly, mFRI dropped to around 50 years, whereas mFRI lengthened to ~125 years during the colder Little Ice Age a few centuries later (Lucas and Lacourse 2013).

At times throughout the record, climate does not appear to be the main factor controlling the fire regime at Roe Lake. Between 7000 and 5000 cal yr BP, there is an increase in fire frequency despite climate continuing to cool and moisten (Figures 4b-c, 7c-d). The cause for this increase in fire remains unclear. Most paleoclimate proxies do not suggest conditions conducive to more frequent fire with the exception of warm ENSO events becoming more common than they had been previously (Moy et al. 2002; Figure 7g). This may have caused summer climate to be less stable, possibly leading to periodic summer droughts. However, the relationship between warm ENSO events and fire on long timescales remains generally unclear, with contradictory findings among studies (Walsh et al. 2015). While the increase in warm ENSO events may have played some role in regulating the fire regime at Roe Lake at the time, it is possible that a factor other than climate was driving the shift between 7000-5000 cal yr BP. A change in vegetation composition rather than climate may have caused this notable increase in fire frequency.

The Role of Forest Composition in Regulating Fire Regimes

Forest communities on Pender Island change subtly through the Holocene (Lucas and Lacourse 2013). The main shift consists of a closure of the canopy towards the modern *Pseudotsuga menziesii* dominated forests on Pender Island today, as well as the rise and fall of *Quercus garryana* in the middle Holocene. Early in the record, between ~10,000 and 7500 cal yr BP, *P. menziesii* forests in the area were more open than they are today and herbaceous taxa were more prevalent (Figure 4c-e). The vegetation present around Roe Lake during this time was generally more adapted to frequent fire, with endurers (e.g. *Pteridium aquilinum, Polypodium, Cicuta*) and invaders (e.g. *Pinus contorta, Alnus rubra, Alnus viridis*) being the most common fire survival strategies of plant taxa in the pollen record (Figure 6e-f). These open canopy forests or woodlands were likely maintained by the more frequent fire of the time.

Pteridium aquilinum is one of the most prominent fern taxa in the record during this time (Lucas and Lacourse 2013; Figure 6d). *Pteridium aquilinum* is considered a fire promoting species, being both an impressive early invader following disturbance and adding highly flammable dry fronds to the forest litter every year (Agee and Huff 1987). Its common presence in the early Holocene helped contribute to the higher fire frequency and further indicates that fire was likely an important factor in maintaining the relatively open forests around Roe Lake at the time.

With climate heavily regulating the fire regime, fire becomes less frequent over the middle and late Holocene. With less disturbance, late successional taxa can outcompete many of the herbaceous taxa that were common in the early Holocene, allowing the canopy to close and gradually leading to *P. menziesii* dominated closed-canopy forests (Figures 4, 5). The decrease in palynological richness over time is also indicative of decreased disturbance and the

establishment of a mid- to late successional community (Figure 4f). Endurer and invader taxa, many of which are early successional herbaceous taxa, become less common in the pollen record as most can be easily outcompeted as disturbance decreases (Figure 6). Among these, *P. aquilinum*, an endurer, decreases considerably, reducing its impact on the fire regime at Roe Lake. In turn, avoider and resister taxa increase over time (Figure 6e). *Pseudotsuga menziesii* is the only resister (Appendix D), explaining the increase in resisters over the course of the record. Avoiders, however, consist of several taxa that are generally sensitive to fire and avoid establishing in environments that frequently burn. The increase in avoiders, although small around Roe Lake, may indicate increased survivorship and is another indication of less frequent fire over time.

Similar to the fire regime, the vegetation composition around Roe Lake is heavily dependent on climate. These climate-driven shifts in vegetation contributed to changes in the fire regime, further demonstrating the importance of climate in regulating the long-term fire regime on Pender Island throughout the record both directly and indirectly.

Quercus garryana *and its Relationship with Fire*

Fire frequency at Roe Lake varies considerably over the course of the last 7500 years despite climate trending towards cooler and wetter conditions over time. A period of frequent fire similar to that of the warm and dry early record occurs between 7000 and 5000 cal yr BP followed by a period of very infrequent fire between 4000 and 2000 cal yr BP (Figure 4). Interestingly, the pollen assemblages from Roe Lake generally do not vary in a similar way during these periods. Instead, the pollen record consistently shows high proportions of arboreal taxa compared to herbaceous taxa, decreased palynological richness over time, and a decrease in

endurer and invader taxa, all indicative of an environment with infrequent fire (Figures 5, 6). The main change in vegetation during this period of more frequent fire between 7000 and 5000 cal yr BP is a marked increase in *Quercus garryana* pollen. Representing under 3% of the pollen assemblage for most of the record, the mean proportion of *Q. garryana* pollen increases to over 5% between 6820 and 5770 cal yr BP, reaching a maximum of 16% of the assemblage by ~6490 cal yr BP (Lucas and Lacourse 2013).

Quercus garryana and its associated communities are present in much of the Pacific Northwest and appear throughout the Holocene. At Beaver Lake, in Oregon, *Q. garryana* is well established as early as ~11,000 cal yr BP and persists until today (Walsh et al. 2010). Further south, at high elevation sites in northern California and southern Oregon, *Q. garryana* is present in trace amounts prior to 11,000 cal yr BP but becomes much more abundant later (Brilles et al. 2005; 2008) with pollen reaching above 20% of the assemblage by ~9000 cal yr BP at Sanger Lake (Brilles et al. 2008). In southern Washington, at Battle Ground Lake, *Q. garryana* is present throughout the Holocene but is especially abundant between 11,000 and 5000 cal yr BP (Barnosky 1985; Walsh et al. 2008). On southern Vancouver Island, *Q. garryana* arrives later, with its first appearance in the pollen record occurring around 11,000 cal yr BP (Pellatt et al. 2001; Brown et al 2019). It remained present only in trace amounts until ~8000 cal yr BP. A peak in oak pollen, similar to the one seen at Roe Lake between 6820 and 5770 cal yr BP (Lucas and Lacourse 2013), then occurs between 8000 and 6000 cal yr BP (Pellatt et al. 2001; Brown et al 2019). Genetic similarities between the two population (Ritland et al. 2005) indicate that Garry Oak likely migrated from Vancouver Island to the Gulf Islands. Both populations see a decline at a similar time, indicating the decreased abundance in *Q. garryana* ~6000 cal yr BP was probably largely climate driven. As climate cooled, fire became less common, allowing the closed canopy

P. menziesii forests on Pender Island to gradually outcompete the remaining *Q. garryana* communities. Today, there are no defined patches of *Q. garryana* savanna near Roe Lake (Pellatt et al. 2015).

Although Garry oak is classified as an endurer in this study (Appendix D), it exhibits both endurer and resister traits (Nemens et al. 2019). Seedlings have deep taproots that allow for resprouting following fire and adults have a thick fire-resistant bark (Agee 1993, 1996; Fuchs 2001; Nemens et al. 2019). *Quercus garryana* seedlings are also often found on frequently disturbed sites along with other early successional seedlings (Agee 1993). These adaptations allow it to outcompete many other woody species in environments with frequent low-severity fire, particularly Douglas-fir (Sprenger and Dunwiddie 2011; Nemens et al. 2019). Therefore, Garry oak and its associated savanna or woodland communities would require fire to avoid *P. menziesii* encroachment on Pender Island. At other paleoecological sites within its range, the presence of *Q. garryana* and associated taxa were more common in periods of more frequent fire (Walsh et al. 2008, 2010). The increased fire frequency at Roe Lake between 7000 and 5000 cal yr BP likely helped maintain the higher abundance of *Q. garryana* on Pender Island in the middle Holocene. In turn, the open grasslands or savannas were more fire-prone than the surrounding forests, and likely burned more frequently.

