5,000-year Fire History in the Strait of Georgia Lowlands, British Columbia: Implications for Restoration and Management

by

Sinead Flanagan Murphy

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Name:	**Sinead Flanagan Murphy**
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Examining Committee:	**Chair:** Celeste Barlow Master of Resource Management Candidate

Karen Kohfeld
Senior Supervisor
Associate Professor

Marlow Pellatt
Supervisor
Adjunct Professor

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Abstract

Improved knowledge of long-term fire regimes and climate-fire-human relationships can play an important role in informing effective management of south coastal forests in British Columbia, Canada. In this study, we used high-resolution charcoal analysis (~17-year intervals) along with strong chronological control (^{210}Pb and AMS-^{14}C age constraints) to provide new mid to late Holocene fire history information for Moist Maritime Coastal Douglas Fir (CDFmm) forests around Somenos Lake on southeastern Vancouver Island and Dry Maritime Coastal Western Hemlock (CWHdm) forests around Chadsey Lake in the central Fraser Valley. Our results indicate that fire frequency at both sites varied throughout the mid to late Holocene, suggesting that CDFmm and CWHdm fire regimes in the Strait of Georgia Lowlands have been non-stationary over the last ~5000 years. In general, fire frequency between the two sites was largely synchronous during the mid to late Holocene, indicating that broad-scale climatic changes were primarily driving fire occurrence in the Strait of Georgia Lowlands during the past ~5000 years. However, a period of asynchrony occurred between 3500 and 2000 cal yr BP when fire frequency was low at Somenos Lake (i.e., the CDFmm site) and high at Chadsey Lake (i.e., the CWHdm site). Neoglacial conditions during this time would have limited fire ignition, thus resulting in low fire activity at Somenos Lake. However, because climate conditions were not conducive to fire (i.e., cool and moist), we suggest that a combination of local scale factors were primarily responsible for high fire activity at Chadsey Lake between 3500 and 2000 cal yr BP. Overall, our results exemplify the spatial-temporal dynamics of fire activity in the in the Strait of Georgia Lowlands during the past ~5000 years and highlight the importance for forest managers to look at the variability of fire occurrence over time and across different sites to disclose the temporal and spatial variability of fire activity and better understand the mechanisms that drive changes.

Keywords: charcoal analysis; paleoecology; fire history; ecological restoration; fire management; mid to late Holocene

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List of Acronyms

^{14}C	Radioisotope of carbon (C)
^{210}Pb	Radioisotope of lead (Pb)
AMS	Accelerator mass spectrometry
BC	British Columbia
cal yr BP	Calibrated years before present (i.e., 1950 AD)
CDFmm	Moist Maritime Coastal Douglas Fir
CHAR	Charcoal accumulation rate (pieces/cm^2/yr)
CRS	Constant rate of supply model
CWHdm	Dry Maritime Coastal Western Hemlock
FVFP	Fraser Valley Fire Period
GOEs	Garry oak ecosystems
GOF	Goodness-of-fit
LIA	Little Ice Age
mFRI	Mean fire return interval
MWP	Medieval Warm Period
SNI	Signal-to-noise ratio
TSLF	Time since last fire

Chapter 1. Introduction

For several decades, paleoecology has been recognized as a key component of science-based policy and management plans in restoration ecology (Froyd & Willis, 2008; Jackson & Hobbs, 2009; Swetnam, Allen, & Betancourt, 1999; Watson et al., 2011). Studies examining environmental change over time can inform restoration strategies by providing a unique perspective on long-term environmental dynamics and the response of ecosystems to change. For example, paleoecological data can determine the natural range of variability of an ecosystem and its disturbance regimes which can help practitioners to identify baselines or reference conditions to evaluate how much current ecosystems have deviated from their natural state prior to human influence and identify ecological trajectories to recognize the direction of ecosystem change (Battarbee, 1999; Landres, Morgan, & Swanson, 1999; Swetnam et al., 1999). Together this information provides the basis by which the overarching goal of restoration, to maintain and enhance the ecological integrity of degraded ecosystems, can be achieved (*Canada National Parks Act*, 2000; Canada, 2009).

In North America, much of the paleoecological research used in restoration ecology has focused on reconstructing long-term fire regimes (i.e., fire history) to inform restoration of ecosystems that have been adversely affected by fire suppression (Korb, Fulé, & Wu, 2013; Larson, Van De Gevel, & Grissino-Mayer, 2009; Lynch, Calcote, & Hotchkiss, 2006; Marcoux et al., 2015; Odion et al., 2014; Pellatt, McCoy, & Mathewes, 2015; Wendel & Zabowskl, 2010; Whitlock, Shafer, & Marlon, 2003). Over the last century, forest managers in North America actively suppressed fire disturbances to prevent fire damage to human settlement, property, and natural resources. However, the exclusion of fire has led to negative impacts on forest health and significant build-up of fuels, leading to uncontrollable and costly wildfires (Ahlgren, 1976; Allen et al., 2002; Harmon, 1984; Stephens & Ruth, 2005). Consequently, forest managers have used fire suppression less frequently, and the focus of fire management has switched from suppressing fire at all costs to restoring natural fire regimes. More recently, restoration plans have adopted prescribed fire and other fire management activities to help re-establish natural fire regimes in fire-adapted ecosystems in hopes of restoring some former condition of ecological integrity (Fernandes & Botelho, 2003). While researchers caution that the past cannot be used as a perfect analog for the future (Hallett & Walker, 2000; Whitlock et al., 2003), particularly where novel ecosystems have emerged (Hobbs, 2013; Millar, Stephenson, & Stephens, 2007), paleoecological studies provide the only window into fire regime dynamics operating at long-term scales which is essential to understand if prescribed fire and other fire management activities are to be successful.

One commonly used proxy to reconstruct long-term fire history is charcoal accumulation in lake sediments. Fire events are indicated by peaks of charcoal accumulation within a lake sediment core (Whitlock & Larson, 2001). Since lake sediments can span over millennia, sedimentary-charcoal records can provide long-term fire history information with decadal to multidecadal scale resolution (Higuera, Whitlock, & Gage, 2010b). However, charcoal deposited during non-fire years and sediment mixing within the lake can increase the level of noise within the record and therefore obscure results (Whitlock & Larson, 2001). Nevertheless, background noise within sediment-charcoal records is limited by the physical properties of charcoal that restrict the extent of its redistribution (Clark, 1988) and can be separated from the primary charcoal signal related to fire events using a variety of different decomposition models (Higuera, Gavin, Bartlein, & Hallett, 2010a).

The mean fire return interval (mFRI) is the statistic that is consistently reported in the literature and fire management plans to quantify fire history of a specific ecosystem and its natural range of variability. Typically, a mFRI is calculated by averaging the time period between fire episodes (Agee, 1993); however, it can also be calculated by dividing a defined time period by the number of fire episodes in that time period (Agee, Finney, & Gouvenain, 1990). The 95 % confidence intervals of mFRI are used to characterize the natural range of variability of fire activity (Cyr, Gauthier, Bergeron, & Carcaillet, 2009). More recently, fire frequency, commonly defined as the number of fires occurring within a 1000-year time period, has also been used in the literature to define fire history and the variability of fire occurrences over time.

In addition to mFRI and fire frequency calculations, forest restoration and management plans can also benefit from interpretations of long-term fire activity that assess the natural and anthropogenic mechanisms that drive fire occurrence over time. In particular, details about the fire regimes prior to Euro-American settlement and before fire suppression efforts can provide important insight into how changes in human activity and climatic conditions have shaped fire regimes over time (Whitlock et al., 2003). Additionally, combining this retrospective knowledge with current understanding of modern climate-fire-human linkages can help predict future changes in fire regimes that could help set appropriate forest management goals with projected changes in climate and vegetation (Gavin et al., 2007).

Although prescribed fire and other fire management activities are increasingly accepted throughout western North America (Parks Canada, 2009; United States Fish and Wildlife Service, 2001; United States National Park Service, 2014; Verdiel & Small, 2007), limited knowledge of long-term fire regimes and climate-fire-human relationships presents challenges to effective management of south coastal forests in the Strait of Georgia Lowlands, southwestern British Columbia (BC). This limitation is particularly profound for Garry oak (*Quercus garryana*) ecosystems (GOEs) located within south coastal forests in BC and along the Pacific coast to southern California. While these ecosystems are considered to be biological hot spots and support over 100 species at risk (Pellatt et al., 2007), they have rapidly declined over the past two decades and are now considered one of the most endangered ecosystems in Canada (Fuchs, 2001). Studies estimate that between 1 and 5 % of Garry oak habitat exists in Canada in its natural, un-altered state today (Hebda & Aitkens, 1993). Currently, the only GOEs in Canada are located in the Strait of Georgia Lowlands, with the exception of one outlier population near Yale, BC in the Fraser Lowland ecoprovince (Ritland, Meagher, Edwards, & El-Kassaby, 2005; Ward, Radcliffe, Kirkby, Illingworth, & Cadrin, 1998).

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has stated that GOEs are threatened by fragmentation as a result of land development, conifer encroachment due to fire suppression, and invasion by exotic plant species (Fuchs, 2001). Some studies argue that the most significant alteration of this ecosystem has been the suppression of fire (MacDougall, Beckwith, & Maslovat, 2004). As a result, a number of researchers suggest that GOE restoration plans should focus on fire management as a method to prevent further degradation and maintain and enhance ecological integrity (Peterson & Reich, 2001). However, while a number of long-term (i.e., charcoal-inferred) fire history reconstructions have been undertaken within the range of GOEs, the majority are not practical for forest managers because they are either based on short time periods (i.e., < 1800 years) (Gavin, Brubaker, & Lertzman, 2003; Lucas & Lacourse, 2013; Pellatt et al., 2015) or long time periods (i.e., > 10,000 years) with coarse resolution (i.e., > 100 yr/cm) and/or coarse chronological control (i.e., no ^{210}Pb and few ^{14}C age constraints that may not be Accelerator Mass Spectrometry (AMS)) (Brown & Hebda, 2002a; Brown & Hebda, 2002b, 2003; Gavin, Brubaker, & Greenwald, 2013; Gavin, Mclachlan, Brubaker, & Young, 2001; Hallett, Lepofsky, Mathewes, & Lertzman, 2003; Prichard, Gedalof, Oswald, & Peterson, 2009; Wainman & Mathewes, 1987; Walsh, Marlon, Goring, Brown, & Gavin, 2015) (Figure 1; Table 1). Additionally, no paleoecological study has assessed the variability of fire disturbances and influences of climate and human activity on fire occurrence in Dry Maritime Coastal Western Hemlock (CWHdm) forests located in the central Fraser Valley. Therefore, to ensure fire management and prescribed burn plans for south coastal forests and GOEs are effective, additional information on long-term fire history and regional variability of fire disturbances and climate-fire-human relationships in the Strait of Georgia Lowlands through time is needed.

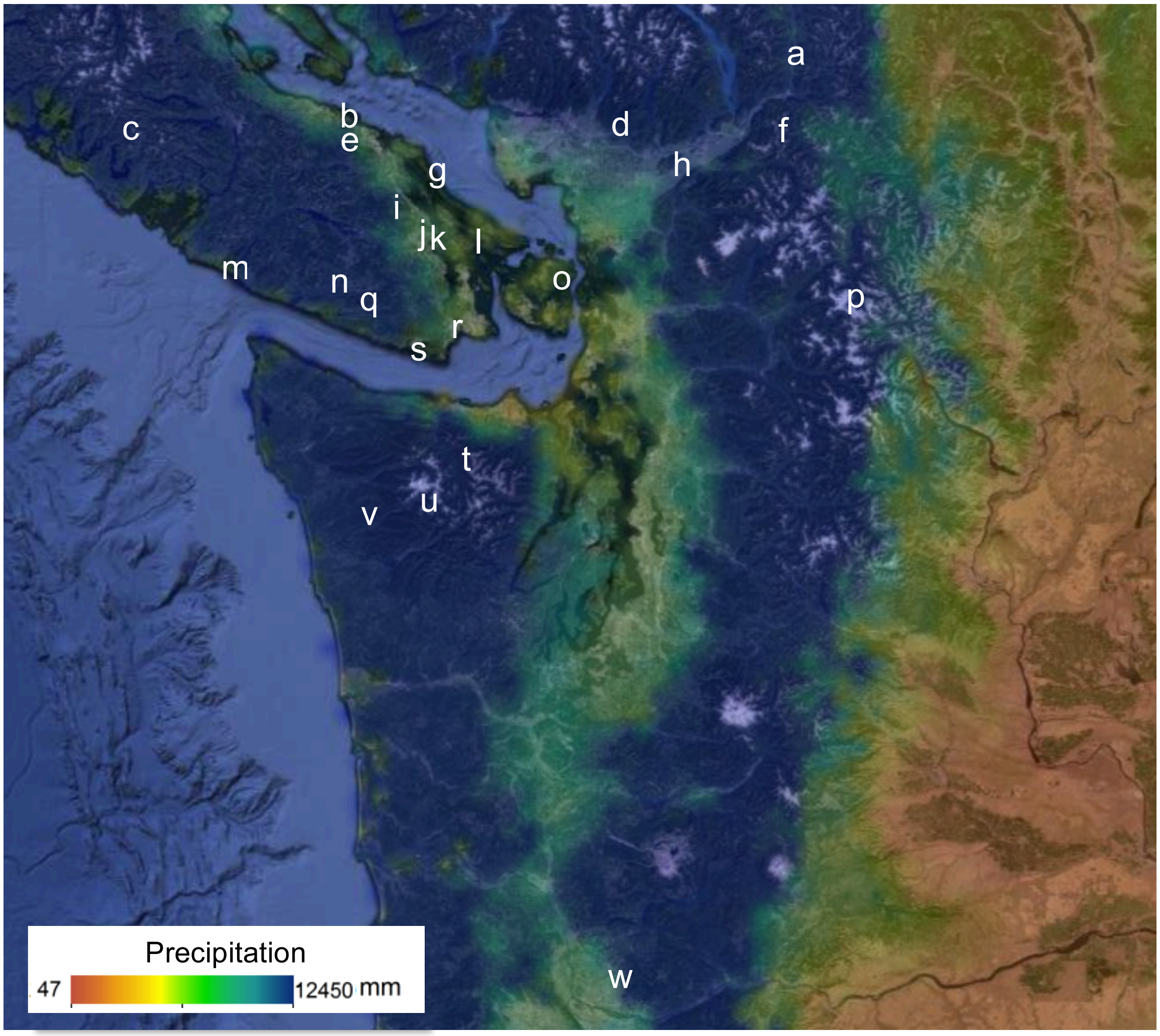

Figure 1. Map of western North America showing the location of the study area (Strait of Georgia Lowlands), study sites (Somenos Lake and Chadsey Lake), and other paleoecological studies referred to in the text. Study sites include: (a) Frozen Lake (Hallett et al., 2003); (b) Enos Lake (Brown & Hebda, 2002a); (c) Clayoquot Lake (Gavin et al., 2003); (d) Marion Lake (Wainman & Mathewes, 1987); (e) Boomerang Lake (Brown & Hebda, 2002a); (f) Mt. Barr Cirque Lake (Hallett et al., 2003); (g) Valdes Island On-site (i.e., Shingle Point) and Off-site Bogs (Derr, 2014); (h) Chadsey Lake (this study); (i) Porphyry Lake (Brown & Hebda, 2003); (j) Somenos Lake (this study); (k) Quamichan Lake (Pellatt et al., 2015); (l) Roe Lake (Lucas & Lacourse, 2013; Pellatt et al., 2015); (m) Whyac Lake (Brown & Hebda, 2002b); (n) Pixie Lake (Brown & Hebda, 2002b); (o) Mount Constitution Small Hollow sites (Sugimura, Sprugel, Brubaker, & Higuera, 2008); (p) Panther Potholes (Prichard et al., 2009); (q) Walker Lake (Brown & Hebda, 2003); (r) Florence Lake (Pellatt et al., 2015); (s) East Sooke Fen (Brown & Hebda, 2002b); (t) Moose Lake (Gavin et al., 2001); (u) Martins Lake (Gavin et al., 2001); (v) Yahoo Lake (Gavin et al., 2013); and (w) Battle Ground Lake (Walsh, Whitlock, & Bartlein, 2008). Base layer is from ClimateWNA (Wang, Hamann, Spittlehouse, & Murdock, 2012) using PRISM precipitation data (Daly, Gibson, Taylor, Johnson, & Pasteris, 2002).

Table 1. Previous charcoal-inferred fire history reconstructions in southwestern British Columbia and western Washington.

Site	Latitude and Longitude	Elevation (masl)	BC Biogeo-climatic Zone or US General Forest Zone	Start of Record (cal yr BP)	Length of Record (yrs)	Age-depth Model Method	Charcoal Extraction Method and Source Area	Mean Sample Resolution (yr/cm)	Primary Measure of Fire Activity	Reference
Somenos Lake	48.48ºN 123.42ºW	16	CDFmm	-64	5089	^{210}Pb CRS[a] & AMS-^{14}C linear interpolation	1 cm 5% $(NaPO_3)_6$ for 24 hrs & 6% H_2O_2 for 1 hr > 125 µm	17	Frequency (1000 yrs)	This study
Chadsey Lake	49.07ºN 122.08ºW	620	CWHdm	-64	4570			18		
Quamichan Lake	48.46ºN 123.40ºW	33	CDFmm	-54	250	^{210}Pb CRS[a] & one AMS-^{14}C in Florence Lake	1 cm 30% KOH for 24 hrs & dilute H_2O_2 > 125 µm	6	mFRI	Pellatt et al. (2015)
Florence Lake	48.27ºN 123.30ºW	81	CDFmm	-54	564		2 cm 30% KOH for 24 hrs & dilute H_2O_2 > 125 µm	10		
Roe Lake	48.46ºN 123.18ºW	117	CDFmm	-54	250		0.5 cm 30% KOH for 24 hrs & dilute H_2O_2 > 125 µm	3		
Roe Lake	48.46ºN 123.18ºW	117	CDFmm	-61	1300	^{210}Pb CRS[a] & AMS-^{14}C linear interpolation	0.5 & 1 cm 10% $Na_4P_2O_7$ & 3% H_2O_2 for 24 hrs > 150 µm	6[b]	mFRI	Lucas and Lacourse (2013)

Site	Latitude and Longitude	Elevation (masl)	BC Biogeo-climatic Zone or US General Forest Zone	Start of Record (cal yr BP)	Length of Record (yrs)	Age-depth Model Method	Charcoal Extraction Method and Source Area	Mean Sample Resolution (yr/cm)	Primary Measure of Fire Activity	Reference
Clayoquot Lake	49.12ºN 125.30ºW	17	CWHvm	-50	1800	^{210}Pb cublic spline & AMS-^{14}C linear regression	1 cm 10% $(NaPO_3)_6$ overnight and 6% H_2O_2 for 8hrs 150-500 µm	6[c]	Frequency (200 yrs)	Gavin et al. (2003)
Marion Lake	49.18ºN 122.32ºW	305	CWHdm	0	12,350	^{14}C linear interpolation	10 & 5 cm 70% alcohol > 250 µm	142yr/10cm[c] 71yr/5cm[c]	Charcoal pieces	Wainman and Mathewes (1987)
Enos Lake	49.28ºN 124.15ºW	47	CDFmm	0	12,840	^{14}C linear interpolation	1 cm 10% $(NaPO_3)_6$ overnight and 6% H_2O_2 for 8 hrs > 150 µm	13[c]	CHAR	Brown and Hebda (2002a)
Boomerang Lake	49.18ºN 124.15ºW	373	CWHxm	0	10,270			20[c]		
Whyac Lake	48.40ºN 124.50ºW	15	CWHvh	0	10,860			24[c]		
Pixie Lake	48.35ºN 124.11ºW	70	CWHvm	0	12,990			15[c]		
East Sooke Fen	48.21ºN 123.40ºW	155	CWHxm	0	11,700			13[c]		
Walker Lake	48.31ºN 124.00ºW	950	MHmm	0	12,240			24[c]		
Porphyry Lake	48.54ºN 123.50ºW	1100	MHmm	0	12,540			50[c]		

