

# Contrasting early- and late-Holocene vegetation and wildfire regimes in a high-value drinking water supply area, Canada

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10 **Abstract.** Paleoenvironmental reconstructions of past ecosystems and fire regimes can strengthen interpretations of modelled future fire environments. In this study, sediment cores from four lakes in a high-value municipal water supply area are used to compare climate, vegetation, and fire along a regional east-west precipitation gradient, contrasting between warm-dry early- and cool-moist late-Holocene conditionsintervals. Results indicate that inferred precipitation was lower in the past, with more open-canopy xeric Douglas-fir forests compared to present-day closed-canopy mesic western hemlock and cedar forests. Overall, the wettest and western-most site experienced the greatest change, with more frequent early-Holocene fires yielding to longer fire return intervals in the late-Holocene. This implies that northern coastal temperate rain shadow forests, currently experiencing little fire, may become more vulnerable in the future. It also highlights susceptibility to fire regime shifts consistent with regional observations and models suggesting current and future increases in extreme fire disturbance.

## 1 Introduction

20 Climate change is driving an increase in global wildfire activity with significant economic, social, and environmental consequences (Liu *et al.*, 2010; Wang *et al.*, 2023; MacCarthy *et al.*, 2024; Bowman *et al.*, 2017; Mattioli *et al.*, 2022; Clarke *et al.*, 2023; Chen *et al.*, 2024, Burton *et al.*, 2024). Temperate coniferous forests, typically located in coastal and mountainous regions and characterized by cool-wet winters and warm dry summers, are not exempt. Over the last two decades, these forests experienced a disproportionate abundance of extreme fire events and are forecast to see a further 25% increase in conditions conducive to fire by the end of the century (Senande-Rivera *et al.*, 2022; Cunningham *et al.*, 2024). In western North America, area burned and frequency of large fires are increasing, with models forecasting more extreme fire weather over the coming decades (Flannigan *et al.*, 2005; Westerling *et al.*, 2006; Wang *et al.*, 2015, 2017; Hanes *et al.*, 2019). The 2023 wildfire season in the Canadian province of British Columbia (BC), was the worst on record. Within BC, an estimated 2.84 million hectares (ha) burned, multiple lives were lost and approximately CAN\$817 million was spent on wildfire suppression (BC Wildfire Service, 2024). The implications are profound, highlighting the need for greater insight into the processes influencing these changes.

**Commented [RH1]:** From Referee #1: The manuscript presents excellent research that could be further enhanced by refining its storytelling. I recommend clarifying the introduction to clearly state the knowledge gap.

**Commented [RH2R1]:** We have re-structured the Introduction and Study Setting sections to improve the clarity of knowledge gaps, objectives, and story cohesiveness

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In western North America, area burned and frequency of large fires across a range of forest types are increasing, with models forecasting more extreme fire weather over the coming decades (Flannigan *et al.*, 2005; Westerling *et al.*, 2006; Wang *et al.*, 2015, 2017; Hanes *et al.*, 2019). For example, the 2023 wildfire season in the western Canadian province British Columbia (BC), was the worst on record. Within BC, an estimated 2.84 million hectares (ha) burned, multiple lives were lost, and approximately CAN\$17 million was spent on wildfire suppression (BC Wildfire Service, 2024). While fire activity in coastal BC was historically limited by climate, ignition potential, and vegetation structure, recent notable wildfire seasons (i.e. 2017, 2018, 2021 and 2023) reflect a fire regime in transition (Parisien *et al.*, 2023). In particular, the Coastal Fire Centre recorded 291 fires combusting 175,008 ha of forested land in 2018, and 365 fires burning 89,750 ha during the 2023 season (BC Wildfire Service, 2024). These trends, along with climate envelope modelling and fire simulations, are challenging assumptions that the moist forests in the Pacific region of North America are less susceptible to fire disturbance (Wang *et al.*, 2017; Dye *et al.*, 2023), raising new questions about the significance of shifting fire regimes in areas previously overlooked.

To a large extent, the linkages between climate and fire systems are well established (Overpeck, 1990; Agee, 1993; Whitlock *et al.*, 2003; Power *et al.*, 2008; Marlon *et al.*, 2009; Fishcer *et al.*, 2015), but the uncertainty produced by global climate models (GCM) and climate-fire non-stationarity complicates analyses of forest response to future projected warming (Littell *et al.*, 2018; Dye *et al.*, 2023). While predictive models offer key insights into wildfire risk and climate adaptation, they are limited by incomplete historical fire data, lack of fire records, and human land management practices such as fire exclusion (Westerling *et al.*, 2006; Moritz *et al.*, 2014; Hessburg *et al.*, 2019). Furthermore, northern temperate forests often exhibit mixed-severity fire regimes and have highly variable fire return intervals (FRI) with multiple extrinsic and intrinsic drivers of disturbance (Agee, 2005; Halofsky *et al.*, 2018). In BC coastal forests, FRIs convey high spatial variability in the region, ranging from <100 years on drier eastern sites (Pellatt *et al.*, 2015) to longer intervals (>1000 years) reported at sites in wetter settings (Brown and Hebda, 2002a; Gavin *et al.*, 2003b). Despite these complexities, climate envelope modelling and fire simulations are producing a growing consensus that tests long held assumptions; while fire activity in coastal BC was historically limited by climate, ignition potential, and vegetation structure, recent notable wildfire seasons (i.e. 2017, 2018, 2021 and 2023) reflect a fire regime in transition (Parisien *et al.*, 2023). It is no longer valid to assert that moist temperate forests in the Pacific region of North America are less susceptible to fire disturbance (Wang *et al.*, 2017; Dye *et al.*, 2023). This raises new questions about the significance of shifting fire regimes in areas previously overlooked.

Paleoecological investigations can help elucidate some of these issues by improving understanding of long-term shifts in climate and fire activity, contributing to the strength of interpretation and validation of models (Marlon, *et al.*, 2009, 2020; Brown *et al.*, 2019; 2022; 2023). Specifically, pollen sequences offer insights into vegetation and climate, while charcoal records can be used to reconstruct past fire regimes, extending insights beyond the comparatively short period of observed and satellite records (Brown and Power, 2013; Chevalier *et al.*, 2020). None the less, the past does not provide a direct analogue for the future. Instead, it reveals how ecological systems and processes change in response to various drivers.

Paleoecological investigations help elucidate these issues by improving understanding of long-term shifts in climate and fire activity, contributing to the strength of interpretation and validation of models (Marlon, *et al.*, 2009, 2020; Brown *et al.*, 2019; 2022; 2025). Specifically, pollen sequences offer insights into vegetation and climate, while charcoal records can be used to reconstruct past fire regimes, extending insights beyond the comparatively short period of observed and satellite records (Brown and Power, 2013; Chevalier *et al.*, 2020). Although the past does not provide a direct analogue for the future, it reveals how ecological systems and processes change in response to various drivers. For example, the early-Holocene interval is characterized as a comparatively warm climatic phase (Wanner *et al.*, 2008; Renssen *et al.*, 2012; Nakagawa *et al.*, 2021). With ongoing greenhouse gas emissions and climate warming, it represents a climate state that may resemble current or near future fire regime projections, thus making it an important period to investigate. Indeed, the early-Holocene (ca. 7000 – 11,700 cal. yrs BP) interval in coastal BC was warmer and drier compared to present (Mathewes and Heusser, 1981; COHMAP, 1988; Hebda, 1995; Rosenberg *et al.*, 2004; Brown *et al.*, 2006). The expansion of shade intolerant Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) after 11,700 cal yrs BP, together with grasses (Poaceae), roses (Rosaceae), and bracken ferns (Pteridium), implies that open canopy forest prevailed, likely in response to both climate and frequent fire disturbance (Cwynar, 1987; Brown *et al.*, 2008; Lucas and Lacourse, 2013). Indeed, prevailing low streamflow, as a proxy for fire season length, suggests that fire seasons were likely of longer duration (Brown *et al.*, 2019; 2025). In contrast, over the last 4000 years, comparatively cooler and moister climatic conditions prevailed, facilitating establishment of modern temperate forests, with changing fire regime. On Vancouver Island, fire return intervals (FRI) convey high spatial variability in the region, ranging from <100 years on drier eastern sites (Pellatt *et al.*, 2015) to longer intervals (>1000 years) reported at sites in wetter settings (Brown and Hebda, 2002a; Gavin *et al.*, 2003b). With ongoing greenhouse gas emissions and climate warming, it is possible that some characteristics of the early-Holocene fire regime may soon remerge. Thus, the objectives of this study are to (1) examine changes in vegetation and fire disturbance across a regional climatic gradient in a northern coastal temperate rain shadow forest and (2) assess how fire regimes changed through time to determine if past conditions could reflect evolving trends. This study compares two distinct climate intervals using lake sediment cores extracted from four sites located in a high value municipal drinking water supply area on Vancouver Island, BC, Canada. Given that wildfire threatens the provision of drinking water for a substantial population in the area (ca. 430,000 people), the persistent long-term effects of forest and fire regime change is of interest to regional water purveyors. The general applicability of this research within similar contexts will have universal appeal for practitioners developing wildfire risk reduction and adaptation strategies.

This study compares two distinct climate intervals (early- and late-Holocene) using lake sediment cores extracted from four sites located in the northern temperate rain shadow forests of a high value municipal drinking water supply area on Vancouver Island, BC, Canada. The objectives are to (1) examine changes in vegetation and fire disturbance across a regional east-west climatic gradient and (2) evaluate how fire regimes changed through time to determine if the past can provide insights into contemporary and future fire activity. Given that wildfire threatens the provision of drinking water for a substantial population in the area (ca. 430,000 people), the persistent-long term effects of forest and fire regime change is of interest to regional water

**Commented [RH3]:** From Referee #1: The authors introduce early-Holocene as a potential analogue but correctly caution that past does not provide a direct analogue." However, you can strengthen the connection by explicitly clarifying that, although no direct analogue, the early-Holocene represents a climate state that may resemble near-future projections, making it an important period to study for understanding processes and sensitivities.

**Commented [RH4R3]:** Response: We have strengthened the connection by re-structuring the Introduction. In paragraph three, we introduce the well documented and widespread early-Holocene climatic warming phase (Wanner *et al.*, 2008; Renssen *et al.*, 2012; Nakagawa *et al.*, 2021). We then allude to current climate warming and the potential for past states to resemble current or future fire regime projections.

**Commented [RH5]:** Referee #2: Don't italicize family names

**Commented [RH6R5]:** Response: Revised, done.

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**Commented [RH7]:** From Referee #1: In the final objective paragraph, the phrase "to determine if past conditions could reflect evolving trends" (P2. L63) is somewhat vague. Do the authors mean "...to evaluate if past fire regimes provide insights into contemporary fire activity"?

**Commented [RH8R7]:** Response: Yes, we do. Framing the early-Holocene as a potential indirect analogue for future fire regimes and contrasting that with the cool moist late-Holocene formed the foundation of this research. The "evolving trend" the current fire regime in transition and projections that point to increased future fire activity (Flannigan *et al.*, 2005; Westerling *et al.*, 2006; Wang *et al.*, 2015, 2017; Hanes *et al.*, 2019; Parisien *et al.*, 2023). Thank you for your accurate synthesis of our research objective. We have revised the language based on your recommendations to clarify our intentions.

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### 1.1 Study setting

The Greater Victoria Water Supply Area (GVWSA) occupies 20,549 hectares (ha) of forested land on southern Vancouver Island (48.4°N to 48.6° N; -123.5°W to -123.9°W; Fig. 1). It is composed of three watersheds (Goldstream, Sooke, and Leech) that are managed by the Capital Regional District (CRD), a regional government for 13 municipalities, and protected by controlled access. Drinking water is largely sourced from the Sooke Lake Reservoir, with minimal treatment (CRD, 2022). Local climate is strongly influenced by proximity to the ocean and mountainous topography, where regular wet frontal low pressure systems in winter are punctuated by persistent warm-dry conditions in the summer from blocking highs (Dermachi, 2011). Regarding vegetation, BC uses a nested zonal system of biogeoclimatic ecological classification (BEC; Meidinger and Pojar, 1991), in which the forests within the watersheds are classified as Coastal Western Hemlock (CWH). Two main BEC subzones are delineated by the east-west precipitation gradient, with CWHxm (xeric maritime) in the drier east and CWHmm (moist maritime) in the moister west (Table 1; Fig.1). Further east of the water supply area, another third BEC subzone, Coastal Douglas-fir (CDF), occupies the driest climate niche on Vancouver Island. A distinction in fire regime characteristics between these zones and subzones provides the rationale behind study site selection, with higher fire frequency occurring in the CDF and longer FRIs with more variability in CWH (Brown and Hebda, 2002a; Gavin *et al.*, 2003; Wong *et al.*, 2004).

Four sites were selected for study based on their contrasting biogeoclimatic conditions (Table 1). Frog Lake is the southeastern most study site and represents the driest and warmest climate, with the surrounding topography distinguished by south-southwestern aspects, steep rocky bluffs below the site, and hummocky terrain above. Surrounding vegetation consists of Douglas-fir (*P. menziesii*) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), with western red cedar (*Thuja plicata* Donn ex. D. Don), Salal (*Gaultheria shallon* Pursh), Oregon grape (*Mahonia nervosa* (Pursh) Nutt.), and red huckleberry (*Vaccinium parvifolium* Sm. In Rees) dominate the shrub layer together with small amounts of oceanspray (*Holodiscus discolor* (Pursh) Maxim.) and baldhip rose (*Rosa gymnocarpa* Nutt.). Bigleaf maple (*Acer macrophyllum* Pursh) and red alder (*Alnus rubra* Bong.) are common in the area. The herb layer consists mainly of twinflower (*Linnaea borealis* ssp. *Longiflora* (Torr.) Hulten), Vanilla leaf (*Achlys triphylla* (Sm.) DC.), sword fern (*Polystichum munitum* (Kaulf.) Presl), and bracken fern (*Pteridium aquilinum* (L.) Kuhn). Begbie Lake is the lowest elevation site, with the basin having the smallest surface area of all sites investigated. It is located just north of the main Sooke Lake Reservoir. At this site, the topography is generally flat with a marginal wetland around the lake giving rise to a hill with dominant southeastern aspects above the site. Vegetation is similar to Frog Lake, though with Sweet gale (*Myrica gale* L.) present along the lake margin.

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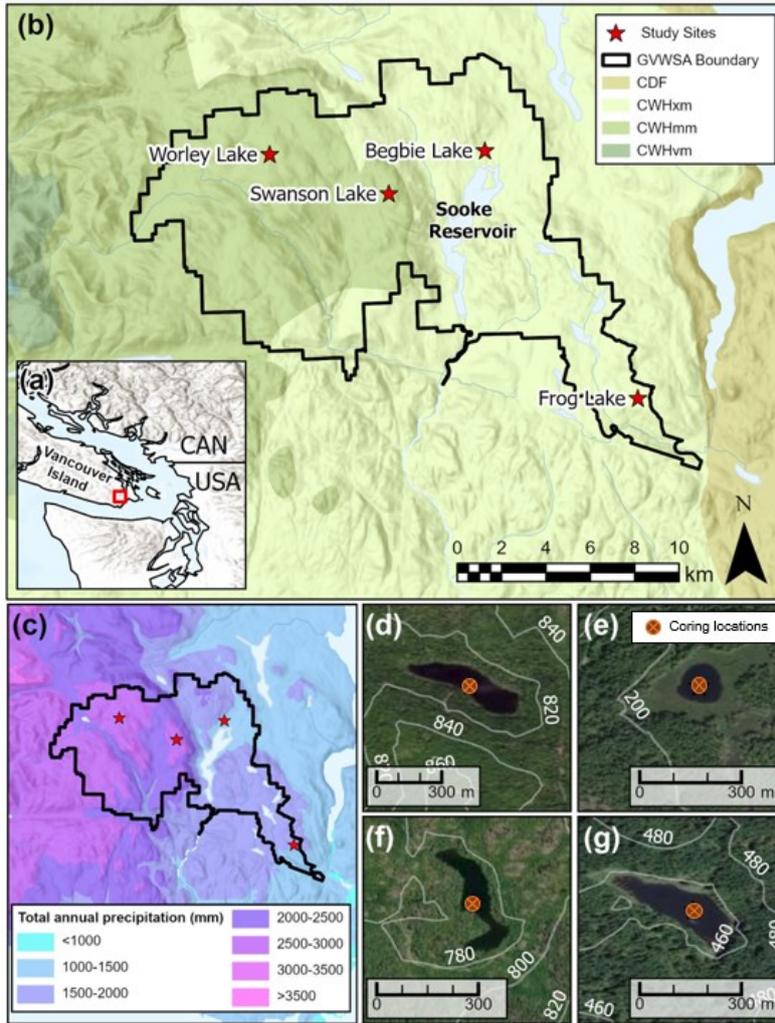
**Commented [RH9]:** From Referee #1: To improve clarity, suggest synthesizing site details by emphasizing the east-west gradient.

This section is very detailed, but the authors could clarify the focus by separating the basic context from the methodological details. To strengthen the introduction, it should emphasize the rationale behind selecting the regional climatic gradient across the GVWSA, its watersheds, and the key BEC zones (CWHxm, CWHmm, and CDF). The specific site-level details, such as topography, aspect, and detailed species lists for the shrub and herb layers at Frog, Begbie, Swanson, and Worley Lakes, are important but relate more to "methodological" in nature.

**Commented [RH10R9]:** Response: As recommended, the Study setting subsection has been revised so that it includes important background information and introduces the Greater Victoria Water Supply Area (GVWSA). We highlight the rationale for selecting the regional climatic gradient. Fire regime characteristics follow this gradient, with higher fire frequency occurring in the dry eastern Douglas-fir dominated forests and longer FRIs with more variability in wetter western hemlock-dominated forests (Brown *et al.*, 2002; Gavin *et al.*, 2003; Wong *et al.*, 2004). Also, site specific details for each lake have been moved to the Methods section and the paragraphs have been shortened by moving the descriptions of vegetation to Table 1. This allows for comparison of study site characteristics in a format that is easier to digest.

**Commented [RH11]:** Reviewer #2: Don't use acronyms unless you use them more than 7-10 times in the paper. They clog the paper and the reader gets cranky trying to look them up. CWHmm is such an example perhaps.

**Commented [RH12R11]:** Response: Thank you for highlighting this issue. We do not wish to bog down the reader with acronyms and appreciate this being brought to our attention. Regarding biogeoclimatic ecological classifications, we feel they are readily represented in their acronym form (containing information about the location, dominant species, and climate variant). With only two subzones represented in the paper, we feel that including those particular acronyms is a descriptive trade-off. However, the paper has been revised to reduce other acronyms and improve readability. We re-wrote these classifications in full at the beginning of new sections so the reader does not need to refer to acronyms in the Introduction. In addition, we have chosen to write out arboreal and non-arboreal pollen throughout, instead of using acronyms (AP and NAP).



**Figure 1:** Study area map of the **Greater Victoria Water Supply Area (GVWSA)**. (a) Regional overview and study area **outline** (inset red box), **with** world hill shade **topography** (ArcGIS Map Service, 2024; Esri, Maxar, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap, and the GIS user community). (b) The GVWSA with site locations and **biogeoclimatic ecological classification (BEC) zones and subzones** (Government of BC, 2021). (c) Average total annual precipitation, 1991 – 2020 (Wang *et al.*, 2016). (d – g). Worley Lake, Begbie Lake, Swanson

**Commented [RH13]:** Referee #2: Figures and tables and the captions have to be able to stand apart from their text, so you should write acronyms in the captions out in full.

**Commented [RH14R13]:** Response: We have revised the captions as recommended.

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Lake, and Frog Lake respectively, showing coring locations, surrounding topography (20 m contours, white lines) and scale (0 – 300 m), world imagery (ArcGIS Map Service, 2024; Esri, Maxar, Earthstar Geographics, and the GIS User Community).