Human Role in Regulating Fire on Pender Island

After 2500 cal yr BP, fire frequency again begins to increase at Roe Lake, this time with no clear correlation with changes in vegetation or climate. Human activities may have been the main factor controlling this shift in the fire regime. Brown and Hebda (2002) estimate human populations on southern Vancouver Island ranged anywhere from a few hundred to nearly 9000

prior to European contact and argue that the higher estimate is more likely. Early European settlers on southern Vancouver Island noted that fire was used on a nearly yearly basis to promote the growth of certain foods, particularly camas bulbs found within Garry oak savannas (Turner 1999; Lepofsky and Lertzman 2008). On nearby islands in Washington state, fire was also used to facilitate deer hunting (Turner 1999). Archeological evidence suggests active Indigenous fire management practices were occurring on southern Vancouver Island by at least 2000 cal yr BP (McCune et al. 2013). Indigenous populations in the Gulf Islands likely practiced similar fire management strategies (Carlson and Hobler 1993).

Despite the increase in fire frequency on Pender Island in the late Holocene, the mFRI was still relatively high, with a mFRI of around 118 years at its lowest (Figure 4b). If there were human-set fires on Pender Island in the early Holocene, they would not likely have been large or intense enough to produce significant peaks in the charcoal record (McCune et al. 2013). Studies on southern Vancouver Island and elsewhere in the Pacific Northwest commonly find more frequent fires in the late Holocene (Walsh et al. 2015), suggesting that intentional burning by Indigenous populations was perhaps a common practice throughout the region (e.g. Brown and Hebda 2002; Prichard et al. 2009; Gavin et al. 2013; Walsh et al. 2015; Hoffman et al. 2016; Brown et al. 2019).

The human history of Pender Island is poorly documented. The island had permanent European settlers by the 1880s (Eis and Craigdale 1980), but very little is known of the Indigenous populations before and after colonization. Archeological excavations from the 1980s on Pender Island found midden deposits dating as early as 5000 cal yr BP (Carlson and Hobler 1993). These deposits suggest the presence of a major village prior to 2200 cal yr BP, but only that of a seasonal camp consistent with those of the Coast Salish afterwards (Carlson and Hobler

1993; Ewonus et al. 2020). This seasonal camp was likely inhabited during the spring and summer (Ewonus et al. 2020). The reason for this shift is unclear but coincides with the increase in fire frequency around Roe Lake after ~2500 cal yr BP. Ewonus et al. (2020) also suggest a change in resource management between 2800 and 2450 cal yr BP with the appearance of new fish species in the zooarchaeological record. These fish were likely present in the area much earlier, but were not actively fished until then despite having the technology to do so, suggesting that something had made the fishing of these species justifiable and feasible, perhaps an increase in population numbers within groups (Ewonus et al. 2020). It is possible that something similar occurred with fire management, with fewer but larger groups of people allowing for certain resource management practices to become more feasible or necessary, leading to an increase in fire after 2500 cal yr BP followed. Around a millennia later, there is a shift towards smaller groups inhabiting more sites and these new fish are phased out of the zooarchaeological record, which Ewonus et al. (2020) argue is likely due to group fishing no longer being viable in a smaller group. The decrease in fire frequency around 1000 cal yr BP may also be related to this shift towards smaller groups. However, no direct proof of this has been found on Pender Island and is entirely speculative.

It can also be argued that the increase in fire after 2500 cal yr BP is due to increased variability in the climate leading to longer fire seasons, largely due to increased warm ENSO events (Walsh et al. 2015). However, the link between ENSO events and fire in the Pacific Northwest remains unclear, and it is not currently possible to know if it, or use of fire by Indigenous peoples for land management, is the primary cause for this increase in fire frequency.

Conclusions and Implications for Conservation and Forest Management

Fire regimes on Pender Island are heavily dependent on climate, forest composition and structure, and human resource management. Fire was relatively frequent between ~10,000 and 7190 cal yr BP with a mFRI of 100 ± 29 years. As climate cooled and precipitation increased, the mFRI lengthened by nearly 1.75× to 167 ± 43 years. These long-term fire frequencies are generally consistent with similar studies elsewhere in the region, with climate being the principal factor regulating fire for most of the Holocene both through direct and indirect means. Some variation in the fire regime cannot be explained solely by changes in climate, notably between 7000 and 5000 cal yr BP and after 2500 cal yr BP. The increased fire frequency between 7000 and 5000 cal yr BP likely helped maintain *Q. garryana* communities, but as climate continued to cool and moisten, fire frequency decreased and these savannas were outcompeted by *P. menziesii* forests. The increase in fire starting ~2500 years ago may be due to Indigenous burning practices. Overall, the fire regime on Pender Island was mostly driven by changes in climate.

Today's climate is trending towards progressively warmer and drier conditions and wildfires are becoming an increasingly important aspect of forest management in British Columbia. Despite acknowledging that its ecosystem is historically dependant on fire, the Gulf Islands National Park Reserve (GINPR), where Roe Lake is situated, currently maintains fire suppression as its main form of fire management (Parks Canada 2010). No significant fires have occurred on Pender Island since the 1930s (Lucas and Lacourse 2013). However, the charcoal record from Roe Lake shows that large fires tend to occur after long periods without fire, further indicating that fire suppression may not be the ideal nor the safest management strategy to efficiently protect the forests of the GINPR. As fire management in Canada shifts towards more sustainable practices, this study offers the GINPR baseline information on the long-term fire

regime on Pender Island. In particular, past mFRIs can be helpful in developing prescribed burning timelines adequate to the changing forests and climate of the area. Mimicking the low-severity fires of the early Holocene through prescribed burns could be a feasible and sustainable approach for the GINPR as climate trends towards progressively warmer and drier summer conditions. The mFRI of 100 years of the early record can be used as a guideline in developing a strategy for these intentional burns within the park.

CONCLUSIONS

Summary

The charcoal record at Roe Lake spans the last 10,000 years. Charcoal concentrations and accumulation rates were high until around 7190 cal yr BP. The fire regime until that time was characterized by relatively frequent low-severity fire with a mFRI of 100 ± 29 years. Climate and vegetation reconstructions are consistent with this fire regime, with indications of an open canopy forest, warmer and drier summer climate, high seasonality, as well as the presence of fire-adapted and fire-promoting taxa. After ~7190 cal yr BP, charcoal concentrations and accumulation rates drop and mFRI increases to 167 ± 43 years on average. Fire-adapted taxa become less common during this time and are replaced by fire avoiding and late successional taxa. Simultaneously, climate cooled and the canopy closed, further indicating decreased disturbance. Fire severity remained similar even with lower frequency. High severity fire is rare throughout the record and generally only occurred after long periods without fire due to fuel build up over time. The middle Holocene is characterized by more frequent fire between 7000 and 5000 cal yr BP, inconsistent with climate reconstructions that indicate cooler, wetter conditions with decreased seasonality. *Quercus garryana* becomes more prominent in the record around the same time, perhaps due to increased wildfire disturbance. As climate continued to cool and moisten and fires became less frequent, these *Q. garryana* communities were outcompeted by closed-canopy *Pseudotsuga menziesii* forests. The more frequent fire over the last 2500 years may be linked to intentional burning by Indigenous populations as a component of resource management practices. Overall, the long-term fire regime on Pender Island was primarily driven directly and indirectly by changes in climate over the last 10,000 years.

Study Limitations

This research was successful at reconstructing the long-term fire regime at Roe Lake over the last 10,000 years. However, there are limitations to this research. Peak magnitude can give an indication of changes in fire severity through time but cannot be used as a direct proxy for fire severity as it does not take distance between the source of the fire and the study site into account. A large distant fire and a small nearby fire could have similar peak magnitudes in the charcoal record despite being very different events. Charcoal deposition is also heavily reliant on wind and its direction. Fires that occurred on Pender Island downwind of Roe Lake are likely under-represented in the charcoal record and/or incorrectly appear to be of low severity.