Site	Latitude and Longitude	Elevation (masl)	BC Biogeo-climatic Zone or US General Forest Zone	Start of Record (cal yr BP)	Length of Record (yrs)	Age-depth Model Method	Charcoal Extraction Method and Source Area	Mean Sample Resolution (yr/cm)	Primary Measure of Fire Activity	Reference
Walker Lake	48.31ºN 124.00ºW	950	MHmm	0	14,160	^{14}C linear interpolation	5 cm > 150 µm	136 yr/5cm[c]	CHAR	Brown and Hebda (2003)
Porphyry Lake	48.54ºN 123.50ºW	1100	MHmm	0	14,680			292 yr/5cm[c]		
Whyac Lake	48.40ºN 124.50ºW	15	CWHvh	0	10,860	^{14}C linear interpolation	1 cm 10% $(NaPO_3)_6$ overnight and 6% H_2O_2 for 8 hrs 150-500 µm	24[c]	CHAR	Brown and Hebda (2002b)
Pixie Lake	48.35ºN 124.11ºW	70	CWHvm	0	12,990			15[c]		
East Sooke Fen	48.21ºN 123.40ºW	155	CWHxm	0	11,700			13[c]		
Frozen Lake	49.36ºN 121.28ºW	1180	MHmm	0	11,400	AMS-^{14}C linear interpolation	1 cm 10% $(NaPO_3)_6$ for 24 hrs > 125 µm	45	Frequency (1000 yrs)	Hallett et al. (2003)
Mt. Barr Cirque Lake	49.16ºN 121.31ºW	1376	MHmm	0	7500			15		
Panther Potholes	48.39ºN 121.02ºW	1100	Montane Forest	12	10,557	^{210}Pb CRS[a] & AMS-^{14}C locally weighted regression	1 cm 10% $(NaPO_3)_6$ for 72 hrs and 8% H_2O_2 for 8hrs 150-500 µm	13	Frequency (1000 yrs)	Prichard et al. (2009)
Moose Lake	47.53ºN 123.21ºW	1508	Sub Alpine Forest	0	13,100	^{14}C & AMS-^{14}C linear interpolation	5 &15 cm 10% KOH overnight > 150 & > 500 µm	250 yr/15cm	Charcoal concentra-tion	Gavin et al. (2001)
Martins Lake	47.42ºN 123.32ºW	1415		0	11,200			250 yr/5cm		

<table>
<tr><th>Site</th><th>Latitude and Longitude</th><th>Elevation (masl)</th><th>BC Biogeo-climatic Zone or US General Forest Zone</th><th>Start of Record (cal yr BP)</th><th>Length of Record (yrs)</th><th>Age-depth Model Method</th><th>Charcoal Extraction Method and Source Area</th><th>Mean Sample Resolution (yr/cm)</th><th>Primary Measure of Fire Activity</th><th>Reference</th></tr>
<tr><td>Yahoo Lake</td><td>47.84ºN 124.80ºW</td><td>710</td><td>Pacific Silver Fir</td><td>0</td><td>13,700</td><td>AMS-^{14}C cubic spline</td><td>1 cm
5% KOH at 40C for 20 mins
150-500 µm</td><td>34[c]</td><td>Frequency (1000 yrs)</td><td>Gavin et al. (2013)</td></tr>
<tr><td>Valdes Island Off-site Bog</td><td>49.40ºN 123.40ºW</td><td>< 300</td><td>CDFmm</td><td>0</td><td>2738</td><td rowspan="2">AMS-^{14}C linear interpolation</td><td rowspan="2">1 cm
10% $(NaPO_3)_6$ for 12-24 hrs and 5% bleach for 24 hrs
125-500 µm</td><td>33[c]</td><td rowspan="2">CHAR</td><td rowspan="2">Derr (2014)</td></tr>
<tr><td>Valdes Island On-site Bog (i.e., Shingle Point)</td><td>49.20ºN 123.38ºW</td><td>140</td><td>CDFmm</td><td>0</td><td>6671</td><td>68[c]</td></tr>
<tr><td>Mt. Constitu-tion C11</td><td rowspan="3">48.39ºN 122.50ºW</td><td>660</td><td rowspan="3">Western Hemlock</td><td>> 0</td><td>~7650</td><td rowspan="3">^{210}Pb polynomial & AMS-^{14}C linear interpolation and regression</td><td rowspan="3">0.25 & 0.5 cm
10% $(NaPO_3)_6$ for 72 hrs and 6% H_2O_2 for 8 hrs
150-500 µm</td><td>125</td><td rowspan="3">CHAR</td><td rowspan="3">Sugimura et al. (2008)</td></tr>
<tr><td>Mt. Constitu-tion C32</td><td>660</td><td>> 0</td><td>~3800</td><td>102</td></tr>
<tr><td>Mt. Constitu-tion C38</td><td>685</td><td>> 0</td><td>~7200</td><td>66</td></tr>
</table>

Site	Latitude and Longitude	Elevation (masl)	BC Biogeo-climatic Zone or US General Forest Zone	Start of Record (cal yr BP)	Length of Record (yrs)	Age-depth Model Method	Charcoal Extraction Method and Source Area	Mean Sample Resolution (yr/cm)	Primary Measure of Fire Activity	Reference
Battle Ground Lake	45.08ºN 122.49ºW	154	Western Hemlock	0	14,300	AMS-^{14}C 4th order polynomial	1 & 0.5 cm 5% $(NaPO_3)_6$ for >24 hrs and weak bleach for 1 hr > 125 µm	10[b]	Frequency (1000 yrs)	Walsh et al. (2008)

[a] Constant rate of supply model (CRS)
[b] Median sample resolution (yr/cm)
[c] Mean calculated based on published sampling interval (cm) and total lengths of the record (yr) and core (cm)
Biogeoclimatic zones: Coastal Douglas Fir (CDF), Coastal Western Hemlock (CWH), and Mountain Hemlock (MH)
Biogeoclimatic subzones: Very Wey Hypermaritime (vh), Very Wet Maritime (vm), Moist Maritime (mm), Dry Maritime (dm), and Very Dry Maritime (xm)

In this study, we addressed the lack of practical, long-term fire history studies by using high-resolution charcoal analysis (~17-year intervals) with strong chronological control (^{210}Pb and AMS-^{14}C age constraints) to reconstruct the long-term fire history of the two main forest types – Coastal Douglas Fir (CDFmm) and Coastal Western Hemlock (CWHdm) – in the Strait of Georgia Lowlands. The overall aim of the project was to inform forest managers when developing fire management strategies for south coastal forests and GOEs in southwestern BC using two objectives. Our first objective was to better understand the local history of mid to late Holocene (i.e., between ca. 5000 cal yr BP and present) fire responses between the CDFmm and CWHdm forest types in the Strait of Georgia Lowlands. Our second objective was to combine our fire history results with other charcoal-inferred fire records in southwestern BC and western Washington to assess the synchrony of fire occurrence in the broader region during the mid to late Holocene. Comparisons were also made with previously documented Holocene climate oscillations and archeological information in the Pacific Northwest to evaluate how variations in climate and anthropogenic land-use in the broader region have influenced fire occurrence over time. Specific research questions included: (1) Do the CDFmm and CWHdm fire regimes in the study area remain stationary over the mid to late Holocene?; (2) Is fire regime behaviour in the CDFmm and CWHdm sites synchronous throughout the mid to late Holocene?; and (3) If long-term fire regimes are non-stationary, can variation in fire occurrence be tied to changes in climate or human activity through the mid to late Holocene?

Chapter 2. Methods

2.1. Study Area: Strait of Georgia Lowlands, BC

The Strait of Georgia Lowlands is one of nine ecoprovinces in BC and encompasses southeastern Vancouver Island, the Gulf Islands, and a portion of the Lower Mainland (Figure 1). The interaction between two semi-permanent pressure systems over the Pacific Ocean – the Aleutian Low and the Pacific High – drives the modern Mediterranean climate of this area. The Aleutian Low dominates in the winter and provides warm air that cools over land and subsequently delivers abundant precipitation to the coast (Walker & Pellatt, 2003). In the spring, the Pacific High brings dry air from the northwest to the coast and blocks westerly storms. As a result, the Pacific High dominates in the summer and produces very warm and dry conditions that increase the duration and severity of summer droughts and forest fires in the study area (Agee, 1993; Gedalof, Peterson, & Mantua, 2005). However, the Pacific High can also intensify during the winter and block westerly storm tracks, subsequently lowering precipitation and increasing forest fire risk.

Another characteristic feature of the summer dry, Mediterranean climate of the Strait of Georgia Lowlands is the sharp precipitation gradient created by the orographic effects of both the Vancouver Island Mountain Range and the Coast Mountain Range. As a result, areas west of these mountains experience wet conditions while areas on the eastern side of these mountain ranges experience drier conditions. This sharp, east-west precipitation gradient creates local variation in the extent of summer drought and forest fires in the study area (Figure 1).

2.2. Study Sites

For this study, charcoal in the sediments of Somenos Lake, located on southeastern Vancouver Island, BC, and Chadsey Lake, located on Sumas Mountain in the central Fraser Valley, was used to provide new long-term fire history information for CDFmm and CWHdm forests in the Strait of Georgia Lowlands. We selected sites based on proximity to GOEs and preferable characteristics for local fire history reconstruction. Because charcoal particles can travel great distances following a fire event, the source area can be from local (i.e., within the lake's catchment), extra-local (i.e., near but not within the catchment), or regional (i.e., distant) fires (Whitlock & Larson, 2001). Studies have shown that smaller lakes provide a better record of local fires than larger lakes because they typically have a smaller catchment area (Whitlock & Millspaugh, 1996). In addition, macroscopic charcoal particles (> 125 μm diameter) are not transported far from their source and are thus more representative of local fire events than microscopic particles (< 125 μm diameter) (Clark & Royall, 1995; Clark, 1988; Whitlock & Millspaugh, 1996). Therefore, to obtain a local fire history we selected Somenos Lake and Chadsey Lake because of their relatively small surface areas and focused our analysis on the macroscopic charcoal particles (> 125 μm diameter) contained within each lake sediment core.

2.2.1. Somenos Lake, BC

Somenos Lake is located on southeastern Vancouver Island, approximately 2 km from Duncan, BC at 16 masl (48.48ºN, 123.42ºW) (Figure 1j). The lake has a 97.2 ha surface area with a maximum depth of 6.5 m, three inflows (Richards, Bings Menzies, and Averill Creeks), and one outflow (Somenos Lake Creek). The watershed is 7000 ha and is situated in the Moist Maritime Coastal Douglas Fir (CDFmm) biogeoclimatic zone in the rainshadow of the Coast Mountains and is characterized by warm, dry summers and wet, mild winters (Meidinger & Pojar, 1991). The mean annual precipitation for the area is similar to that of the nearby City of Duncan (1509 mm/yr) (Environment Canada, 2015). The area surrounding the lake is relatively flat and consists of a range of wetland types and limited mature overstory canopy. Some vegetation in the wetland includes: Indian plum (*Oemleria cerasiformis*), Scotch broom (*Cytisus scoparius*), Oceanspray

(*Holodiscus discolor*), Smartweed (*Polygonum coccineum*), and Reed managrass (*Glyceria grandis*) (Rasmussen, 2012). Mature overstory canopies are located at the fringe of agriculture fields and in close proximity to creeks and include species such as the Pacific willow (*Salix lucida*), Scouler's willow (*Salix scouleriana*), Garry oak (*Quercus garryana*), and Black cottonwood (*Populus balsamifera trichocarpa*) (Rasmussen, 2012). The entire lowland area surrounding the lake is designated Agricultural Land Reserve (ALR), which includes a 170 ha conservation land area owned by Ducks Unlimited Canada and The Nature Trust of BC. The Somenos Lake Garry Oak Protected Area is located on the southeastern end of the lake.

The Somenos Lake watershed has a wide variation in land-use and topographic patterns. In recent years, considerable land development and clearing has occurred, including diking, logging, road construction, commercial and residential development, and agricultural practices. The majority of urban and residential development has occurred on the east side of the lake, while the north and west sides remain predominately rural and agricultural. After the early 20th century, agricultural development amplified when the wetlands surrounding Somenos Lake were drained to produce better farmland (Rasmussen, 2012). Although riparian lowlands still exist around the lake, the majority are used for agricultural purposes. Seasonal flooding of these agricultural and riparian lowlands occurs during periods of high discharge when the Cowichan River backfloods into Somenos Lake Creek. Conversely, all creeks in the watershed become increasingly low and sometimes intermittently dry during low late summer water flows, between July and September (Burns, 1999). During this time, high nutrient levels in the lake and creeks cause algae blooms and low dissolved oxygen levels (Williams & Radcliffe, 2001). These algal blooms significantly limit recreational activities (e.g., fishing, kayaking, canoeing, and waterskiing) that normally occur on the lake during the summer months.

2.2.2. Chadsey Lake, BC

Chadsey Lake is located on the north-facing side of Sumas Mountain in the central Fraser Valley at 620 masl (49.07ºN, 122.08ºW) (Figure 1h). The lake has a 5.6 ha surface area with a maximum depth of 16 m, one inflow (Chadsey Lake Creek), and no known outflowing streams. The watershed is situated in the Dry Maritime Coastal Western Hemlock (CWHdm) biogeoclimatic zone and is characterized by relatively high rainfall, cool summers and mild winters. On average, the CWH zone is the rainiest biogeoclimatic zone in BC with a mean annual precipitation ranging from 1000 to 4400 mm (Meidinger & Pojar, 1991). However, Chadsey Lake is situated in the drier portion of the CWH zone (i.e., Dry Maritime (dm)) and likely receives a mean annual precipitation closer to that of the nearby City of Abbotsford, BC (1538 mm/yr) (Environment Canada, 2015). Western hemlock (*Tsuga heterophylla*), Western redcedar (*Thuja plicata*), and Douglas-fir (*Pseudotsuga menziesii*) dominate the open canopy around the lake (Meidinger & Pojar, 1991). A steep slope is located on the south side of the lake and the west and east flank of the mountain, including Chadsey Lake, are protected within the Sumas Mountain Regional Park. A 20 ha stand of Garry oak, located on the lower, steep southeast facing slope of the mountain (49.05ºN, 122.08ºW), is not within the Park boundaries but is designated as an ecological reserve.

Land-use within the Chadsey Lake watershed is a mix of industrial, recreational, and conservational use. Since the 1900s, the watershed has been extensively logged. Prior to 1981, lands were harvested at a rate of 47 ha per year (Perkins, 2007). Today, the Ministry of Forests controls logging on a license basis. Recreational activities vary from fishing on Chadsey Lake to mountain biking, hiking, and horseback riding. A variety of conservation efforts, including Sensitive Ecosystems Inventory mapping and Wildlife Habitat Suitability Rating, have been conducted within the watershed (Durand, 2010).

2.3. Fieldwork

Sediments were retrieved using a hard bottomed, inflatable boat anchored over the deepest part of each lake. In 2013, a 4.94 m composite core (i.e., 0.54 m surface core and 4.4 m piston core) was collected from Somenos Lake using a 5 cm diameter modified Livingstone piston corer (Wright, Mann, & Glaser, 1984) and a 5 cm diameter plexiglas tube connected to the Livingstone. In 2014, a 5.08 m composite core (i.e., 0.42 m surface core and 4.66 m piston core) was collected from Chadsey Lake using a 7.6 cm diameter modified Glew gravity corer (Glew, 1988) and a 5 cm diameter modified Livingstone piston corer (Wright et al., 1984). In both cases, the sediment-water interface was intact; however, the entire sedimentary sequence since the last deglaciation (ca. 13,700 cal yr BP (Pellatt, Mathewes, & Clague, 2002)) was only captured in the Somenos Lake composite core. The build-up of pressure during coring of deep sediments limited our ability to collect the entire sedimentary sequence at Chadsey Lake.

After collection, each composite core was photographed, stored, and refrigerated until needed for analysis. Surface cores were extruded on-site at 1 cm intervals using a close-interval sectioning device (Glew, 1988) and sealed in Whirl-pak® sample bags. Piston cores were wrapped in cellophane and aluminum foil and encased in two halves of polyvinyl chloride (PVC) tubing for transport and storage.

2.4. Laboratory

2.4.1. Lithology and Chronology

Following core retrieval, the lithology for each composite core was documented. The lithologic characteristics of the surface cores were documented in the field. The lithology of the piston cores was described after they were split longitudinally and photographed in the laboratory.

Sediment mass accumulation rates and the age of each 1 cm increment for each composite core were estimated by age-depth models based on ^{210}Pb and AMS-^{14}C age determinations and Mazama tephra layers (Tables 2 and 3). Sediment samples from each surface core were sent to MyCore Scientific Inc. in Dunrobin, Ontario for ^{210}Pb dating (Table 2). Macrofossil, pollen, and bulk sediment samples from the piston cores were sent to the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory in Livermore, California for AMS-^{14}C dating (Table 3). Macrofossil samples were washed with distilled water, and pollen samples were extracted using a modified procedure from (Brown, Nelson, Mathewes, Vogel, & Southon, 1989). Pollen samples were boiled in 6 % potassium hydroxide (KOH) for 20 minutes, treated with hot 1 N hydrochloric acid (HCl), sieved at 90 μm, treated with 48 % hydrofluoric acid (HF) in a boiling water bath for 10 minutes, and bleached with 3 %

sodium hypochlorite (NaOCl) for 5 minutes. AMS-^{14}C ages were converted to calendar years before present (cal yr BP) using CALIB 7.0.2 (Stuiver & Reimer, 1993) and the IntCal13.14c dataset (Reimer et al., 2013). The median ages produced by the program were used in the age-depth model (Table 3). Since the deposition of the Mazama tephra was likely a rapid event, the thickness of the tephra in both composite cores was subtracted from the true core depths to create adjusted total core depths.