## 2 Material and Methods

Four sites were selected for study within the GVWSA based on their contrasting biogeoclimatic conditions (Table 1). Frog Lake is the southeastern most study site and represents the driest and warmest climate (CWHxm), with the surrounding topography distinguished by south-southwestern aspects, steep rocky bluffs below the site, and hummocky terrain above. Begbie Lake, also in CWHxm, is the lowest elevation site, with the basin having the smallest surface area of all sites investigated. It is located just north of the main Sooke Lake Reservoir. At this site, the topography is generally flat with a marginal wetland around the lake giving rise to a hill with dominant southeastern aspects above the site. Swanson and Worley lakes lie within the moist CWHmm subzone. Swanson Lake is the shallowest lake studied and sits just inside the Leech watershed near the western boundary of the Sooke where it represents the most eastern extent of CWHmm. The site occurs on top of a prominent undulating ridge. A few small craggy features protrude above the site providing both north and southwest facing local aspects. The ridge slopes steeply down from the site to the north and east. Worley Lake is the western most site, as well as the largest and deepest lake. The site sits on a bench surrounded by gentle, hummocky terrain and local topography that reflects both north and south aspects.

Swanson and Worley lakes lie within the moist CWHmm subzone. Swanson Lake is the shallowest lake studied and sits just inside the Leech watershed near the western boundary of the Sooke where it represents the most eastern extent of CWHmm. The site occurs on top of a prominent undulating ridge. A few small craggy features protrude above the site providing both north and southwest facing local aspects. The ridge slopes steeply down from the site to the north and east. Primary tree species include western hemlock, Douglas fir, amabilis fir (*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes), and yellow cedar (*Chamaecyparis nootkatensis* (D. Don) Oerst. ex D.P. Little). Lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *contorta*) is also notable at the site. The shrub layer is mainly Alaskan blueberry (*Vaccinium alaskaense* Howell) and salal with five leaved bramble (*Rubus pedatus* Sm.). Worley Lake is the western most site, as well as the largest and deepest lake. The site sits on a bench surrounded by gentle, hummocky terrain and local topography that reflects both north and south aspects. Vegetation is represented by western hemlock, Douglas fir, amabilis fir, and yellow cedar and a shrub layer that consists mainly of Alaskan blueberry, salal and other *Vaccinium* species. The herb layer is less well developed compared to eastern sites, consisting mainly of vanilla leaf amongst dominant moss cover.

**Table 1: Characteristics of study lakes within the Greater Victoria Water Supply Area (GVWSA). Location and coordinates, elevation above sea level (asl), mean annual precipitation (MAP) from Climate BC (Wang *et al.*, 2016), lake area, lake depth, biogeoclimatic ecological classification (BEC) subzones (BC Forest Analysis and Inventory Branch, 2024), and dominant vegetation BEC subzones (BC Forest Analysis and Inventory Branch, 2024), elevations in metres above sea level (asl), and annual precipitation (ppt) in millimetres (mm) from Climate BC (Wang *et al.*, 2016).**

**Commented [RH15]:** Reviewer #2: In particular, the Methods section needs to be expanded to fully explain what was done so that a beginning grad student is able to reproduce the various analyses and apply them to their own data. For example, fully explain how you standardized charcoal influxes and calculated the bootstrapped CIs. Explain what is the goal of each statistical test: "in order to ...."

**Commented [RH16R15]:** Response: We have expanded the methods section to improve interpretation for replicability. The standardization of charcoal influxes and calculation of bootstrapped CIs adapts methods developed by Blarquez *et al.* (2014) with published R scripts and analysis overview. As recommended, we now provide step-by-step explanation in our methods, including how data were rescaled by min-max, submitted to Box-cox transformation with maximum likelihood estimation of lambda, then passed to Z-scores using the mean and standard deviation. The data are then binned by 20-year steps defined by a base period with beginning and ending ages (early and late-Holocene). The composite curve is a smoothed local regression (lofit()) unresampled with bootstrapped confidence intervals (at 0.95 and .05) resampled from site replacement (5 iterations). Throughout the methods, a few short sentences have been added to describe the purpose of various statistical tests.

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Site	Coordinates (°N, °W)	Watershed	BEC Zone/ Subzone	Elevation (m asl)	Annual ppt (mm)	Lake size (ha)	Depth (m)
Frog Lake	48.48, 123.59	Goldstream	CWHxm	460	1,587	2.31	7.9
Begbie Lake	48.58, 123.68	Sooke	CWHxm	189	1,511	0.77	8.3
Swanson Lake	48.57, 123.74	Leech	CWHmm	774	2,396	1.65	5.0
Worley Lake	48.59, 123.81	Leech	CWHmm	809	2,884	3.56	10.6

Lake (watershed)	Coord. (°N, °W)	Elev. (m asl)	MAP (mm)	Area (ha)	Depth (m)	BEC subzone	Dominant Vegetation		
							Trees	Shrubs	Herbs
Frog (Goldstream)	48.48, 123.59	460	1,587	2.31	7.9	CWHxm	<i>Pseudotsuga menziesii</i> , <i>Tsuga heterophylla</i> , <i>Thuja plicata</i>	<i>Gaultheria shallon</i> , <i>Mahonia nervosa</i> , <i>Vaccinium parvifolium</i> , <i>Holodiscus discolor</i> , <i>Rosa gymnocarpa</i> , <i>Acer macrophyllum</i> , <i>Alnus rubra</i>	<i>Linnaea borealis</i> ssp. <i>Longiflora</i> , <i>Achlyx triphylla</i> , <i>Polystichum munitum</i> , <i>Pteridium aquilinum</i>
Begbie (Sooke)	48.58, 123.68	189	1,511	0.77	8.3	CWHxm	<i>Pseudotsuga menziesii</i> , <i>Tsuga heterophylla</i> , <i>Thuja plicata</i>	<i>Gaultheria shallon</i> , <i>Mahonia nervosa</i> , <i>Vaccinium parvifolium</i> , <i>Holodiscus discolor</i> , <i>Rosa gymnocarpa</i> , <i>Myrica gale</i> , <i>Acer macrophyllum</i> , <i>Alnus rubra</i>	<i>Linnaea borealis</i> ssp. <i>Longiflora</i> , <i>Achlyx triphylla</i> , <i>Polystichum munitum</i> , <i>Pteridium aquilinum</i>
Swanson (Leech)	48.57, 123.74	774	2,396	1.65	5.0	CWHmm	<i>Tsuga heterophylla</i> , <i>Pseudotsuga menziesii</i> , <i>Abies amabilis</i> , <i>Chamaecyparis nootkatensis</i> , <i>Pinus contorta</i>	<i>Vaccinium alaskaense</i> , <i>Gaultheria shallon</i>	<i>Rubus pedatus</i>
Worley (Leech)	48.59, 123.81	809	2,884	3.56	10.6	CWHmm	<i>Tsuga heterophylla</i> , <i>Pseudotsuga menziesii</i> , <i>Abies amabilis</i> , <i>Chamaecyparis nootkatensis</i>	<i>Vaccinium alaskaense</i> , <i>Gaultheria shallon</i>	<i>Achlyx triphylla</i>

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## 2 Material and Methods

Sediment cores were recovered from the deepest part of each lake basin. Upper unconsolidated sediment was recovered using a 50-cm long Kajak corer (Kajak *et al.*, 1965), whereas a Livingstone piston corer (Wright, 1967; Livingstone, 1955) was used to retrieve deeper sediment in 1 m increments. To establish chronologies, bulk sediment samples and plant macrofossils were

sent to the University of Ottawa A.E. Lalonde AMS Laboratory for radiometric ( $^{14}\text{C}$ ) age determination. Radiocarbon ages were calibrated to calendar years using OxCal v4.4 (Ramsey, 2009) and the IntCal20 calibration curve (Reimer *et al.*, 2020). A volcanic ash layer, consisting of glass shards when viewed under a compound microscope, was observed in all cores. Given its stratigraphic location relative to other radiocarbon dates coupled with the known distributions of regional ash plumes, it is likely to be Mazama ash (Egan *et al.*, 2015). The age-depth model was established using the *Bacon* package for *R* (V 4.1.1), which uses a Bayesian approach to estimate accumulation rates from radiocarbon dates through Markov Chain Monte Carlo (MCMC) iterations (Blaauw and Christen, 2011). Given that Mazama ash is an instantaneous event, its thickness was omitted from modelling. Priors for the accumulation rate were modelled using a gamma distribution, with memory (autocorrelation) defined using a beta distribution (Fig. 2). Default parameters (Goring *et al.*, 2012) were applied to all models except Worley Lake where the *acc.shape* was decreased to reduce the peakedness of the prior distribution and produce a better fit.

Magnetic susceptibility profiles were developed for each core using a Bartington MS3 metre and MS2E core logging sensor (area of response  $3.8 \times 10.5$  mm, depth of response 50% at 1 mm and 10% at 3.5 mm) recorded through Bartssoft PCv4.0 (Bartington Instruments, 2013). Measurements were taken at 0.5 cm intervals for Kayak samples and at 1 cm intervals for the Livingston cores, applying regular temperature drift corrections at every fifth reading. Each section was repeat measured and plotted to validate the profile with offsets applied as necessary.

Pollen and spores (henceforth pollen) were analyzed using traditional methods (Moore *et al.*, 1991). For each targeted section of core, a  $1\text{cm}^3$  sediment sample was collected every 5 cm and sieved at  $150\ \mu\text{m}$ , retaining the finer component. An exotic *Lycopodium* tablet was added as a spike to each sample ( $20,848 \pm 1,546$  spores tablet $^{-1}$ ; Department of Quaternary Geology, University of Lund, batch no. 1031). Pollen were extracted through chemical digestion involving HCl and acetolysis (Moore *et al.*, 1991), with residues mounted in glycerine in the resultant slides. A minimum of 300 grains per slide were tallied using a Fisher Scientific Micromaster compound microscope at 400-1000 $\times$  magnification, with identification aided by published keys (Moore *et al.*, 1991; Kapp, 1969; and McAndrews *et al.*, 1973) and reference slides. Taxa that were not definitively identified to genus or species were harmonized by family. Pollen counts were standardized using the *decostand* function in the *vegan* package for *R* 4.1.1 (Oksanen *et al.*, 2022) and expressed as percentage of pollen per sample. Pollen diagrams were plotted using the *Rioja Plot* V0.1-20 package (Juggins, 2023) with a subset (relative abundance  $<5\%$ ) of taxa removed. Using the complete pollen dataset, with the exception of but excluding aquatics, taxa were classified as arboreal (AP) and non-arboreal (NAP) and grouped into fire-related functional categories (invaders, avoiders, evaders, endurers, resisters, and unknowns), which are indicative of fire adaptations (Rowe, 1983; Agee, 1993; Wirth, 2005; Giuliano and Lacourse, 2023). Invaders are early-successional species that are killed by fire but widely dispersed and may be able to re-sprout or germinate quickly after disturbance. Avoiders are killed by fire and possess no fire adaptations. These species are shade-tolerant and dominate late-successional forests where fire is rare. Evaders are highly flammable (fire promoting), serotinous, and early reproducers. Endurers are typically top killed by fire but can re-sprout from surviving underground adventitious buds or rhizomes. Resisters

**Commented [RH17]:** Referee # 2: Line 229 – have you tried significance tests correcting for autocorrelation (referring to change in relative abundance of fire-related functional pollen types).

**Commented [RH18R17]:** Response: We started conducting various unconstrained (principal components analysis, detrended correspondence analysis) and constrained (Redundancy analysis) ordination on pollen data and functional groups, but given the length of the current manuscript and multiplicity of analyses already included we felt additional analysis was getting outside the scope of the current paper. We hope to explore these relationships further in the future.

**Commented [RH19]:** Reviewer #2: As the paper is now written it is targeted towards a very narrow specialized group of readers: pollen and charcoal people working in the Pacific Northwest who know that literature well. It needs to be made more accessible to a wider community, especially as *Climate of the Past* is a European journal. It can be greatly improved simply adding explanatory parenthetical phrases where commented. For example, define in Methods what are your tree classes: invaders, resisters, etc, instead of having the reader guess.

**Commented [RH20R19]:** Response: To expand the appeal of the manuscript beyond specialized paleoecologists in the Pacific Northwest, we have made substantial revisions to improve overall clarity and to synthesize results without overwhelming taxonomic detail that detract from the main findings. On the advice of the reviewer, a few sentences are added to the methods defining fire-related functional groups, which provides greater context for readers and supports interpretation of the results. Given that the work is being undertaken in a municipal water supply area, water purveyors are considering the results in program-level climate change adaptation strategies. Due to the traditionally foundational nature of paleoecological research, we can also add a few sentences, if the Editor wishes, describing how the research being used to generate actionable outcomes, in this case managing forests and fire to preserve high quality drinking water.

survive fires of low to moderate severity due to their thick bark, self-pruning, and longevity and can be highly resistant to fire at maturity. Cumulative graphs of functional groups were also plotted using *Rioja Plot*.

205 Macrocharcoal (>150 µm) was quantified from sieved subsamples (3 cm<sup>3</sup>) collected contiguously in 1 cm increments and  
treated with 5% H<sub>2</sub>O<sub>2</sub>. Charcoal was defined as vegetative material altered by fire, resulting in black, opaque particles with  
 vestigial cellular structure and submetallic lustre that was brittle upon manipulation (Brown and Power, 2013). The total  
 number of charcoal fragments per sample (fragments cm<sup>-3</sup>) were tallied using a Leica stereomicroscope at 30 – 45×  
 magnification. To infer the origin of burnt materials, charcoal fragments were classified into four functional categories (woody  
 210 materials, graminoids, deciduous/herbaceous materials, and unclassified) based on morphology (Enache and Cumming, 2006;  
 Mustaphi and Pisaric, 2014; Feurdean, 2021). Key distinguishing features included presence of tracheids and bordered pits in  
 wood charcoal (principally from conifers in the study area), rectangular cells and oval stomata in graminoid types, and  
 diverging branches and netted venation in deciduous/herbaceous types (Jensen *et al.*, 2007).

Charcoal peak detection was conducted using *tapas* (Finsinger and Bonnici, 2022) representing an R script version of trend  
 215 and peak CharAnalysis (Higuera *et al.*, 2009; 2011). CHAR (fragments cm<sup>-2</sup> yr<sup>-1</sup>) records were resampled and binned to equally  
 spaced time intervals using median sample resolution, and subsequently decomposed using robust locally weighted scatterplot  
 smoothing to separate background from peak components. Smoothing window widths were defined for each record using  
 sensitivity screening. The peak component was identified by a local Gaussian mixture model and minimum-count test at a 0.95  
 threshold, with suitability evaluated using a signal-to-noise index (SNI; Kelly *et al.*, 2011). An index of fuels combusted was  
 220 developed based on the ratio of graminoid to woody charcoal influx (GWI; Eq. (1)) where  $CHAR_G$  and  $CHAR_W$  represent the  
 interpolated charcoal accumulation rates for graminoid and woody materials, respectively. Values closer to one indicate higher  
 rates of wood burning. An overall fuel morphotype index (FMI) was then calculated for each site interval from the average  
graminoid-to-woody charcoal ratio  $GWI$  (Eq. (2)).

Eq. (1)

$$225 \quad GWI = 1 - \left( \frac{CHAR_G}{(CHAR_G + CHAR_W)} \right)$$

Eq. (2)

$$FMI = \frac{\sum_{i=1}^n GWI_i}{n}$$

*Tapas*-derived temporal distribution of peaks yielded estimates of fire frequency and FRIs, with the latter group -factored by  
 site and interval (early- vs. late-Holocene). The distributions of FRIs were tested and failed assumption for normality using a  
 230 Shapiro-wilk's test on residuals of a linear model. To test if FRIs differed between the early- and late-Holocene at each site

(dependent groupings), and to determine if a temporal shift in fire regimes occurred, a non-parametric Wilcoxon test was performed using *rstatix* 0.7.2 (Kassambra, 2022). A Kruskal-Wallis test was performed across all independent groupings (comparing FRIs between sites) followed by Dunn's pairwise comparisons to establish if there were significant spatial differences in fire regimes.

235 Standardized and transformed charcoal influx was used to reduce site effects and variability between records and examine  
~~compare~~ biomass burning in the GVWSA (Marlon *et al.*, 2013; Conedera *et al.*, 2009; Marlon *et al.*, 2016). Charcoal influx  
was calculated from charcoal concentrations for each record using their respective age-depth model. Base periods were defined  
representing the early (11,000 – 8,000 cal yr BP) and late-Holocene (3000 – 0 cal yr BP). Influx values were scaled by min-  
max to maintain values between 0-1 and a Box-Cox transformation was then applied using boxcox.R in MASS R 7.3 (Ripley,  
240 2023) to homogenize variance (Box-cox shift parameter  $\alpha=0.01$ , maximum likelihood estimation of lambda), with outputs  
rescaled by minmax and passed to Z scores using the mean and standard deviation of the data. The transformed data were  
presampled and binned in 20-year steps for the defined base periods, reducing sample frequency between records to common  
intervals without interpolation. A composite curve was fit using a local regression function (locfit.R from *locfit* 1.5; Loader,  
245 2023) with fixed half window-width (smoothing parameter = 500) and bootstrapped confidence intervals (replacement by sites  
over 5000 replications) (Power *et al.*, 2010; Blarquez *et al.*, 2014; Marlon *et al.*, 2016). Site curves were generated from the  
transformed, prebinned individual site data and fit using the same regression parameters. Chareoal concentrations were  
transformed into influx values, variance homogenized using a Box-Cox transformation, rescaled by minmax, and passed to Z  
250 scores. The transformed data were presampled and binned in 20-year steps for base periods representing the early (11,000–  
8,000 cal yr BP) and late-Holocene (3000–0 cal yr BP). A composite curve was fit by bootstrap of site confidence intervals  
using a local regression function with fixed half window width (smoothing parameter = 500). Individual site curves were  
generated from transformed, prebinned individual site data and fit using the same regression parameters.

To reconstruct climate a pollen derived index (DWHI) of xeric-adapted *P. menziesii* (Douglas-fir) to hydric-affiliated *T.*  
*heterophylla* (western hemlock) was used (Brown *et al.*, 2006). Downcore estimates of mean annual precipitation (MAP) were  
subsequently generated using fossil DWHI values with a previously developed regression model of the regional surface pollen  
255 spectra and gridded mean monthly precipitation from the Parameter-elevation Regressions on Independent Slopes Model  
(PRISM; Brown *et al.*, 2006; Brown and Schoups, 2015; Daly *et al.*, 1994; Hamann and Wang, 2005). The regression is annual  
precipitation =  $737.1563 \times \exp(1.632 \times \text{DWHI})$ , with best estimates ranging from 740-3770 mm (Brown *et al.*, 2019).  
Furthermore, to allow for temperature reconstruction and to compare  $\text{MAP}_{\text{DWHI}}$ , spatially constrained ( $1^\circ \times 1^\circ$ ), time series of  
260 MAP (BIO12) and mean July temperature (Temperature 7) were extracted for the region from the PALEO-PGEM (Holden *et*  
*al.*, 2019; Barreto *et al.*, 2023) and HadCM3 series' (Beyer *et al.*, 2020) using *pastclim* 1.2 (Leonardi *et al.*, 2023). Their  
approach statistically downscales climatic [reconstructions] with a 1,000 year resolution from emulations of an intermediate  
complexity atmosphere-ocean general circulation model. To supplement temperature reconstruction, these are presented

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**Commented [RH21]:** Referee #2: Need a more detailed explanation of how MAP is calculated from DWHI as they seem to be different but you also use them interchangeably.

**Commented [RH22R21]:** Response: We have briefly expanded the methods to clarify how MAP was reconstructed using a pollen derived ratio of Douglas-fir to western hemlock. The two papers cited (Brown *et al.*, 2006 and Brown and Schoups, 2015) provide detailed methodology on the development of the transfer function, a regression model using regional surface pollen spectra and gridded mean monthly precipitation (PRISM; Daly *et al.*, 1994). We also clarify that MAP and mean July temperatures were extracted from additional published models including chironomid-based reconstructions.