This study is heavily reliant on CharAnalysis 1.0 (Higuera et al. 2009). The software is a powerful and efficient tool in charcoal analysis, but also comes with its caveats. The analytical approach in CharAnalysis is most suited for frequent, high-severity fire regimes and will identify fires in those regimes with higher accuracy (Kelly et al. 2011). Although Roe Lake has relatively frequent fire at times, low to medium severity fires dominate the charcoal record. As a result, the accuracy of identified peaks varies through the record. This is notable between 10,000-9000 cal yr BP and 3000-2500 cal yr BP where SNI dips below 3 for these periods of time. Fire episodes may be under or over-represented during these periods.

Future research

There are now high temporal resolution records of both fire and vegetation on Pender Island for the past 10,000 years. However, there are no paleo-climate reconstructions that are specific to Pender Island. Precipitation and temperature reconstructions would be useful in

creating a more complete record of Pender Island's environmental history over the course of the Holocene and could help explain more of the variation in the fire regime.

The results of this study can be used in the development of fire management strategies, such as prescribed burning. However, more research on the short and long-term effects of such practices is needed in order to effectively manage Douglas-fir dominated forests. Roe Lake is also the only site within the Gulf Islands with a fire record of this time scale and temporal resolution. More research is required elsewhere in the Gulf Islands for a more complete fire regime profile of the region in order to sustainably manage its forests.

REFERENCES

Agee, J. K. (1991). Fire history of Douglas-fir forests in the Pacific Northwest. In: Wildlife and Vegetation of Unmanaged Douglas-Fir Forests, Aubry, K. B. and Brookes, M. H. (eds). U.S. Department of Agriculture, Forest Service. pp. 25-33.

Agee, J. K. (1993). Fire Ecology of Pacific Northwest Forests. Island Press, Washington DC, USA.

Agee, J. K., and Huff, M. H. (1987). Fuel succession in a western hemlock/Douglas-fir forest. *Canadian Journal of Forest Research*, 17(7), 697-704

Aquino-López, M. A., Blaauw, M., Christen, J. A., and Sanderson, N. K. (2018). Bayesian Analysis of 210 Pb Dating. *Journal of Agricultural, Biological, and Environmental Statistics*, *23*(3), 317–333.

Barnosky, C.W. (1985). Late Quaternary vegetation near Battle Ground Lake, southern Puget Trough, Washington. *Geological Society of America Bulletin*, 96, 263-271.

Berger A. and Loutre M. F. (1991). Insolation values for the climate of the last 10,000 years. *Quaternary Science Reviews,* 10, 297-317.

Blaauw, M. J. and Christen, A. (2011). Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis*, 6(3), 457-474.

Briles, C. E., Whitlock, C., and Bartlein, P. J. (2005). Postglacial vegetation, fire, and climate history of the Siskiyou Mountains, Oregon, USA. *Quaternary Research*, *64*(1), 44–56.

Briles, C. E., Whitlock, C., Bartlein, P. J., and Higuera, P. (2008). Regional and local controls on postglacial vegetation and fire in the Siskiyou Mountains, northern California, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *265*(1–2), 159–169.

Brown, K. J., and Hebda, R. J. (2002a). Origin, development, and dynamics of coastal temperate conifer rainforests of southern Vancouver Island, Canada. *Canadian Journal of Forest Research*, *32*(2), 353–372.

Brown, K. J., and Hebda, R. J. (2002b). Ancient fires on southern Vancouver Island, British Columbia, Canada: A change in causal mechanisms at about 2,000 ybp. *Environmental Archaeology*, *7*, 1–12.

Brown, K. J., and Hebda, R. J. (2003). Coastal rainforest connections disclosed through a Late Quaternary vegetation, climate, and fire history investigation from the Mountain Hemlock Zone on southern Vancouver Island, British Colombia, Canada. *Review of Palaeobotany and Palynology*, *123*(3–4), 247–269.

Brown, K. J., Hebda, N. J. R., Schoups, G., Conder, N., Smith, K. A. P., and Trofymow, J. A. (2019). Long-term climate, vegetation and fire regime change in a managed municipal water supply area, British Columbia, Canada. *The Holocene*, *29*(9), 1411–1424.

Carlson, R., and Hobler, P. M. (1993). The Pender Canal Excavations and the Development of Coast Salish Culture. *BC Studies: The British Columbian Quarterly*, 99, 25–52.

Colombaroli, D., & Gavin, D. G. (2010). Highly episodic fire and erosion regime over the past 2,000 y in the Siskiyou Mountains, Oregon. *Proceedings of the National Academy of Sciences*, *107(44),* 18909–18914.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A. F., and Krebs, P. (2009). Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews*, *28*(5–6), 555–576.

Eis, S., and Craigdale, D. (1980). Gulf Islands of British Columbia: a Landscape Analysis. *Canadian Forestry Service*, *Pacific Forest Research Centre*, Information Report BC-X-216. Environment Canada, Victoria, Canada.

Egan J., Staff, R., and Blackford J. (2015). A high-precision age estimate of the Holocene Plinian eruption of Mount Mazama, Oregon, USA. *The Holocene*, 25(7), 1054-1067.

Ewonus, P. A., Speller, C. F., Carlson, R. L., and Yang, D. Y. (2020). Toward a geography of foodways in the southern Gulf Islands, Pacific Northwest Coast. *North American Archaeologist*, *41*(1), 3–32.

Higuera, P. E., Sprugel, D. G., and Brubaker, L. B. (2005). Reconstructing fire regimes with charcoal from small-hollow sediments: A calibration with tree-ring records of fire. *The Holocene* 15, 238–251.

Higuera, P. E., Brubaker, L. B., Anderson, P. M., Hu, F. S., and Brown, T. A. (2009). Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. *Ecological Monographs*, *79*(2), 201–219.

Higuera, P. E., Whitlock, C., & Gage, J. A. (2010). Linking tree-ring and sediment-charcoal records to reconstruct fire occurrence and area burned in subalpine forests of Yellowstone National Park, USA. *The Holocene,* 21(2), 327–341.

Hoffman, K. M., Gavin, D. G., Lertzman, K. P., Smith, D. J., and Starzomski, B. M. (2016). 13,000 years of fire history derived from soil charcoal in a British Columbia coastal temperate rain forest. *Ecosphere*, *7*(7), 1–13.

Hoecker, T. J., Higuera, P. E., Kelly, R., and Hu, F. S. (2020). Arctic and boreal paleofire records reveal drivers of fire activity and departures from Holocene variability. *Ecology*, *101*(9), 1–17.

Flannigan, M. D., Logan, K. A., Amiro, B. D., Skinner, W. R., and Stocks, B. J. (2005). Future area burned in Canada. *Climatic Change*, *72*(1–2), 1–16.

Fuchs, M. A. (2001). Towards a Recovery Strategy for Garry Oak and Associated Ecosystems in Canada : Ecological Assessment and Literature Review. *Environment Canada*.

Gavin, D. G., Mclachlan, J. S., Brubaker, L. B., and Young, K. A. (2001). Postglacial history of subalpine forests, Olympic Peninsula, Washington, USA. *The Holocene, 11(2),* 177–188.

Gavin, D. G., Brubaker, L. B., and Lertzman, K. P. (2003a). An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. Canadian Journal of Forest Research, *33(4),* 573–586.

Gavin, D. G., Brubaker, L. B., & Lertzman, K. P. (2003b). Holocene Fire History of a Coastal Temperate Rain Forest Based on Soil Charcoal Radiocarbon Dates. Ecology*, 84(1),* 186–201.

Gavin, D. G., Feng, S. H., Lertzman, K., and Corbett, P. (2006). Weak climatic control of stand-scale fire history during the late Holocene. *Ecology*, *87*(7), 1722–1732.

Gavin, D. G., Hallett, D. J., Feng, S. H., Lertzman, K. P., Prichard, S. J., Brown, K. J., Lynch, J. A., Bartlein, P., and Peterson, D. L. (2007). Forest fire and climate change in western North America: Insights from sediment charcoal records. *Frontiers in Ecology and the Environment*, *5*(9), 499–506.