Table 2. ^{210}Pb **age determinations and sediment mass accumulation rates for Somenos Lake and Chadsey Lake.**

Site	Depth (cm)	Age (cal yr BP)	Standard Deviation (± years)	Sediment Mass Accumulation Rate ($g/m^2/yr$)
Somenos	0.5	-64	0	572
Somenos	3.5	-58	1	456
Somenos	6.5	-50	1	388
Somenos	9.5	-38	3	436
Somenos	12.5	-28	6	474
Somenos	15.5	-18	10	493
Somenos	18.5	-8	10	372
Somenos	21.5	4	21	360
Somenos	24.5	15	24	323
Somenos	27.5	31	36	250
Somenos	30.5	52	52	157
Somenos	33.5	86	86	71
Chadsey	0.5	-64	0	212
Chadsey	3.5	-49	1	322
Chadsey	6.5	-33	2	253
Chadsey	9.5	-11	4	193
Chadsey	12.5	13	5	170
Chadsey	15.5	37	11	218
Chadsey	18.5	51	31	441
Chadsey	21.5	60	30	282
Chadsey	24.5	81	23	73

Table 3. **AMS-^{14}C and calibrated calendar ages for Somenos Lake and Chadsey Lake.**

Site	CAMS ID	Depth (cm)	Material	Radiocarbon Age (^{14}C yr BP ± 1σ)	Calendar Age (cal yr BP)[a]
Somenos	169246	90.5	Pollen	3150 ± 30	3356.5 (3265 – 3448)
Somenos	167357	115.5	Seeds	3245 ± 30	3478 (3396 – 3560)
Somenos	167358	167.5	Sedge	3755 ± 35	4111.5 (3988 – 4235)
Somenos	n/a	492-493	Mazama tephra	6730 ± 40	7590[b] (7514 – 7666)
Chadsey	171932	21.5	Sediment	600 ± 30	597.5[c] (542 – 653)
Chadsey	171933	45.5	Sediment	1445 ± 30	1341.5 (1298 – 1385)
Chadsey	169247	84.5	Pollen	2695 ± 30	2802.5 (2755 – 2850)
Chadsey	169248	140.5	Pollen	3155 ± 30	3359 (3269 – 3449)
Chadsey	169249	199.5	Pollen	4010 ± 30	4491.5 (4418 – 4565)
Chadsey	n/a	406-407	Mazama tephra	6730 ± 40	7590[b] (7514 – 7666)

[a] Median and 2σ range from CALIB 7.0.2 (Stuiver & Reimer, 1993) using the IntCal13.14c dataset (Reimer et al., 2013)
[b] From Hallett, Hills, and Clague (1997)
[c] Only used in the Chadsey Lake AMS-^{14}C-based age-depth model

The chronology for the Somenos Lake composite core was determined by an age-depth model that was constructed based on twelve ^{210}Pb age determinations and a constant rate of supply (CRS) model (Appleby & Oldfield, 1977) and linear interpolation between calibrated calendar ages of three AMS-^{14}C ages (Figure 2a; Appendix A). Because the occurrence of Mazama tephra was observed at depths below (i.e., prior to) a hiatus in sediment accumulation at 380 cm, the age-depth model was created without the tephra age constraint, and the date of the end of the hiatus was based on linear extrapolation. The mean linear sedimentation rate for the composite core was 0.1 cm/yr, with a maximum of 1 cm/yr at the youngest section of the composite core (i.e., at -64 cal yr BP) and a minimum of 0.02 cm/yr between 90 and 33 cm of the composite core (i.e., between ca. 3473 and 3356 cal yr BP) (Figure 2a). The mean sample resolution for the composite core was 17 yr/cm, with a lowest resolution of 57 yr/cm between 90 and 33 cm and a highest resolution of 1 yr/cm at the youngest part of the record.

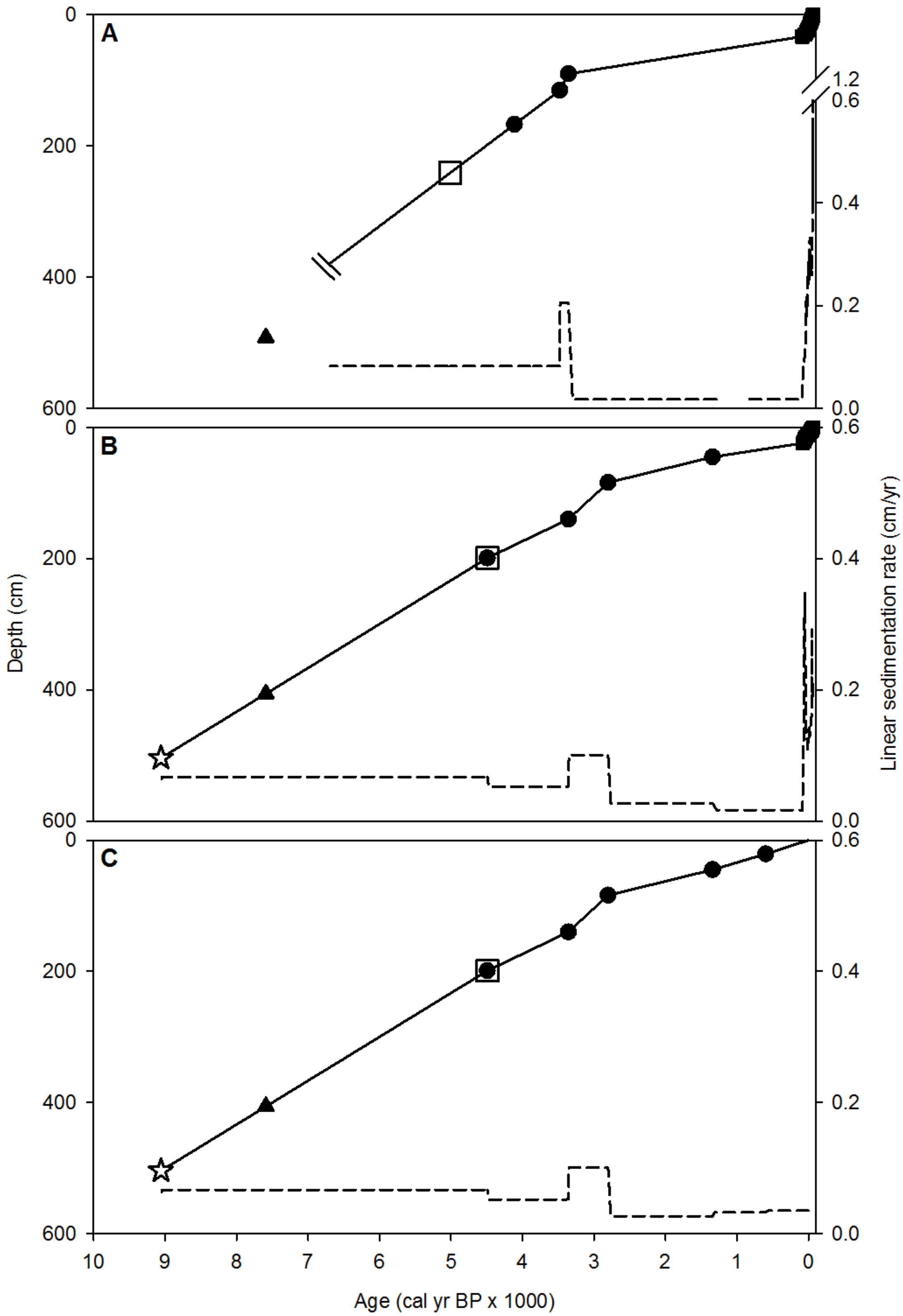

Figure 2. **Age-depth models and linear sedimentation rates (cm/yr) for Somenos Lake and Chadsey Lake composite cores.**

In all panels, squares symbolize ^{210}Pb age determinations; circles denote AMS-^{14}C age determinations; open squares indicate the oldest 1 cm interval analyzed for charcoal; triangles represent Mazama tephra; solid lines signify age-depth model; and dotted lines depict linear sedimentation rates. (a) Age-depth model and linear sedimentation rates for Somenos Lake composite core based on twelve ^{210}Pb age determinations (Table 2) and three calibrated calendar ages derived from AMS-^{14}C analysis (Table 3). Double line marks the extrapolated age of the youngest section of the sediment hiatus (at 380 cm). (b) Age-depth model and linear sedimentation rates for Chadsey Lake composite core based on nine ^{210}Pb age determinations (Table 2), four calibrated calendar ages derived from AMS-^{14}C analysis, and Mazama tephra (Table 3). Open star denotes the extrapolated basal age of the sediment core. (c) Additional AMS-^{14}C-based age-depth model and linear sedimentation rates for Chadsey Lake composite core based on five calibrate calendar ages derived from AMS-^{14}C analysis, and Mazama tephra (Table 3). Open star denotes the extrapolated basal age of the sediment core.

The chronology for the Chadsey Lake composite core was determined by an age-depth model that was constructed based on nine ^{210}Pb age determinations and a CRS model and linear interpolation between calibrated calendar ages of four AMS-^{14}C ages and the Mazama tephra (Figure 2b). The basal date of the core was based on linear extrapolation. The mean linear sedimentation rate for the composite core was 0.07 cm/yr, with a maximum of 0.4 cm/yr between 20 and 18 cm of the composite core (i.e., between ca. 60 and 51 cal yr BP) and a minimum of 0.02 cm/yr between 84 and 24 cm of the composite core (i.e., between 2802 and 81 cal yr BP) (Figure 2b). The mean sample resolution for the composite core was 18 yr/cm, with a lowest resolution of 60 yr/cm between 84 and 24 cm and a highest resolution of 3 yr/cm from 20 to 18 cm of the composite core.

To ensure a continuous chronology, surface and piston cores are typically correlated based on similarities in raw charcoal counts and chronology (Huerta, Whitlock, & Yale, 2009). While we observed a number of similar patterns in the Somenos Lake and Chadsey Lake charcoal stratigraphy between the surface and piston cores, we were unable to use chronology to confirm these correlations due to a large discrepancy between the age of sediment derived from ^{210}Pb and AMS-^{14}C analysis. Dating revealed a 537-year difference between Chadsey Lake sediment dated by ^{210}Pb and AMS-^{14}C methods; i.e., the age of 21-22 cm from Chadsey Lake was ^{210}Pb dated as 60.35 cal yr BP (Table 2) and AMS-^{14}C dated as 597.5 cal yr BP (Table 3). ^{210}Pb and AMS-^{14}C dates can be influenced by a number of different factors such as the Suess effect (Tans, De Jong, & Mook, 1979), contamination with old carbon (Mathewes & Westgate, 1980), and sediment mixing (i.e., bioturbation) (Baskaran, Nix, Kuyper, & Karunakara, 2014). We hypothesize that the 537-year difference in the age of Chadsey Lake sediment may be attributed to old carbon having a greater effect on AMS-^{14}C dating than the effect of mixing on ^{210}Pb dating.

Because uncertainties in age control may affect our estimates of fire history characteristics (e.g., mFRI, CHAR, and fire frequency), we analyzed the Chadsey Lake charcoal data in two ways. First, the Chadsey Lake charcoal data was analyzed using the age-depth model described above (i.e., based on nine ^{210}Pb age determinations and a constant rate of supply (CRS) model and linear interpolation between calibrated calendar ages of four AMS-^{14}C ages and the Mazama tephra) (Figure 2b). Second, the Chadsey Lake charcoal data was analyzed using an "AMS-^{14}C-based age-depth model" based on linear interpolation between calibrated calendar ages of five AMS-^{14}C ages and the Mazama tephra and the assumption that the youngest section of the core is 0 cal yr BP (Figure 2c). This approach allowed us to assess the potential effects of age model uncertainties on Chadsey Lake fire history characteristics (e.g., mFRI and trends in CHAR and fire frequency) during the mid to late Holocene.

While the mean and minimum linear sedimentation rates of the AMS-^{14}C-based age-depth model (mean, 0.06 cm/yr; minimum, 0.03 cm/yr) remained similar to the original age-depth model (mean, 0.07 cm/yr; minimum, 0.02 cm/yr), the maximum linear sedimentation rate of the AMS-^{14}C-based age-depth model (i.e., 0.1 cm/yr) was significantly lower than the original age-depth model (i.e., 0.4 cm/yr) (Figure 2c). Furthermore, although the two age-depth models had an analogous mean sample resolution (i.e., 18 yr/cm), the lowest and highest resolution differed between the AMS-^{14}C-based age-depth model (lowest, 38 yr/cm; highest, 10 yr/cm) and the original age-depth model (lowest, 60 yr/cm; highest, 3 yr/cm).

2.4.2. Charcoal Analysis

Prior to charcoal analysis, we conducted several small experiments to determine the best charcoal extraction method to produce the most reliable representation of our sedimentary-charcoal records. In these experiments, the effects of two commonly used disaggregating chemicals, 5 % sodium hexametaphosphate ($(NaPO_3)_6$) and 10 % potassium hydroxide (KOH), and two commonly used lightening agents, 6 % hydrogen peroxide (H_2O_2) and 5 % sodium hypochlorite (NaClO), on charcoal abundance and condition (i.e., size and shape) were studied. Our preliminary results (summarized in Appendix B) suggested that the charcoal extraction method using 5 % $(NaPO_3)_6$ and 6 % H_2O_2 produced charcoal abundance and condition that best represented the original sample and thus was used in this study.

Charcoal was extracted from 1 cm^3 sediment samples taken at contiguous 1 cm intervals along the length of each composite core. Samples were soaked in a 5 % $(NaPO_3)_6$ solution for 24 hours and a 6 % H_2O_2 solution for 1 hour to disaggregate sediment and remove or lighten non-charcoal, organic material. Samples were gently wet-sieved through a 125 μm sieve, back-washed into a Petri dish, and placed in a 30 ºC oven overnight. Samples were then placed on a transparent, 1 cm gridded counting coaster, and charcoal particles were identified under a Leica® M205C stereomicroscope based on brittleness, reflectance, and evidence of wood or plant cell structure (Clark & Royall, 1995).

Charcoal accumulation rates (CHAR, particles/cm^2/yr) are commonly used to reconstruct fire history because they account for the influence of changing sediment accumulation rates on charcoal abundance and concentration (Whitlock & Larson, 2001). The software package CharAnalysis (Higuera, Brubaker, Anderson, Hu, & Brown, 2009), which is freely available at https://sites.google.com/site/charanalysis/, was used to calculate CHAR, isolate charcoal peaks that represent fire episodes, and estimate mFRIs, fire frequency, and fire-episode (peak) magnitude. We selected the median temporal resolution of each composite core (Somenos Lake, 12 years; Chadsey Lake, 19 years) to interpolate charcoal concentrations (particles/cm^3) and sediment accumulation rates (cm/yr) to regularly spaced time intervals. CHAR were subsequently calculated by multiplying the interpolated charcoal concentrations by the interpolated sediment accumulation rates.

Charcoal peaks were isolated from CHAR by decomposing CHAR into a slowly varying background component and a more rapidly varying peaks component (Clark, Royall, & Chumbley, 1996; Long, Whitlock, Bartlein, & Millspaugh, 1998). The background component indicates the long-term changes in fuel characteristics, secondary charcoal accumulation, and sediment mixing (Higuera, Peters, Brubaker, & Gavin, 2007). The peaks component represents individual "fire episodes" (i.e., one or more fire events occurring within the duration of a charcoal peak) and noise (Long et al., 1998). We used a Lowess smoother robust to outliers with a 700- and 900-year window width to calculate the background component of the Somenos Lake CHAR and Chadsey Lake CHAR, respectively. We used the results of a sensitivity analysis run in the CharAnalysis program to select the sizes of these smoothing windows. Sensitivity results indicated that the sum of the median signal-to-noise ratios (SNI) (i.e., a measure of the separation between fire related peaks and non-fire related peaks) and goodness-of-fit (GOF) (i.e., a measure of how well the noise of the peaks component fits with the noise distribution model) was maximized at 700 and 900 years for Somenos Lake and Chadsey Lake, respectively.

The peaks component was represented by the positive residuals remaining after background CHAR was removed from CHAR. We used a Gaussian mixture distribution to model noise within the peak component of CHAR and selected a threshold value set at the local 99th percentile of the mixture model to isolate fire related peaks from non-fire related peaks. Fire related peaks were screened to eliminate ones that resulted from statistically insignificant variations in charcoal counts (Gavin, Hu, Lertzman, & Corbett, 2006). A peak was removed if its maximum charcoal count had a greater than 5 % chance of coming from the same Poisson-distributed population as the minimum charcoal count within the preceding 75 years (Higuera et al., 2008). The non-parametric Kolmogorov-Smirnov goodness-of-fit test was used to determine if the samples came from the same probability distribution (Higuera et al., 2008).

To estimate mean fire return interval (mFRI) and fire frequency (fires/1000yrs), we selected a 1000-year moving window to smooth the fire-related peaks component of CHAR. Using the more common approach (i.e., averaging the time period between fire episodes (Agee, 1993)), we calculated mFRI for the entire length of each composite record and for three temporal zones based on prior knowledge of shifts in onset or expansion in regional climate, human habitation, and fire activity (i.e., zone 1, ca. 5000 to 3500 cal yr BP; zone 2, 3500 to 2000 cal yr BP; and zone 3, 2000 cal yr BP to present). Fire-episode (peak) magnitude (charcoal pieces/cm^2/charcoal peak) is broadly related to fire severity, size, and taphonomic processes (Higuera et al., 2007) and was also estimated for each of our sedimentary-charcoal records by summing all charcoal counts within a given peak that exceeded the CHAR threshold value. We used the same CharAnalysis parameters used in the analysis of Chadsey Lake to analyze the additional AMS-^{14}C-based composite Chadsey Lake record.

We observed a strong correlation between charcoal abundance and sediment accumulation rate at the youngest section of each sedimentary record which may be attributed to the large, 53- and 18-fold, change in sediment accumulation rates at the top of the Somenos Lake (Figure 2a) and Chadsey Lake (Figure 2b) records, respectively. We noted similarly large increases in CHAR at the beginning of charcoal-based fire history records in other studies where the top sediment of cores were dated with ^{210}Pb methods (e.g., Sugimura et al. (2008)). To compensate for uneven variations in sediment accumulation rates at the top of both our sedimentary records, we included an additional statistical analysis solely on the surface core of each sedimentary record (i.e., from 1405 to -64 cal yr BP at Somenos Lake and from 1161 to -64 cal yr BP at Chadsey Lake). This "surface-only" approach allowed us to provide additional insight into the recent fire history at each site and to determine if the temporal scale over which the sedimentary records are analyzed impacts the estimation of recent fire history characteristics.

For each surface-only analysis on both the Somenos Lake and Chadsey Lake sedimentary records, we used the same age-depth model and CharAnalysis parameters with two exceptions. First, the median sample resolutions used in each surface-only analysis were shorter (Somenos Lake, 6 years; Chadsey Lake, 8 years) than those used in the analysis of each composite core (Somenos Lake, 12 years; Chadsey Lake, 19 years). Second, the window widths used to model and smooth the background CHAR component in each surface-only analysis were smaller (Somenos Lake, 200 years; Chadsey Lake, 300 years) than those used in the analysis of each composite core

(Somenos Lake, 700 years; Chadsey Lake, 900 years). Although the sensitivity analysis indicated that the signal-to-noise ratio (SNI) and goodness-of-fit (GOF) were maximized at 700 years in both surface core records, CharAnalysis would not run with a 700-year window width. Therefore, we selected the largest window width that the software would use (i.e., 200 and 300 years for Somenos Lake and Chadsey Lake, respectively), and interpreted our results with the understanding that narrow window widths can produce a background component that mirrors the peak component of CHAR and therefore detect fewer fire episodes than wider window widths (Mooney & Tinner, 2011).

Finally, to investigate the synchrony of fire activity and climate-fire-human linkages over the last ~5000 years in the broader region, we compared changes in our Somenos Lake and Chadsey Lake fire history reconstructions to previous studies in the Pacific Northwest that document shifts in fire activity, climate, and human habitation over time. We used three informal zones to facilitate discussion of these comparisons and to help determine potential drivers of fire occurrence over the mid to late Holocene at each of our sites. Zones were based on visually identified fire frequency trends in both Somenos Lake and Chadsey Lake charcoal records as well as documented shifts in climate and human habitation (i.e., the onset of Neoglacial conditions ca. 3500 cal yr BP (Walker & Pellatt, 2003) and the development of complex Indigenous societies ca. 2000 cal yr BP (Brown & Hebda, 2002a)): zone 1 (ca. 5000 to 3500 cal yr BP), zone 2 (3500 to 2000 cal yr BP), and zone 3 (2000 cal yr BP to present).