**Commented [RH23]:** Line 378 – statistically or dynamically downscaled or both? Clarification needed.

**Commented [RH24R23]:** Response: The PALEO-PGEM Series is statistically downscaled. It's derived from a statistical emulator of a GCM, spatially downscaled using anomaly-adjustment of modern baseline data (Barreto *et al.*, 2023). This has been indicated in the manuscript.

alongside two previously published chironomid-based (temperature sensitive fossil midge) estimates of mean July air temperature (MJAT) from lakes located 30 and 240 km from the GVWSA (Pellatt *et al.*, 2000; Lemmen and Lacourse, 2018).

265 Mean annual precipitation (MAP) was reconstructed using an index of xeric-adapted *P. menziesii* to hydric-affiliated *T. heterophylla* (DWHI; Brown *et al.*, 2006). Downcore estimates of MAP were subsequently generated using a regression model based on surface pollen spectra and PRISM gridded precipitation (Brown *et al.*, 2006; Brown and Schoups, 2015; Daly *et al.*, 1994; Hamann and Wang, 2005). Furthermore, mean annual precipitation (MAP, BIO12) and mean maximum monthly temperature (Tmax., BIO05) were extracted using *pastelim* 1.2 (Leonardi *et al.*, 2023) to plot the PALEO-PGEM (Barreto *et al.*, 2023) and HadCM3 series' (Beyer *et al.*, 2020). These are presented alongside two chironomid-based estimates of mean July air temperature (MJAT) from lakes located 30 and 240 km from the GVWSA (Pellatt *et al.*, 2000; Lemmen and Lacourse, 2018).

### 3 Results

#### 3.1 Chronologies

275 Sediment cores from all lakes were principally comprised of brown gyttja with basal grey clay (total lengths [cm], Frog = 562, Begbie = 633, Swanson = 654, Worley = 474; Fig. 2). Age-depth models returned mean 95% confidence ranges of 492, 543, 501, and 585 years for Frog, Begbie, Swanson, and Worley lakes, respectively.

**Commented [RH25]:** Referee #2: Line 194 – explain in more detail the chironomid-based temperature estimates

**Commented [RH26R25]:** Response: A brief explanation has been added in parentheses.

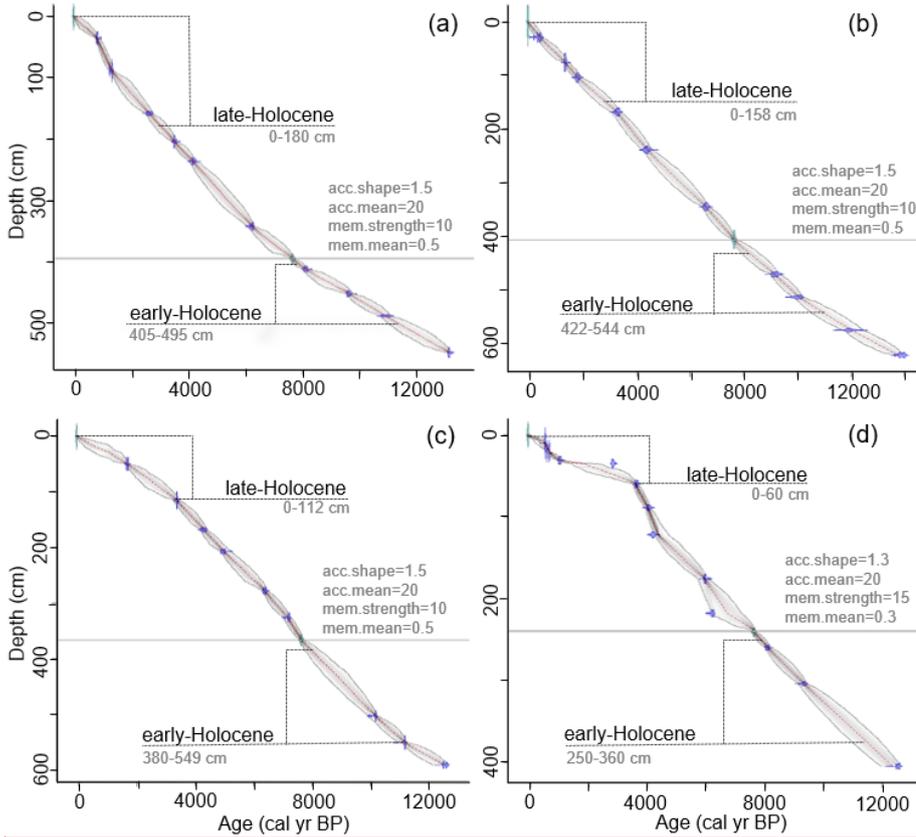
**Commented [RH27]:** From Referee #1: The final paragraph (L188~) is somewhat dense, and readers might need a more detailed explanation, particularly on how to reconstruct MAP. Additionally, the paragraph becomes too long, the authors should clearly differentiate between what you reconstructed yourself (MAP from DWHI) and the data you extracted from published models (PALEO-PGEM and HadCM3) and other paleo-records (chironomid MJAT).

**Commented [RH28R27]:** Response: As recommended, the paragraph has been revised to clarify how MAP was reconstructed using a pollen derived ratio of Douglas-fir to western hemlock, with the regression equation now added to the text. The two papers that are cited (Brown *et al.*, 2006 and Brown and Schoups, 2015) describe the development of the transfer function, using surface pollen spectra and gridded mean monthly precipitation (PRISM; Daly *et al.*, 1994). We also clarify that MAP and mean July temperatures were extracted from additional published models, including chironomid-based reconstructions.

**Commented [RH29]:** Although the results data are comprehensive, the text often reads like a list of observations. To better engage readers, the authors should directly incorporate interpretations and key messages into the results section. Each subsection on pollen and charcoal at the sites would benefit from beginning with a clear, single-sentence summary highlighting the main findings. Furthermore, the narrative can be improved by reducing the taxonomic details in the main text. Overwhelming lists of minor taxa might be summarized in a phrase, such as "along with minor contributions from broadleaf taxa such as *Acer* and *Quercus*," with full details moved to supplementary diagrams. This allows the main text to focus on the main drivers of change. Finally, contrasts between functional groups should be highlighted as a story, not just listed. For example, instead of simply stating percentages, frame them: "This vegetation shift is reflected in the fire-adapted functional groups, which show a clear decline in 'invaders' (71% to 42%) and a rise in 'avoiders' (5% to 23%), consistent with a closing forest canopy."

**Commented [RH30R29]:** Response: We have modified the Results to incorporate interpretations and key messages specific to the respective sites. This section is now much more comprehensive and reinforces the story cohesiveness, leaving the Discussion to highlight bigger picture fire and vegetation change. A summary sentence has been added to the beginning of each paragraph. Minor taxa have been removed unless they signal an important ecological characteristic that differentiates the site and/or fire regime. We have also used trends in fire-related functional groups to highlight changes in both vegetation and fire, by bridging the two analyses.

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Commented [RH31]: Referee #2: Reorder Fig 2 lakes to follow your regular order.

Commented [RH32R31]: Response: Revised, done.

Figure 2: Age-depth models for study sites in the [Greater Victoria Water Supply Area \(GVWSA\)](#). (a) [Frog](#), (b) [Begbie](#), (c) [Swanson](#), and (d) [and Worley](#) lakes. Each panel shows the calibrated  $^{14}\text{C}$  dates (blue), modelled mean age (red dash line), 95% confidence intervals (grey stippled area) and modelling parameters. The horizontal grey line in each panel represents Mazama ash. Dashed brackets indicate targeted sampling intervals for the early- and late-Holocene. Parameter settings are also presented in light grey text; acc.shape, is the prior used to model accumulation rate, acc.mean is the prior for the mean in years/cm, mem.strength is the prior used to model memory, and mem.mean is the prior for the mean used to model memory.

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Table 2: Chronological control points and modelled ages for study sites in the [Greater Victoria Water Supply Area \(GVWSA\)](#).

Site and Sample ID	Method	Material	Depth (cm)	<sup>14</sup> C age (ybp)	±	Mean probability age (cal yr BP)
<b>Frog Lake</b>						
Core top	N/A	N/A	0	N/A	10	-62
UOC-17575	14C	Bulk sediment	35.5 - 36	879	16	760
UOC-17531	14C	Leaves/ organics	88	1337	20	1279
UOC-17532	14C	Twig	158	2492	20	2591
UOC-17533	14C	Plant	204	3267	21	3485
UOC-17534	14C	Organic fragments	236	3769	21	4133
UOC-17535	14C	Needle	342	5386	21	6213
N/A	Tephra	Mazama ash	395	N/A	N/A	7631*
UOC-17536	14C	Twig	412	7298	23	8097
UOC-17537	14C	Twig & Seed	452	8671	24	9618
UOC-17538	14C	Twig	488	9573	25	10,907
UOC-17539	14C	Needle	548	11,256	30	13,138
<b>Begbie Lake</b>						
Core top	N/A	N/A	0	N/A	10	-59
BEG-35	14C	Plant fragment	29	280	20	382
BEG-82	14C	Twig	76	1435	20	1330
BEG-110	14C	Plant fragment	104	1875	25	1803
BEG-174.5	14C	Twig	168.5	3075	20	3236
BEG-245	14C	Bark fragment	239	3935	20	4398
BEG-351	14C	Plant fragment	345	5785	20	6570
N/A	Tephra	Mazama ash	406	N/A	N/A	7631*
BEG-477	14C	Twig	471	8205	25	9153
BEG-519.5	14C	Seed /plant fragment	513.5	8885	25	10,047
BEG-581	14C	Twig	575	10,240	30	12,019
BEG-627.5	14C	Needle and plant frag	621.5	11,960	30	13,721
<b>Swanson Lake</b>						
Core top	N/A	N/A	0	N/A	10	-60
UOC-21458	14C	Bulk sediment	50- 51	1786	14	1679
UOC-21459	14C	Bulk sediment	115- 116	3146	15	3376
UOC-17541	14C	Twig	168	3861	21	4292
UOC-17542	14C	Twig	207	4404	21	4987
UOC-17543	14C	Bark/cone	278	5619	22	6387
UOC-17544	14C	Twig	326	6254	22	7164
N/A	Tephra	Mazama ash	366	N/A	N/A	7631*
UOC-17545	14C	Plant	503	8983	25	10,162
UOC-17546	14C	Plant	551	9742	26	11,191
UOC-17547	14C	Plant fragments	591	10,549	26	12,513
<b>Worley Lake</b>						
Core top	N/A	N/A	0	N/A	10	-59
UOC-245856	14C	Bulk sediment	10 - 11	470	20	457
UOC-24857	14C	Bulk sediment	20 - 21	670	15	644
UOC-24858	14C	Bulk sediment	31 - 32	1110	20	1064
UOC-17549	14C	Twig	35	2738	20	1674**
UOC-21461	14C	Bulk sediment	60- 61	3382	15	3593
UOC-17550	14C	Needle	89	3704	23	4011
UOC-17551	14C	Plant	122	3814	22	4395
UOC-17552	14C	Plant fragments	176	5214	22	5930
UOC-17553	14C	Twig	218	5387	22	6726
N/A	Tephra	Mazama ash	241	N/A	N/A	7631*
UOC-17554	14C	Plant	260	7291	23	8104
UOC-17555	14C	Twig	304	8303	24	9,321
UOC-17556	14C	Twig	405	10,505	26	12,356

N/A: not available; \*modelled age from Egan *et al.* (2015); \*\*sample modelled outside the 95% confidence interval

## 3.2 Frog Lake

300 Results from climate, fire, and vegetation reconstructions reveal that forest characteristics and fire disturbance vary spatially and temporally, driven primarily by climate. Frog Lake's fire regime changes the least compared to other sites in the GVWSA. Estimated MAP from DWHI is 1015 mm in the early-Holocene and 1265 mm in the late-Holocene (Fig. 7a). The pollen record at Frog Lake (Fig. 3a), reflects the presence of woodland-like communities or a patchwork of forest stands and meadows in the early-Holocene. *Pseudotsuga menziesii* (<0.5-23%) increases after 10,000 cal yr BP and Poaceae peaks at 6%. Along with elevated amounts of non-arboreal pollen, understorey taxa such as Rosaceae (1.5-12%), Salix (1-9%), Pteridium (1.5-13%), and Apiaceae (0-3%), indicate an open system (Allen *et al.*, 1999). Diagnostic amounts of Artemesia (0-2%) and Selaginella signal that rocky bluffs prevailed on southwestern aspects above the study site. High relative abundance of fire-related invader pollen types suggests regular disturbance. Charcoal analysis (median SNI =4.3), identifies eleven fire events in the early-Holocene (Fig. 3b), with FRIs ranging from 114-760 years with a mean FRI (mFRI) of 315 years (Fig 8a). Peak magnitudes are relatively low. Along with a fuel morphotype index that suggests lighter fuels are being consumed at higher rates, it's conceivable that frequent fires were of smaller size, lower severity, and/or further from the basin of study.

In the late-Holocene, Cupressaceae (0-22%), *T. heterophylla* (0-15%), Picea (0-8%), and Abies (0-5%), increase in abundance, elevating the cumulative proportion of arboreal pollen (Fig. 3a). *Pseudotsuga menziesii* remains co-dominant and a signal for Poaceae persists despite expansion of late-seral taxa. Sustained understorey indicators like Rosaceae and Pteridium, together with the emergence of additional distinguishing taxa such as Acer (0-1%), Quercus (0-3%), Caprifoliaceae (0-6%), Saxifragaceae (0-1%) and Camassia (0-1%), suggest that these eastern forests maintained an open component. While proportion of invader pollen decreases, resisters increase alongside avoiders. Charcoal analysis for the late-Holocene detected nine fire events (median SNI=3.0). FRIs range from 38-646 years, with a mFRI of 323 years, indicating that fire was still prevalent. Both peak magnitude and charcoal accumulation rate of woody morphotypes increase, suggesting that fires were larger, of higher severity (consuming heavier fuels), and/or in closer proximity to the study site.

320 The early-Holocene Frog Lake pollen record (Fig. 3a), with ranges given in parenthesis, consists of *Pinus* (13-46%) and *Alnus* (29-48%) with *P. menziesii* (<0.5-23%) increasing after 10,000 cal yr BP. *Pteridium* (1.5-13%), *Rosaceae* (1.5-12%), *Salix* (1-9%), and *Poaceae* (<0.5-6%) were important understorey constituents, together with *Apiaceae* (0-3%), *Artemesia* (0-2%) and monolete ferns (0-4%). In the late Holocene, *Cupressaceae* (0-22%), and *Tsuga heterophylla* (0-15%), along with *Picea* (0-8%) and *Abies* (0-5%), increase in abundance, while *Pinus* (5-15%) decreases. *Acer* (0-1%), *Quercus* (0-3%), *Caprifoliaceae* (0-6%), *Saxifragaceae* (0-1%) and *Camassia* (0-1%) emerge as additional distinguishing taxa. AP averages 83% in the early-Holocene, increasing to 85% in the late-Holocene (Fig. 3a). Comparing changes in fire-related plant functional groups between the early and late Holocene, invaders decrease from 71 to 42%, while avoiders and resisters increase from 5 to 23% and 9 to 16%, respectively.

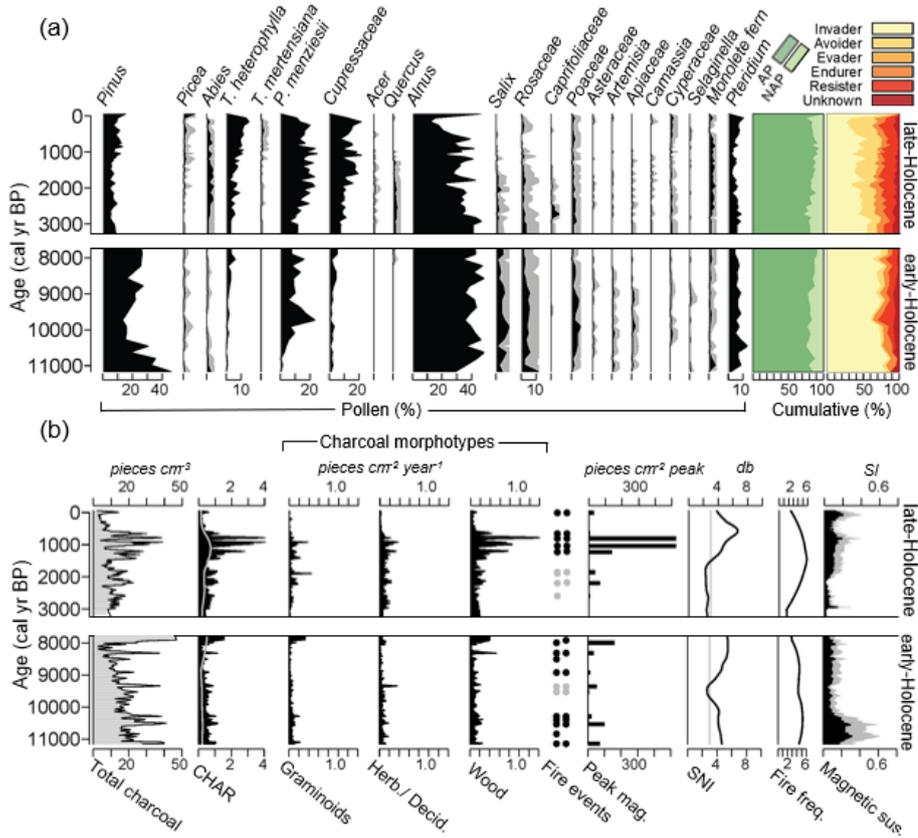
**Commented [RH33]:** Referee #2: I don't see how you can conclude from peak size that the fires were bigger, they could have simply been closer. You are making this assumption several times and it seems not well founded as you do not have charcoal particle size data.

**Commented [RH34R33]:** Response: This is a valid criticism. We agree that we can not conclude if fires were bigger or of higher severity based on peak magnitude. It is possible that proximity to the basin is influencing charcoal deposition and peak size. Notably, in interpreting peak magnitude, we attempt to include other proxies such as magnetic susceptibility and charcoal morphotype accumulation rates. However, given the reviewer's legitimate concern, we have revised statements to ensure no definitive conclusions are drawn where lack of evidence exists.

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330 Charcoal analysis was evaluated with a median SNI of 4.3 in the early-Holocene. While charcoal influx (CHAR) averages  
0.5 *pieces cm<sup>-2</sup> year<sup>-1</sup>*; morphotype influxes vary from 0.05, 0.12, and 0.06 *pieces cm<sup>-2</sup> year<sup>-1</sup>* for graminoids, wood, and  
herbaceous/deciduous materials, respectively (Fig. 3b). Eleven fire events are identified, with peak magnitude averaging 43  
335 *pieces cm<sup>-2</sup> peak*. FRIs range from 114-760 years with a mean FRI (mFRI) of 315 years. In contrast, median SNI was 3.0 in  
the late Holocene, with CHAR averaging 0.8 *pieces cm<sup>-2</sup> year<sup>-1</sup>*. Mean morphotype influx is 0.05 (graminoids), 0.20 (wood),  
and 0.09 (herbaceous/deciduous) *pieces cm<sup>-2</sup> year<sup>-1</sup>*. Nine fire events were detected, with peak magnitude averaging 225 *pieces*  
*cm<sup>-2</sup> peak*. FRIs range from 38-646 years with a mFRI of 323 years (Fig. 7a).

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340 Figure 3: Early- and late-Holocene pollen and charcoal results for Frog Lake. (a) Pollen diagram from left to right: taxa with relative  
 345 abundance >5% (black area represents scaled pollen abundance (%) with 5x exaggeration (grey curve), cumulative pollen  
 abundance (%) for arboreal (AP) and non-arboreal pollen (NAP) types, and fire functional groups. (b) Charcoal diagram from left  
 to right: charcoal concentration, charcoal accumulation rate (CHAR) with grey curve showing 95% threshold, charcoal morphotype  
 influxes, significant positive fire peaks with a low signal-to-noise index (SNI<sub>i</sub>) (grey dots) at a 95% and 99%  
 threshold, SNI, smoothed fire frequency, magnetic susceptibility with black representing raw values and grey 2X  
 exaggeration.