Gavin, D. G., Brubaker, L. B., Greenwald, D. N., Gavin, D. G., Brubaker, L. B., and Greenwald, D. N. (2013). Postglacial climate and fire-mediated vegetation change on the western Olympic Peninsula. *Ecological Monographs*, 83(4), 471-489.

Gedalof, Z., Pellatt, M., and Smith, D. J. (2006). From prairie to forest: Three centuries of environmental change at Rocky Point, Vancouver Island, British Columbia. *Northwest Science*, *80*(1), 34–46.

Glew J.R., Smol J.P., and Last W.M. (2001) Sediment core collection and extrusion. In: Last W.M., Smol, J.P., (eds.), *Tracking Environmental Change Using Lake Sediments*. Vol. 1. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 73–105.

Iversen, J. (1941). Land Occupation in Denmark's Stone Age. *Danmarks Geologiske Forenhandlungen, II*. pp. 1-68.

Kelly, R. F., Higuera, P. E., Barrett, C. M., and Hu, F. S. (2011). A signal-to-noise index to quantify the potential for peak detection in sediment-charcoal records. *Quaternary Research*, *75*(1), 11–17.

Killick, R., and Eckley, I. A. (2014). changepoint: An R Package for Changepoint Analysis. *Journal of Statistical Software*, *58*(3), 1–19.

Lemmen J. and Lacourse T. (2018). Fossil chironomid assemblages and inferred summer temperatures for the past 14,000 years from a low-elevation lake in Pacific Canada. *Journal of Paleolimnology,* 59, 427-442.

Lepofsky, D. and Lertzman, K. (2008). Documenting ancient plant management in the northwest of North America. *Botany*, 86. 129-145.

Long, C. J., Shinker, J. J., Minckley, T. A., Power, M. J., and Bartlein, P. J. (2019). A 7600 yr vegetation and fire history from Anthony Lake, northeastern Oregon, USA, with linkages to modern synoptic climate patterns. *Quaternary Research*, *91*(2), 533–547.

Long, C. J., Whitlock, C., and Bartlein, P. J. (2007). Holocene vegetation and fire history of the Coast Range, western Oregon, USA. *The Holocene*, *17*(7), 917–926.

Lucas, J. D., and Lacourse, T. (2013). Holocene vegetation history and fire regimes of Pseudotsuga menziesii forests in the Gulf Islands National Park Reserve, southwestern British Columbia, Canada. *Quaternary Research*, *79*(3), 366–376.

MacDougall, A. S., Beckwith, B. R., and Maslovat, C. Y. (2004). Defining conservation strategies with historical perspectives: A case study from a degraded oak grassland ecosystem. *Conservation Biology*, *18*(2), 455–465.

Mah, S. (2000). Relationship between vital attributes of Ktunaxa plants and natural disturbance regimes in Southeastern British Columbia. MSc Thesis. Department of Forest Science, University of British Columbia.

Mathewes R. W. and Heusser L. (1981). A 12 000 year palynological record of temperature and precipitation trends in Southwestern British Columbia. *Canadian Journal of Botany,* 59, 707-710.

McCoy, M. M. (2006). High resolution fire and vegetation history of Garry oak ecosystems in British Columbia. MSc Thesis. Department of Biological Sciences, Simon Fraser University.

McCune, J. L., Pellatt, M. G., and Vellend, M. (2013). Multidisciplinary synthesis of long-term human-ecosystem interactions: A perspective from the Garry oak ecosystem of British Columbia. *Biological Conservation*, *166*, 293–300.

McDadi, O. and Hebda, R. J. (2008). Change in historic fire disturbance in a Garry oak (*Quercus garryana*) meadow and Douglas-fir (*Pseudotsuga menziesii*) mosaic, University of Victoria. British Columbia, Canada: A possible link with First Nations and Europeans. *Forest Ecology and Management*, 256(10), 1704-1710.

Minckley, T. A., and Long, C. J. (2016). Paleofire severity and vegetation change in the Cascade Range, Oregon, USA. *Quaternary Research*, *85*(2), 211–217.

Molinari, C., Carcaillet, C., Bradshaw, R. H. W., Hannon, G. E., and Lehsten, V. (2020). Fire-vegetation interactions during the last 11,000 years in boreal and cold temperate forests of Fennoscandia. *Quaternary Science Reviews*, *241*, 106408.

Moy C. M., Seltzer G. O., Rodbell D. T., and Anderson D. M. (2002). Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature,* 420, 162-165.

Murphy, S. F., Pellatt, M. G., and Kohfeld, K. E. (2019). A 5,000-year fire history in the Strait of Georgia Lowlands, British Columbia, Canada. *Frontiers in Ecology and Evolution*, *7*, 1–15.

Nemens, D. G., Varner, J. M., and Dunwiddie, P. W. (2019). Resilience of Oregon white oak to reintroduction of fire. *Fire Ecology*, *15*(29).

NGRIP. (2004). High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Quaternary Research*, *431*, 147–151.

Nichols, G. J., Cripps, J. A., Collinson, M. E., and Scott, A. D. (2000). Experiments in waterlogging and sedimentology of charcoal: results and implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 164, 43-56.

Nuszdorfer, F.C., Klinka, K., and Demarchi, D.A. (1991). Chapter 5: Coastal Douglas-fir Zone. In: Meidinger, D., Pojar, J. (eds.), *Ecosystems of British Columbia*. British Columbia Ministry of Forests, Special Report Series 6. pp. 81-93.

Oris, F., Ali, A. A., Asselin, H., Paradis, L., Bergeron, Y., and Finsinger, W. (2014). Charcoal dispersion and deposition in boreal lakes from 3 years of monitoring: Differences between local and regional fires. *Geophysical Research Letters,* 41(19), 6743–6752.

Parks Canada. (2010). *State of the park report 2003-2008: Gulf Islands National Park Reserve*. Retrieved from: https://www.pc.gc.ca/en/agence-agency/bib-lib/rapports-reports/~/media/BBF2F8D762D44123A4A473672F6346C0.ashx

Pellatt, M. G., Hebda, R. J., & Mathewes, R. W. (2001). High-resolution Holocene vegetation history and climate from Hole 1034B, ODP leg 169s, Saanich Inlet, Canada. *Marine Geology*, *174*(1–4), 211–226.

Pellatt, M. G., and Gedalof, Z. (2014). Environmental change in Garry oak (*Quercus garryana*) ecosystems: The evolution of an eco-cultural landscape. *Biodiversity and Conservation*, *23*(8), 2053–2067.

Pellatt, M. G., McCoy, M. M., and Mathewes, R. W. (2015). Paleoecology and fire history of Garry oak ecosystems in Canada: implications for conservation and environmental management. *Biodiversity and Conservation*, *24*(7), 1621–1639.

Prichard S. J., Gedalof Z., Oswald, W. W., and Peterson, D. L. (2009). Holocene fire and vegetation dynamics in a montane forest, North Cascade Range, Washington, USA. *Quaternary Research*, 72, 57-67.

Province of British Columbia. (2021). *Wildfire season summary*. Retrieved from: https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-history/wildfire-season-summary

Province of British Columbia. (2020). *Wildfire Averages*. Retrieved from: https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-statistics/wildfire-averages

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Burr, G. S., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., McCormac F. G., Manning S. W., Reimer R. W., Richards D. A., Southon J. R., Talamo S., Turney C. S., van der Plicht J., and Weyhenmeyer, C. E. (2009). IntCal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years CAL BP. *Radiocarbon*, *51*(4), 1111–1150.

Reimer, P. J., Austin, W. E. N., Bard, E., Bayliss, A., Blackwell, P. G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kromer, B., Manning, S. W., Muscheler, R., Palmer J. G., Pearson C., van der Plicht J., Reimer R. W., Richards D. A., Scott E. M., Southon J. R., Turney C. S. M., Wacker L., Adolphi F., Buntgen U., Capano M., Fahrni S. M., Fogtmann-Schulz A., Friedrich R., Kohler P., Kudsk S., Miyake F., Olsen J., Reinig F., Sakamoto M., Sookdeo A., Talamo, S. (2020). The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0-55 cal kBP). *Radiocarbon*, *62*(4), 725–757.