To our knowledge, charcoal-based fire history studies have been conducted and published on twenty-three sites in southwestern BC and western Washington (Figure 1; Table 1). While nineteen of these study sites were long enough to be compared to our ~5000-year reconstructions, three were based on shorter timer periods (i.e., < 2700 years) (Derr, 2014; Gavin et al., 2003; Lucas & Lacourse, 2013) and were thus only able to be compared to the fire history over the last ~2000 years (i.e., zone 3) of our records. Furthermore, an additional three study sites with fire histories shorter than 560 years (Pellatt et al., 2015) were only used for comparing the estimated timing of modern fire episodes in our records. Finally, because of the wide variation in charcoal analysis techniques (i.e., charcoal extraction method, charcoal source area, sample resolution, chronological control, and measure used to infer fire activity (e.g., CHAR or fire frequency)) (Table 1), only general comparisons of fire activity between sites were made.

Chapter 3. Results

3.1. Lithology

We identified three lithologic units in the 4.94 m Somenos Lake composite core (Appendix C). From the oldest section of the core to 380 cm, the sediment consists of a sedge-like material; clay extends from 380 to 265 cm of the core; and highly organic sediment is found in the top 265 cm of the core. Clay normally lines the bottom of a typical lake; therefore, the sedge-like sediment found in the oldest section of the core is likely an interruption of sediment accumulation (i.e., a hiatus) caused by transitions of the lake from a marsh to a body of water. Tephra from the Mt. Mazama eruption, estimated to have occurred ca. 6730 ± 40 ^{14}C yr BP (ca. 7590 cal yr BP) (Hallett et al., 1997) in southern Oregon, is found at 492 to 492.4 cm depth.

We identified one lithologic unit in the 5.08 m Chadsey Lake composite core (Appendix D). From the oldest to the youngest section of the core, the sediment is comprised of gyttja (i.e., a fine-grained organic-rich sediment). The Mazama tephra is found at 406 to 409 cm depth.

3.2. Somenos Lake Charcoal Record (5025 to -64 cal yr BP)

To obtain a robust reconstruction of local fire history using peak analysis, a sedimentary-charcoal record should have a signal-to-noise index (SNI) greater than three (Kelly, Higuera, Barrett, & Hu, 2011). While the global SNI for the Somenos Lake charcoal record meets the SNI threshold (median global SNI, 4.48), the local SNI for two short sections of the record is below the minimum threshold of three. From 5025 to 4148 cal yr BP, the mean local SNI is 2.77, and from 2804 to 1844 cal yr BP, the mean local SNI is 1.92 (Figure 3). Low local SNIs during these two time periods suggests a poor separation between large, fire related peaks and the noise-attributable, non-fire related peaks (i.e., a weak signal) and thus indicates that all fire history characteristics (e.g., CHAR, background CHAR, mFRI, and fire frequency) in these sections must be interpreted with caution (Kelly et al., 2011).

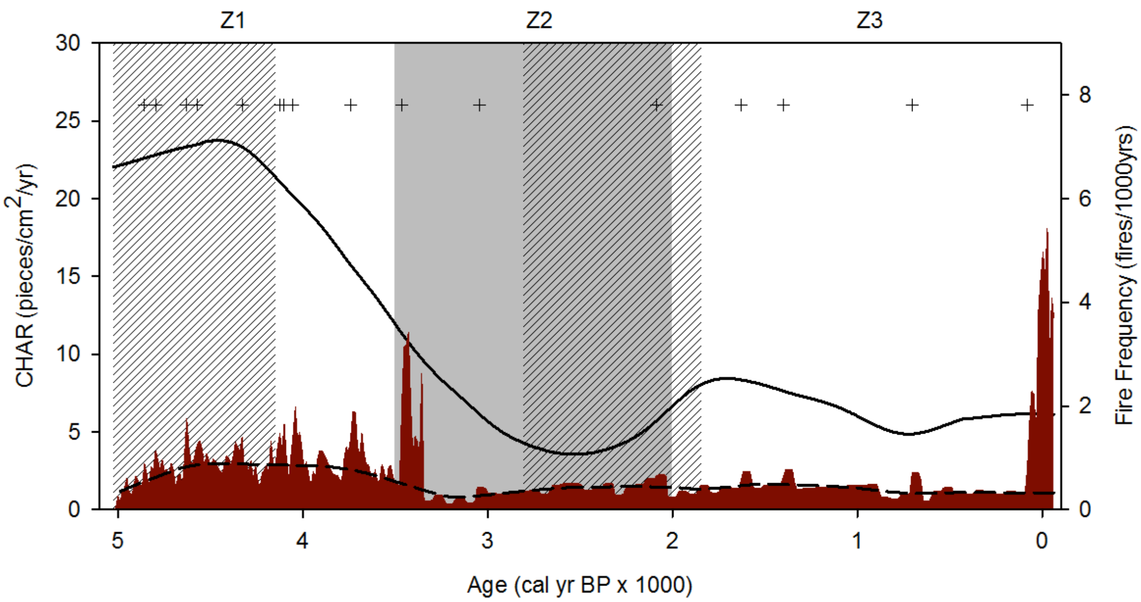

Figure 3. Somenos Lake CHAR, background component, fire frequency, and fire episodes over the last ~5000 years.
Grey shaded area represents zone 2 (3500 to 2000 cal yr BP); diagonal lined areas show where local SNI is < 3; red shaded area depicts the interpolated CHAR (median sample resolution = 12 years); dashed line symbolizes low-frequency background CHAR defined by 700-year trends; black line indicates the variation in smoothed fire frequency (fires/1000yrs); and crosshairs mark fire episodes.

The mean CHAR in the Somenos Lake charcoal record (interpolated to 12-year sample intervals) is 2.22 pieces/cm^2/yr, with two periods of high CHAR occurring between 5025 and 3356 cal yr BP and between 80 and -64 cal yr BP (Figure 3). Two of the largest peaks in the record (peak magnitude, 890.51 and 2957.59 pieces/cm^2/peak) occur during these two periods of high CHAR at fire episodes that we estimate to have occurred ca. 3464 and 80 cal yr BP, respectively. Two separate sections characterize the background component. The first, from 5025 to 3188 cal yr BP, is distinguished by a relatively higher background (mean, 2.29 pieces/cm^2/yr). The second, from 3188 cal yr BP to present, is distinguished by a relatively lower background (mean, 1.29 pieces/cm^2/yr).

In total, 16 significant fire episodes are detected in the Somenos Lake charcoal record (Figure 3). The current fire-free interval (i.e., time since last fire (TSLF)) is 144 years. The longest fire-free interval over the entire mid to late Holocene record is ~960 years between fire episodes at 3044 and 2084 cal yr BP. The mFRI for the entire composite core is 318 years, with a natural range of variability of 199 to 459 years. The mFRIs for zone 1 (ca. 5000 to 3500 cal yr BP), zone 2 (3500 to 2000 cal yr BP), and zone 3 (2000 cal yr BP to present) are 140 (77 to 209), 690, and 516 years, respectively.

Fire frequency increases from 6.61 fires/1000yrs at the oldest part of the core to the maximum fire frequency of the record (i.e., 7.12 fires/1000yrs) ca. 4484 cal yr BP (Figure 3). It subsequently decreases to 1.07 fires/1000yrs ca. 2576 cal yr BP and then increases to 2.53 fires/1000yrs ca. 1736 cal yr BP. Fire frequency decreases to 1.46 fires/1000yrs ca. 752 cal yr BP and then remains consistently low for the remainder of the record (i.e., between 1.46 and 1.85 fires/1000yrs).

3.3. Chadsey Lake Charcoal Record (4506 to -64 cal yr BP)

Overall, the Chadsey Lake charcoal record has a high global signal-to-noise index (SNI) (median global SNI, 4.84) with a marginally low local threshold (mean local SNI, 2.65) occurring at the oldest part of the record (i.e., between 4506 and 3907 cal yr BP) (Figure 4). The mean CHAR (interpolated to 19-year sample intervals) is 5.74 pieces/cm^2/yr. Two periods of high CHAR occur between 3166 and 2862 cal yr BP and between 69 and -64 cal yr BP. Three sections characterize the background component of the CHAR record. The first, from 4506 to 3508 cal yr BP, has a relatively higher background (mean, 3.78 pieces/cm^2/yr). The second, from 3508 to 1057 cal yr BP, is distinguished by an increasing trend from 2.51 to 5.76 pieces/cm^2/yr (mean, 4.06 pieces/cm^2/yr). The third, from 1057 to -64 cal yr BP, is distinguished by a decreasing trend from 5.76 to 0.60 pieces/cm^2/yr (mean, 3.39 pieces/cm^2/yr). While the largest peak (peak magnitude, 6685.12 pieces/cm^2/peak) is substantially higher than the rest of the record (mean peak magnitude of record, 599.61 pieces/cm^2/peak), it occurs during the lowest background level of the record (i.e., at 68 cal yr BP).

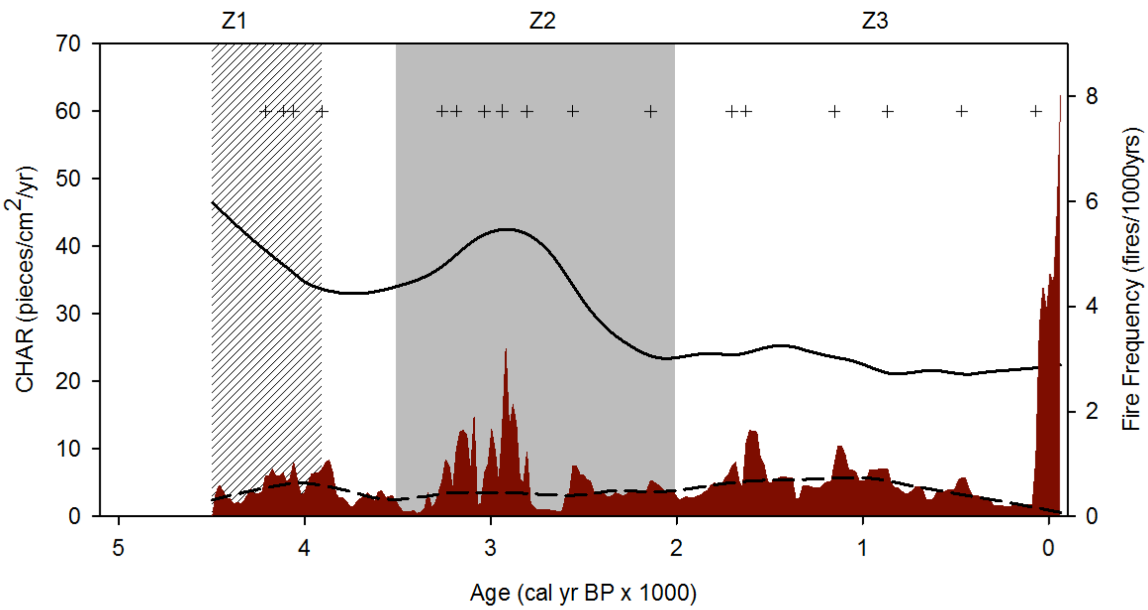

Figure 4. **Chadsey Lake CHAR, background component, fire frequency, and fire episodes over the last ~5000 years.**
Grey shaded area represents zone 2 (3500 to 2000 cal yr BP); diagonal lined area shows where local SNI is < 3; red shaded area depicts the interpolated CHAR (median sample resolution = 19 years); dashed line symbolizes low-frequency background CHAR defined by 900-year trends; black line indicates the variation in smoothed fire frequency (fires/1000yrs); and crosshairs mark fire episodes.

Overall, 17 significant fire episodes are detected in the Chadsey Lake composite core yielding a mFRI of 259 years for the entire record with a natural range of variability of 175 to 353 years (Figure 4). The time since last fire (TSLF) is 133 years and the longest fire-free interval is ~646 years between fire episodes at 3906 and 3260 cal yr BP. The mFRIs for zone 1 (ca. 5000 to 3300 cal yr BP), zone 2 (3300 to 2200 cal yr BP), and zone 3 (2200 cal yr BP to present) are 101, 187 (105 to 288), and 327 (203 to 445) years, respectively.

Fire frequency decreases from the highest fire frequency of the record (i.e., 5.97 fires/1000yrs) ca. 4506 cal yr BP to 4.24 fires/1000yrs ca. 3755 cal yr BP (Figure 4). It then increases to 5.47 fires/1000yrs ca. 2919 cal yr BP and decreases again to 3.01 fires/1000yrs ca. 2083 cal yr BP. Fire frequency remains relatively consistent for the rest of the record with a slight increase occurring between 2083 and 1475 cal yr BP.

3.4. Comparison of Somenos Lake and Chadsey Lake Charcoal Records

Overall charcoal concentrations are approximately three times greater at Chadsey Lake (mean, 131 pieces/cm^3; range, 8 to 629 pieces/cm^3) than at Somenos Lake (mean, 46 pieces/cm^3; range, 5 to 147 pieces/cm^3). CHAR are also approximately two and a half times higher at Chadsey Lake (mean, 5.74 pieces/cm^2/yr; range 0.45 to 62.31 pieces/cm^2/yr) than at Somenos Lake (mean, 2.22 pieces/cm^2/yr; range of 0.11 to 18.08 pieces/cm^2/yr) (Figure 5a). The steep slope on the south side of Chadsey Lake likely contributes to a higher charcoal influx as a result of greater slope wash processes bringing more charcoal into the lake (Meyer, Wells, & Jull, 1995). In addition, the mature overstory canopy around Chadsey Lake increases woody fuel abundance, leading to higher severity fires and thus higher CHAR values. In contrast, the relatively flat terrain and surrounding wetland vegetation with limited mature overstory near Somenos Lake likely limits the movement of charcoal into the basin and produces a relatively lower fuel load than what occurs at Chadsey Lake, leading to reduced charcoal influx in the Somenos Lake basin (Terasmae & Weeks, 1979; Whitlock & Millspaugh, 1996).

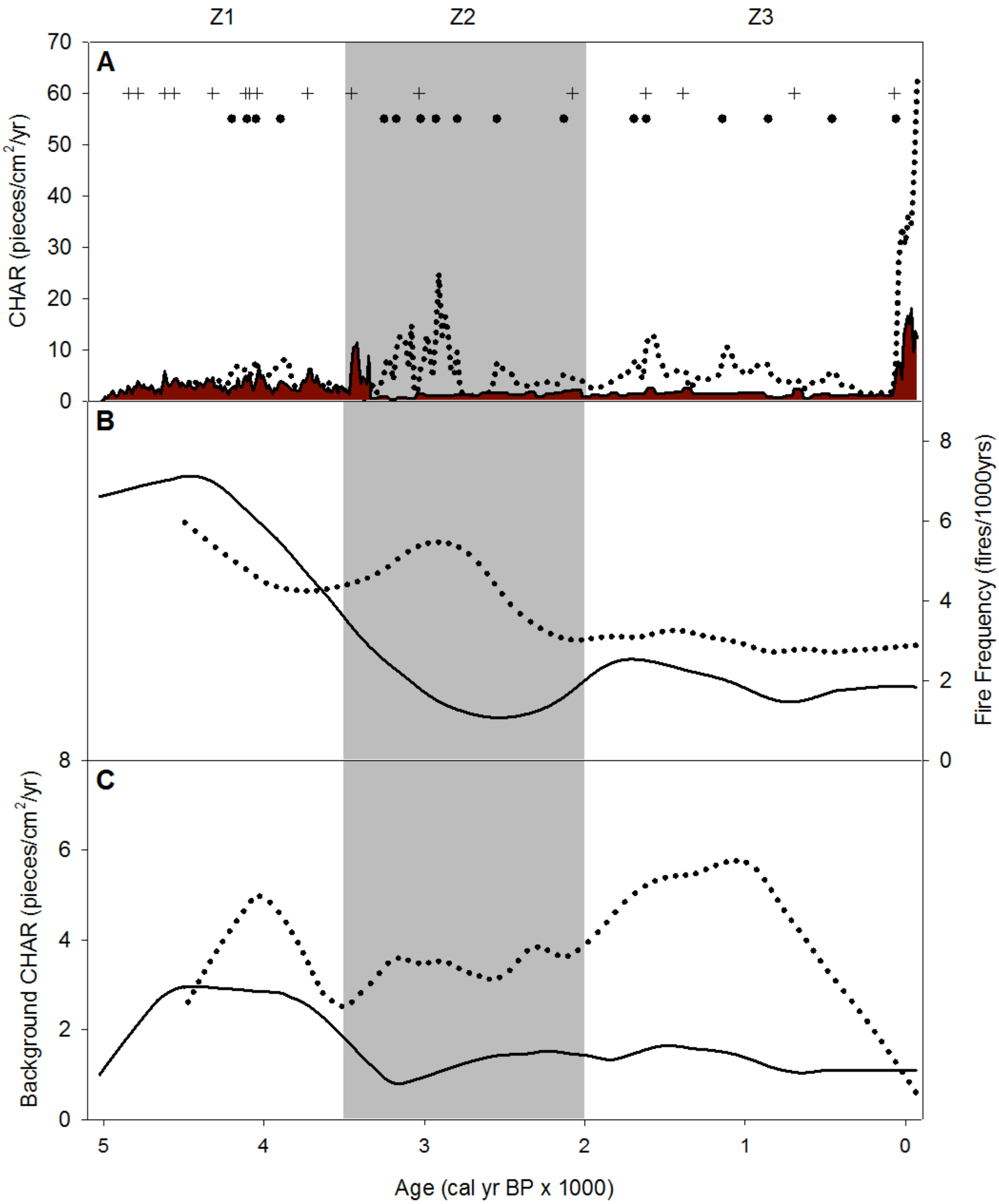

Figure 5. **Comparison of fire history characteristics between Somenos Lake and Chadsey Lake charcoal records over the last ~5000 years.**

In all panels, grey shaded area represents zone 2 (3500 to 2000 cal yr BP). (a) Crosshairs mark fire episodes in the Somenos Lake record; dots mark fire episodes in the Chadsey Lake record; red shaded area depicts the 12-year interpolated Somenos Lake CHAR; and dotted line represents the 19-year interpolated Chadsey Lake CHAR. (b) Solid line indicates Somenos Lake fire frequency and dotted line signifies Chadsey Lake fire frequency. (c) Solid line depicts background CHAR in the Somenos Lake record and dotted line represents background CHAR in the Chadsey Lake record.

Over the last ~5000 years, both sedimentary-charcoal records show a similar number of fire episodes (Somenos Lake, 16 fires; Chadsey Lake, 17 fires), resulting in comparable mFRIs between the two sites (Somenos Lake, 318 years (199 to 459); Chadsey Lake, 259 years (175 to 353)) (Table 4). Five of these fire episodes occur during very similar time periods at each site (i.e., when the gap between the ages of fire episodes at each site is within the 95 % confidence interval of the age model (ranges around ±30 years at these dates)). These similar episodes occur at 4124, 4052, 3044, 1628, and 80 cal yr BP at Somenos Lake, and at 4115, 4058, 3032, 1626, and 68 cal yr BP at Chadsey Lake. However, the temporal distribution of the remaining fire episodes is quite different between the two sites. During zone 1 (ca. 5000 to 3500 cal yr BP), the Somenos Lake record has five more fire episodes than the Chadsey Lake record (Figure 5a). In contrast, the Chadsey Lake record has four and two more episodes than the Somenos Lake record in zones 2 (3500 to 2000 cal yr BP) and 3 (2000 cal yr BP to present), respectively (Figure 5a).