### 3.3 Begbie Lake

At Begbie Lake, MAP from DWHI increases from 965 mm in the early-Holocene to 1610 mm in the late-Holocene (Fig. 7a), with changes in climate reflected in vegetation composition and FRIs. The early-Holocene pollen record is characterized by a high proportion of *P. menziesii* (9-43%), which peaks at ca. 9500 cal yr BP. Poaceae (0-3%) and Rosaceae (1-4%) appear in lesser amounts than at Frog Lake, but their presence, along with a strong signal for Pteridium (4-12%) and high cumulative non-arboreal pollen support the theory that open forests with well-developed understories occupied eastern areas at this time (Brown *et al.*, 2019; Fig. 4a). The incursion of Cyperaceae (0.5-8%) at the site near the top of the interval could indicate the beginning of regional moistening. The proportion of fire-related invaders are high, along with resisters, while avoiders are low, suggesting forests are fire-maintained. The early-Holocene charcoal analysis (Fig. 4b) at Begbie Lake (median SNI=3.5) shows fire return intervals range from 88-704 years with a mFRI of 290 years (Fig. 8a). A number of high peak magnitude events suggest that large, high severity, and/or localized fires occurred at the site.

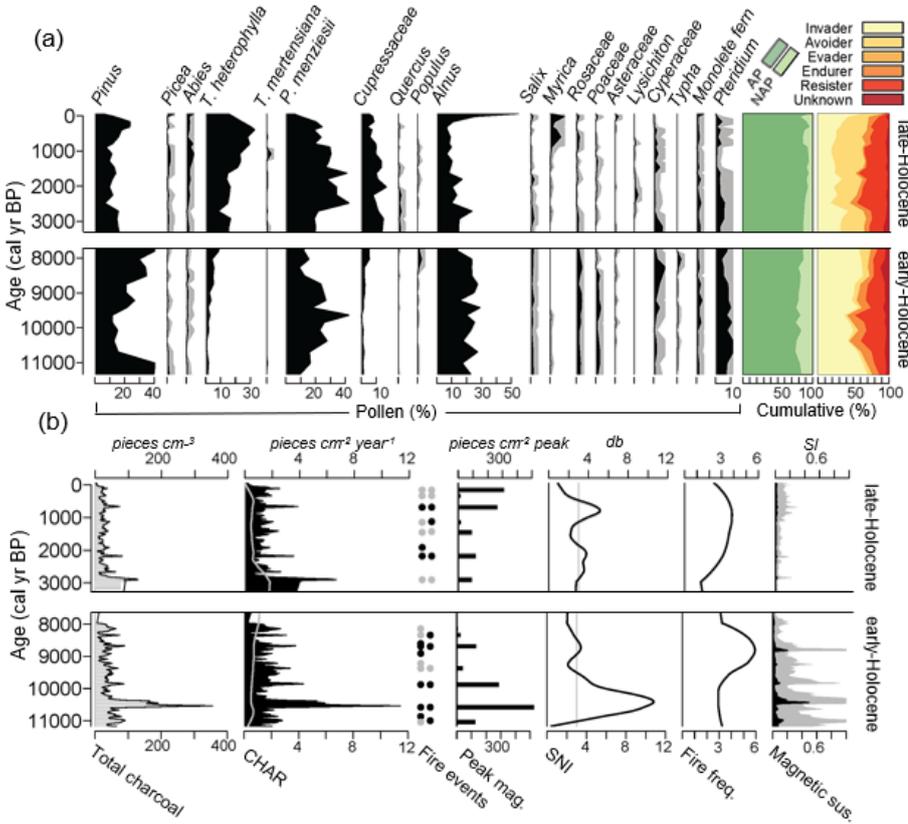
In the late-Holocene, the arboreal pollen spectra increases as more closed canopy forests developed. *Pseudotsuga menziesii* (5-42%) continues to persist at the site as *T. heterophylla* (8-33%) and Cupressaceae (4-17%) emerge as co-dominants. *Picea* (0-5%) and *Abies* (<0.5-5%) also increase. Slight decreases in Roasaceae (0-2%), Poaceae (0-1.5%), and Pteridium (0-6%) are evident. An increase in Lysichiton (0-2.5%) occurs after ca. 3000 cal yr BP implying sub-canopy swamp formation, while *Myrica* (0-10%) establishes vigorously at the site after ca. 1000 cal yr BP (Fig. 4a) reflecting local wetland development, which currently characterises the low-lying terrain around Begbie (Brown *et al.*, 2019). Relative abundance of invaders decreases while avoiders and resisters increase. Eight positive peaks are identified in the charcoal analysis (SNI=3.0), with FRIs ranging from 176-726 years and a mFRI of 394 years (Fig. 8a).

At Begbie Lake *Pinus* (12-40%), *Pseudotsuga* (9-43%), and *Alnus* (14-29%) dominate the tree component during the early-Holocene, with *Pseudotsuga* peaking at ca. 9,600 cal yr BP. *Salix* (1-2%) is found in lesser amounts. The main shrub is *Rosaceae* (1-4%), with *Pteridium* (4-12%), *Cyperaceae* (0.5-8%), and *Poaceae* (0-3%) also prevalent in the understory (Fig. 4a). In the late Holocene, *Pinus* (5-24%) and *Pseudotsuga* (5-42%) continue to persist at the site as *T. heterophylla* (8-33%) and *Cupressaceae* (4-17%) emerge as co-dominants. *Picea* (0-5%) and *Abies* (<0.5-5%) also increase. Slight decreases in *Roasaceae* (0-2%), *Poaceae* (0-1.5%), and *Pteridium* (0-6%) are evident compared to the early Holocene. An increase in *Lysichiton* (0-2.5%) occurs after ca. 3000 cal yr BP while *Myrica* (0-10%) establishes vigorously at the site after ca. 1000 cal yr BP (Fig. 4a). AP comprise an average of 80% of the pollen spectra in the early Holocene versus 90% in the late (Fig. 4a). Invaders decrease in abundance between the early (51%) and late Holocene (29%) while avoiders (7%; 34%) and resisters (20%; 25%) increase.

A median SNI of 3.5 was calculated from the early-Holocene charcoal analysis at Begbie Lake (Fig. 4b). CHAR averages 2.0  $\text{pieces cm}^{-2} \text{year}^{-1}$ . Eleven fire-related peaks are detected with peak magnitudes averaging 985  $\text{pieces cm}^{-2} \text{peak}$ . FRIs range

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from 88-704 years with a mFRI of 290 years (Fig. 7; a). In the late-Holocene, median SNI is 3.0. CHAR averages  $1.4 \text{ pieces cm}^{-2} \text{ year}^{-1}$ , and eight positive peaks are identified along with average peak magnitudes of  $91 \text{ pieces cm}^{-2} \text{ peak}$ . FRIs range from 176-726 years with a mFRI of 394 years (Fig. 7a).



385 Figure 4: Early- and late-Holocene pollen and charcoal results for Begbie Lake. (a) Pollen diagram from left to right: taxa with relative abundance  $>5\%$  (black area represents scaled pollen abundance (%) with 5x exaggeration grey curve), cumulative pollen abundance (%) for **arboreal pollen (AP)** and **non-arboreal pollen (NAP)** types, and fire functional groups. (b) Charcoal diagram from left to right: charcoal concentration, **charcoal accumulation rate (CHAR)** with grey curve showing 95% threshold, significant positive fire-related peaks (black dots) and positive peaks with a low **signal-to-noise index (SNI<sub>i</sub>)** (grey dots) at a 95% and 99% threshold, SNI, smoothed fire frequency, magnetic susceptibility with black representing raw values and grey 2X exaggeration.

### 3.4 Swanson Lake

Moving west to Swanson Lake, a higher contrast is evident between early- and late-Holocene climate. The reconstruction from DWHI at the site estimates MAP increases from 1255 mm in the early-Holocene to 2550 mm in the late-Holocene (Fig. 7a). *Pinus* (28-62%) and *Alnus* (0-50%) dominate the pollen record in the early-Holocene, along with stable amounts of *P. menziesii* (Fig. 5a). Distinguishing quantities of Plantaginaceae pollen (believed to be *Penstemon* spp.) reflect dry rocky out-crops around the site (Douglas *et al.*, 1999). The proportion of invaders is the highest of all records, while resisters and avoiders are both low, an indication that vegetation on the exposed ridge was frequently disturbed. Evaluation of the early-Holocene charcoal analysis (median SNI=3.2) produces seventeen positive fire events through the interval (Fig. 5b), with FRIs ranging from 57-361 years and a mFRI of 195 years (Fig. 8a). Peak magnitudes are low and the fuel morphotype index points to combustion of lighter fuels alongside woody materials.

In the late-Holocene, *T. heterophylla* (8-34%) increases along with Cupressaceae (1-9%), *Picea* (0-5%) and *Abies* (0-5%). *Pinus* (5-39%), *P. menziesii* (1.5-12%), and *Alnus* (21-46%) remain relatively constant. Overall, arboreal pollen abundance increases as canopy closes. A notable decrease in invaders occurs as avoiders increase. Ten positive peaks are recorded from the charcoal analysis (median SNI =2.4). FRIs range from 80-620 years with a mFRI of 311 years (Fig. 8a). Peak magnitude remains low but charcoal accumulation rate of woody morphotypes dominates, coinciding with the succession of late-seral forests and a potential change in fuel stratification.

At Swanson Lake, median SNI (3.2 and 2.4) was slightly lower compared to the other sites despite comparable sediment accumulation rates and good sampling resolution. However, it is important to recognize that SNI decreased at all sites in the late-Holocene relative to the early-Holocene, with values hovering around three. It is possible that this decrease is related to local wetland expansion intercepting overland charcoal inputs (Agee, 1993; Higuera *et al.*, 2007; Kelly *et al.*, 2011). The SNI at Swanson Lake is of greatest concern since it is generally below the threshold for suitable peak detection (Fig. 5b). Given that Swanson is the shallowest of the lakes studied, it is posited that it experienced more charcoal mixing, though not enough to entirely impede peak detection. The preponderance of fire-invading *Pinus* around Swanson Lake, however, suggests that fires did indeed continue to burn around the site. The site's location and exposure to elevated ignition probability (Perakis *et al.*, 2025), could be a sustained driver of high-frequency, low-severity fires through both the early and late-Holocene intervals, with estimates of FRIs consistent with Begbie and Frog lakes. Thus, while cautious interpretation of the late-Holocene fire record is warranted for Swanson Lake, it is presumed that the results generally reflect the fire regime.

The early-Holocene tree stratum at Swanson Lake (Fig. 5a) contains *Pinus* (28-62%), *Pseudotsuga* (4-12%), and *Alnus* (0-50%). *T. heterophylla* (1-13%) increases throughout the interval, with Cupressaceae (<0.5-2%), *Abies* (<0.5-3%) and *Salix* (0-2%) contributing to background forest composition. The understory consists of *Rosaceae* (0-4%), with *Poaceae* (0-2%),

**Commented [RH35]:** Referee # 2: Did you play with the smoother type to see if you could get SNI > 3? Moving mode can work well.

**Commented [RH36R35]:** Response: Yes. We adjusted the smoothing parameters and tried all of the detrending options available in *Tapas.R*. We used the sensitivity screening to optimize our smoothing window width. We found that the rol Lowess consistently performed the best. We address the low SNI in a new paragraph in the Discussion addressing limitations of the approach used. Reduced SNI can have meaningful interpretations and may emphasize causal mechanisms such as environmental conditions (bioturbation) or could be characteristic of frequent low-severity fires where there is little variation in charcoal production (Agee, 1993; Kelly, 2011). We caution interpretation of charcoal records with low SNI but are confident that our interpretation within the context is justified.

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425 *Plantaginaceae* (0.2%), and *Pteridium* (2.6%). In the late-Holocene, *T. heterophylla* (8.34%) increases along with *Cupressaceae* (1.9%), *Picea* (0.5%) and *Abies* (0.5%). *Pinus* (5.39%), *Pseudotsuga* (1.5-12%), and *Alnus* (21.46%) remained relatively constant. In general, shrubs and herbs decrease, except for a minor expansion of *Ericaceae* (0.2%). AP types average 90% of the population in the early-Holocene as opposed to 95% in the late-Holocene (Fig. 5a). Invaders decrease from an average of 74% in the early-Holocene to 61% in the late-Holocene, while avoiders increase from 7% to 27%. Resisters decrease at the site from 8% in the early-Holocene to 6% in the late-Holocene.

430 Evaluation of the early-Holocene charcoal analysis produces a median SNI of 3.2 (Fig. 5b). CHAR averages 0.8 *pieces cm<sup>-2</sup> year<sup>-1</sup>* while charcoal influx per morphotypes is 0.12 (graminoids), 0.19 (wood), and 0.15 (herbaceous/deciduous) *pieces cm<sup>-2</sup> year<sup>-1</sup>*. Seventeen positive fire events are identified with peak magnitudes averaging 20 *pieces cm<sup>-2</sup> peak*. FRIs range from 57-361 years with a mFRI of 195 years (Fig. 7a). During the late-Holocene, analysis results in a median SNI of 2.4. CHAR averages 0.4 *pieces cm<sup>-2</sup> year<sup>-1</sup>* and morphotype influx is 0.02, 0.12, and 0.03 *pieces cm<sup>-2</sup> year<sup>-1</sup>* for graminoid, wood and herbaceous/deciduous charcoal, respectively. Ten positive peaks are recorded with peak magnitudes averaging 15 *pieces cm<sup>-2</sup> peak*. FRIs range from 80-620 years with mFRI of 311 years.

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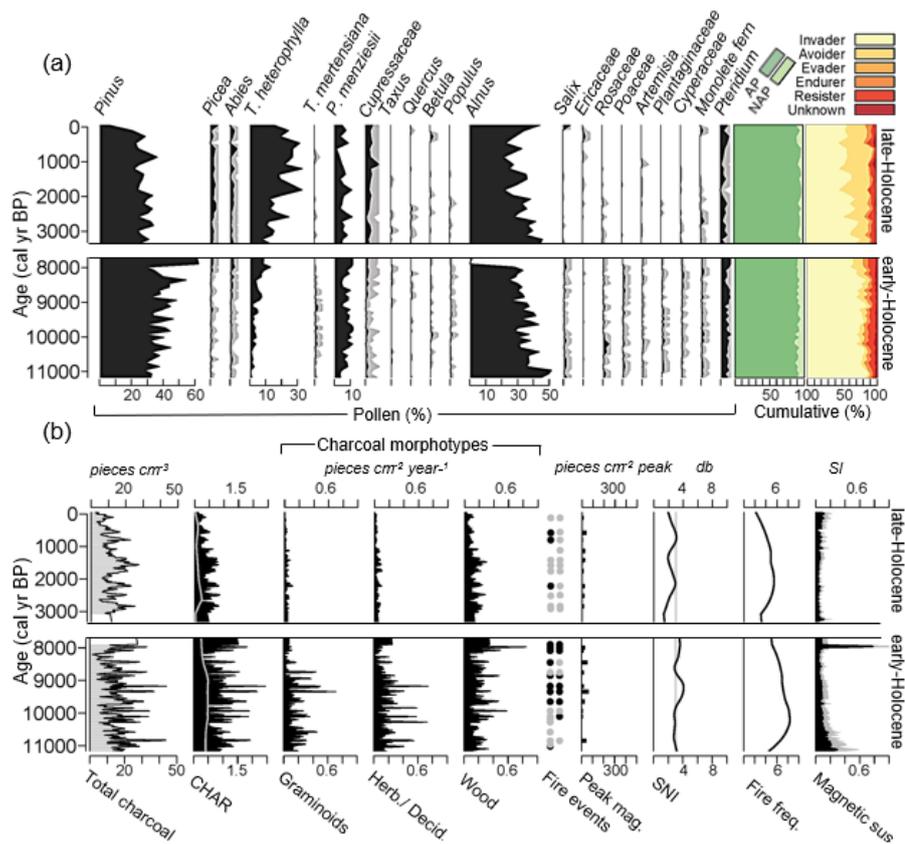


Figure 5: Early- and late-Holocene pollen and charcoal results for Swanson Lake. (a) Pollen diagram from left to right: taxa with relative abundance >5% (black area represents scaled pollen abundance (%) with 5x exaggeration grey curve), cumulative pollen abundance (%) for **arboreal pollen (AP)** and **non-arboreal pollen (NAP)** types, and fire functional groups. (b) Charcoal diagram from left to right: charcoal concentration, **charcoal accumulation rate (CHAR)** with grey curve showing 95% threshold, charcoal morphotype influxes, significant positive fire-related peaks (black dots) and positive peaks with a low **signal-to-noise index (SNI)** (grey dots) at a 95% and 99% threshold, SNI, smoothed fire frequency, magnetic susceptibility with black representing raw values and grey 2X exaggeration.

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### 3.5 Worley Lake

450 It is evident that a significant change in climate, vegetation, and fire regime occurs at the western most Worley Lake. Estimated MAP<sub>DWHI</sub> increases from 1340 mm to 3170 mm between the early- and late-Holocene, respectively (Fig. 7a). The early-Holocene pollen record at Worley Lake is characterised by *P. menziesii* (3-20%) at ca. 10,000 cal yr BP, along with abundant *Alnus* (32-62%). *Tsuga heterophylla* (0-22%) increases sharply after ca. 9000 cal yr BP, signalling that climate driven changes in forest composition and structure may have been occurring earlier in the western part of the study region (Fig. 6a). Both Swanson and Worley Lakes had comparatively underdeveloped shrub and herbaceous layers, implying that western forests were less open than contemporaneous eastern forests. Evaluation of charcoal analysis (median SNI=4.9) for the early-Holocene record produces thirteen positive fire-related peaks (Fig. 6b) and FRIs range from 87-377 years, with mFRI of 230 years (Fig. 8a). Peak magnitude is high, demonstrating potential for large, high severity, and/or localized fires at the site.

455 In the late-Holocene, a substantial decrease in *P. menziesii* (1-5%) at Worley Lake coincides with increases in *T. heterophylla* (10-40%), *Picea* (0.5-5%), *Abies* (1-4%), and *Cupressaceae* (3-35%). The cupressaceous pollen, possibly derived from both *T. plicata* and *C. nootkatensis*, increases considerably over the last 1000 years, during which time *P. menziesii* pollen decreases. Arboreal pollen increases with avoiders, while invaders and resisters decrease signalling characteristics of a late-seral closed forest. Only four significant peaks are detected from charcoal analysis in the late-Holocene (median SNI=3.5). FRIs range from 609-1856 years and mFRI significantly increases to 1082 years. At least one fire with a high peak magnitude is detected, signifying that despite significant changes to disturbance intervals, the potential for large, high severity, and/or nearby fires exists at the site.

465 At Worley Lake *Pinus* (7-29%), *Pseudotsuga* (3-20%), and *Alnus* (32-61%) are the main tree species in the early-Holocene (Fig. 6a). *T. heterophylla* (0-22%) increases at the top of the interval while *Salix* (0-1%) is present in detectable quantities until ca. 8000 cal yr BP. *Roasaceae* (0-2.5%) helps define the shrub layer. *Poaceae* (0-1%), *Cyperaceae* (0-2%), monolete ferns (0.5-3%), and *Pteridium* (1-9%) make up the understory. In the late-Holocene, *T. heterophylla* (10-40%) and *Cupressaceae* (3-35%) dominate the overstory, alongside *Pinus* (8-20%). The cupressaceous pollen, possibly derived from both *T. plicata* and *C. nootkatensis*, increases considerably over the last 1000 years, during which time *Pseudotsuga* (1-5%) pollen decreases. *Picea* (0.5-5%) and *Abies* (1-4%) form minor components of the forest. *Alnus* (13-44%) decreases slightly compared to the early portion of the record, as do most understory taxa. AP types make up 89% of the record in the early-Holocene, contrasted with an average of 93% in the late-Holocene (Fig. 6a). Fire-related functional groups show invaders decreasing from an average of 63% in the early-Holocene to 45% in the late-Holocene as avoiders increase from 10% to 46%. Resisters also decrease from 9% in the early-Holocene to 3% in the late-Holocene.