Remy, C. C., Fouquemberg, C., Asselin, H., Andrieux, B., Magnan, G., Brossier, B., Grondin, P., Bergeron, Y., Talon, B., Girardin, M. P., Blarquez, O., Bajolle, L., and Ali, A. A. (2018). Guidelines for the use and interpretation of palaeofire reconstructions based on various archives and proxies. *Quaternary Science Reviews*, *193*, 312–322.

Ritland, K., Meagher, L. D., Edwards, D. G. W., and El-Kassaby, Y. A. (2005). Isozyme variation and the conservation genetics of Garry oak. *Canadian Journal of Botany*, 83, 1478–1487.

Rius, D., Galop, D., Doyen, E., Millet, L., and Vannière, B. (2014). Biomass burning response to high-amplitude climate and vegetation changes in Southwestern France from the Last Glacial to the early Holocene. *Vegetation History and Archaeobotany*, *23*(6), 729–742.

Rowe, J. S. (1983). Concepts of Fire Effects on Plant Individuals and Species. In: The Role of Fire in Northern Circumpolar Ecosystems, Wein, R. W., and MacLean, D. A. (eds.). John Wiley and Sons. Pp. 135-155.

Scott, A. C. (2010). Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *291*(1–2), 11–39.

Schlachter, K. J. D., and Horn, S. P. (2010). Sample preparation methods and replicability in macroscopic charcoal analysis. *Journal of Paleolimnology* 44, 701–708.

Sprenger, C. B., and P. W. Dunwiddie. (2011). Fire history of a Douglas-fir – Oregon white oak woodland, Waldron Island, Washington. *Northwest Science*, 85, 108-119

Statistics Canada. (2016). *Census profile, 2016 census, North Pender Island trust area, Island Trust*. Retriedved from: https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=DPL&Code1=590009&Geo2=PR&Code2=59&SearchText=North%20Pender%20Island%20Trust%20Area&SearchType=Begins&SearchPR=01&B1=All&GeoLevel=PR&GeoCode=590009&TABID=1&type=0

Sugimura, W.Y., Sprugel, D.G., Brubaker, L.B., and Higuera, P.E. (2008). Millennial-scale changes in local vegetation and fire regimes on Mount Constitution, Orcas Island, Washington, USA, using small hollow sediments. *Canadian Journal of Forest Research*, 38(3), 539-552.

Turner, N.J. (1999). “Time to burn” traditional use of fire to enhance resource production by aboriginal peoples in British Columbia, In: *Indians, Fire, and the Land in the Pacific Northwest*, Boyd, R. (ed.). Oregon State University Press, Corvallis. pp. 185-218.

United States Department of Agriculture (USDA). (2021). *Fire Effects Information System (FEIS)*. Retrieved from: https://www.feis-crs.org/feis/

Vellend, M., Bjorkman, A. D., and McConchie, A. (2008). Environmentally biased fragmentation of oak savanna habitat on southeastern Vancouver Island, Canada. *Biological Conservation*, *141*(10), 2576–2584.

Walsh, M. K., Lukens, M. L., McCutcheon, P. T., and Burtchard, G. C. (2017). Fire-climate-human interactions during the postglacial period at Sunrise Ridge, Mount Rainier National Park, Washington (USA). *Quaternary Science Reviews*, *177*, 246–264.

Walsh, M. K., Marlon, J. R., Goring, S. J., Brown, K. J., and Gavin, D. G. (2015). A Regional Perspective on Holocene Fire–Climate–Human Interactions in the Pacific Northwest of North America. *Annals of the Association of American Geographers*, *105*(6), 1135–1157.

Walsh, M. K., Whitlock, C., and Bartlein, P. J. (2008). A 14,300-year-long record of fire-vegetation-climate linkages at Battle Ground Lake, southwestern Washington. *Quaternary Research*, *70*(2), 251–264.

Walsh, M. K., Whitlock, C., and Bartlein, P. J. (2010). 1200 years of fire and vegetation history in the Willamette Valley, Oregon and Washington, reconstructed using high-resolution macroscopic charcoal and pollen analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *297*(2), 273–289.

Wang, T., Hamann, A., Spittlehouse, D., Carroll, C., (2016). Locally downscaled and spatially customizable climate data for historical and future periods for North America. *PLOS ONE*, *11(6),* e0156720.

White, A., Briles, C., and Whitlock, C. (2015). Postglacial vegetation and fire history of the southern Cascade Range, Oregon. *Quaternary Research*, *84*(3), 348–357.

Whitlock, C., and Scott Anderson, R. (2003). Fire History Reconstructions Based on Sediment Records from Lakes and Wetlands. In: Veblen T. T., Baker W. L., Montenegro G., and Swetnam T. W., (eds) *Fire and Climatic Change in Temperate Ecosystems of the Western Americas.* Ecological Studies 160, Springer-Verlag, New York, USA, pp. 3–31.

Whitlock C., and Larsen C. (2001). Charcoal as a Fire Proxy. In: Smol J.P., Birks H.J.B., Last W.M., (eds.) *Tracking Environmental Change Using Lake Sediments*, Vol. 3. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 75-97.

Wright, H. E., Mann, D. H., and Glaser, P. H. (1984). Piston corers for peat and lake sediments. *Ecology* 65, 657–659.

APPENDIX A: AGE-DEPTH MODEL FOR ROE LAKE, PENDER ISLAND

The age-depth model for Roe Lake was originally produced in Lucas and Lacourse (2013). The same ^{210}Pb and ^{14}C measurements were used in this study (Tables A1 and A2) and an updated age-depth model (Figure A1) was produced by Terri Lacourse using IntCal20 (Reimer et al. 2020) and Bayesian approaches in Bacon 2.3 (Blaauw and Christen 2011) and rplum 0.1.4 (Aquino-Lopez et al. 2018).

Table A1: ^{210}Pb measurements on the lake sediment core from Roe Lake (from Lucas and Lacourse 2013).

Depth (cm)	Bulk Density (g/cm^3)	^{210}Pb (Bq/kg)	^{210}Pb StdDev (Bq/kg)
0.0 - 0.5	0.0133	674.69	43.78
1.5 - 2.0	0.0306	682.80	33.04
3.0 - 3.5	0.0281	869.72	56.26
4.5 - 5.0	0.0376	708.69	38.12
6.5 - 7.0	0.0430	665.94	28.04
8.5 - 9.0	0.0448	459.43	20.51
10.5 - 11.0	0.0416	371.76	18.13
12.5 - 13.0	0.0433	327.25	15.91
14.5 - 15.0	0.0529	251.51	17.56
16.5 - 17.0	0.0437	245.11	14.10
18.5 - 19.0	0.0532	158.76	8.98
20.5 - 21.0	0.0407	136.95	7.07
22.5 - 23.0	0.0364	118.15	6.69
24.5 - 25.0	0.0395	79.52	4.75
26.5 - 27.0	0.0477	54.70	5.45
28.5 - 29.0	0.0413	49.49	4.02
30.5 - 31.0	0.0421	25.11	2.12
30.5 - 36.0	0.0498	8.22	1.26
41.0 - 41.5	0.0553	4.20	0.87

Table A2: AMS ^{14}C ages for the lake sediment core from Roe Lake, Pender Island, BC.