Table 4. Comparison of mean fire return intervals (mFRI) and natural ranges of variability (i.e., 95 % confidence intervals of mFRI) for Somenos Lake and Chadsey Lake between each ~5000-year sedimentary-charcoal record and for each of the three temporal zones over the mid to late Holocene.

Age	Somenos Lake	Chadsey Lake
ca. 5000 cal yr BP to present	318 (199 to 459)	259 (175 to 353)
Zone 1 (ca. 5000 to 3500 cal yr BP)	140 (77 to 209)	101[a]
Zone 2 (3500 to 2000 cal yr BP)	690[a]	187 (105 to 288)
Zone 3 (2000 cal yr BP to present)	516[a]	327 (203 to 445)

[a] 95 % confidence intervals unavailable.

Fire frequency trends and mFRIs calculated for each of the three temporal zones in each record also indicate differences between the temporal distribution of fire episodes at each site. In zone 1, both records reveal high fire frequency followed by a decreasing fire frequency trend to the end of the zone (i.e., 3500 cal yr BP) (Figure 5b). While the Chadsey Lake charcoal record does not have as many fire episodes as the Somenos Lake record during zone 1, the mFRI for Chadsey Lake (mFRI zone 1, 101 years) is within the natural range of variability (i.e., 95 % confidence interval) of the mFRI for Somenos Lake (mFRI zone 1, 140 (77 to 209) years) (Table 4). Comparable mFRIs between the two sites during zone 1, despite the different number of fire episodes, may appear contradictory. However, this difference is a direct result of how mFRI was calculated in this study (i.e., by averaging the time period between fire episodes (Agee, 1993)) and highlights the importance of documenting the formula used to calculate mFRI in fire history studies.

In zone 2, opposite fire frequency trends and different mFRIs occur between the two sites. While fire frequency is low at the Somenos Lake between 3500 and 2000 cal yr BP, it is high at Chadsey Lake (Figure 5b). Similarly, the mFRI for Somenos Lake (mFRI zone 2, 690 years) exceeds the natural range of variability of the mFRI for Chadsey Lake (mFRI zone 2, 187 (105 to 288) years) (Table 4). Finally, although fire frequency trends appear to be similar between the two sites in zone 3, the 516-year mFRI for Somenos Lake slightly exceeds the natural range of variability of the 327-year mFRI for Chadsey Lake (i.e., 203 to 445 years) (Table 4). In addition, both records reveal a significant increase in peak magnitude in zone 3 during the most recent fire episode in each record (Somenos Lake, 80 cal yr BP; Chadsey Lake, 68 cal yr BP) (Figure 5a).

Background CHAR trends at both sites are high in zone 1 (ca. 5000 to 3500 cal yr BP) and low in zone 2 (3500 to 2000 cal yr BP) (Figure 5c). However, in zone 3 (2000 cal yr BP to present), the background CHAR trends differ between the two sites. While background remains low between 2000 cal yr BP to present at Somenos Lake, it increases ca. 1000 cal yr BP and then sharply decreases to present at Chadsey Lake (Figure 5c).

3.5. Comparison of the Original Age-Depth Model and AMS-^{14}C-based Age-Depth Model in the Chadsey Lake Composite Core (4506 to 0 cal yr BP)

When we base the age-depth model for the Chadsey Lake sediment core exclusively on our AMS-^{14}C stratigraphy (and exclude all ^{210}Pb dates) we observe some differences in fire history characteristics. While the majority of fire episodes are coeval between the two records, the AMS-^{14}C-based composite record contains six more fire episodes (occurring at 4161, 3933, 3097, 1235, 342, and 152 cal yr BP) than the original composite record (Figure 6a). Furthermore, two fire episodes observed in the original record (occurring at 2805 and 69 cal yr BP) are not detected in the analysis of the AMS-^{14}C-based record (Figure 6a). Largely because of the additional fire episodes detected in the analysis of the AMS-^{14}C-based composite record, other fire history characteristics are also different between the types of analyses (i.e., the original age-depth model and AMS-^{14}C-based age-depth model Chadsey composite records) (for details see Tables 5 and 6).

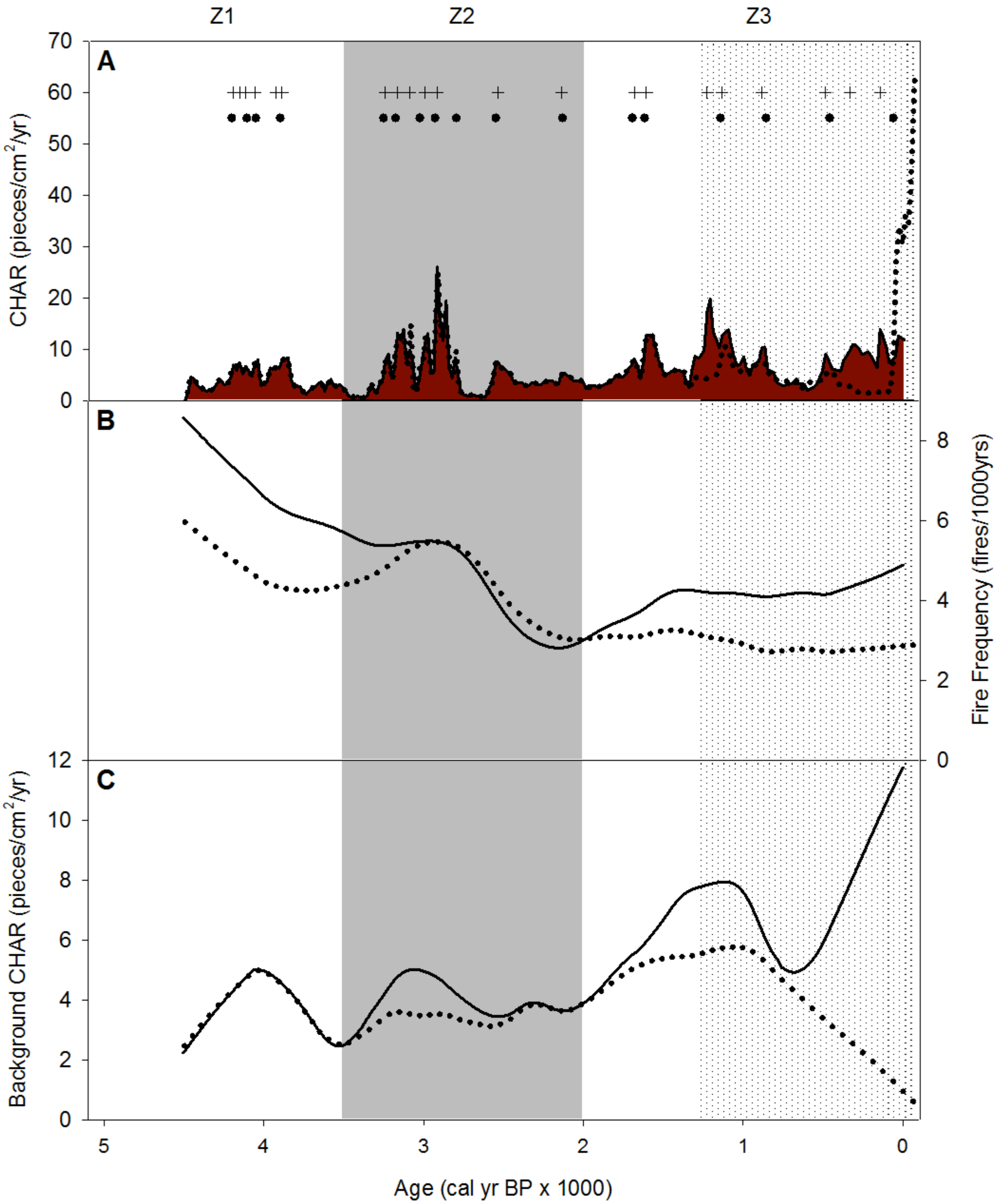

Figure 6. **Comparison of Chadsey Lake fire history characteristics between the analysis using the original (i.e., ^{210}Pb and AMS-^{14}C-based age-depth model) and the analysis using the AMS-^{14}C-based age-depth model over the last ~5000 years.**

In all panels, grey shaded area represents zone 2 (3500 to 2000 cal yr BP) and dotted area identifies where the age-depth model differs between the two records. (a) Crosshairs mark fire episodes in the AMS-^{14}C-based composite record; dots mark fire episodes in the original composite record; red shaded area depicts the 19-year interpolated AMS-^{14}C-based CHAR; and dotted line represents the 19-year interpolated CHAR of the original composite record. (b) Solid line indicates the AMS-^{14}C-based fire frequency and dotted line signifies fire frequency of the original composite record. (c) Solid line depicts background CHAR in the AMS-^{14}C-based composite record and dotted line represents background CHAR in the original composite record.

Table 5. Differences in fire history characteristics between the original age-depth model and AMS-^{14}C-based age-depth model in the Chadsey Lake composite core.

Metric	Original composite core record	AMS-^{14}C-based composite core record
Fire episodes	17	21
CHAR[a]	5.7 (0.4 to 62.3)	5.8 (0.5 to 26.0)
Background CHAR[a]	3.8 (0.6 to 5.8)	5.2 (2.2 to 11.8)
Background CHAR trend	Decrease last 700 years	Increase last 700 years
Fire frequency[b]	3.8 (2.7 to 6.0)	4.8 (2.8 to 8.6)
Fire frequency trend	Increase 3700 to 3000 cal yr BP Consistent last 2000 years	Decrease 3700 to 3000 cal yr BP Increase last 2000 years

[a] Mean and range of charcoal accumulation rate (CHAR, pieces/cm^2/yr).
[b]Mean and range of fires/1000yrs.

Table 6. Comparison of mean fire return intervals (mFRI) and natural ranges of variability (i.e., 95 % confidence intervals of mFRI) between the Chadsey Lake composite core record and the Chadsey Lake AMS-^{14}C-based composite core record for each ~5000-year record and for each of the three temporal zones over the mid to late Holocene.

Age	Original composite core record	AMS-^{14}C-based composite core record
ca. 5000 cal yr BP to present	259 (175 to 353)	202 (129 to 279)
Zone 1 (ca. 5000 to 3500 cal yr BP)	101[a]	61 (38 to 99)
Zone 2 (3500 to 2000 cal yr BP)	187 (105 to 288)	184 (79 to 336)
Zone 3 (2000 cal yr BP to present)	327 (203 to 445)	220 (136 to 327)

[a] 95 % confidence interval unavailable.

3.6. Comparison of Recent Fire History Characteristics Between Somenos Lake and Chadsey Lake Composite and Surface-Only Sediment Cores (1405 and 1161 to -64 cal yr BP)

We observe several notable differences in the recent fire history characteristics between the past 1469 years of the Somenos Lake composite core and the entire 1469-yearlong Somenos Lake surface core (Figure 7) and between the past 1225 years of the Chadsey Lake composite core and the entire 1225-yearlong Chadsey Lake surface core (Figure 8). In general, each surface-only analysis detects more fire episodes than the composite core analyses. Analysis of the Somenos surface core detects an additional four fire episodes at 518, 26, -4, and -16 cal yr BP (Figure 7). Analysis of the Chadsey surface core detects an additional three fire episodes at 1088, 736, and -40 cal yr BP (Figure 8). However, the oldest occurring fire episodes in the analysis of both composite core records (i.e., at 1400 and 1152 cal yr BP in the Somenos Lake and Chadsey Lake records, respectively) are not detected in the respective surface-only analyses (Figures 7 and 8). Largely because of the additional fire episodes in each of the two surface-only analyses, other fire history characteristics (e.g., mFRI, fire frequency, background CHAR and TSLF) are also different between analyses of the surface-only and composite cores (For details see Table 7).

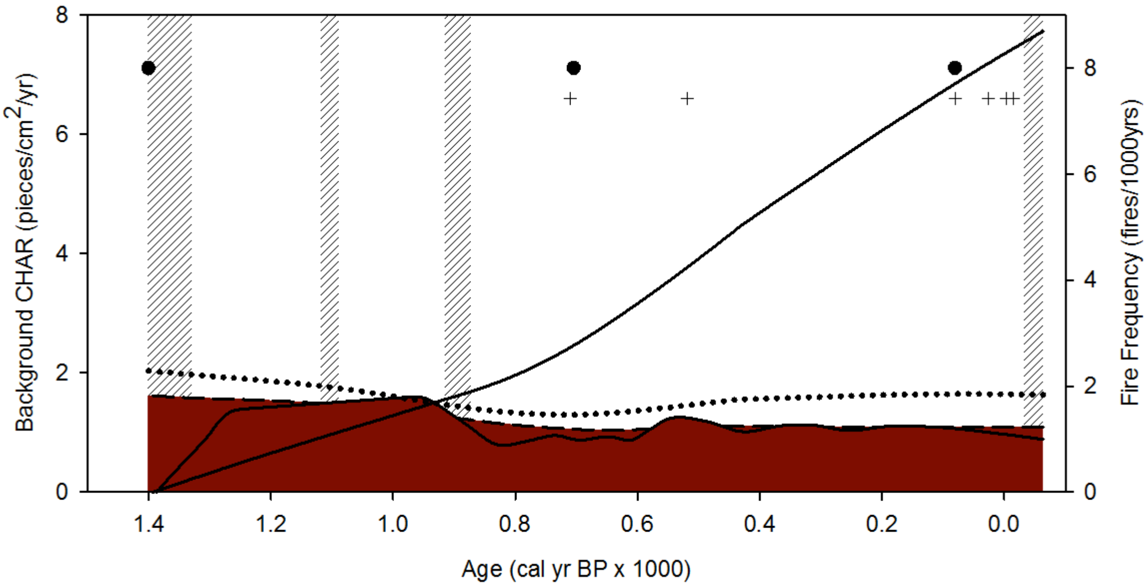

Figure 7. **Comparison of recent fire history characteristics between Somenos Lake composite and surface-only sedimentary-charcoal records over the last 1469 years.**
Dots represent fire episodes in the composite core record; crosshairs signify fire episodes in the surface core record; red shaded area with dashed line depicts the 12-year interpolated composite CHAR; red shaded area with solid line indicates the 6-year interpolated surface CHAR; dotted line depicts composite core fire frequency; solid line represent surface core fire frequency; and diagonal lines show where local SNI is < 3 in the surface core record.

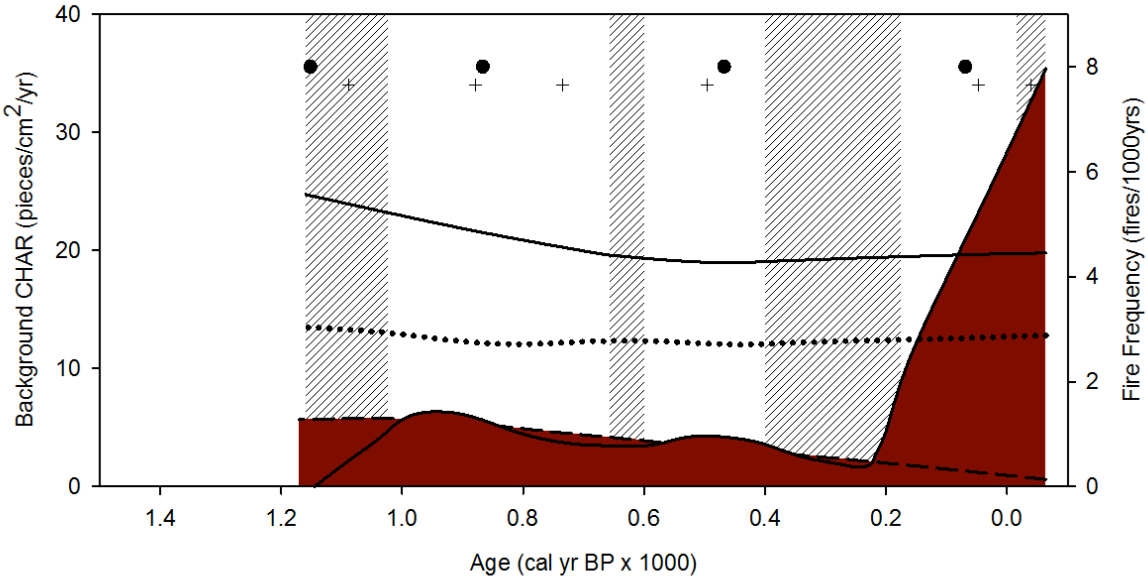

Figure 8. Comparison of fire history characteristics between Chadsey Lake composite and surface-only sedimentary-charcoal records over the last 1225 years.

Dots represent fire episodes in the composite core record; crosshairs signify fire episodes in the surface core record; red shaded area with dashed line depicts the 19-year interpolated composite CHAR; red shaded area with solid line indicates the 8-year interpolated surface CHAR; dotted line depicts composite core fire frequency; solid line represent surface core fire frequency; and diagonal lines show where local SNI is < 3 in the surface core record.

Table 7. Differences in recent fire history characteristics over the last 1469 and 1225 years for Somenos Lake and Chadsey Lake, respectively, between the analyses of composite and surface-only sedimentary-charcoal records.

Site	Metric	Composite[a]	Surface-Only
Somenos	Fire episodes	3	6
Somenos	mFRI	660[c]	145 (28 to 305)
Somenos	TSLF[b]	144	48
Somenos	Fire frequency[d]	1.8 (1.5 to 2.3)	3.7 (0.02 to 8.7)
Somenos	Fire frequency trend	Increase last 1000 years	Consistent last 1000 years
Chadsey	Fire episodes	4	6
Chadsey	mFRI	361[c]	226 (130 to 342)
Chadsey	TSLF[b]	133	24
Chadsey	Fire frequency[d]	2.8 (2.7 to 3.0)	4.6 (4.3 to 5.6)
Chadsey	Background CHAR trend	Low last 250 years	High last 250 years

[a] Only the past 1469 and 1225 years of the Somenos Lake and Chadsey Lake composite cores, respectively, were used to compare results to those of the respective surface cores.
[b] Time since last fire (TSLF).
[c] 95 % confidence intervals unavailable.
[d] Mean and range of fires/1000yrs.

Chapter 4. Interpretation and Discussion

4.1. Zone 1 (ca. 5000 to 3500 cal yr BP)

Between ca. 5000 and 3500 cal yr BP (i.e., zone 1), fire frequency and background CHAR trends were largely synchronous between the two sites (Figures 5b and 5c). Over the past ~5000 years, fire activity was highest during zone 1 at both Somenos Lake (mFRI, 140 years) and Chadsey Lake (mFRI, 101 years). Fire frequencies at both sites were greatest ca. 4500 cal yr BP and then gradually declined by the end of zone 1 (i.e., 3500 cal yr BP) (Figure 5b). Similarly, background CHAR trends at both sites suggest a regional increase in biomass burning between ca. 5000 and ca. 4000 cal yr BP with a decreasing trend from ca. 4000 cal yr BP to the end of zone 1 (i.e., 3500 cal yr BP) (Figure 5c).