475 Evaluation of charcoal analysis for the early-Holocene record produce a median SNI of 4.9 (Fig. 6b). CHAR averages 1.0 pieces cm<sup>-2</sup> year<sup>-1</sup> while influx for charcoal morphotypes averages 0.09 (graminoids), 0.26 (wood), 0.14 (herbaceous/

deciduous)  $\text{pieces cm}^{-2} \text{ year}^{-1}$ . Thirteen positive fire-related peaks are documented with peak magnitudes averaging  $227 \text{ pieces cm}^{-2} \text{ peak}$ . FRIs range from 87–377 years and mFRI is 230 years. In the late-Holocene, median SNI is 3.5 and CHAR averages  $0.25 \text{ pieces cm}^{-2} \text{ year}^{-1}$ . Influx for charcoal morphotypes averages 0.01 (graminoids), 0.08 (wood), and 0.03 herbaceous/deciduous)  $\text{pieces cm}^{-2} \text{ year}^{-1}$ . Four significant peaks were detected with peak magnitudes averaging  $251 \text{ pieces cm}^{-2} \text{ peak}$ . FRIs range from 609–1856 years and mFRI was 1082 years.

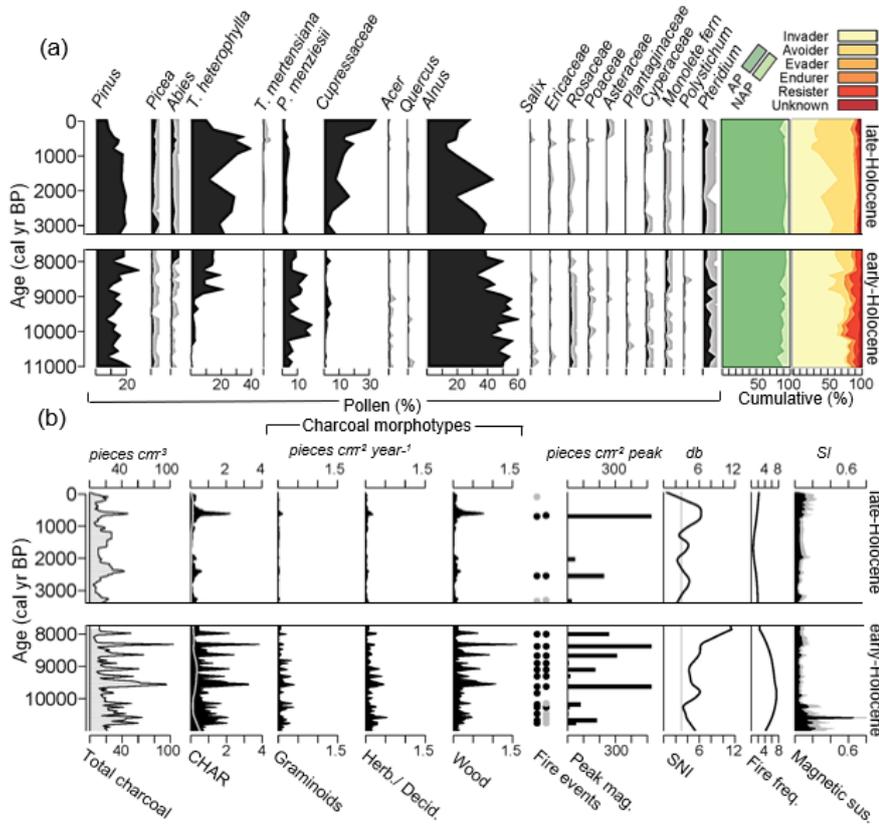


Figure 6: Early- and late-Holocene pollen and charcoal results for Worley Lake. (a) Pollen diagram from left to right: taxa with relative abundance  $>5\%$  (black area represents scaled pollen abundance (%) with 5x exaggeration grey curve), cumulative pollen abundance (%) for **arboreal pollen (AP)** and **non-arboreal pollen (NAP)** types, and fire functional groups. (b) Charcoal diagram from left to right: charcoal concentration, **charcoal accumulation rate (CHAR)** with grey curve showing 95% threshold, charcoal morphotype influxes, significant positive fire-related peaks (black dots) and positive peaks with a low **signal-to-noise index (SNI)**;

(grey dots) at a 95% and 99% threshold, SNI, smoothed fire frequency, magnetic susceptibility with black representing raw values and grey 2X exaggeration.

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### 3.6 Comparison of climate, fire return intervals, and FRIs, biomass burning, and Climate

The synthesis of results from each site in the GVWSA demonstrates how fire regimes changed over time and how local biogeoclimatic conditions influence disturbance. The extraction of data from independent climate models aligns well with pollen derived reconstruction of precipitation and supports assumptions that climate was warmer during periods of greater fire disturbance. Mean annual precipitation (BIO12) from the PALEO-PGEM and HadCM3 series is consistent with the trend that precipitation increased from early- (PALEO-PGEM ranges = 1150-1240 mm; HadCM3 = 1534-1660 mm) to late-Holocene (PALEO-PGEM = 1250- 1254 mm; HadCM3 = 1625 - 1675) in the region (Fig. 7b). Further, PALEO-PGEM and HadCM3 reveal that mean July temperature (Temperature 7) is relatively high in the early-Holocene (PALEO-PGEM = 17.3-18.5 °C; HadCM3 = 15.7-16.3 °C), peaking between 8000-10,000 cal yr BP (Fig. 7b). Thereafter, temperature steadily decreases through the late-Holocene (PALEO-PGEM = 15.7-16.1 °C; HadCM3 = 13.5-14.5 °C). Chironomid inferred MJAT likewise establishes warmer conditions in the early-Holocene (11.1-13.9 °C) compared to late-Holocene (5.7-8.8 °C), while the MJAT anomaly suggests that temperatures were consistently 0.5-2°C warmer than modern in the early-Holocene (Fig. 7b.; Pellatt *et al.*, 2000; Lemmen and Lacourse, 2018).

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A Kruskal-Wallis test ( $H=16, p=0.025$ ) indicates that FRIs differ either temporally or spatially in at least one group. Subsequent Wilcoxon test ( $W=0, p.adjusted=0.04, r=0.68$ ) on paired dependent samples shows that FRIs change significantly from the early to late Holocene at Worley Lake, but not at other sites. A Dunn's pairwise comparison ( $Z=3.35, p.adjusted$  (Bonferroni) = 0.022) of all independent groups (i.e. excluding comparisons between early- and late-Holocene FRIs from the same site) shows notable differences in FRIs between Worley Lake in the late Holocene and Swanson Lake in the early-Holocene but did not detect differences between other pairings (Fig. 7a).

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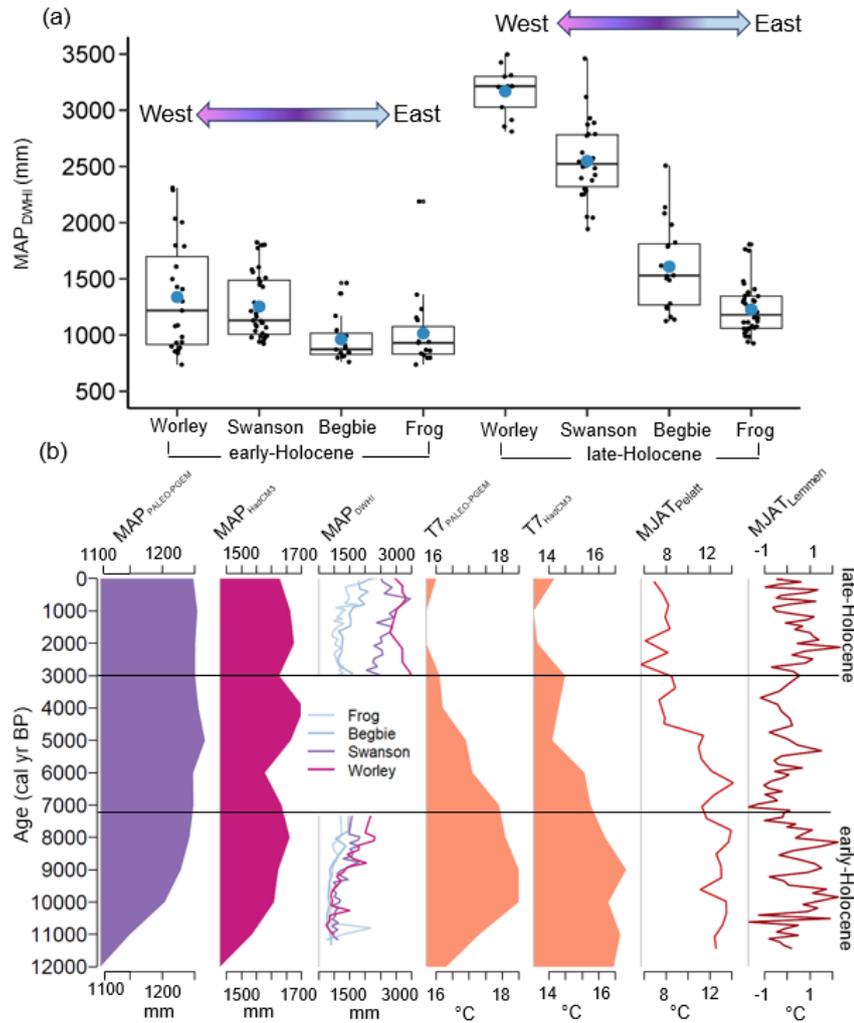
Transformed and binned  $Z$  scores of charcoal influx are relatively synchronous during the early Holocene, based on agreement between site-specific locally regressed curves and narrower boot-strapped confidence intervals (CI). Charcoal influx is highest between ca. 9500-11,000 cal-yr BP (overall above average  $Z$  scores), decreasing thereafter (Fig. 7b). The curve for Frog Lake corresponds to a minimum for the early Holocene, falling outside of bootstrapped 95% confidence intervals. The late Holocene shows greater variability, with charcoal influx between ca. 2000-3000 and 0-500 cal yr BP being somewhat synchronous. However, a pattern of asynchronicity is also evident at this time at Frog and Worley lakes, with dips in biomass burning at Worley Lake coinciding with increased burning at Frog Lake.

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**Commented [RH37]:** From Referee #1: The synthesis in Sec 3.6 is the cornerstone of your Results and must be very clear to effectively present the overall story of the paper. To improve this authors should start by stating the main finding up front. After that you need to go beyond merely reporting statistical values and include interpretation in simple language. For example, instead of just listing  $H$  and  $p$ -values, explain that the significant Kruskal-Wallis test indicates FRIs differ across sites and time, with follow-up pairwise tests showing the large increase at Worley Lake as the leading cause. Furthermore, the description of the composite charcoal curve should be clarified to highlight its key point: an early Holocene period of increased regional biomass burning followed by a general decline. Additionally, the climate data, although well-presented, can be more effectively integrated by explicitly connecting it to your fire reconstruction. Clearly state that the climatic shift to a cooler, wetter late Holocene aligns with your pollen-based precipitation reconstructions and is supported by independent model outputs and temperature proxies.

**Commented [RH38R37]:** Response: As recommended, we have revised and re-structured this section to better present the key takeaways. We highlight the main findings and add simple interpretations of statistical outputs, reinforcing the methodological context for selected tests. Independent model outputs for climate are emphasized in their supporting role for pollen-based reconstructions of precipitation. We have expanded on how the composite curve represents biomass burning and connect the climate reconstruction to fire regime characteristics.

520 Estimated MAP from DWHH is 1015 mm at Frog, 965 mm at Begbie, 1255 mm at Swanson, and 1340 mm at Worley lakes during the early Holocene (Fig. 8a). In contrast, precipitation increases in the late Holocene to 1265, 1610, 2550, and 3170 mm, respectively, with the wettest climate prevailing at Worley Lake through time. Extraction of MAP (BIO12) from the PALEO-PGEM and HadCM3 series are consistent with the trend that precipitation increased from early (PALEO-PGEM ranges = 1150-1240 mm; HadCM3 = 1444-1588 mm) to late Holocene (PALEO-PGEM = 1250-1254 mm; HadCM3 = 1572-1627) in the region (Fig. 8b). Further, PALEO-PGEM and HadCM3 (BIO5) reveals that T<sub>max</sub> was relatively high in the early Holocene (PALEO-PGEM = 17.3-18.5 °C; HadCM3 = 24.6-25.3 °C), peaking between 8000-10,000 cal yr BP (Fig. 8b).  
525 Thereafter, temperature steadily decreases through the late Holocene (PALEO-PGEM = 17.0-16.2 °C; HadCM3 = 22.4-23.2 °C). Chironomid-inferred MJAT likewise establishes warmer conditions in the early Holocene (11.1-13.9 °C) compared to late Holocene (5.7-8.8 °C), while the MJAT anomaly also suggests that temperatures were consistently 0.5-2 °C warmer than modern in the early Holocene (Fig. 8b.; Pellatt *et al.*, 2000; Lemmen and Lacourse, 2018).



**Commented [RH39]:** Referee #2: Why did you use Tmax from the GCMs instead of Mean July air temp which is what you are comparing to?

**Commented [RH40R39]:** Response: This is a valid point. Initial analysis considered Tmax to capture greatest seasonal temperature trends with majority of fires in western Canada occurring during the mid- to late-summer. We have changed analysis to present mean July temperature (Temperature\_7), this is more directly comparable to the MJAT paleo proxy reconstructions and still adequately captures the seasonality.

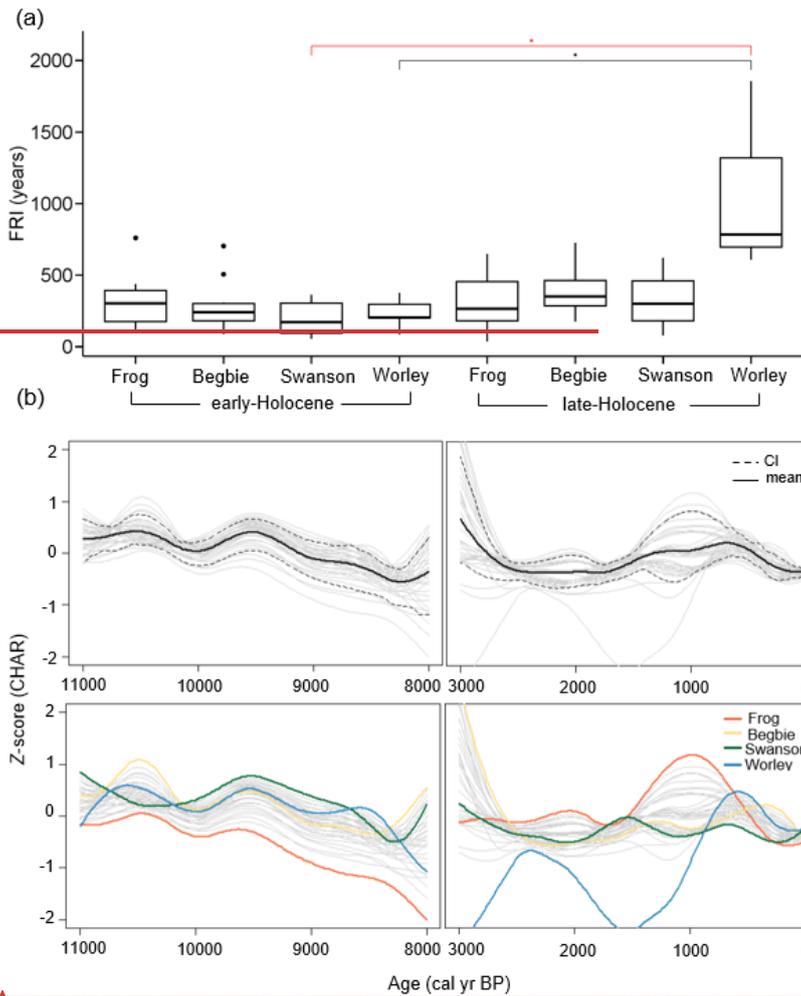
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530 **Figure 7: Regional climate reconstruction for the Holocene. (a) Boxplots for the Douglas-fir/western hemlock index estimates of mean annual precipitation (MAP<sub>DWHI</sub>). Blue dots are means. (b) From left to right: MAP (BIO12) from PALEO-PGEM series (Baretto *et al.*, 2023), MAP (BIO12) from HadCM3 (Bever *et al.*, 2020), down core MAP<sub>DWHI</sub> precipitation estimates for each site, mean July temperature (T7<sub>PALEO-PGEM</sub>) in degrees Celsius from PALEO-PGEM series (Baretto *et al.*, 2023), mean July temperature**

(T7<sub>HadCM3</sub>) from HadCM3 (Beyer *et al.*, 2020), chironomid inferred mean July air temperature (MJAT) (Pelatt *et al.*, 2000), and chironomid inferred (MJAT) anomalies (Lemmen and Lacourse, 2018).

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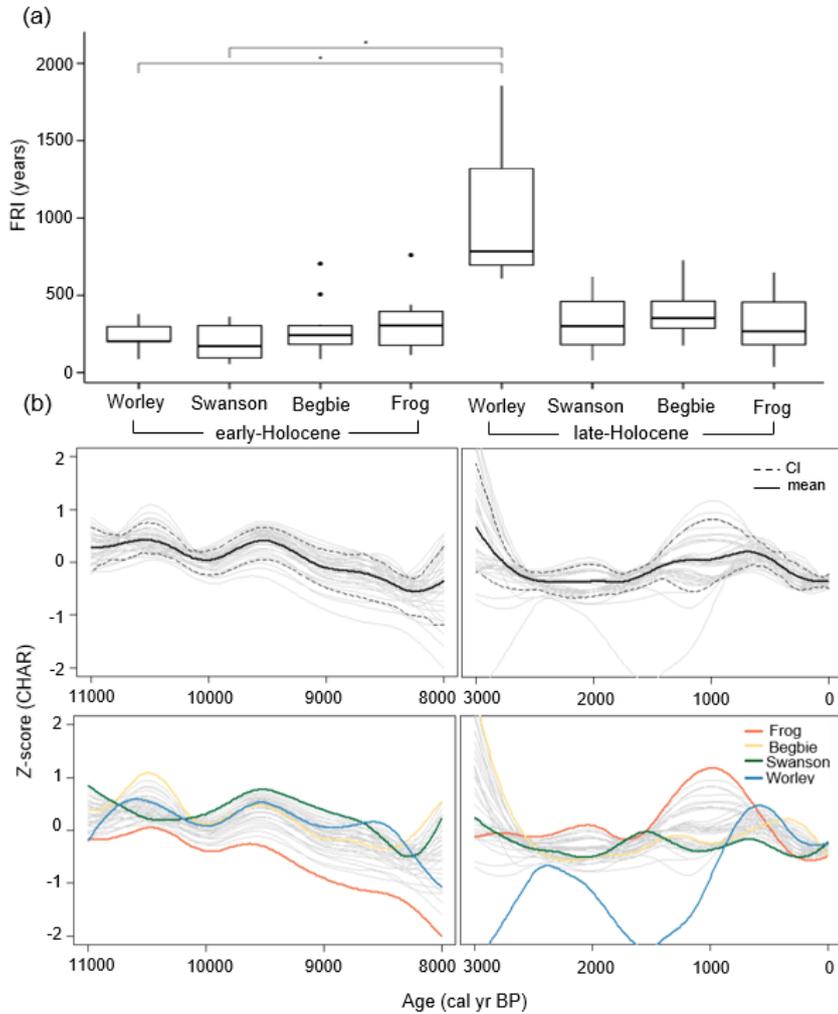
Figure 7: Comparison of FRI and biomass-burning. (a) FRI box and whisker plots comparing sites. Boxes represent the first Q1 and third Q3 quartiles, black line shows the median, whiskers are minimum and maximum range and black dots are outliers. Top

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545 black bracket and asterisks shows results of Wilcoxon signed rank test on paired samples ( $W=0$ ,  $p$ .adjusted=0.04,  $r=0.68$ ). Top red bracket and asterisks denotes results of Dunn's pairwise comparison ( $Z=3.35$ ,  $p$ .adjusted (Bonferroni)= 0.022). (b) Standardized charcoal influx ( $Z$  scores) showing biomass burning based on a regression of presampled and binned records at 20 year time step and 500 year half width smoothing. Bootstrapped confidence intervals (CI) and mean from 5000 resampled iterations. Coloured curves present local fits for each site.