Depth (cm)	Material	Age (^{14}C yr BP)	2 sigma Calendar Age Range (cal yr BP)	Source
117.5	Male *Thuja plicata* cone	1323 ± 15	1178 - 1293	Lucas and Lacourse (2013)
385	Wood	4411 ± 20	4874 - 5205	Lucas and Lacourse (2013)
573.0 - 573.5	Mt. Mazama tephra	-	7584 - 7682	Egan et al. (2015)
614.5	Wood	7125 ± 25	7872 - 8009	Lucas and Lacourse (2013)
892.25 - 894.0	Organic lake sediment	8780 ± 50	9555 - 10,118	Lucas and Lacourse (2013)

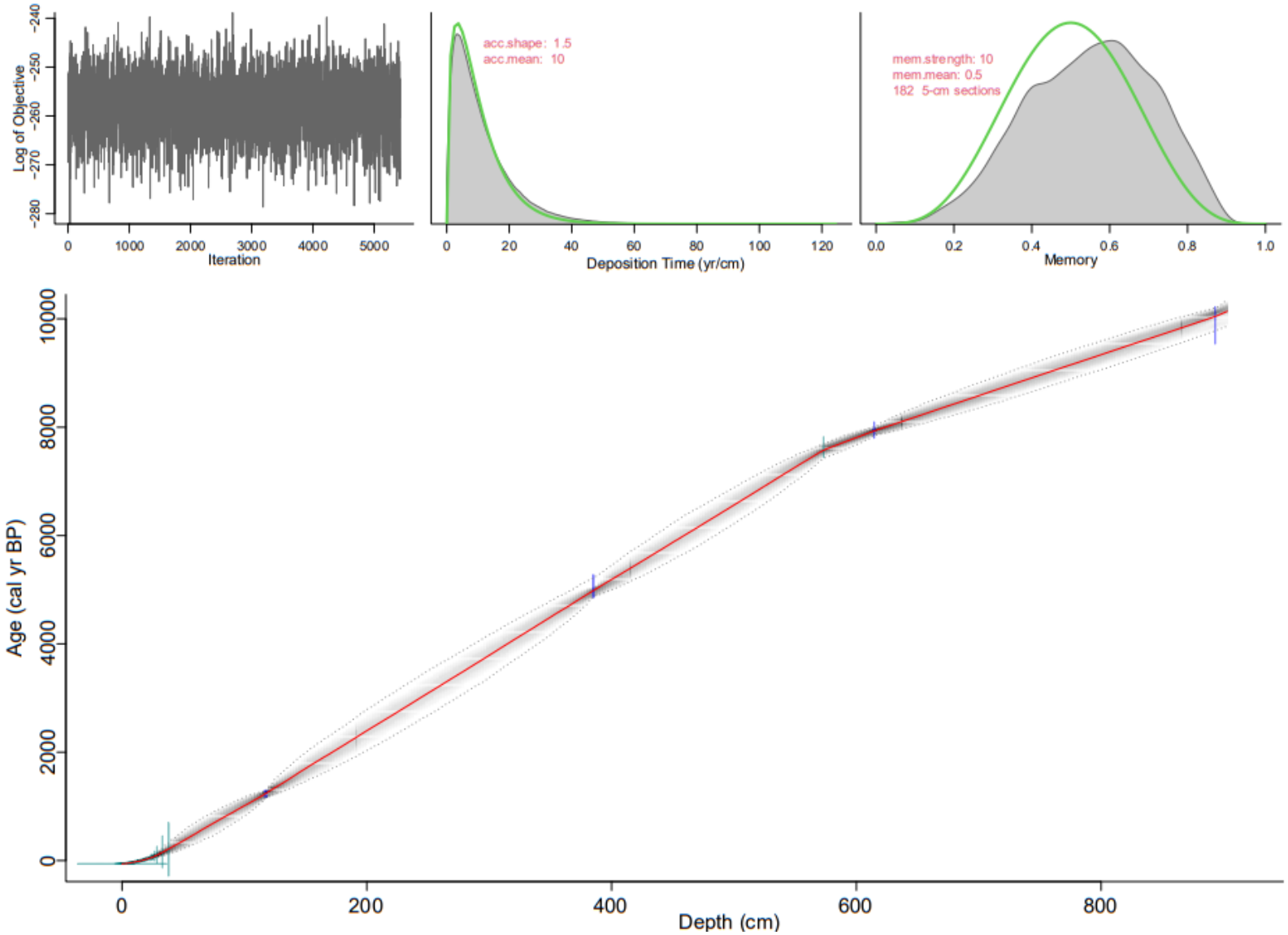

Figure A1: Age-depth model for the lake sediment core from Roe Lake

APPENDIX B: ESTABLISHING A SMOOTHING WINDOW FOR BACKGROUND CHARCOAL ESTIMATION

A 900-year smoothing window was chosen to estimate the background charcoal for the Roe Lake dataset in CharAnalysis 1.0. This window was chosen based on its signal-to-noise index (SNI). This index quantifies the level of distinction between signals (charcoal peaks) and noise (background charcoal). Larger SNI values indicate larger separation between signal and noise and in turn, indicate more clearly defined charcoal peaks (Kelly et al. 2011). SNIs for smoothing windows of various lengths were plotted and compared (Figures B1 and B2, Table B) to determine which was optimal for the Roe Lake charcoal dataset. As a general rule, the median global SNI should be above 3 to ensure better accuracy in peak identification (Kelly et al. 2011). This condition was met with all tested smoothing windows. However, all windows had a median SNI value below 4 and SNI fluctuated below 3 in parts of the record. Ultimately, the 900-year smoothing window was chosen as it had the highest global median SNI (3.297) and spent the most time with an SNI above 3 (84% of the record) compared to the other tested windows (Table B). Although the number of identified charcoal peaks is relatively similar among smoothing windows, the 900-year window had fewer peaks identified when SNI was below 3 compared to most of the tested windows. Smoothing windows above 1000 years were not tested to avoid over-smoothing the record and under-representing significant charcoal peaks.