In contrast to our sites, the large majority of charcoal-inferred, mid to late Holocene fire history studies in southwestern BC and western Washington document an opposite pattern of relatively low or medium fire activity between ca. 5000 and 3500 cal yr BP compared to the rest of the late Holocene (Brown & Hebda, 2002a; Brown & Hebda, 2002b; Gavin et al., 2013; Gavin et al., 2001; Prichard et al., 2009; Sugimura et al., 2008; Wainman & Mathewes, 1987). The observation of less fire during this time period is largely supported by a variety of palynological studies that indicate that climate in the Pacific Northwest was transitioning ca. 5000 cal yr BP from the warm, dry xerothermic conditions of the early Holocene (ca. 9500 to 7000 cal yr BP, Mathewes and Heusser (1981)) to the warm, moist mesothermic conditions of the mid Holocene (ca. 7000 to 4500 cal yr BP, Hebda (1995)) and the cooler and wetter climate of the late Holocene (ca. 4500 cal yr BP to present, Heusser (1983), Brown, Nielsen, Fitton, and Hebda (2008), and Sugimura et al. (2008)). Given that moist conditions typically lead to fuels that are too wet to burn, this change toward a cooler and wetter climate likely reduced the probability of fire ignition between ca. 5000 and 3500 cal yr BP at these sites in southwestern BC and western Washington.

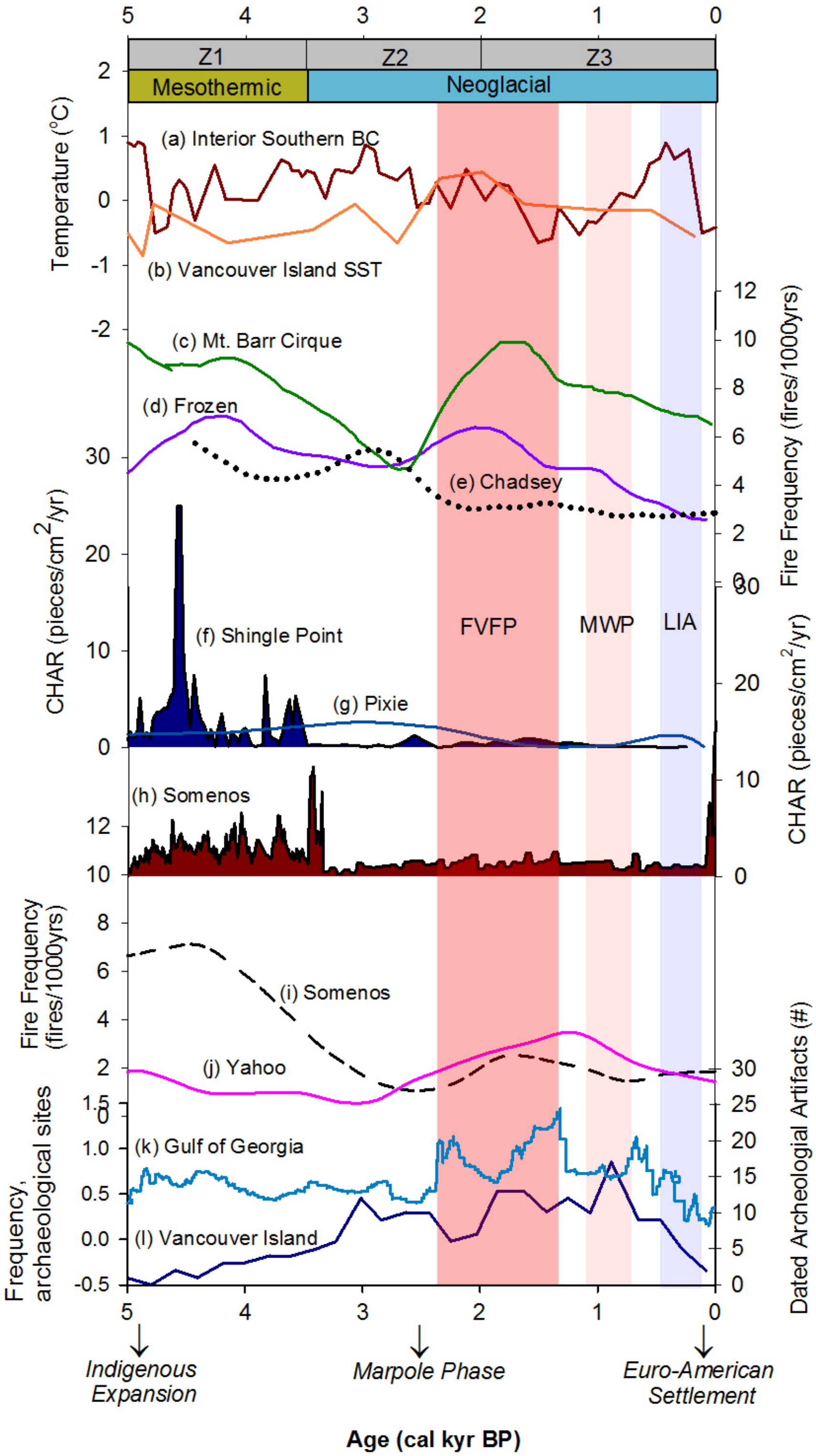

Figure 9. **Regional synthesis of charcoal-inferred fire activity and major anthropogenic and climatic changes in southwestern British Columbia and western Washington over the last ~5000 years.**

Grey bars indicate timing of zones 1 (i.e., ca. 5000 to 3500 cal yr BP), 2 (i.e., 3500 to 2000 cal yr BP), and 3 (i.e., 2000 cal yr BP to present). Yellow and blue bars represent approximate timing of the warm, moist Mesothermic (Hebda, 1995) and the cool, moist Neoglacial (Walker & Pellatt, 2003), respectively. Vertical shaded bars depict the timing of the Fraser Valley Fire Period (FVFP, medium red, Hallett et al. (2003)), the Medieval Warm Period (MWP, light red, Mann et al. (2009)), and the Little Ice Age (LIA, light blue, Grove (2001)). Temperature anomaly records are from (a) interior southern BC (red line, Gavin et al. (2011)) derived from chironomid reconstructions from four lakes in southern-to-southeastern BC (Chase, Bleskie, Walker, Gavin, & Hu, 2008; Palmer, Walker, Heinrichs, Hebda, & Scudder, 2002; Rosenberg, Walker, Mathewes, & Hallett, 2004) and (b) alkenone-derived sea-surface temperatures from deep-sea core JT96-09PC off the coast of Vancouver Island (Kienast & McKay, 2001). The mean temperature estimated over 0 to 10,000 cal yr BP was subtracted from all values. Fraser Valley fire frequency records include: (c) Mt. Barr Cirque Lake (Hallett et al., 2003), (d) Frozen Lake (Hallett et al., 2003), and (e) Chadsey Lake (this study). CHAR records are taken from: (f) Valdes Island On-site Bog from Shingle Point (Derr, 2014), (g) Pixie Lake (Brown & Hebda, 2002b), and (h) Somenos Lake (this study). Vancouver Island fire frequency records include: (i) Somenos Lake (this study) and (j) Yahoo Lake (Gavin et al., 2013). Indications of human presence prior to Euro-American settlement are taken from: (k) frequency of calibrated radiocarbon dates from archaeological sites compiled for the Gulf of Georgia region (Lepofsky, Lertzman, Hallett, & Mathewes, 2005), and (l) the frequency of radiocarbon-dated artifacts from 71 archeological sites on the eastern side of southern Vancouver Island (data from Morlan (2005) and compiled by McCune, Pellatt, and Vellend (2013)). Arrows point to the timing of Indigenous cultural expansion (Grier, Dolan, Derr, & McLay, 2009; Grier & Kim, 2012), the start of the Marpole Phase (2500 to 1000 cal yr BP) (Matson & Coupland, 1995), and the beginning of Euro-American settlement (Boyd, 1999) in the Strait of Georgia Lowlands.

Of the nineteen other sites with charcoal-inferred mid to late Holocene fire histories in southwestern BC and western Washington, only six report similar observations of the high fire incidence between ca. 5000 and ca. 3500 cal yr BP, and most of these increases are generally attributed to local scale factors. For example, Walsh et al. (2008) claim that the establishment of modern forests, as indicated by pollen analysis, increased fuel production and subsequently led to an increase in fire frequency between ca. 5400 and 4600 cal yr BP at Battle Ground Lake in southwestern Washington. Brown and Hebda (2002a) and Hallett et al. (2003) propose that increased fire activity between ca. 5000 and 3500 cal yr BP at their high elevation sites (i.e., Porphyry, Walker, Mt. Barr Cirque (Figure 9c), and Frozen (Figure 9d) Lakes) either reflected anthropogenic use of fire to increase the availability of high elevation food sources (e.g., fruiting shrubs) or increased natural ignitions from more high elevation lightning strikes resulting from unstable air masses (Rorig & Ferguson, 1999). Derr

(2014) also argues that higher charcoal influx between ca. 5000 and 3500 cal yr BP at the low-elevation site on Valdes Island (i.e., Shingle Point Bog) (Figure 9f) is attributed to human activity as it coincides with some of the earliest archeological evidence of Indigenous peoples in the Strait of Georgia Lowlands (Grier et al., 2009; Grier & Kim, 2012; Lepofsky et al., 2009). In summary, since regional climate was not conducive to fire (i.e., cool and moist) during zone 1, high fire activity at these six sites between ca. 5000 and ca. 3500 cal yr BP is attributed to local scale factors such as human activity, lightning strikes, and fuel production.

While increased anthropogenic and natural (i.e., lightning) ignitions and increased fuel production are all plausible explanations for high fire activity at Somenos Lake and Chadsey Lake between ca. 5000 and 3500 cal yr BP, the lack of local, long-term pollen studies at both sites, as well as the lack of archaeological studies of human habitation or anthropogenic use of fire near the Chadsey Lake site, precludes our ability to conclusively link any of these local scale drivers to high fire incidence at our sites. In the broader region, human presence prior to Euro-American settlement is indicated by the frequency of calibrated radiocarbon dates from archaeological sites in the Gulf of Georgia (Lepofsky et al., 2005) (Figure 9k). However, the closest local archaeological sites to Chadsey Lake are located to the east and west of Sumas Mountain in the central Fraser Valley (Lepofsky, Formosa, Schaepe, Lenert, & Blake, 2013). While some of these archaeological sites pre-date our ~5000-year sedimentary-charcoal record at Chadsey Lake and support the possibility of human influence (e.g., the Stave site near Mission, BC, Locher and Berna (2014)), more evidence is required to link human habitation conclusively to enhanced fire activity at Chadsey Lake between ca. 5000 and 3500 cal yr BP (i.e., zone 1).

We suggest that the onset of summer droughts during this time may have also contributed to high fire occurrence between ca. 5000 and 3500 cal yr BP. Even though regional climate was relatively cool and moist during zone 1 (ca. 5000 to 3500 cal yr BP), evidence of summer droughts during this time period is growing. Terrestrial and marine proxy data from the northeastern Pacific indicate that prior to 4000 cal yr BP, winters were dominated by a weak Aleutian Low and summers were dominated by a strong Pacific High (Barron & Anderson, 2011). As a result, a large portion of the interior of western North America experienced widespread summer drought between 8000 and 4000 cal yr BP (Fritz, 1996), with a particularly dry interval terminating between 6500 and 4300 cal yr BP in Washington, Oregon, and northwestern California (Briles, Whitlock, & Bartlein, 2005). These severe summer droughts likely set up conditions appropriate for extensive wildfires, and thus contributed to high fire frequency between ca. 5000 and 3500 cal yr BP.

The synchronous increase in fire activity at both of our sites and six other sites across the region in zone 1 (ca. 5000 to 3500 cal yr BP) could indicate a strong relationship between summer droughts and fire activity. However, because we cannot rule out the influence of human activity, lightning ignitions, or increased fuel abundance, we suggest that a combination of these local scale factors (e.g., fuel conditions and abundance, lightning, human ignition, weather, and/or topography) was likely responsible for high fire activity between ca. 5000 and 3500 cal yr BP at both Somenos Lake and Chadsey Lake.

4.2. Zone 2 (3500 to 2000 cal yr BP)

While background CHAR at each site reflected a regionally synchronous level of biomass burning between 3500 and 2000 cal yr BP (Figure 5c), the local fire activity, as indicated by fire frequency data, differed between Somenos Lake and Chadsey Lake (Figure 5b). During this 1500-year period, overall background CHAR at each site was low, indicating reduced biomass burning in the region. However, local fire frequency data indicates that while fire activity was low at Somenos Lake between 3500 and 2000 cal yr BP, it was high at Chadsey Lake (Figure 5b). In fact, zone 2 represents the period of lowest fire activity at Somenos Lake (mFRI, 690 years) and second highest fire activity at Chadsey Lake (mFRI, 187 years) over the last ~5000 years.

Interestingly, even though fire frequency trends differed between the two sites, some of the largest charcoal peaks, as indicated by peak magnitude data, occurred in both records during zone 2 (Figure 5a). Peaks estimated to have occurred around 3464 cal yr BP at Somenos Lake and 3184 and 2937 cal yr BP at Chadsey Lake were particularly notable for their size. While fire extent and severity are generally not determinable from CHAR records, the magnitude of these peaks was substantially higher than any other peak in zones 1 or 2 in both records and thus points to significant biomass burning around this time. We hypothesize that these high CHAR fire episodes may represent one or more large or high severity fires during zone 2. The ~650-year fire free period between fire episodes at 3906 and 3260 cal yr BP at Chadsey Lake supports our hypothesis as there would have been a considerable amount of fuel build-up prior to the fire episodes at 3184 and 2937 cal yr BP (Figure 5a). However, the charcoal peak, and inferred fire episode, at 3464 cal yr BP in the Somenos Lake record is unusual considering it occurred prior to a ~960-year fire free period between ca. 3000 and ca. 2000 cal yr BP (Figure 5a) and when local fire frequency was decreasing (Figure 5b). By examining trends in fire frequency and charcoal morphology (e.g., woody vs. grass-like charcoal) on Valdes Island, Derr (2014) argues that the large increase in CHAR at Shingle Point Bog ca. 4000 cal yr BP was likely caused by a shift in anthropogenic use of fire, from clearance of the land during the initial occupation period to maintenance of vegetation states, ca. 4000 cal yr BP (Figure 9f). Given that Shingle Point Bog is located ~25 km southwest of Somenos Lake, the high CHAR fire episode estimated to be around 3464 cal yr BP in the Somenos Lake record could also represent one or several land clearing fires ignited by humans during this time (Figure 9h).

The lowest fire activity over the entire ~5000-year Somenos Lake record (mFRI, 690 years) occurred in zone 2 (3500 to 2000 cal yr BP). Fire frequency at Somenos Lake decreased ca. 2500 cal yr BP and then increased until the end of the zone (i.e., 2000 cal yr BP) (Figure 9i). Out of the nineteen other charcoal-inferred mid to late Holocene fire histories in southwestern BC and western Washington, fifteen document similarly low to medium fire occurrence between 3500 and 2000 cal yr BP (Brown & Hebda, 2002a; Brown & Hebda, 2002b, 2003; Derr, 2014; Gavin et al., 2013; Gavin et al., 2001; Hallett et al., 2003; Sugimura et al., 2008; Wainman & Mathewes, 1987; Walsh et al., 2008). Low fire activity at this time is consistent with an enhanced Aleutian low and weakened Pacific High post 4000 cal yr BP (Barron & Anderson, 2011) that produced cool and moist Neoglacial conditions ca. 3500 to 2500 cal yr BP (Walker & Pellatt, 2003) and subsequent advancement of the Tiedemann, Peyto, and Robson glaciers within the region (Luckman, 1995; Luckman, Holdsworth, & Osborn, 1993; Ryder & Thomson, 1986). These climate-fire linkages suggest that the lack of fires that occurred around Somenos Lake between 3500 and 2000 cal yr BP was most likely a result of the cool and moist Neoglacial climate during that time. Relatively low levels of biomass burning in the region between ca. 3500 and 2000 cal yr BP, as indicated by background CHAR trends at both Somenos Lake and Chadsey Lake (Figure 5c), supports our hypothesis that climate was primary responsible for low fire occurrence at Somenos Lake in zone 2.

Despite cool and moist Neoglacial conditions during zone 2, the second highest period of local fire activity (mFRI, 187 years) occurred at Chadsey between 3500 and 2000 cal yr BP. Fire frequency peaked ca. 2900 cal yr BP and then declined to the end of zone 2 (i.e., 2000 cal yr BP) (Figure 9e). Of the nineteen other charcoal-inferred fire histories in southwestern BC and western Washington, only Pixie Lake (Brown & Hebda, 2002b) (Figure 9g), Panther Potholes (Prichard et al., 2009), and Martins Lake (Gavin et al., 2001) reveal similarly high fire incidence between 3500 and 2000 cal yr BP. Prichard et al. (2009) broadly discuss a number of different local scale factors that could have contributed to higher fire frequency between 3000 and 2000 cal yr BP at their site, including: more productive forests producing more high-severity fires, an increase in high-elevation lightning ignitions (Rorig & Ferguson, 1999), more anthropogenic ignitions (Lepofsky et al., 2005), and summer drought conditions (Hallett et al., 2003). However, the evidence Prichard et al. (2009) provide for increased anthropogenic ignitions (i.e., the Marpole Phase, 2500 to 1000 cal yr BP, Lepofsky et al. (2005)) and summer drought conditions (i.e., the Fraser Valley Fire Period (FVFP), 2400 to 1300 cal yr BP, Hallett et al. (2003)) occurred after the increase in fire incidence ca. 3000 cal yr BP and are therefore not likely to have been responsible for increased fire frequency starting ca. 3000 cal yr BP. In addition, because charcoal production between 3500 to 2000 cal yr BP is relatively small in comparison to extensive charcoal influx occurring in the early Holocene, Brown and Hebda (2002b) and Gavin et al. (2001) do not fully explain possible drivers of increased CHAR and charcoal concentrations during zone 2 at Pixie and Martins Lakes, respectively.

Higher fire activity ca. 2900 cal yr BP at Chadsey Lake may be a result of intensified summer drought conditions in the Pacific Northwest and possible increased anthropogenic ignitions near the site. Although a strong Aleutian Low and weak Pacific

High was established post 4000 cal yr BP (Barron & Anderson, 2011), indicating that regional climate in the Pacific Northwest continued to moisten during zone 2 (3500 to 2000 cal yr BP), some studies indicate an onset of dry conditions starting between ca. 3600 and 3250 cal yr BP. Southern BC diatom data suggest lowered lake levels and reduced moisture after ca. 3600 cal yr BP (Bennett et al., 2001) and Saanich Inlet varve studies imply a transition to a drier interval ca. 3250 cal yr BP (Nederbragt & Thurow, 2001). Interior southern BC chironomid data also show an increasing temperature trend culminating ca. 3000 cal yr BP (Gavin et al., 2011) (Figure 9a). The observed transition to drier conditions is consistent with the development of increased El Nino Southern Oscillation (ENSO) activity between 3500 and 2500 cal yr BP (Moy, Seltzer, Rodbell, & Anderson, 2002) and an enhanced positive Pacific Decadal Oscillation (PDO) in the North Pacific after ca. 3200 cal yr BP (Barron & Anderson, 2011). Studies in the interior of the Pacific Northwest indicate a correlation between positive (i.e., warm) ENSO and PDO phases and increased fire activity (Heyerdahl, Brubaker, & Agee, 2002; Wright & Agee, 2004) as a result of longer fire seasons due to reductions in snowpack during positive ENSO and PDO phases (Heyerdahl et al., 2002).