550 The drier and warmer climate in the early-Holocene corresponds with shorter FRIs (more frequent fire) and higher rates of biomass burning across all sites. However, as climate cooled and moistened in the late-Holocene a significant shift in fire regime occurs, with FRIs lengthening at Worley Lake. The Kruskal-Wallis test ( $H=16$ ,  $p=0.025$ ) compares FRI length between all sites and confirmed that they differ temporally or spatially. Subsequent Wilcoxon test ( $W=0$ ,  $p$ .adjusted=0.04,  $r=0.68$ ) on paired dependent samples (comparing early and late-Holocene FRIs at same sites) further demonstrate that FRIs change significantly at Worley Lake, but not at other sites. A Dunn's pairwise comparison ( $Z=3.35$ ,  $p$ .adjusted [Bonferroni]= 0.022) of all independent groups (i.e. excluding comparisons between early- and late-Holocene FRIs from the same site) shows notable differences in FRIs between Worley Lake in the late-Holocene and Swanson Lake in the early-Holocene but it did not detect differences between other pairings (Fig. 8a). Overall, rates of biomass burning, (evaluated from transformed and binned

555  $Z$ -scores of charcoal influx), are relatively synchronous during the early-Holocene. This is based on agreement between site-specific locally regressed curves (coloured lines; Fig. 8b) and the narrower boot-strapped confidence intervals (Blarquez *et al.*, 2014). Charcoal influx is highest between ca. 9500-11,000 cal yr BP, decreasing thereafter (Fig. 8b). The late-Holocene shows greater variability as site curves diverge, confidence intervals widen, and charcoal influx at Worley Lake slows.



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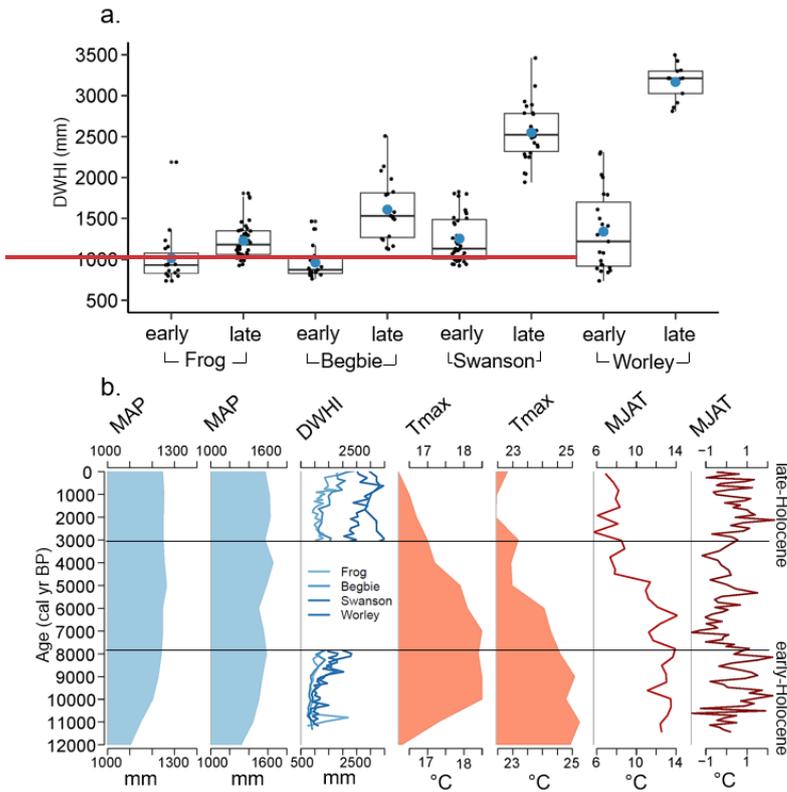
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560 **Figure 8: Comparison of fire return intervals (FRI) and biomass burning. (a) FRI box and whisker plots comparing sites. Boxes represent the first and third quartiles, black line shows the median, whiskers are minimum and maximum range and black dots are outliers. Top black bracket and asterisks shows results of Wilcoxon signed rank test on paired samples ( $W=0$ ,  $p_{\text{adjusted}}=0.04$ ,  $r=0.68$ ) and results of Dunn's pairwise comparison ( $Z=3.35$ ,  $p_{\text{adjusted (Bonferroni)}}=0.022$ ).** (b) Standardized charcoal influx (Z-scores) showing biomass burning based on a regression of presampled and binned records at 20-year time step and 500-year half

565 width smoothing. Bootstrapped confidence intervals (CI) and mean from 5000 resampled iterations. Coloured curves present local fits for each site.

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570 **Figure 8: Regional climate reconstruction for the Holocene. (a) Boxplots for Douglas-fir—western hemlock index estimates of mean**  
**annual precipitation MAP (DWHI). Blue dots are means. (b) From left to right: MAP (BIO12) from PALEO-PGEM series (Baretto**  
***et al.*, 2023), MAP (BIO12) from HadCM3 (Beyer *et al.*, 2020), down core DWHI precipitation estimates for each site, mean maximum**  
**monthly temperature (Tmax) in degrees Celsius from PALEO-PGEM series (Baretto *et al.*, 2023), Tmax from HadCM3 (Beyer**  
***et al.*, 2020), chironomid-inferred mean July air temperature (MJAT) (Pelatt *et al.*, 2000), and chironomid-inferred (MJAT) anomalies**  
**(Lemmen and Lacourse, 2018).**

575

## 4 Discussion

The pollen and charcoal records examined in this study indicate that climate-driven expansion of Coastal Douglas-fir (CDF)-like temperate forests occurred during the warm-dry early-Holocene, extending westward within the GVWSA and supporting an active fire regime characterized by both surface and crown fires (Gavin *et al.*, 2003a; Giuliano and Lacourse, 2023; Brown *et al.*, 2019, 2022; Hebda *et al.*, 2024). In contrast, moistening and cooling in the late-Holocene corresponds with the establishment of modern moist Coastal Western Hemlock (CWH) forests, which experience less frequent mixed-severity fire. Notably, this early- to late-Holocene transition is most pronounced around western Worley Lake, where CDF-like forest with frequent fire was replaced by CWHmm forest with much longer fire return intervals. This change emphasizes that western regions are particularly sensitive to future changes in forest composition and disturbance, creating potential challenges for water security.

### 4.1 Early-Holocene cClimate, vVegetation, and fFire

Climate reconstructions for western North America indicate that the early-Holocene was characterized by a warm-dry climate with greater seasonality and intensified summer drought (Mathewes and Heusser, 1981; COHMAP, 1988; Hebda, 1995; Rosenberg *et al.*, 2004; Brown *et al.*, 2006), with maximum temperatures occurring around ca. 9000 - 10,500 cal yr BP (Walker and Mathewes, 1987; Pellatt *et al.*, 2000; Lemmen and Lacourse, 2018; Beyer *et al.*, 2020; Brown *et al.*, 2022; Baretto *et al.*, 2023; Fig. 7b). On Vancouver Island, where a steep precipitation gradient exists today, reconstructed MAP similarly indicates that widespread dry conditions (i.e. MAP generally <1500 mm) prevailed in the GVWSA at this time (Brown *et al.*, 2019) together with longer fire seasons (Brown *et al.*, 2025). For perspective, these values are comparable to the driest sites on Vancouver Island in the modern CDF subzone (Meidinger and Pojar, 1991; Wong *et al.*, 2004; Fig. 1b, c; Fig. 7a).

Consistent with this warm dry climate, open xeric forests prevailed across the GVWSA (Figs. 3a, 4a, 5a, 6a), extending >100 km west of their present distribution (Brown and Hebda, 2002a). These forests were dominated by *P. menziesii*, a shade intolerant, thick-bark species adapted to frequent low- to moderate-severity fires (Agee, 1993; Wirth, 2005). Except for *Pinus*, other coniferous taxa were generally scarce until after ca. 9000 cal yr BP, when *Picea*, *Abies*, *T. heterophylla* and *Cupressaceae* gradually increased in abundance. Crucially, early-successional taxa, such as *Pinus* (most likely *Pinus contorta*), *Alnus*, *Salix*, and *Poaceae*, were also widely abundant, suggesting regular disturbances that favoured pioneering species with high rates of dispersal, germination, and/or re-sprouting (Agee, 1993; Wirth, 2005). Fire-promoting *Pteridium*, whose deep rhizomes enable it to endure disturbance, also prevailed at this time (Crane, 1990).

Charcoal records indicate that fires were more frequent at all sites across the GVWSA in comparison to the late-Holocene (Fig. 8a), with no clear east-west differentiation in fire return intervals. Lower peak magnitudes at Frog and Swanson lakes could suggest smaller or lower severity fires, whereas higher peak magnitudes at Begbie and Worley lakes, occasionally with

**Commented [RH41]:** From Referee #1: Although the data in this section is comprehensive, the main arguments and their implications could be presented more strongly and clearly. The manuscript would benefit from explicitly stating the central finding at the very beginning of the Discussion section, immediately providing context for the reader.

Additionally, in Sections 4.1 and 4.2, the key conclusions for each period should be clearly summarized at the start of each section. This would make the main points more obvious and easier to understand rather than requiring the reader to piece them together from the detailed evidence that follows.

**Commented [RH42R41]:** Response: We thank the reviewer for this suggestion and have added a statement in the first paragraph describing the profound change around Worley Lake in the western GVWSA. However, regarding sections 4.1 and 4.2, we feel that the new information included in the first paragraph in the discussion appropriately summarizes these sections too. Thus, to avoid repetition, we opt not to add similar sentences at the beginning of these sections.

**Commented [RH43]:** From Referee #1: The discussion provides a robust analysis, but its impact could be improved by combining ideas to enhance clarity and rhetorical strength. Currently, the site-by-site vegetation descriptions, while detailed, may overwhelm the reader. An integrated approach that clearly highlights the strong west gradient in vegetation openness would be more effective. The concept of synthesis also applies to the fire regime conclusions. The key finding that an east-west gradient was not evident in the early Holocene but became more pronounced later should be emphasized more prominently. Lastly, the various drivers proposed for late-Holocene fire variability represent a key complexity. Their influence would be stronger if organized into a single, focused paragraph that explores how these factors interacted as the dominant influence of a uniformly warm and dry climate started to weaken.

**Commented [RH44R43]:** Response: We have modified the text to reduce the site-by-site comparisons, instead emphasizing trends and drivers. For example, instead of referring explicitly to changes at sites or attempting to compare nuances between sites (these details are now included in the results), we discuss how temporal and spatial climatic variation influenced fire regime overall, highlighting the key differences between more open and drier eastern forests versus moister western forests. We note, however, that the new text spans several paragraphs, detailing characteristics of climate, vegetation, and fire disturbance.

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610 coinciding magnetic susceptibility peaks, indicate larger and/or higher severity fires (Rummery *et al.*, 1981; Gedye *et al.*, 2000; Dunnette *et al.*, 2014; Figs. 3b, 4b, 5b, 6b). Charcoal morphotypes further show that graminoid-to-woody charcoal influx ratios were higher at all sites, suggesting that both surface and crown fires were burning, with the former possibly in open, dry, and/or exposed areas. Transformed and amalgamated total charcoal influx reveal that biomass burning was synchronous and widespread at this time, peaking around ca. 10,500 cal yr BP, coincidental with the regional thermal maximum (Mathewes and Heusser, 1981; Walker and Pellatt, 2003; Brown *et al.*, 2022; Fig. 7b). An overall reduction in charcoal influx around 8200 cal yr BP could be related to northern hemisphere cooling (Alley *et al.*, 1997; Barber *et al.*, 1999).

615 In the early Holocene, climate reconstructions for western North America identify a warm-dry period with greater seasonality and augmented summer drought due to increased summer insolation (Mathewes and Heusser, 1981; COHMAP, 1988; Hebda, 1995; Rosenberg *et al.*, 2004; Brown *et al.*, 2006). Multi-proxy paleoclimate data from sites in BC and spatially-downscaled global climate series simulations suggest that regional temperature peaked around ca. 9000–10,500 cal yr BP (Walker and Mathewes, 1987; Pellatt *et al.*, 2000; Lemmen and Lacourse, 2018; Beyer *et al.*, 2020; Brown *et al.*, 2022; Baretto *et al.*, 2023; Fig. 8b). Pollen-derived DWHI values from the lakes within the GVWSA similarly suggest widespread dry conditions during 620 the early Holocene (Brown *et al.*, 2019), with MAP <1500 mm. For perspective, these conditions are consistent with the driest sites in the region today and in the range of the modern and relatively dry Coastal Douglas-fir (CDF) zone (Meidinger and Pojar, 1991; Wong *et al.*, 2004; Fig. 1b, c; Fig. 8a).

In response to a warming climate in the early Holocene, open, xeric forests largely prevailed across the GVWSA, with NAP averaging 10–20% amongst sites (Figs. 3a, 4a, 5a, 6a). Overall, the canopy was dominated by shade-intolerant, thick-barked, 625 *P. menziesii*, a fire-resister that can survive frequent low-to-moderate-severity fires (Agee, 1993; Wirth, 2005). Except for *Pinus*, other coniferous taxa were scarce in the area until after ca. 9000 cal yr BP, when *Picea*, *Abies*, *T. heterophylla* and *Cupressaceae* gradually increased in abundance. Post-fire invaders, such as *Pinus* (most likely *Pinus contorta*), *Alnus*, *Salix*, and *Poaceae* are also abundant, suggesting regular disturbances that favoured pioneering species with high rates of dispersal, germination, and/or re-sprouting (Agee, 1993; Wirth, 2005). *Pteridium*, a fire-promoting species whose deep rhizomes enable it to endure disturbance, is also pervasive in the early Holocene (Crane, 1990). 630

At Frog Lake, in the driest eastern regions of the GVWSA, *Poaceae* pollen peaks at 6%, possibly reflecting the presence of woodland-like communities or a patchwork of meadows in a forested system (Allen *et al.*, 1999). Open woodland and shrubland consisting of *Salix*, *Rosaceae*, and *Apicaceae* thrived and were probably common (Fig. 3a). *Artemisia* also appears at this time, along with diagnostic amounts of *Selaginella* that are indicative of open rocky bluffs, likely prevailing on 635 southwestern aspects above and below the study site (Allen, 1999; Fig. 1g). Begbie Lake is mostly characterized by its surrounding high proportion of *P. menziesii*, which peaked at ca. 9500 cal yr BP. *Poaceae* and *Rosaceae* appear in lesser amounts than at Frog, but their presence, along with a strong signal for *Pteridium* support the theory that open forests with well-developed understories occupied eastern areas (Brown *et al.*, 2019; Fig. 4a). The incursion of *Cyperaceae* at the site near

the top of the interval could indicate the beginning of regional moistening and resultant wetland development, which currently characterises the low-lying terrain around Begbie.

In the west, *Pinus* dominates at Swanson Lake in the early Holocene, an indication that vegetation on the exposed ridge was frequently disturbed (Fig. 5a). Distinguishing quantities of *Plantaginaceae* pollen (believed to be *Penstemon* spp.) in the early-Holocene reflect dry rocky outcrops around the site (Douglas *et al.*, 1999). Worley Lake is characterised by an increase in *P. menziesii* at ca. 10,000 cal yr BP, along with abundant *Alnus* and perceptible *Rosaceae* and *Poaceae* (Fig. 6a). *T. heterophylla* increases sharply after ca. 9000 cal yr BP, signaling that climate-driven changes in forest composition and structure may have been occurring earlier in the western part of the study region. Both Swanson and Worley Lakes had otherwise underdeveloped shrub and herbaceous layers, implying that these western forests were less open than contemporaneous eastern forests. Even so, high relative proportions of *P. menziesii*, *Poaceae*, *Rosaceae*, and *Pteridium* do not indicate a closed canopy at either site (Fig. 5a, 6a). Other pollen records from southern Vancouver Island establish that CDF-like forests in the early Holocene could have extended 100 km west of the zone's current range (Brown and Hebda, 2002a), with the strong presence of *P. menziesii* at Swanson and Worley helping verify the timing and extent of that expansion.

Regarding early-Holocene fire disturbance, median SNI exceeded the acceptable threshold ( $>3$ ; Kelly *et al.*, 2011) at all sites, demonstrating that the records were suitable for peak detection. At Swanson Lake, however, median SNI (3.2) was slightly lower compared to the other sites despite comparable sediment accumulation rates and good sampling resolution. Noting that Swanson is the shallowest of the lakes studied, it is posited that it experienced more charcoal mixing, though not enough to entirely impede peak detection. The charcoal records reveal that fires were indeed more frequent at all sites across the water supply area when compared to the late-Holocene interval, with mean early-Holocene FRIs ranging from 195–315 years (Fig. 7a). Critically, an east-west delimitation of fire regimes is not evident in the early-Holocene. Lower peak magnitudes at Frog and Swanson lakes compared to Begbie and Worley lakes suggests that less-severe events characterised the former locations, which share similar site characteristics including exposed locations and rocky outcroppings. The peak magnitudes at Begbie and Worley lakes demonstrate that large or high-severity fires occurred where fuels were available. Based on charcoal morphotype distinctions, the proportion of graminoid to woody charcoal influx was higher at all sites in the early-Holocene, with Frog and Swanson capturing slightly higher ratios of graminoid burning (Table 3). This implies that both surface and crown fires were occurring with surface fires potentially more frequent at open, dry, and/or exposed sites. Indeed, several charcoal-magnetic peaks coincide with charcoal peaks, indicating the presence of high-severity fires (Rummery *et al.*, 1981; Gedye *et al.*, 2000; Dunnette *et al.*, 2014; Figs. 3b, 4b, 5b, 6b).

**Table 3. Fuel Morphotype Index (FMI) for sites in the GVWSA. Values closer to 1.0 indicate higher rates of wood combustion. Begbie Lake not included as morphotypes were not analysed at the time the core was sampled.**

	Frog Lake	Swanson Lake	Worley Lake
FMI-early-Holocene	0.72	0.65	0.75

FMH late-Holocene 0.82 0.87 0.84

670 Transformed and amalgamated total charcoals from each site shows that overall biomass burning was synchronous and widespread in the early-Holocene. The highest rates of charcoals occurred around ca. 10,500 cal-yr BP, coinciding with the regional thermal maximum, and decreased steadily after ca. 9500 cal-yr BP (Mathewes and Heusser, 1981; Walker and Pellatt, 2003; Fig. 7b), with a overall reduction at 8200 cal-yr BP that could be related to northern hemisphere cooling (Alley *et al.*, 1997; Barber *et al.*, 1999). In the driest area, around Frog Lake, lower rates of charcoals could reflect a moderately fuel-constrained landscape (Fig. 7b). Overall, the pollen and charcoals records reveal that CDF-like temperate forests expanded westward in the GVWSA during the warm-dry early-Holocene, supporting an active fire regime with surface and crown disturbance (Gavin *et al.*, 2003a; Giuliano and Lacourse, 2023; Brown *et al.*, 2019, 2022; Hebda *et al.*, 2024).