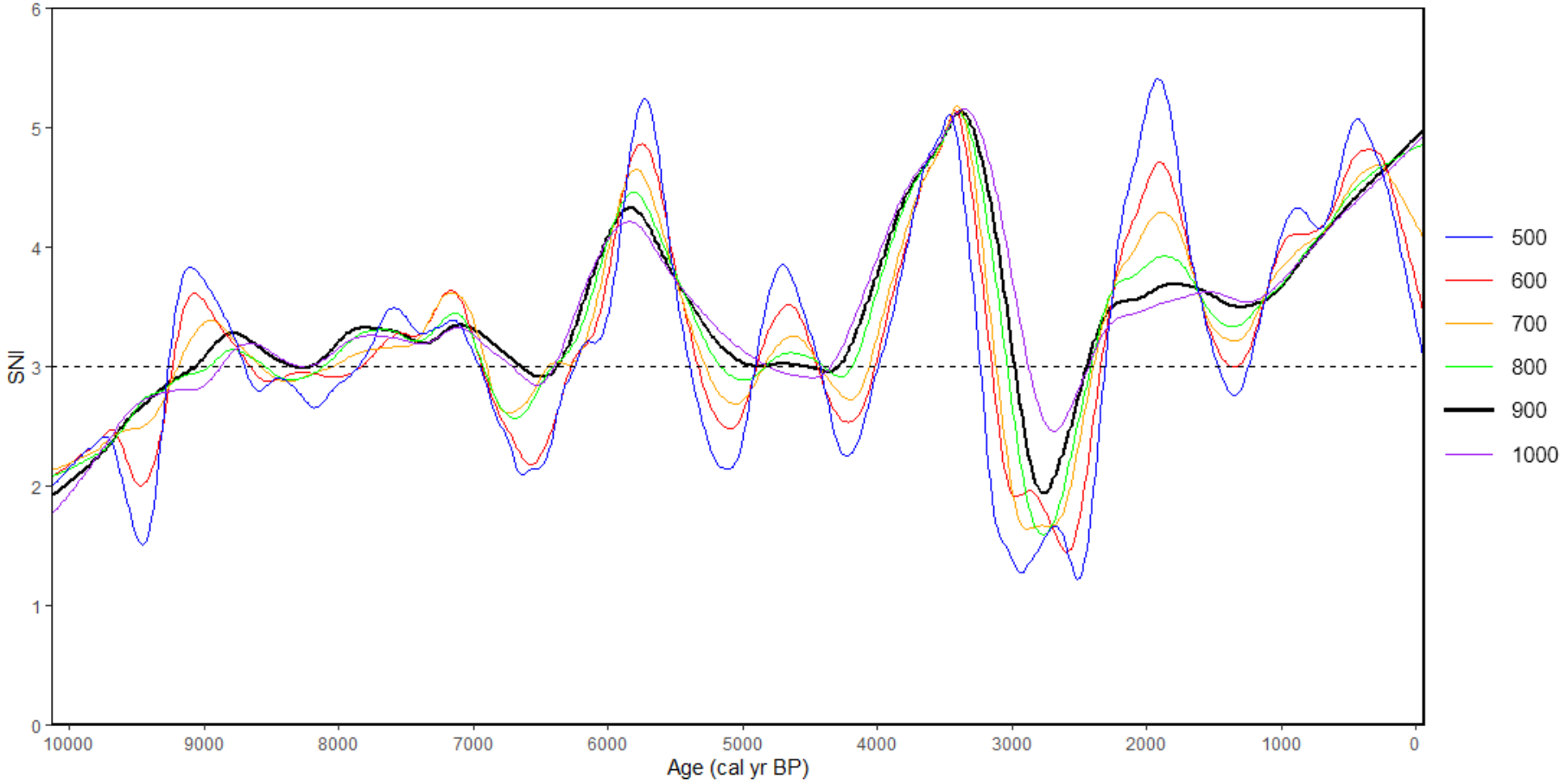

Figure B1: Signal-to-noise index (SNI) for the Roe Lake charcoal dataset for all tested smoothing windows (500, 600, 700, 800, 900, and 1000 years).

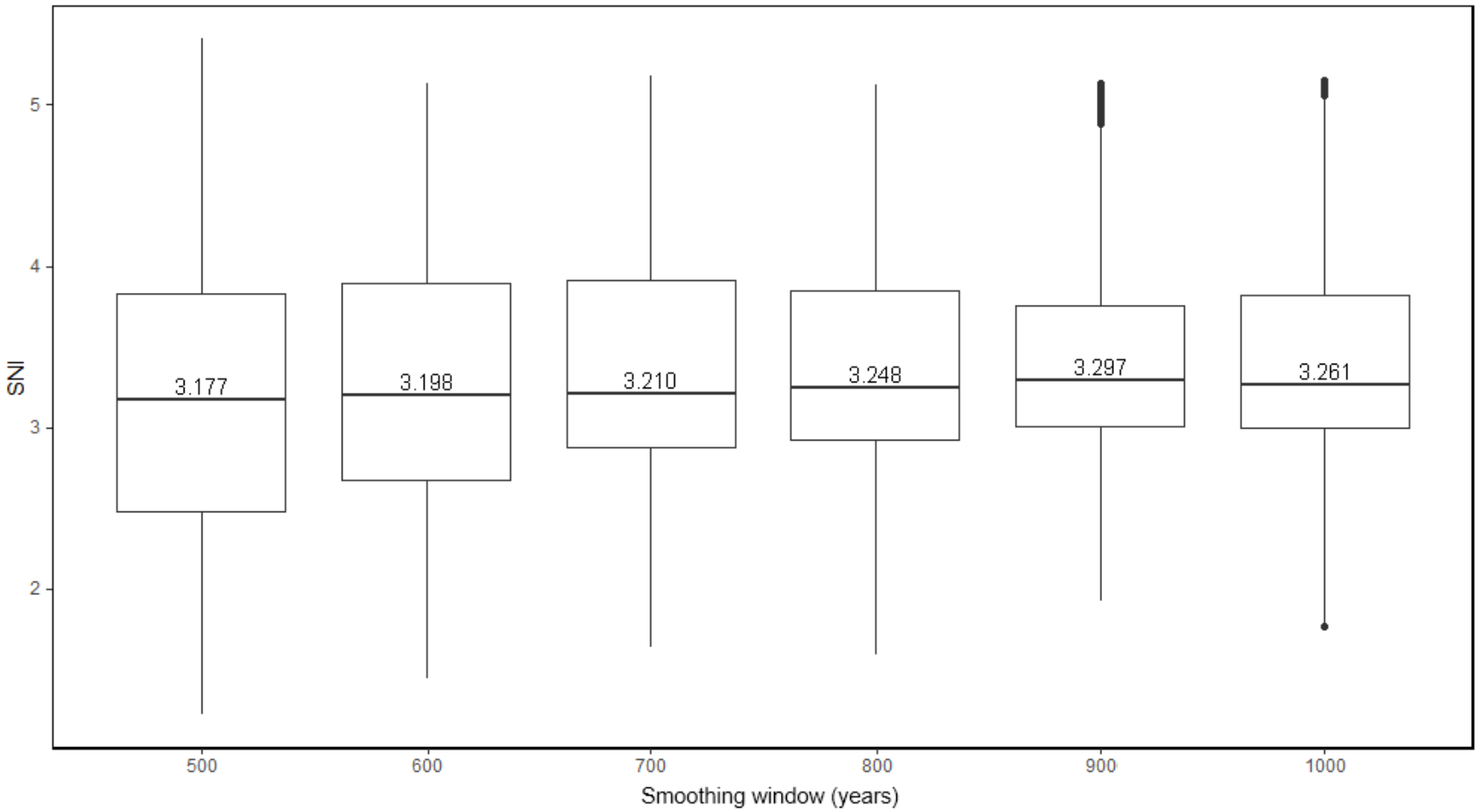

Figure B2: Boxplots of signal-to-noise index (SNI) for the Roe Lake charcoal dataset for each smoothing window. Values represent global median SNI values for each smoothing window.

Table B1: Summary statistics of the signal-to-noise index (SNI) for the Roe Lake charcoal dataset for each smoothing window.

Smoothing window	500 years	600 years	700 years	800 years	900 years	1000 years
Median SNI	3.177	3.198	3.210	3.248	3.297	3.261
Minimum SNI	1.219	1.446	1.638	1.593	1.921	1.764
Maximum SNI	5.406	5.137	5.175	5.126	5.133	5.154
Time with SNI below 3 (in years)	4238	3796	3068	2769	1638	2171
Percentage of record with SNI above 3 (in %)	58.4	62.8	69.9	72.8	83.9	78.7
Number of significant charcoal peaks	76	74	73	72	71	69