Evidence for anthropogenic influence on higher fire occurrence at Chadsey Lake during zone 2 is supported by a period of increased human presence in the region starting around ca. 3400 cal yr BP (McCune et al., 2013) (Figure 9l). While the lack of local information on historical human activity around Chadsey Lake limits our ability to conclusively link anthropogenic ignition to increased fire incidence during zone 2, we suggest that humans were probably the primary ignition source near Chadsey Lake that lead to increased fire activity between 3500 and 2000 cal yr BP. Even though broad scale summer droughts and other local scale factors may have set up conditions conducive to high fire activity (i.e., dry fuels), an ignition source would have been needed. Using this logic and evidence of increased human presence in the region around this time (McCune et al., 2013) (Figure 9l), we conclude that a combination of broad scale summer drought conditions and local scale factors (e.g., fuel conditions and abundance, lightning, human ignition, weather, and/or topography) created the conditions necessary for increased human ignition of fire, subsequently leading to higher fire activity at Chadsey Lake in zone 2 (3500 and 2000 cal yr BP).

4.3. Zone 3 (2000 cal yr BP to present)

Although local fire occurrence was fairly synchronous between the two sites over the last 2000 years, zone 3 (2000 cal yr BP to present) represents a moderate fire activity level over the entire Somenos Lake record (mFRI, 516 years) and the lowest fire activity over the entire Chadsey Lake record (mFRI, 327 years) (Figure 5b). In general, local fire frequency at both sites peaked ca. 1650 cal yr BP and then remained consistent until present. A small decrease in frequency occurred ca. 700 cal yr BP at Somenos Lake. In contrast, background CHAR trends largely differed between the two sites. While background remained stable during zone 3 at Somenos Lake, it significantly increased until ca. 1000 cal yr BP and then decreased to present at Chadsey Lake (Figure 5c).

One of the most interesting fire history characteristics in zone 3 is the exceptionally large charcoal peak of the most recent fire episode detected in the composite cores of both records (Somenos Lake, 80 cal yr BP; Chadsey Lake, 68 cal yr BP) (Figure 5a). Both of these fire episodes are an order of magnitude larger than any other peak in either ~5000-year record and correspond to tree-ring evidence of widespread regional fires occurring in western Oregon and Washington and parts of the Fraser Valley, Coast Mountains, and Gulf Islands in BC at 82 cal yr BP (Eis, 1962) and localized charcoal-inferred fire episodes occurring at 80 and 71 cal yr BP at both Roe Lake and Quamichan Lake (Pellatt et al., 2015). Since Euro-American occupation in the Strait of Georgia Lowlands occurred prior to these high charcoal peaks (ca. 100 cal yr BP, Boyd (1999)), extensive land clearance as a result of settlement likely caused these high-severity fires. This idea is supported by a Saanich Inlet sediment core which indicates that charcoal influx doubled at the time of Euro-American settlement (Heusser, 1983).

All of the twenty-one sites with at least a 2000-year, charcoal-inferred fire history in southwestern BC and western Washington document higher fire activity or renewed fire occurrence starting between ca. 2000 and 1650 cal yr BP (Brown & Hebda, 2002a; Brown & Hebda, 2002b, 2003; Derr, 2014; Gavin et al., 2003; Gavin et al., 2013; Gavin et al., 2001; Hallett et al., 2003; Sugimura et al., 2008; Wainman & Mathewes, 1987).

Small increases in fire activity were also seen at Somenos Lake during this time period (Figures 5b and 9i), although increases were far less pronounced at Chadsey Lake (Figures 5b and 9e). The other exceptions occur at Yahoo Lake (Gavin et al., 2013) (Figure 9j) and Panther Potholes (Prichard et al., 2009) where the shift to higher fire activity occurred earlier (ca. 2500 cal yr BP) than the majority of sites in southwestern BC and western Washington.

Interpretations of an increasingly stronger and more eastward Aleutian Low and more positive PDO state ca. 1500 cal yr BP (Barron & Anderson, 2011) are supported by a number of pollen and tree line studies that indicate that regional climate over the last 2000 years became even more moist and cool compared to the rest of the Holocene (Brown & Hebda, 2002a; Brown & Hebda, 2002b; Hebda, 1995; Pellatt & Mathewes, 1994; Whitlock, 1992). Therefore, because regional climate conditions were generally unfavorable for fire ignition, another factor other than regional climate must have been responsible for increased and/or renewed fire ca. 2000 cal yr BP. Wainman and Mathewes (1987) suggest that increased charcoal pieces ca. 2000 cal yr BP at Marion Lake could reflect increased runoff and mass movements associated with greater precipitation. In contrast, Brown and Hebda (2002a) argue that closed canopy forests during the last 2000 years, evident from pollen reconstructions at their sites, likely reduced erosive runoff of charcoal and that the development of sophisticated human societies (e.g., the Marpole Phase ca. 2400 cal yr BP), as documented in the regional archeological evidence (Lepofsky et al., 2005; Matson & Coupland, 1995), is more likely to have been responsible for increased CHAR at their Vancouver Island sites than regionally cool and moist climate (Figure 9). While both increased fuel production and anthropogenic burning may have contributed to increased charcoal influx and fire activity ca. 2000 cal yr BP, we are unable to confirm the impact of these mechanisms on fire until long-term, local vegetation reconstructions and archeological evidence of human occupation at each site are obtained.

Although regional climate continued to moisten, a number of pollen, charcoal, and fossil midge records suggest an onset of summer drought conditions ca. 2000 cal yr BP (Brown & Hebda, 2002a; Palmer et al., 2002; Sugimura et al., 2008). A warming trend starting ca. 2600 cal yr BP is evident in central BC (Gavin et al., 2011), Vancouver

Island (Kienast & McKay, 2001) (Figure 9b), and Orcas Island in the Georgia Strait (Sugimura et al., 2008) and corresponds to increased ENSO activity ca. 2800 and 1600 cal yr BP evident from modeling and tropical proxies (Barron & Anderson, 2011). Furthermore, an extensive drought period in the Fraser Valley, aptly named the Fraser Valley Fire Period (FVFP), is documented between 2400 and 1300 cal yr BP (Hallett et al., 2003) (Figure 9). Regional synchrony of high fire occurrence ca. 2000 cal yr BP across southwestern BC and western Washington could provide evidence of dry summer conditions after 2000 cal yr BP that could have increased the probability of both human and lightning fire ignitions.

Over the past ~1000 years, several southwestern BC and western Washington fire history studies correlate changes in fire activity to centennial-scale climate variability. Lucas and Lacourse (2013) (Roe Lake), Walsh et al. (2008) (Battle Ground Lake), and Hallett et al. (2003) (Frozen and Mt. Barr Cirque Lakes) all suggest that the warm, dry conditions during the Medieval Warm Period (MWP) between ca. 1100 and 700 cal yr BP (Mann et al., 2009) facilitated more frequent fires while the cool, moist conditions of the Little Ice Age (LIA) between ca. 500 and 100 cal yr BP (Grove, 2001) created the conditions that reduced the frequency of fire. While Florence Lake (Pellatt et al., 2015) and Clayoquot Lake (Gavin et al., 2003) sediment records are too short to infer the influence of MWP on fire activity, Pellatt et al. (2015) and Gavin et al. (2003) also attribute low fire incidence between ca. 500 and 100 cal yr BP at their sites to LIA conditions.

Conversely, fire frequency data at Somenos Lake and Chadsey Lake did not indicate the same centennial-scale correlation between fire and climate variability. Despite temperature and precipitation changes over the last ~1000 years, fire frequency data indicates that fire activity remained relatively consistent at Chadsey Lake (Figure 9e). In addition, while fire frequency at Somenos Lake slightly decreased during the warm, dry MWP (i.e., between 1100 and 700 cal yr BP) and increased during the cool, moist LIA (i.e., between 500 and 100 cal yr BP), these changes were not very pronounced (Figure 9).

We suggest that greater seasonality may have influenced fire activity over the last ~1000 years at Somenos Lake and Chadsey Lake. While tree-ring records indicate that conditions were warm and dry during the MWP and cool and wet during the LIA (Jones, Osborn, & Briffa, 2001; Weisberg & Swanson, 2003), oxygen isotope measurements from lake sediments show that during the MWP, Pacific Northwest winters were exceptionally wet and during the LIA the Pacific Northwest was generally drier (Steinman, Abbott, Mann, Stansell, & Finney, 2012). These seasonal changes in climate may have been the reason why we did not observe a very strong correlation in fire activity to centennial-scale climate variability at our sites.

4.4. Impact of Age Model Uncertainties on Chadsey Lake Fire History Characteristics

To assess the potential effects of age model uncertainties on the interpretation of fire activity at Chadsey Lake, we examined the differences in mid to late Holocene fire history characteristics between those obtained using the original, ^{210}Pb and AMS-^{14}C age-depth model and those of the age-depth model solely based on AMS-^{14}C age determinations (Figure 6). We found that the estimation of fire history characteristics at Chadsey Lake changed depending on the type of age-depth model used (Tables 5 and 6), but that the majority of these differences did not alter the overall interpretation of long-term fire history at Chadsey Lake.

The different age models produced two main differences in the youngest section of the Chadsey Lake sedimentary-charcoal record, which could affect interpretation of recent fire history over the past century. First, when the original, ^{210}Pb and AMS-^{14}C age-depth model was used, CHAR estimates during the last ~60 to 100 years were two and a half times higher than CHAR estimates made with the AMS-^{14}C-based age-depth model (Figure 6a; Table 5). Modern fire episodes with higher CHAR in the analysis using the original age-depth model could be interpreted as high severity fires. In addition, if we based fire activity on CHAR instead of fire frequency, the higher CHAR could also be interpreted as indicating overall higher fire activity during the last ~60 to 100 years. The absence of high CHAR estimates using the AMS-^{14}C-based age-depth model could result in interpretations of moderate, or even low, fire activity and severity. Second, trends in background CHAR over the last ~700 years also differed when different age-depth models were used, resulting in opposite interpretations of the trend and extent of regional biomass burning over the past century (Figure 6c; Table 5). Background CHAR decreased when the original ^{210}Pb and AMS-^{14}C age-depth model was used, indicating a reduced level of regional biomass burning over the last ~700 years. In contrast, background CHAR increased when the AMS-^{14}C-based age-depth model was used, suggesting that regional biomass burning was increasing over the past ~700 years.

In spite of these two main differences, the use of two different age-depth models in the analysis of the Chadsey Lake sedimentary-charcoal record did not substantially alter the overall interpretation of long-term fire activity or recommendations for fire management and restoration. Although the analysis using the AMS-^{14}C-based composite record detected more fire episodes than the analysis using the original, ^{210}Pb and AMS-^{14}C age-depth model (Table 5), mFRI calculations over the past ~5000 years and for each of the three temporal zones for both records were within the ranges of natural variability (i.e., 95 % confidence intervals) of each other (Table 6). Additionally, the mean, range, and trend of fire frequency between the two analyses using different age-depth models did not substantially differ and thus did not change the overall interpretation of long-term fire history at Chadsey Lake (Figure 6b; Table 5).

In conclusion, our estimates of long-term (i.e., ~5000-year) fire history characteristics for Chadsey Lake remained similar between the two different age models and only became substantial when the recent (~100-year) fire history recorded in the youngest section of the record was considered. Given that most sedimentary-charcoal fire history reconstructions are based on similar, AMS-^{14}C-based age-depth models (Brown & Hebda, 2002a; Brown & Hebda, 2002b, 2003; Gavin et al., 2013; Gavin et al., 2001; Hallett et al., 2003; Wainman & Mathewes, 1987), our results suggest that analyzing these charcoal records with a stronger temporal resolution at the top of each record (i.e., including ^{210}Pb age determinations) may offer a different perspective on the recent fire activity at these sites.

4.5. Impact of Temporal Scale of Analysis on Recent Fire History Characteristics

To determine if the temporal scale of charcoal analysis impacts the interpretation of recent fire history, we compared fire history characteristics over the past 1469 and 1225 years (at Somenos Lake and Chadsey Lake, respectively) between the original analysis of the composite core and the additional surface-only analysis at each site (Figures 7 and 8). In general, we found that recent fire history characteristics at both sites changed depending on the temporal scale over which the sedimentary-charcoal record was analyzed. Over the same time period, the analysis of each surface core record detected more fire episodes than the analysis of each composite core record (Table 7). As a result, other fire history characteristics such as mFRI and time since last fire (TSLF) were also shorter in the surface-only analysis at each site (Table 7).

Differences in recent fire history characteristics between the two temporal scales of analysis have several implications for restoration and management of south coastal forests in BC. The Somenos Lake sedimentary-charcoal record had the most substantial differences in recent fire history characteristics between the two types of analysis. At Somenos, the number of fire episodes, mFRI, TSLF, and the range and overall trend of fire frequency all varied substantially between the two temporal scales of analysis and ultimately changed the interpretation of recent fire history from a consistently low level fire activity over the past 1469 years to an increasingly high level of fire activity over the past 1469 years (Figure 7; Table 7). The fact that the 660-year mFRI of the past 1469 years of the Somenos Lake composite core record substantially exceeded the natural range of variability (i.e., 95 % confidence interval) of the 1469-year long surface core record mFRI (28 to 305 years) (Table 7) supports our claim that the temporal scale over which fire activity is reconstructed can change the interpretation of recent fire history. However, even though the interpretation of modern fire activity was different between the two temporal scales of analysis, the recommendation for fire management and restoration remained the same. While the TSLF at Somenos Lake was shorter in the surface record (48 years) than in the composite record (144 years), both were within the natural range of variability of the surface core record (28 to 305 years) (Table 7), indicating that prescribed burns do not need to be implemented to restore and/or manage the CDFmm forests or GOEs around Somenos Lake.

Differences in recent fire history characteristics between the two types of analysis observed in the Chadsey Lake sedimentary-charcoal record were not substantial enough to alter the interpretation of modern fire activity. While the surface-only analysis detected more fire episodes than the analysis of the composite core, the mFRI over the past 1225 years in the Chadsey Lake composite record (361 years) hardly surpassed the natural range of variability of the 1225-year long surface record (130 to 342 years) (Table 7). However, recommendations for fire management differed depending on the temporal scale of analysis. Because the TSLF in the surface core record (24 years) was well below the natural range of variability of the surface core record (130 to 342 years), prescribed burns are not needed to restore and/or manage the CWHdm forests and GOEs near Chadsey Lake. Conversely, because the TSLF in the composite core record (133 years) was just within the natural range of variability of the surface core record (130 to 342 years), prescribed burns may be needed in the future to restore and/or manage the CWHdm forests and GOEs surrounding Chadsey Lake (Table 5).

The only substantial difference between the two temporal scales of analysis at Chadsey Lake was the trend in background CHAR over the last ~250 years. Over the same time period, analysis of the Chadsey Lake composite core revealed that background gradually decreased but the surface-only analysis of the Chadsey Lake record showed a substantial increase in background CHAR (Figure 8; Table 7). This significant increase in background was likely caused by the size of the window width we used to define the background CHAR component when analyzing the Chadsey Lake surface core. Instead of using the 700-year window width that maximized the signal-to-noise ratio (SNI) and goodness-of-fit (GOF), we used a 300-year window as it was the largest window width that CharAnalysis would accept. However, narrower window widths can produce a background CHAR that largely mirrors the peaks component of CHAR (Mooney & Tinner, 2011). As a result, when the peaks component of the Chadsey Lake CHAR substantially increased within the last 264 years, the background component of CHAR also substantially increased. When background was similar to the peaks component, fewer fire episodes were detected (Mooney & Tinner, 2011), which also explains why fire frequency trends were similar between the composite core and surface-only analysis at Chadsey Lake. This analysis highlights the potential importance of the choice of averaging window used to isolate the slowly varying background component of CHAR, which ultimately influences the identification of peak fire events from CHAR.

Another likely reason for the differences in background CHAR between the two temporal scales of analysis is the 53- and 18- fold changes in sediment accumulation rates during the last ~150 years of the Somenos Lake (Figure 2a) and Chadsey Lake records (Figure 2b), respectively. As a result of this substantial variation in accumulation rates, the median sample resolution of each composite core was much larger (Somenos Lake, 12 years; Chadsey Lake, 19 years) than that of each surface core (Somenos Lake, 6 years; Chadsey Lake, 8 years). Consequently, when the larger median sample resolutions were used to interpolate the CHAR series of each composite core record into regularly spaced time intervals, fewer recent fire episodes were detected in the youngest sections of each core (where higher sediment accumulation rates and sample resolutions occurred) (Higuera et al., 2010a).

In conclusion, our results highlight the tradeoffs that exist between using short (i.e., < ~1500 years) versus longer (i.e., ~5000 years) records to establish fire history characteristics. Record length can influence both the optimal averaging window used as well as the estimation of median sample resolution, both of which affect the identification of peak fire and background CHAR components. In some cases, such as the Somenos Lake record (Figure 7), the temporal scale at which fire activity is reconstructed can change the estimation of fire history characteristics such as fire frequency trends and mFRI and alter the interpretation of fire activity. A number of paleoecological studies are based on the analysis of short cores (Gavin et al., 2003; Lucas & Lacourse, 2013; Pellatt et al., 2015) and thus are likely to avoid these complications when estimating recent fire histories. At the same time, while these short core records can provide additional insight into recent fire history that longer cores may fail to detect, shorter records limit the ability to obtain long-term statistics on fire activity and its temporal variability over time that forest managers need.

Ultimately, the scale at which fire history is reconstructed should depend on the goal of the study and the management objective that the study is aiming to inform. Fire activity inferred from the analysis of short cores is advantageous if the goal is to examine the effects of recent fire suppression or understand contemporary fire-climate linkages to help predict future changes in fire regimes with projected changes in climate and vegetation. However, if the objective is to better understand long-term trends and natural ranges of variability of fire activity prior to human influence or to assess the natural and anthropogenic mechanisms that drive fire occurrence over time, then longer, Holocene-length records may prove more useful. Nonetheless, even if longer records are advantageous to the goal of the study, analyzing the records at near modern time frames (i.e., less than 500 years) where ^{210}Pb dating can provide better temporal resolution should be considered, particularly if recent fire history characteristics are being compared between studies based on different temporal scales of analysis (e.g., Table 1).

Chapter 5. Conclusion

This study presents new sedimentary-charcoal records from Somenos Lake and Chadsey Lake to provide unique insights into the local fire history of CDFmm and CWHdm forests in the Strait of Georgia Lowlands that can be used to inform fire management and prescribed burn plans for south coastal forests and GOEs in southwestern BC. While the majority of charcoal-based fire history reconstructions in southwestern BC and western Washington are based on coarse resolution (i.e., > 100 yr/cm) and/or coarse chronological control (i.e., no ^{210}Pb and few ^{14}C age constraints that may not be AMS), our fire history reconstructions are based on high resolution charcoal analysis (~17-year intervals) with strong chronological control (^{210}Pb and AMS-^{14}C age constraints).

We place these new data in the context of a regional synthesis of long-term fire history studies to better understand the spatial and temporal complexity of fire responses in southwestern BC and western Washington to changes in climate and human activity over the last ~5000 years. In general, analysis indicates that local fire occurrence at both sites varied throughout the mid to late Holocene, suggesting that CDFmm and CWHdm fire regimes in the Strait of Georgia Lowlands have been non-stationary over the last ~5000 years. Furthermore, variation during the mid to late Holocene is largely synchronous between sites, apart from a 1500-year period between 3500 and 2000 cal yr BP (i.e., zone 2) when fire activity was low at Somenos Lake and high at Chadsey Lake. The lack of synchrony during this time period highlights that local site factors (e.g., fuel conditions and abundance, lightning, human ignition, weather, and/or topography) can have a substantial influence on fire occurrence. In contrast, synchrony of fire activity between Somenos Lake and Chadsey Lake and across southwestern BC and western Washington during zone 1 (ca. 5000 and 3500 cal yr BP) and zone 3 (2000 cal yr BP to present) suggests that broader-scale climatic changes, in particular summer droughts, were primarily responsible for driving changes in fire activity during these two time periods.