#### 4.2 Change in Late-Holocene Climate and Shifting Fire Regime

680 Regional cooling and moistening occurred after 6000 cal BP, leading to the steep precipitation gradient that characterizes the coastal rainforest complex today, including the GVWSA (COHMAP, 1988; Hebda, 1995; Brown *et al.*, 2006; Rosenberg *et al.*, 2004). These changes were driven by decreasing solar activity and changes in atmospheric pressure systems and oceanic currents (Wanner *et al.*, 2008; Marlon *et al.*, 2012). Regional temperature reconstructions show that mean July temperatures were lower in the late-Holocene compared to preceding millennia (Mathewes and Heusser, 1981; Pellatt *et al.*, 2000; Beyer, 2020; Baretto *et al.*, 2023; Fig. 7b). Regarding precipitation, reconstructed MAP<sub>DWHJ</sub> remained relatively stable at eastern Frog Lake, though a marked early-to-late Holocene shift is evident at western Worley Lake, where precipitation increased from ca. 1340 to >3000 mm (Fig. 7a).

690 These climatic changes had a marked effect on vegetation composition and distribution. Arboreal pollen increased at all sites as *T. heterophylla* and Cupressaceae (*T. plicata* and *C. nootkatensis*) expanded regionally (Fig. 3a, 4a, 5a, 6a). These shade-tolerant, late-successional fire avoiders are poorly adapted to fire disturbance, as are *Picea* (likely *Picea stichensis*) and *Abies* (likely *Abies amabilis*), which likewise increased in abundance. Concurrently, plants classified as fire invaders decreased, suggesting that mixed-conifer late-seral closed forests with infrequent disturbance developed across much of the GVWSA, excluding eastern forests where *P. menziesii* remained a key species.

695 Fire is less frequent in the GVWSA during the late-Holocene compared to the early-Holocene (Fig. 8a). Isolated events with larger peak magnitudes and increases in magnetic susceptibility, together with increases in woody charcoal morphotypes, punctuate records, and demonstrate the potential for higher severity, larger, and/or localized events that likely initiated crown involvement or consumed coarser fuels (Fig. 3b, 6b). Further, the increase in magnetics in recent centuries likely reflects human expansion, logging, and reservoir development (Wu *et al.*, 2015; Magiera *et al.*, 2019; Trofymow *et al.*, 2025; Figs. 3b, 4b, 5b, 6b). In general, transformed charcoal influx show that biomass burning in the GVWSA was more variable in the late-

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700 Holocene compared to the early-Holocene (Fig. 8b). While periods of synchronous biomass burning occurred, asynchrony also emerged. Although there appears to be an overall decrease in charcoal influx in the GVWSA during the late-Holocene, some records indicate that increases did occur as climate cooled and moistened, consistent with other regional records (Brown and Hebda, 2002b; Hallett *et al.*, 2003). On the adjacent mainland, Hallett *et al.*, (2003) reveal elevated fire activity from ca. 1500 - 2500 cal yr BP, referring to it as the Fraser Valley Fire Period. In the GVWSA, coincident increases in burning around 1000 cal yr BP may better align with the Medieval Climate Anomaly (ca. 750-1250 cal yr BP). However, past human activity has also been proposed to explain the trend (Brown and Hebda, 2002b; Gavin *et al.*, 2007; Walsh *et al.*, 2015).

705 Within the late-Holocene ecoclimatic framework, it is noted that *Quercus garryana* emerged as a minor forest constituent between 2000-3000 cal BP, especially in drier eastern areas (Figs. 3a, 4a, 5a, 6a). In these drier forests, this was accompanied by an increase in Caprifoliaceae, possibly *Lonicera hispidula*, an understory plant sometimes associated with oak (Pojar *et al.*, 1994; Fairbarns, 2023). *Quercus garryana* is a fire enduring species capable of re-sprouting from lateral roots or forming new crowns after fire (Agee, 1996). While it reached its maximum extent during the mid-Holocene (Pellatt *et al.*, 2001; Lucas and Lacourse, 2013), its subtle resurgence in the late-Holocene is less recognized (Allen, 1995; Brown *et al.*, 2019) and possibly linked to Indigenous land management activities (Pellatt and Gedalof, 2014; Pellatt *et al.*, 2015; Brown *et al.*, 2002b, 2019; Barlow *et al.*, 2021). An archaeological impact assessment within the GVWSA recovered artefacts of Marpole origin (Burley, 1980; Vincent *et al.*, 2002), a cultural period that dates to as early as 2350 yrs BP, overlapping with the *Quercus* signal in the sediment records, suggesting that the oak signal may be related to human activity.

720 Cooling, moistening, and the establishment of contemporary precipitation patterns on southern Vancouver Island occur after 6000 cal-yr BP (COHMAP, 1988; Hebda, 1995; Brown *et al.*, 2006; Rosenberg *et al.*, 2004). The decrease in temperature is variously related to decreasing solar activity from orbital forcing and changes in oceanic currents (Wanner *et al.*, 2008; Marlon *et al.*, 2012;). Regional temperature reconstructions show that the monthly mean maximum temperatures were declining in the late Holocene (Mathewes and Heusser, 1981; Pellatt *et al.*, 2000; Beyer, 2020; Baretto *et al.*, 2023; Fig. 8b), with substantial variability in MJAT anomalies (Lemmen and Lacourse, 2018). Regarding precipitation, a stronger east-west gradient characterised the GVWSA compared to the early Holocene. For example, while MAP did not change profoundly at eastern Frog Lake through time, a marked early-to-late Holocene shift is evident at western Worley Lake, with precipitation increasing from 1340 mm in the early-Holocene to >3000 mm in the late-Holocene (Fig. 8a).

725 The changes in climate had a noticeable effect on vegetation composition and distribution. Arboreal pollen increased in abundance across all sites as *T. heterophylla* and *Cupressaceae* (*T. plicata*) expanded throughout the region (Fig. 4a, 5a, 6a, 7a). Notably, both species are shade tolerant, late successional fire avoiders that are poorly adapted to fire disturbance. *Picea* (likely *Picea stichensis*) and *Abies* (likely *Abies amabilis*), also avoiders, likewise increased in abundance. Fire invaders decreased at all sites in the late Holocene, suggesting that mixed-conifer late-seral closed forests with infrequent disturbance developed across much of the GVWSA.

735 Despite these significant changes, fire-adapted *P. menziesii*, remained co-dominant at Frog and Begbie lakes in the east. At Frog Lake, a signal for *Poaceae* persisted even with the expansion of *T. plicata* and *T. heterophylla* (Fig. 3a). Along with sustained understory indicators such as *Roasaceae* and *Pteridium*, it is likely that eastern forests in the GVWSA maintained an open component. Between ca. 2000–3000 cal yr BP, *Caprifoliaceae* (possibly *Lonicera hispidula*) emerged at Frog Lake in the understory. *L. hispidula*, or pink honeysuckle, is typically found in mesic to dry forests where it is sometimes associated with oak (Pojar et al., 1994; Fairbarns, 2023). At Begbie Lake, a decrease in *Pteridium*, in conjunction with the emergence of *Lysichiton*, *Myrica*, and further persistence of *Cyperaceae* tracks expanding wetlands around the site due to increased moisture input (Brown et al., 2019; Fig. 4a).

740 *Quercus* (likely *Quercus garryana*) also emerged as a minor forest constituent around Frog and Begbie lakes (and to a lesser degree Swanson and Worley lakes) between ca. 2000–3000 cal yr BP (Fig. 3a, 4a, 5a, 6a). *Q. garryana* is classified as a fire endurer with the ability to re-sprout from lateral roots or grow new crowns after fire (Agee, 1996). Its expansion during the mid-Holocene is well documented from sites on east Vancouver Island (Pellatt et al., 2001; Lucas and Lacourse, 2013), whereas the late-Holocene persistence of *Q. garryana* in interior island forests is less recognized (Allen, 1995; Brown et al., 2019). Together with the species' response to fire, it has been linked to Indigenous land management in the region (Pellatt and Gedalof, 2014; Pellatt et al., 2015; Brown et al., 2002b, 2019; Barlow et al., 2021). An archaeological impact assessment for the CRD at the Sooke Lake Reservoir found artefacts of Marpole origin, a cultural period that dates to as early as 2350 yrs BP and overlaps with the *Q. garryana* signal in the watershed (Burley, 1980; Vincent et al., 2002), suggesting that the oak signal may be related to human activity in the eastern sector of the GVWSA at that time.

750 In the west, *Pinus* and *Alnus* remained dominant at Swanson Lake reflecting the sites' continued exposure to disturbance. *T. heterophylla* increases steadily through the interval along with *Picea* and *Abies* while *P. menziesii* remains a constant. Traceable amounts of *Ericaceae* (*Vaccinium* spp.) pollen appear after ca. 2000 cal yr BP (Fig. 5a). Most herbaceous taxa fade from the record. At Worley Lake, a substantial decrease in *P. menziesii* coincides with increases in *T. heterophylla*, *Picea*, *Abies*, and *Cupressaceae* (Figs. 5a, 6a).

760 Regarding late-Holocene fire disturbance, a marked decrease in SNI occurred across all sites, with values hovering around three at most sites. It is possible that this decrease is related to local wetland expansion intercepting overland charcoal inputs (Agee, 1993; Higuera et al., 2007; Kelly et al., 2011). The SNI at Swanson Lake is of greatest concern since it is generally below the threshold for suitable peak detection (Fig. 5b). However, the preponderance of fire-invading *Pinus* around Swanson Lake suggests that fires did indeed continue to burn around the site, with the emergent estimates of FRIs consistent with those from Begbie and Frog lakes. Thus, while cautious interpretation of the late-Holocene fire record is warranted for Swanson Lake, it is presumed that the results generally reflect the fire regime.

Overall, fire is less frequent in the GVWSA during the late-Holocene compared to the early-Holocene. Mean FRIs range from 311–1082 years, reflecting slightly longer times between fires (Fig. 7a). While fire severity varies between sites, all basins record a period when fires were likely small and/or of low severity between ca. 1500 and 3000 cal yr BP, as evidenced by generally low peak magnitudes and magnetic susceptibilities. A marked increase in magnetics occurs at the top of all records, likely tracking human expansion and logging development (Wu *et al.*, 2015; Magiera *et al.*, 2019; Figs. 3b, 4b, 5b, 6b). Additionally, larger peak magnitudes, coinciding with increases in magnetic susceptibility, are noted at Frog Lake after 1500 cal yr BP and at Worley Lake at 700 cal yr BP. Elevated inputs of woody charcoal morphotypes correspond with these events, implying that these fires were of higher severity and likely initiated crown involvement or consumed coarser fuels (Fig. 3b, 6b). Likewise, the *FMI* showed increases in the combustion of woody materials at all sites in the late-Holocene (Table 3).

In general, transformed charcoal influx showed that biomass burning exhibited greater variability across the water supply in the late-Holocene compared to the early-Holocene (Fig. 7b). While periods of synchronous biomass burning occurred, asynchrony also emerged. For example, at Worley Lake, charcoal influx was much lower compared to the other sites and fluctuated considerably through time, possibly tracking background charcoal as climate became wetter and more variable. As canopy closed at the site, it likely intercepted precipitation reducing residual charcoal influx in the absence of local fires. Although there appears to be an overall decrease in charcoal influx in the GVWSA during the late-Holocene, curves show that some increases did occur as climate cooled and moistened. These trends have been identified in other regional records (Brown and Hebda, 2002b; Hallett *et al.*, 2003), with several causal mechanisms proposed to explain the pattern. For example, while open forests largely prevailed in the early-Holocene, denser forests with elevated fuel loads expanded in the late-Holocene, potentially contributing to a contrasting mosaic of stand-replacing events (Gavin *et al.*, 2007). Increased lightning with greater climatic variability could also promote fires given higher ignition probability during periods of seasonal drought. On the adjacent mainland, Hallett *et al.*, (2003) reveal elevated fire activity from ca. 1500–2500 cal yr BP, referring to it as the Fraser Valley Fire Period. In the GVWSA, coincident increases in burning around 1000 cal yr BP may better align with the Medieval Climate Anomaly (ca. 750–1250 cal yr BP). Lastly, the possible escalation of human activity has been proposed along with cultural uses of fire (Brown and Hebda, 2002b; Gavin *et al.*, 2007; Walsh *et al.*, 2015). Findings from both the pollen and charcoal records in the late-Holocene correspond well with the establishment of modern moist CWH forests, which experience less frequent but mixed-severity fire. These fire regimes are complex and sometimes drivers of disturbance are not clear, but they can be characterised by periods of fire absence that often leads to larger stand-replacing events (Agee, 1995; Brown *et al.*, 2002a; Gavin *et al.*, 2007; Brown *et al.*, 2019).

### 4.3 Informing Future Fire Regime Change in Temperate Forest

The potential for past trends to reflect future changes in climate, vegetation, and fire is conceivable given that palaeoecological interpretations and predictive models are in good agreement. For example, the substantial changes in fire disturbance that occur at Worley Lake demonstrate the extent of shifting fire regimes in the past, providing first-order insights into possible future

**Commented [RH45]:** From Referee #1: The analysis in section 4.3 can be enhanced by highlighting key insights. First, for the dry eastern sites, the main finding suggests that past and future changes are more influenced by shifts in fire severity and fuel connectivity than fire frequency. The paleodata show these sites have always experienced fire, hinting at a possible future with more frequent, lower-severity fires, but with a notable risk of high-severity events during climatic transitions, as evidenced by the period 500–1500 BP. Second, the moist western sites are most at risk of a complete regime shift. The record from Worley Lake acts as a key analogy showing it was once as fire-prone as the eastern sites are today; this emphasizes that no part of this landscape is immune to major changes, which is important for management strategies. Lastly, the influence of humans, from Indigenous burning to current suppression efforts, must be considered. Briefly explaining how human impacts interact with the climate-driven baseline will lead to a more complete and practical conclusion.

**Commented [RH46R45]:** Response: We agree with this point and are modifying this section, highlighting findings for dry eastern areas as well as wetter western areas. Regarding Indigenous burning, we present some evidence that is tantalizing to interpret as being related to human burning. At the same time, we recognize that there is some debate about climate vs human fire signal in the region, and stress that the drivers of the slight resurgence in oak is not definitively established here. In fact, an important aspect of this work is that it documents a subtle regional increase in oak that has not previously been described or discussed.

conditions (Figs. 6b, 8a). Early-to-late Holocene differences in DWHI establish a historical precedent for a return to a much drier climate (Fig. 7a). While forecasting precipitation is complicated by seasonal variability and low confidence (Bush and Lemmen, 2019), predictions for the region suggest overall increases in annual precipitation, coupled with worsening summer drought. ~~Further, c~~Coastal regions could potentially see a 23% (-48 to -5%) reduction in summer precipitation in a high-emissions scenario (SSP5-8.5) compared to baseline (Bush and Lemmen, 2019; PCIC, 2024). Mean annual temperature in British Columbia is projected to increase by 1.6 (1.1, 2.1) – 5.2 (4.3, 6.5) °C by the end of the century, depending on the emissions scenario (RCP2.6, RCP8.5) and region, with the coast experiencing the least amount of warming (Bush and Lemmen, 2019; PCIC, 2024). These changes are in line with the estimates of past mean monthly maximum temperature fluctuations (2 – 5 °C) during the early-Holocene but are projected to occur on a much shorter time span.

Forest change simulations ~~likewise~~ align well with observations of past vegetation change. For example, the increase in *P. menziesii* that previously occurred ~~in the western GVWSA at Worley Lake~~ in the early-Holocene may recur in the future based on models examining climate niche envelopes (Wang *et al.*, 2012). ~~The likelihood of these predictions is reinforced by the pollen record, which establishes the existence of a past *P. menziesii* dominated forest at a site that is currently well situated in CWHmm (Figs. 1b, 6a).~~ Although Wang *et al.*, (2012) found that the area suitable for *P. menziesii* could double by the end of the century, CDF forest is only expected to expand with a net gain that reflects a 20% increase in its currently restricted range (0.2 million ha). ~~A~~The more nuanced interpretation is *P. menziesii* increases will be affiliated with the likely expansion of drier CWHxm as it displaces Vancouver Island interior and western rainforest. Increased disturbance and preferential reforestation with climate adapted species will also favor future expansion of *P. menziesii* (Uchytil, 1991).

With respect to fire disturbance, the paleofire reconstruction similarly favours model forecasts, ~~with, c~~Current trends ~~supporting suggest the notion~~ that wildfire disturbance is increasing in the region (Hanes *et al.*, 2019; Parisien *et al.*, 2023). ~~While this study reveals Characterization of the early-Holocene fire regime in this study proposes~~ that fire increased regionally in the past (Pellatt *et al.*, 2001; Lucas and Lacourse, 2013; Cwynar, 1987; Allen, 1995; Brown and Hebda, 2002a; Fig. 6c). ~~At Frog Lake, the most xeric site, FRI's actually change little in eastern xeric areas through time, between the early and late-Holocene despite the former being warmer and drier (Fig. 7a). Given the similarities in FRIs between the early and late-Holocene, the with lower charcoal-peak magnitudes and charcoal morphotypes flux may indicate~~ that the fire mosaic was ~~somewhat generally~~ less severe in the early-Holocene, ~~possibly likely in response due~~ to reduced fuel loading. ~~Thus, for dry eastern areas, it is suggested that past and future changes are likely to be governed more by shifts in fire severity and fuel connectivity than frequency. The fire reconstruction shows that the eastern GVWSA has experienced fire throughout the Holocene, implying that the future may be characterized by more frequent, lower-severity events. Further, smaller peak magnitude, in conjunction with forests dominated by *P. menziesii*, exemplifies a fire-resistant type of community. During the late-Holocene, a period of similar fire regime characteristics prevails at the site until ca. 2000 cal-yr BP. Archaeological evidence and oral histories cite hunting as one of the likely cultural uses for the area around the Sooke reservoir (Eldridge and~~

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825 Seip, 2002). Along with the presence of *Q. garryana* during the late-Holocene at Frog and Begbie Lakes, it is feasible that  
fire was used to maintain eastern forests for that purpose. Given these interpretations, a future fire regime under a warmer,  
drier climate might look like one that supports frequent low-severity fires in the eastern regions of the GVWSA as fuel loads  
become lighter. However, paleofire reconstructions also show that larger magnitude events are possible in the interim, as  
830 observed at Frog Lake between ca. 500–1500 cal yr BP. During the 2024 wildfire season, the Old Man Lake fire burned 230  
ha just 5 km south of the Sooke Reservoir and 8 km west of Frog Lake within CWHxm. Human causes were suspected,  
although it was above average July temperatures and persistent drought conditions on the coast that subsequently elevated fire  
danger ratings and led to the fires' spread.

In contrast to present-day, moister western regions in the GVWSA were previously as fire-prone as the eastern sites are today,  
revealing the potential for a future marked change in fire regime. Paleofire reconstructions reveal that western GVWSA was  
835 characterized by large-magnitude events and higher charcoal influx during the early-Holocene, suggesting greater past fire  
activity compared to present (Figs. 6b, 8a, b). Similarly, simulations of future fire regimes for coastal temperate forests in the  
Pacific Northwest region of North America show that the largest projected increases in burn probability, fire size, and fire  
frequency, could occur in the coolest, wettest, and most northern areas (Dye *et al.*, 2023), like the western GVWSA.

The role of humans in modifying fire regime, including Indigenous burning and more recent activities such as forest clearance,  
840 reservoir development, and modern fire suppression must also be acknowledged. Archaeological evidence and oral histories  
suggest cultural burning in central and eastern GVWSA (Eldridge and Seip, 2002), consistent with the presence of *Q. garryana*.  
Such use likely maintained open forests for hunting and resource access. Understanding how human activity interacts with  
climate-driven baselines will provide a more complete and practical understanding of future fire regimes. As shown by the  
845 2024 Old Man Lake fire, which burned near the study location, anthropogenic ignitions under suitable fire weather conditions  
can trigger rapid fire spread. The convergence of cultural, climatic, and ecological drivers suggests that both eastern and  
western portions of the GVWSA are entering a period of heightened vulnerability, where adaptive management and fire-  
informed restoration strategies will be critical.