APPENDIX C: POLLEN DIAGRAM FOR ROE LAKE, PENDER ISLAND

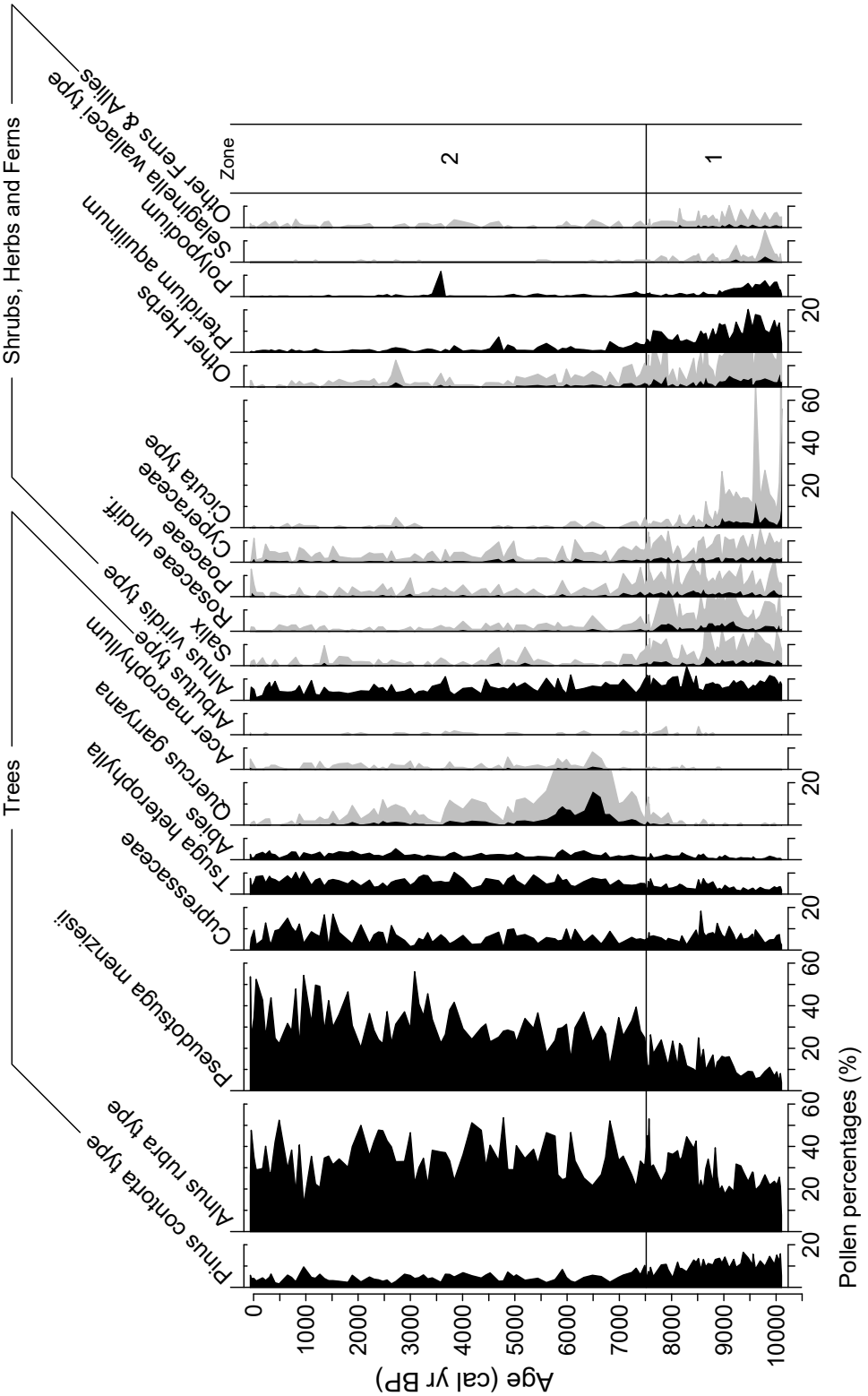

Figure C1: Pollen and spore percentages of major taxa for Roe Lake, Pender Island. Grey silhouettes for select taxa are 5× exaggeration of the data. Horizontal line at 7510 cal yr BP marks the boundary between two main pollen assemblage zones identified by cluster analysis. Data and cluster analysis are from Lucas and Lacourse (2013) and from T. Lacourse (unpublished data).

APPENDIX D: ROE LAKE POLLEN TAXA AND FIRE CLASSIFICATION

All pollen taxa identified in the Roe Lake pollen record were classified according to five fire survival strategies: avoiders, invaders, evaders, endurers, and resisters (Table D1). This classification scheme was first introduced in Rowe (1983). Avoiders are usually shade-tolerant and the least adapted to fire. They are easily killed by fire and slowly return to disturbed sites. Invaders are also usually killed by fire, but very quickly recolonize burned sites usually through wind dispersal of seeds or spores. Evaders will also usually be killed by fire, but have seed banks in the soil or canopy that allow for rapid germination following a fire. Endurers are usually top-killed by fire, but can quickly resprout from roots or rhizomes. Finally, resisters are usually shade-intolerant taxa with thick bark that allows the aboveground portion of the plant to survive low to moderate severity fire. The only resister present in the pollen assemblages at Roe Lake is *Pseudotsuga menziesii*.

Classifications for the specific taxa found at Roe Lake were based on those delineated in Rowe (1983) as well as a variety of resources using similar classification schemes (Mah 2000; Agee 1993; Molinari et al. 2020; USDA 2021). Taxa labeled as N/A in Table D1 were not assigned to one of the four categories for one or many reasons. Some had conflicting information among different sources, others had too little information to properly assign a category, and larger taxonomic groups were too broad to be accurately placed into a single category.

At least 89% of each pollen assemblage at Roe Lake was categorized in this way. On average, only 3.3% of all pollen was not categorized in each assemblage, with higher proportions earlier in the record, reaching a maximum of 10.6% uncategorized pollen around 9190 cal yr BP. This can mainly be attributed to the common presence of Rosaceae and Cyperaceae pollen early in the record, both of which were too broad to assign to a fire survival category.

Table D1: Latin name, common name, and fire survival classification of pollen taxa at Roe Lake. Taxa labeled as N/A were not assigned to a fire survival category if there was too little information available to assign a category, sources provided conflicting information or suggested multiple strategies, and/or they consist of large taxonomic groups or pollen types that correspond with morphotypes rather than individual taxa.

Latin name	Common name	Fire survival classification
Abies	Fir	Avoider
Acer glabrum	Douglas maple	Endurer
Acer macrophyllum	Big leaf maple	Endurer
Alnus rubra type	Red alder	Invader
Alnus viridis type	Green alder	Invader
Ambrosia type	Ragweed	N/A
Angelica type	Angelica	Endurer
Apiaceae undiff.	Carrot family	N/A
Arbutus type	Madrone	Endurer
Artemisia	Mugwort	Invader
Asteraceae (Ligul.)	Aster family	N/A
Asteraceae (Tubul.)	Aster family	N/A
Athyrium felix-femina type	Lady fern	Endurer
Betula	Birch	Invader
Botrychium virginianum type	Rattlesnake fern	N/A
Brassicaceae	Mustard family	N/A
Caltha type	Marsh-marigold	N/A
Caryophyllaceae	Pink family	N/A
Chenopodiaceae	Goosefoot family	N/A
Cicuta type	Water hemlock	Endurer
Cornus canadensis	Canadian bunchberry	Endurer
Cornus sericea type	Red-osier dogwood	Evader
Corylus	Hazel	Endurer
Cupressaceae	Cypress family	Avoider
Cyperaceae	Sedge family	N/A
Cystopteris type	Bladderfern	Endurer
Dryopteris type	Wood fern	Endurer
Epilobium	Fireweed	Invader
Ericaceae undiff.	Heather family	Endurer
Fraxinus latifolia	Oregon ash	Endurer
Galium	Bedstraw	Invader
Gaultheria shallon	Salal	Endurer
Heracleum maximum	Cow parsnip	N/A

Latin name	Common name	Fire survival classification
Hippuris	Mare's tail	N/A
Liliaceae	Lily family	N/A
Lonicera ciliosa type	Orange honeysuckle	Avoider
Lysichiton americanum	Skunk cabbage	N/A
Menyanthes trifoliata	Buckbean	N/A
Myrica gale	Sweet gale	Endurer
Picea sitchensis	Sitka spruce	Avoider
Pinus contorta type	Shore pine	Invader
Plectritis	Sea blush	Invader
Poaceae	Grass family	Invader
Polygonum	Knotweed	N/A
Polypodiaceae undiff. (Filicales)	Common fern family	Endurer
Polypodium	Polypodies	Endurer
Polystichum	Shield fern	Endurer
Pseudotsuga menziesii	Douglas-fir	Resister
Pteridium aquilinum	Bracken fern	Endurer
Quercus garryana	Garry oak	Endurer
Ranunculus type	Buttercup	N/A
Rosaceae undiff.	Rose family	N/A
Rumex/Oxyria	Dock/Sorrel	N/A
Salix	Willow	Invader
Sambucus	Elderberry	N/A
Selaginella selaginoides	Club spikemoss	Avoider
Selaginella wallacei type	Wallace's spikemoss	Avoider
Shepherdia canadensis	Canada buffaloberry	Evader
Symphoricarpos type	Snowberry	N/A
Taxus brevifolia	Pacific yew	Avoider
Thalictrum	Meadow-rue	Avoider
Tsuga heterophylla	Western hemlock	Avoider
Tsuga mertensiana	Mountain hemlock	Avoider
Urtica	Common nettle	Endurer
Valeriana	Valerian	N/A