Nonetheless, because humans have inhabited the Strait of Georgia Lowlands during the entire ~5000-year sedimentary-charcoal records analyzed in this study, human activity likely influenced fire incidence at both of our sites over the mid to late Holocene. However, until new archaeological evidence on local human habitation and the use of fire is obtained at each site, we are unable to conclusively make these human-fire connections. In addition, because of the lack of long-term local vegetation reconstructions around Somenos Lake and Chadsey Lake, we are also unable to determine if changes in fuel type, abundance, and/or condition were driving variation in mid to late Holocene fire regimes at our sites. Future research should therefore focus on filling these knowledge gaps to continue to improve our understanding of climate-fire-human linkages in the Strait of Georgia Lowlands.

Overall, our results exemplify how fire history characteristics can vary on both temporal and spatial scales and thus have several important implications for fire management and prescribed burn plans of south coastal forests in southwestern BC. First, our results support the argument of Whitlock et al. (2003) that the variability of fire occurrence over time at both of our sites “contradicts the notion of a static fire return interval [mFRI] that is often referred to in ecosystem management plans”. mFRI may prove useful in defining the natural range of variability of fire disturbances and can subsequently assist forest managers in assessing when ecosystem variability has exceeded previous norms or crossed critical thresholds (Landres et al., 1999; Swetnam et al., 1999). However, mFRI is not the only metric that should be considered when developing fire management and prescribed burn plans. Other fire history characteristics may be more valuable and in fact may be better indicators of fire driven ecosystem structure than mFRI alone. For example, because smoothed fire frequency data are not summed over a period of time like mFRI, they provide additional information on the variability of fire occurrence over time that is necessary to identify the changing role of humans and climate in driving fire regimes shifts over time. Second, our comparative analysis between the composite and surface cores at Somenos Lake and Chadsey Lake indicates that the interpretation of recent fire history can change depending on the temporal scale used in the analysis of the sedimentary-charcoal record. Thus, forest managers should seek to use a variety of different studies that interpret fire history over both long and short time frames in order to better understand recent fire regime changes, long-term trends and natural ranges of variability, and climate-fire-human linkages over time. Third, the asynchrony between our sites demonstrates that the estimation of fire history characteristics can also change depending on the spatial scale over which they are assessed. For example, during zone 2 (3500 to 2000 cal yr BP) local fire frequency data infer opposite patterns of fire activity between Somenos Lake (i.e., low fire activity) and Chadsey Lake (i.e., high fire activity). This spatial complexity is largely driven by the diversity of local scale controls on fire activity (e.g., fuel conditions and abundance, lightning, human ignition, weather, and/or topography) and supports future research focused on understanding the natural range of variability of fire disturbances and climate-fire-human linkages on a local, site-by-site basis. Furthermore, the asynchrony observed between our two sites during zone 2 (3500 to 2000 cal yr BP) highlights the importance of developing site-specific fire management and prescribed burn plans that do not use uniform generalized fire prescriptions.

In conclusion, although retrospective data on the natural variability of fire disturbances (i.e., fire history) provides important information, such as the natural range of variability of fire disturbances, that can assist forest managers in developing appropriate restoration strategies for south coastal forests and GOEs, managers must consider fire history results in the context of the assumptions that were made and the limitations of the data. In particular, this study highlights the importance of considering the impact of the temporal scale of analysis and age model uncertainties on the interpretation of fire history. Our results also indicate the important role of local scale factors in driving fire activity in the Strait of Georgia lowlands. Thus, while this study provides a sound basis for understanding the temporal and spatial variability of fire activity and the mechanisms that drive changes, additional site-specific work is needed to better understand the extent of individual local controls (i.e., weather, fire ignitions, topography, watershed size, landscape connectivity, and fuel availability) on CDFmm and CWHdm fire regimes in the Strait of Georgia Lowlands.

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Appendix A.

Linear Regression vs. Bayesian Accumulation Age-Depth Models

Since age-depth models based on linear regression assume a constant sedimentation rate between dated intervals and do not provide errors with the modeled age estimates, we also considered Bayesian accumulation models for our data. Bacon (Blaauw & Christen, 2011) was used to develop an age-depth model that takes into account prior assumptions based on expert knowledge about accumulation rates and its variability over time (Goring et al., 2012). Prior assumptions such as stratigraphic ordering were considered and sediment accumulation rates were modeled as a function of depth using a simple gamma autoregressive process. Although Bayesian accumulation models "avoid the use of simple smoothing algorithms and prevent unrealistic changes in sedimentation rates when interpolating between ages" (Shanahan et al., 2012), the models developed for Somenos Lake overestimated confirmed ^{210}Pb and AMS-^{14}C age determinations (Table A1). Furthermore, because of the hiatus in the Somenos Lake composite core, the prior knowledge used to develop the Bacon model was not well supported. The mean sediment accumulation rate for the last 500-1000 years across eastern North American is ~10 yrs/cm, while the mean for the rest of the Holocene is ~20 yrs/cm (Goring, personal communication, 2014). Since sedge is likely to compress less than silty sediment, a slightly higher sediment accumulation rate of 15 cm/yr was set as a prior for the inferred hiatus at the clay-sedge interface (Goring, personal communication, 2014). CharAnalysis was run using both the linear regression and Bacon age-depth models. The mFRI, fire frequency, and fire-episode (peak) magnitude between the two models were similar. Therefore, the simplest, linear regression based, age-depth model was used for charcoal analysis in this study.

Table A1. **The difference between raw dates and Bacon modeled dates in cal yr BP for Somenos Lake.**

Dating Method	Raw Dates (cal yr BP)	Bacon Hiatus Model (cal yr BP)	Difference (cal yr BP)
^{210}Pb	-63.55	-62.6	0.95
^{210}Pb	-57.53	-56.5	1.02
^{210}Pb	-50	-48	2
^{210}Pb	-38.44	-37.1	1.34
^{210}Pb	-27.67	-26.8	0.87
^{210}Pb	-18.05	-16.6	1.45
^{210}Pb	-8.26	-4.9	3.36
^{210}Pb	3.15	9.1	5.59
^{210}Pb	15.49	25.1	9.61
^{210}Pb	31.42	51.2	19.78
^{210}Pb	52.24	85.4	33.16
^{210}Pb	85.66	149.5	63.84
^{14}C	3478	3450.6	-27.4
^{14}C	4111.5	4131.3	19.8
Mazama	7590	7915.9	325.9

Appendix B.

The Effect of Different Chemicals on Charcoal Abundance and Condition

Prior to charcoal analysis on Somenos Lake and Chadsey Lake sedimentary records, three small experiments were conducted to study the effects of different chemicals commonly used in the charcoal extraction process on charcoal abundance and condition (i.e., size and shape). The aim of these experiments was to provide guidance as to what chemicals should be used for charcoal analysis in this study that would minimize the potential of misrepresenting the sedimentary charcoal record.

In general, two types of chemicals are used to extract charcoal out of the sediment and facilitate counting under the microscope. One type of chemical is used to disaggregate or disperse the sediment and the other type is used to lighten non-charcoal, organic material to assist in the identification of charcoal. In these experiments, two different charcoal extraction methods were used to test the chemical effects on charcoal abundance and condition. In our first experiment, we selected two methods adapted from Gavin et al. (2003), Walsh, Pearl, Whitlock, Bartlein, and Worona (2010), and Enache and Cumming (2006). The first method involved soaking sediment samples in 20 mL of a 5 % sodium hexametaphosphate ($(NaPO_3)_6$) solution for 24 hours and 15 mL of a 6 % hydrogen peroxide (H_2O_2) solution for one hour. The second method involved treating sediment with 20 mL of a 10 % potassium hydroxide (KOH) solution overnight and 10 mL of a 5 % sodium hypochlorite (NaClO) solution for 48 hours.

To begin the first experiment, 1 cm^3 sediment samples from three 1 cm increments (i.e., 2-3, 20-21, and 29-30 cm) of the Somenos Lake surface core were placed in 50 mL Falcon Tubes. Samples were treated using the two extraction methods described and the $\geq$125 μm size fraction was retained for counting. Charcoal abundance was calculated by counting all charcoal particles in each sample using a Leica® M205 C stereomicroscope.

The results indicate that extracting charcoal using the second method (10 % KOH and 5 % NaClO) may misrepresent the sedimentary charcoal record. When compared to the first method (i.e., 5 % $(NaPO_3)_6$ and 6 % H_2O_2), overall charcoal abundance in the 1 cm^3 samples treated with the second method (i.e., 10 % KOH and 5 % NaClO) was lower. Charcoal abundance in the 2-3, 20-21, and 29-30 cm increments treated with the first method (i.e., 5 % $(NaPO_3)_6$ and 6 % H_2O_2) were 8, 95, and 65 pieces respectively. Whereas, charcoal abundance in the 2-3, 20-21, and 29-30 cm increments treated with the second method (i.e., 10 % KOH and 5 % NaClO) were 2, 19, and 19 pieces respectively.

To confirm these results, a second small experiment was conducted to determine if similar results would be produced if the time period over which samples were treated was the same in each of the two methods. In this experiment, the effects of two disaggregating chemicals, 5 % $(NaPO_3)_6$ and 10 % KOH, and two lightening chemicals, 6 % H_2O_2 and 5 % NaClO, on charcoal abundance and condition (i.e. size and shape) were studied.

To begin the second experiment, wood, needles, bark, and leaves were collected from the key trees (Garry oak (*Quercus garryana*) and Douglas-fir (*Pseudotsuga menziesii*)), shrubs (Indian plum (*Oemleria cerasiformis*), Scotch broom (*Cytisus scoparius*), and Oceanspray (*Holodiscus discolor*)) and grass taxa around the Somenos Lake study area. Samples were dried in a 50 ^oC over overnight and burned with a BIC® MegaLighter until thoroughly charred. The resulting charcoal was wet-sieved through 250 µm and 125 µm sieves to obtain the 125-250 µm size fraction. This size fraction was used as it has been proven to convey the same charcoal concentration information as the smaller, 63-125 µm size fraction and is substantially easier to count (Long et al., 1998; Mohr, Whitlock, & Skinner, 2000; Whitlock & Millspaugh, 1996). The course fraction (125-250 µm) of charcoal was retained and washed into four plastic weighing dishes with distilled water. Each dish was separately treated with 5 % $(NaPO_3)_6$, 10 % KOH, 6 % H_2O_2, and 5 % NaClO. Using a pipette, 4 micro centrifuge tube caps for each chemical treatment were filled with the treated charcoal. Once caps were filled, a photo of each cap was taken immediately using the Leica® M205 C program to help count the amount of charcoal particles in each cap and assess their condition. Charcoal samples treated with 6 % H_2O_2 and 5 % NaClO were left for one hour while samples treated with 5 % $(NaPO_3)_6$ and 10 % KOH were left for 24 hours. After each treatment time period, photos were retaken and charcoal in each cap was recounted and assessed for changes in size and shape.

Results from this experiment suggest that the disaggregating and lightening chemicals with the smallest effect on charcoal abundance and condition are 5 % $(NaPO_3)_6$ and 6 % H_2O_2 respectively. On average, charcoal treated with 10 % KOH lost 14 % of its particles while charcoal treated with 5 % $(NaPO_3)_6$ lost only 2 %. Therefore, charcoal treated with 10 % KOH destroyed 12 % more particles than charcoal treated with 5 % $(NaPO_3)_6$. On average, charcoal treated with 5 % NaClO lost 25 % of its particles while charcoal treated with 6 % H_2O_2 lost 8 %. Consequently, charcoal treated with 5 % NaClO destroyed 17 % more particles than those treated with 6 % H_2O_2. The results on charcoal condition (i.e. size and shape) are somewhat inconclusive. On average, charcoal treated with 5 % $(NaPO_3)_6$ lost 13 µm in size, while charcoal treated with 10 % KOH gained 19 µm in size. Since charcoal should not theoretically increase in size after being treated with a disaggregating chemical, the increase in charcoal size post treatment may be a result of inadequate measuring techniques. Nonetheless, results between the two lightening chemicals indicate that charcoal condition is influenced more by 5 % NaClO than 6 % H_2O_2. On average, charcoal treated with 5 % NaClO lost 20 µm in size while charcoal treated with 6 % H_2O_2 lost 15 µm in size.

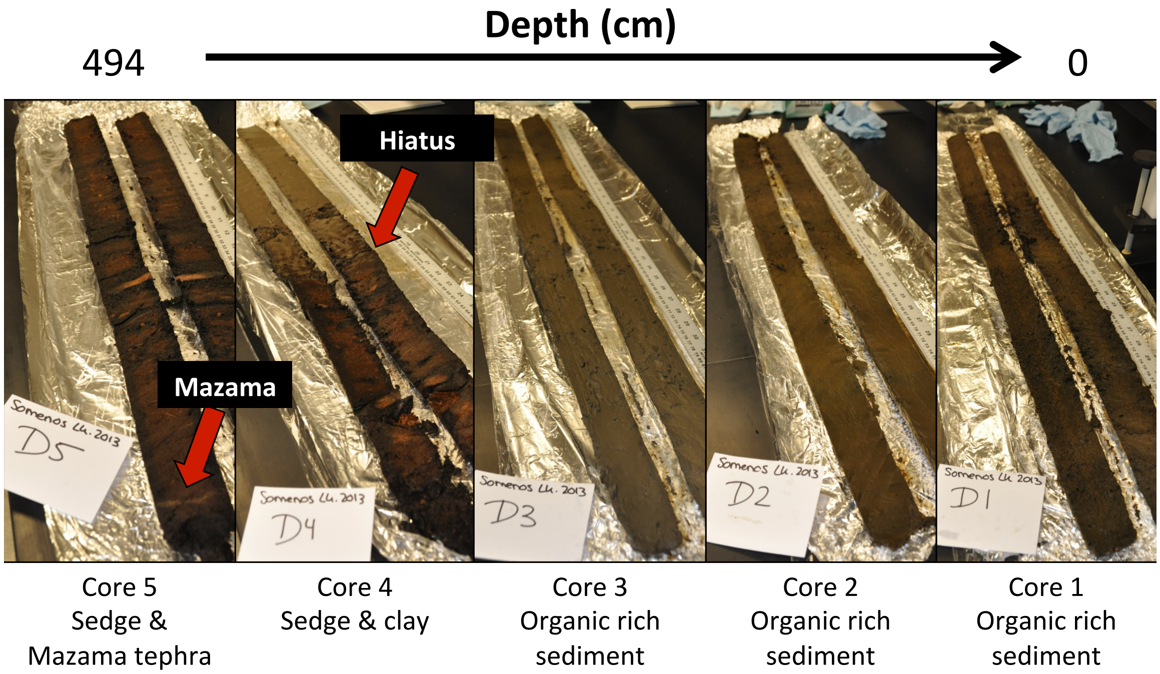
Finally, the third experiment was conducted to study the average percent of charcoal lost when using 5 % $(NaPO_3)_6$ and 6 % H_2O_2 collectively to extract charcoal out of sediment. The aim of this experiment was to determine the average percent charcoal lost when samples are treated with 5 % $(NaPO_3)_6$ and 6 % H_2O_2 and correct all sediment samples for that loss to ensure the charcoal record is not misrepresented. The 125-250 µm charcoal previously created in the laboratory from the wood, needles, bark, and leaves of key taxa around the Somenos Lake study site was treated with 5 % $(NaPO_3)_6$ and transferred into 4 micro centrifuge tube caps with a pipette. A photo was taken immediately using the Leica® M205 C program. After 24 hours, another photo was taken and each sample was treated with 6 % H_2O_2 and photographed again. After one hour, a final photo was taken of each sample. Charcoal abundance was calculated by counting all charcoal particles in each sample using a Leica® M205C stereomicroscope.

The results from this experiment indicate that on average 1.4 % of charcoal particles are lost when using 5 % $(NaPO_3)_6$ and 6 % H_2O_2 to extract charcoal out of sediment. However, because the percentage is low and not statistically significant, a correction value was not placed on the Somenos Lake or Chadsey Lake sedimentary charcoal records in this study.

In conclusion, the results from these three experiments indicate that using 5 % $(NaPO_3)_6$ and 6 % H_2O_2 to extract charcoal out of the sediment is less likely to misrepresent the sedimentary charcoal record than using 10 % KOH and 5 % NaClO. Therefore, 5 % $(NaPO_3)_6$ and 6 % H_2O_2 was used as the charcoal extraction method for Somenos Lake and Chadsey Lake in this study. However, because these experiments were relatively small, results were not statistically significant. Further studies, with a sample size big enough to obtain statically significant results, are needed to examine the effects of different chemicals commonly used in the charcoal extraction process on charcoal abundance and condition (i.e., size and shape).

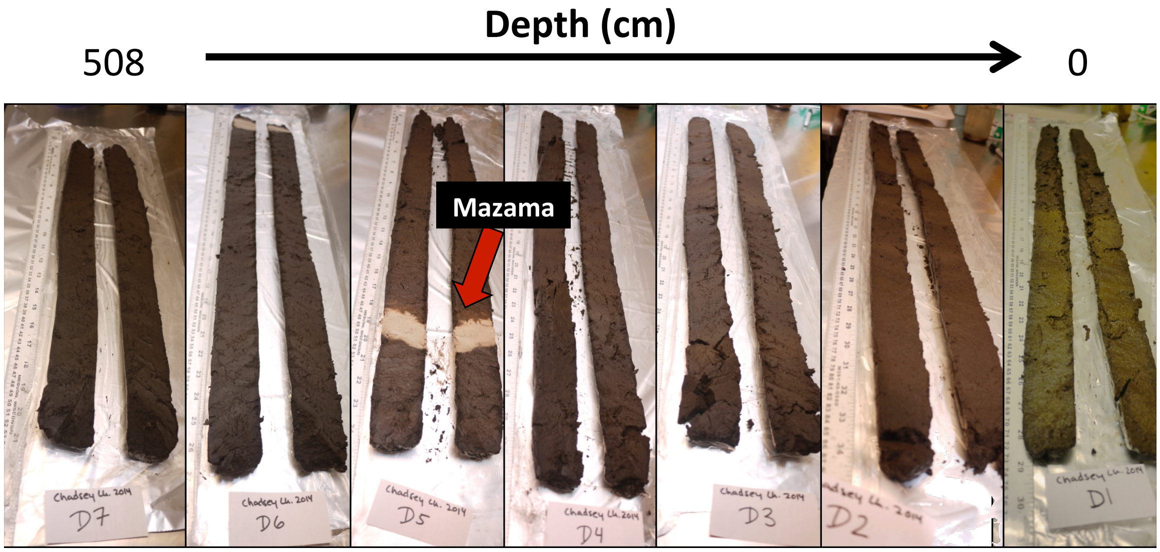
Appendix C.

Photos of Somenos Lake Piston Cores



Appendix D.

Photos of Chadsey Lake Piston Cores



Core 7 Gyttja | Core 6 Gyttja | Core 5 Gyttja & Mazama tephra | Core 4 Gyttja | Core 3 Gyttja | Core 2 Gyttja | Core 1 Gyttja