Swanson similarly experienced high rates of fire disturbance in the past, but comparison of FRIs is complicated by the low  
SNI during the late-Holocene. Swanson Lake is located on a ridge that has been identified as an area of high to extreme  
850 wildfire risk in recent models, driven in part by the probability of ignition from lightning (Perakis *et al.*, 2018; Perakis *et al.* in  
press). Two fires ignited from lightning near the study site during the 2020 season. These fires were kept small in size (5.9 and  
2.1 ha) due to aggressive suppression, though they illustrate the fire potential (Scott, 2020; BC Wildfire Service, 2024). The  
site's location and exposure to elevated ignition probability, could be a sustained driver of high-frequency, low-severity fires  
through both the early and late-Holocene intervals.

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Commented [RH47]: Line 470 – Did local indigenous nations use the mast [of Garry Oak] to make flour?

Commented [RH48R47]: Response: Good question. The association with local Indigenous nations and Garry oak is related to cultural management of forests in the area. Traditionally, fire maintained open oak savannas were used to promote important plant foods and game (Pellatt and Gedalo 2014; Pellat *et al.*, 2015). We are not aware of acorns being used for flour but we will reach out to local ethnobotanists to see if an association exists. Regarding Indigenous burning, we present some evidence that is tantalizing to interpret as being related to human burning. At the same time, we recognize that there is some debate about climate vs human fire signal in the region, so we stress that the drivers of the slight resurgence in oak is not definitively established here. In fact, the important aspect of this work is that it documents a subtle regional increase in oak that has not previously been described or discussed.

855 The significant difference in early- versus late-Holocene FRIs, coupled with changes in charcoal influx and the prevalence of high peak-magnitude events at Worley Lake during the early-Holocene, indicate that the site was previously more vulnerable to fire than it is today (Fig. 6b, 7a,b). Dye *et al.*, (2023) found that the largest magnitude of projected changes in burn probability, fire size, and number of fires corresponds with the coolest, wettest, and most northern areas in their simulations of future fire regimes for coastal temperate forests of the Pacific Northwest, reflecting settings similar to those around Worley Lake. The current vulnerability of the region to large stand-replacing events as fire regime transitions appears imminent and it is unlikely that cooler-moister forests in the west will be spared.

#### 4.4 Limitations

865 The decomposition of charcoal records in this study follows a widely used methodology for identifying past fire events (Higuera *et al.*, 2010). In using this approach, important factors to consider include quality of data, low-counts sections, variability in sedimentation rates, and sediment focusing processes. However, robust peak detection can typically be achieved if non-peak samples contain >10 charcoal fragments and peak samples  $\geq$ 20 fragments, coupled with the application of a locally defined threshold and minimum-count test, as was the case with the records analysed in this investigation. Given the numerous parameter choices involved (i.e., interpolation intervals, data transformations, background smoothing algorithms, window widths, and threshold criteria), it is also advised that the output be evaluated using sensitivity analyses to examine how the settings influence the number and timing of detected fire events. More recently, however, Anderson *et al.* (2023) highlighted key limitations of the method, including violations of the Poisson assumption for background charcoal and edge effects. Consequently, it was recommended that particle count totals should be in the hundreds and that charcoal records should be evaluated using smoothed influx rather than discrete events. Adding further to these perspectives, several charcoal peaks in the Begbie Lake core identified as fire events using the approach of Higuera *et al.* (2010) were subsequently subsampled at 2 mm resolution to determine if fire-impacts could be detected (Hebda, 2022; Hebda *et al.*, 2024). By combining high-resolution sampling with hierarchical clustering, the analysis was able to differentiate pre-fire, fire, and post-fire intervals, revealing changes in algal communities, inorganic sediment, ash-derived cations, metals (e.g., iron and chromium), and turbidity across charcoal peaks. Other studies similarly detected fire-related biogeochemical changes across charcoal peaks (Dunnette *et al.*, 2014; Clark-Wolf *et al.*, 2023), supporting the interpretation that the peaks identified do indeed correspond to fire events. Thus, while charcoal records provide valuable insights into past fire, further research is needed to resolve methodological uncertainties.

#### 5 Conclusion

Comparison of climate, vegetation, and fire at four sites along ecological and climate gradients in a BC coastal temperate forest, revealed a significant temporal shift in fire regime between the early- and late-Holocene intervals. The magnitude of

**Commented [RH49]:** Referee #2: Please add a paragraph criticizing your approach and outlining its uncertainties and limitations. Leslie Anderson's 2022 paper in Quat. Res. showing there are serious problems with using charcoal counts rather than particle numbers should be mentioned here. I am not recommending that you change your analysis from that of charcoal particle numbers to surface area but I am asking you to be upfront about this problem in the discussion.

**Commented [RH50R49]:** Response: The reviewer raises an important point regarding uncertainties and limitations in the approach. In response, we have added a paragraph to the manuscript addressing these issues, highlighting key considerations when using CharAnalysis and identifying factors that are necessary to robustly identify charcoal peaks. We contrast these with the limitations (e.g., violations of the Poisson assumption and edge effects) and recommendations made by Anderson *et al.* (2023). We then discuss studies that integrate multiple proxies to assess fire impacts across established charcoal peaks, seemingly capturing both terrestrial and aquatic post-fire signals that would suggest the peaks do indeed reflect fire events. We respectively conclude the paragraph by emphasizing that additional research is needed to resolve the methodological uncertainties.

**Commented [RH51]:** From Referee #1: While the distinction between top-down and bottom-up controls is an important and insightful part of the authors' conclusion, its current presentation could be more impactful. The argument would be clearer if you replaced the hesitant phrasing and vague reference to "intrinsic factors" with a more direct and explicit explanation. Specifically, the main finding is the feedback loop the authors observed: climate as the primary top-down driver of initial vegetation change, which then alters fuel structures in a bottom-up manner. This bottom-up change in fuels significantly modifies the fire regime itself, demonstrating a tightly coupled and dynamic system.

**Commented [RH52R51]:** Response: We agree with this assessment. The intrinsic drivers that emerge can best be qualified by the persistence of Douglas-fir in areas where the feedback between fire frequency and fire adapted vegetation likely support a lower severity disturbance regime. Our hesitations stem from well-meaning caution when interpreting fire regime characteristics, such as fire severity and/or fire size from the indirect charcoal-based fire reconstruction. We are improving our conclusion to explicitly state how extrinsic and intrinsic climate, vegetation, and fire interactions emerge in this tightly coupled system. Further, we have added a limitations section to the Discussion to underscore limits of our methods and interpretations.

885 change was most pronounced at the coolest and wettest end of the study area, suggesting that top-down climatic forcing was a  
 significant driver of fire in the past, even in wetter forests that are less prone to disturbance today. At the same time, the  
persistence of species like Douglas-fir, along with regular fire at drier eastern sites, suggests a tight feedback between climate  
and vegetation, demonstrating the potential for intrinsic drivers like fuel structure to influence fire regimes. As first-order  
 analogues, the records suggest that more fire will be present on the land in the future, a finding that is consistent with predictive  
 890 models that forecast increased fire associated with climate change and vegetation response (Wang *et al.*, 2012; Wang *et al.*,  
 2015, 2017; Sheehan *et al.*, 2015; Dye *et al.*, 2023). Yet, there appears to be an indication that on both ends of the gradients,  
intrinsic factors play an important role in fire regime variability; namely, feedback from vegetation response to climate and  
fire appears to exert bottom-up control over fire regimes due to changes in the structure of forests and fuels. In some cases,  
there is a coincidence of more open *P. menziesii* pollen assemblages with a charcoal record that insinuates periods of lower  
 895 fire-severity. Where late-seral closed forests emerge in the late-Holocene pollen sequence, stretches of fire absence in the  
charcoal record are punctuated by large or high-severity events.

These findings ~~have~~ differences have strong implications for management in a high-value water supply area. For instance, as  
 population grows and demand increases on southern Vancouver Island, the regional water purveyor (CRD) has purchased land  
 in a watershed (Leech; Fig. 1), west of the study area with plans to expand water supply (CRD, 2022). Contemporary  
 900 observations indicate that western areas have a moister climate and experience less fire, while the paleo history shows that  
 these forests are vulnerable to change. On-going activities are on-going to secure and protect this future source of water involve  
reforestation and rehabilitation of lands, wildfire protection, and forest fuel management. ~~the decision to suppress a wildfire~~  
~~is one that demands careful evaluation of costs (both financial and human life) and impacts (downstream effects of the~~  
~~disturbance, especially on water quality).~~ One consideration is that exclusion and suppression can result in negative  
 905 consequences for ecosystems (Hoffman *et al.*, 2019; 2021). For example, wildfires can provide valuable ecosystem services,  
such as pest regulation and nutrient cycling (DeLuca *et al.*, 2016; Pausas and Keeley, 2019). Although a consensus has not yet  
emerged, it is clear that under the right conditions, negative feedbacks from suppression can add to a build-up of fuels and  
alter fire regimes, leading to more impactful high-severity fires (Stephens *et al.*, 2014; Hai *et al.*, 2023). All this must be  
weighed against the overarching objective to protect an essential resource. ~~Indeed, by distinguishing showing~~ how changes in  
 910 past climate altered vegetation and fire regime, this study provides critical insight into the current and future susceptibility of  
 managed high-value watersheds to anthropogenic climate change impacts.

#### Data availability

Data are available on the Neotoma Database. DOI are still being processed.

**Commented [RH53]:** Referee #1: While the distinction between top-down and bottom-up controls is an important and insightful part of the authors' conclusion, its current presentation could be more impactful. The argument would be clearer if you replaced the less precise phrasing and vague reference to "intrinsic factors" with a more direct and explicit explanation. Specifically, the main finding is the feedback loop the authors observed: climate acts as the primary top-down driver of initial vegetation change, which then alters fuel structures in a bottom-up manner. This bottom-up change in fuel structure significantly modifies the fire regime itself, demonstrating a tightly coupled and dynamic system.

**Commented [RH54R53]:** Response: We agree with this assessment. The intrinsic drivers that emerge can best be qualified by the persistence of Douglas-fir in areas where the feedback between fire frequency and fire adapted vegetation likely support a lower severity disturbance regime. Our hesitations stem from well-meaning caution when interpreting fire regime characteristics, such as fire severity and/or fire size from the indirect charcoal-based fire reconstruction. We are improving our conclusion to explicitly state how extrinsic and intrinsic climate, vegetation, and fire interactions emerge in this tightly coupled system. Further, we have added a limitations section in the Discussion to underscore limits of our methods and interpretations.

**Commented [RH55]:** From Referee #1: The management implications are relevant but would be more compelling if linked more directly and authoritatively to your specific findings. The discussion of fire suppression, while important, currently feels somewhat disconnected from the paleodata just presented. To improve this, the authors could clearly frame the management implications through the lens of the two fire regime types they identified. This study offers essential long-term context for understanding what defines a climate-driven fire regime across various landscapes; the conclusion should emphasize this unique contribution to move beyond general statements and provide concrete, evidence-based guidance.

**Commented [RH56R55]:** Thank you for recognizing the valuable application of this paleoecological study in a management context, which goes beyond the foundational literature. To make our conclusion more compelling we are reframing management implications directly with the Capital Regional Districts master plan. To do this we suggest adding short sentence in the Study Site section that alludes to plans for water supply expansion into the western Leech watershed as population growth increases demand. In the Conclusion, we make the connection that these moister western forests, which have experienced little fire recently, will become more vulnerable to fire in the future. This knowledge is essential to water purveyors as they design and invest in future infrastructure.

**Author contributions**

915 CB, JAT, and KJB conceptualized the research. DRH, KJB, and CB conducted fieldwork and core collection. DRH and KJB completed magnetic susceptibility profile of sediment cores. DRH sampled cores, and processed charcoal. NC processed pollen. DRH completed pollen and charcoal identification and tabulation for Worley, Swanson, and Frog Lakes. NC completed pollen identification and tabulation for the Swanson record. DRH performed analysis and prepared figures. DRH and KJB wrote the paper with input from all authors.

**920 Competing interests**

The corresponding author has declared that none of the authors has any competing interests.

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**References**

- Agee, J. K.: Fire ecology of Pacific Northwest forests. Island press. Washington, DC. ISBN 1-55963-229-1,1993.
- Agee, J. K.: Alternatives for implementing fire policy. United States Department of Agriculture Forest Service General Technical Report Int, 107-112. 1995.
- 930
- Agee, J. K.: The influence of forest structure on fire behavior, in: Proceedings of the Seventeenth Annual Forest Vegetation Management Conference, Redding, California, January, 1996.
- Agee, J. K.: The complex nature of mixed severity fire regimes, in: Mixed severity fire regimes: ecology and management, Volume AFE MISC03, edited by: Lagene, L., Zelnik, J., Cadwalladera, S., and Hughes, B., Washington State University Cooperative Extension Service/The Association for Fire Ecology, Spokane, Washington, USA, 1-10. 2005.
- 935
- Allen, G. B.: Vegetation and Climate History of Southeast Vancouver Island, M.Sc. thesis, School of Earth and Ocean Sciences, University of Victoria, British Columbia, Canada, 1995.

UNCLASSIFIED - NON CLASSIFIÉ

Allen, G. B., Brown, K. J., and Hebda, R. J.: Surface pollen spectra from southern Vancouver Island, British Columbia, Canada. *Can. J. Botany*, 77, 786-799. <https://doi.org/10.1139/b99-03>, 1999.

940 Anderson, L., Presnetsova, L., Wahl, D.B., Phelps, G., and Gous A.: Assessing reproducibility in sedimentary macroscopic charcoal count data, *Quaternary Research*: 111, 177–196. doi:10.1017/qua.2022.43, 2023.

Barlow, C. M., Pellatt, M. G., and Kohfeld, K. E.: Garry oak ecosystem stand history in Southwest British Columbia, Canada: implications of environmental change and indigenous land use for ecological restoration and population recovery. *Biodivers. Conserv.*, 30, 1655-1672, <https://doi.org/10.1007/s10531-021-02162-2>, 2021.

945 Barreto, E., Holden, P. B., Edwards, N. R., and Rangel, T. F.: PALEO-PGEM-Series: a spatial time series of the global climate over the last 5 million years (Plio-Pleistocene). *Global Ecol. Biogeogr.*, 32, 1034-1045, <https://doi.org/10.1111/geb.13683>, 2023.

Bartington Instruments: Bartsoft for PC (4.0), Bartington Instruments Ltd [Computer software], 2013.

950 BC Forest Analysis and Inventory Branch: VRI 2023 Forest and Vegetation Composite Polygons [data set], <https://catalogue.data.gov.bc.ca/dataset/vri-2023-forest-vegetation-composite-polygons>, 2023.

BC Wildfire Service: Statistics and Geospatial Data: Wildfire Averages, <https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-statistics/wildfire-averages>, last access: September 10, 2024

BC Wildfire Service: British Columbia Data Catalogue, Fire Incident Locations – Historical [data set], <https://catalogue.data.gov.bc.ca/dataset/bc-wildfire-fire-incident-locations-historical>, 2024.

955 Beyer, R. M., Krapp, M., and Manica, A.: High-resolution terrestrial climate, bioclimate and vegetation for the last 120,000 years, *Scientific data*, 7, 236, <https://doi.org/10.1038/s41597-020-0552-1>, 2020.

Blaauw, M., and Christen, J. A.: Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Anal.*, 6, 457-474, DOI: 10.1214/11-BA618, 2011.

960 Blarquez O., Vanni re B., Marlon J. R., Daniu A.-L. Power M. J. Brewer S. and Bartlein P. J.: paleofire: An R package to analyse sedimentary charcoal records from the Global Charcoal Database to reconstruct past biomass burning, *Computers and Geosciences*, 72, 255-261, 2014.

Bowman, D. M., Williamson, G. J., Abatzoglou, J. T., Kolden, C. A., Cochrane, M. A., and Smith, A. M.: Human exposure and sensitivity to globally extreme wildfire events. *Nat. Ecol. Evol.*, 1, 0058, <https://doi.org/10.1038/s41559-016-0058>, 2017.

## UNCLASSIFIED - NON CLASSIFIÉ

965 Brown, K. J. and Hebda, R. J.: Origin, development, and dynamics of coastal temperate conifer rainforests of southern Vancouver Island, Canada. *Can. J. Forest Res.*, 32: 353–372, <https://doi.org/10.1139/x01-197>, 2002a.

Brown, K. J., and Hebda, R. J.: Ancient fires on southern Vancouver Island, British Columbia, Canada: a change in causal mechanisms at about 2,000 ybp. *Environ. Archaeol.*, 7, 1-12, <https://doi.org/10.1179/env.2002.7.1.1>, 2002b.

970 Brown, K. J., Fitton, R. J., Schoups, G., Allen, G. B., Wahl, K. A., and Hebda, R. J.: Holocene precipitation in the coastal temperate rainforest complex of southern British Columbia, Canada. *Quaternary Sci. Rev.*, 25, 2762-2779, <https://doi.org/10.1016/j.quascirev.2006.02.020>, 2006.

Brown, K. J., Nielsen, A. B., Fitton, R. J., and Hebda, R. J.: Postglacial evolution and spatial differentiation of seasonal temperate rainforest in western Canada. *The Holocene*, 18, 715-727, <https://doi.org/10.1177/095968360809178>, 2008.

Brown, K. J. and Power, M. J.: Charred Particle Analyses. in: Elias S.A. (ed.) *The Encyclopedia of Quaternary Science*, vol. 2, pp. 716-729. Amsterdam: Elsevier, 2013.

975 Brown, K. J., and Schoups, G.: Multi-millennial streamflow dynamics in two forested watersheds on Vancouver Island, Canada. *Quaternary Res.*, 83, 415-426, doi:10.1016/j.yqres.2015.03.003, 2015.

[Brown, K.J., Dietze, E., Walsh, M., Hennebelle, A., and Power, M. Charred Particles and Other Paleofire Proxies. \*In Encyclopedia of Quaternary Science, Volume 3. Edited by R. Bradshaw. Elsevier. pp. 19, 2025.\*](#)

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980 Brown, K. J., Power, M. J., and Hebda, N. J.: Integrating paleoecology into landscape management, DOI: 10.14195/978-989-26-16-506\_127, 2018. Brown, K. J., Hebda, N. J. R., Schoups, G., Conder, N., Smith, K. A. P., and Trofymow, J. A.: Long-term climate, vegetation and fire regime change in a managed municipal water supply area, British Columbia, Canada. *The Holocene*, 29, 1411-1424, <https://doi.org/10.1177/0959683619854523>, 2019.

Brown, K. J., Hebda, N. J., Hebda, R. J., Fitton, R., Trofymow, J. A., and Conder, N.: Development and wildfire dynamics of dry coastal temperate forests, BC, Canada. *Can. J. Forest Res.*, 52, 1320-1333, <https://doi.org/10.1139/cjfr-2022-0020>, 2022.

985 Burley, D. V.: *Marpole: Anthropological Reconstructions of a Prehistoric Northwest Coast Culture Type*. Department of Archaeology Publications 8. Archaeology Press, Simon Fraser University, Burnaby, BC, 1980.

990 Burton, C., Lampe, S., Kelley, D. I., Thiery, W., Hantson, S., Christidis, N., Gudmundsson, L., Forrest, M., Burke, E., Chang, J., Huang, H., Ito, A., Kou-Giesbrecht, S., Lasslop, G., Li, W., Nieradzick, L., Li, F., Chen, Y., Randerson, J., Reyer, C. P. O., and Mengel, M.: Global burned area increasingly explained by climate change. *Nat. Clim. Chang.*, 14, 1186-1192, <https://doi.org/10.1038/s41558-024-02140-w>, 2024.

## UNCLASSIFIED - NON CLASSIFIÉ

Bush, E., and Lemmen, D. S.: Canada's changing climate report; Government of Canada. Ottawa, ON, Canada, 2019.

Chen, B., Wu, S., Jin, Y., Song, Y., Wu, C., Venevsky, S., Xu, B., Webster, C., and Gong, P.: Wildfire risk for global wildland-urban interface areas. *Nat. Sustain.*, 7, 474-484, <https://doi.org/10.1038/s41893-024-01291-0>, 2024.

Chevalier, M., Davis, B. A., Heiri, O., Seppä, H., Chase, B. M., Gajewski, K., Lacourse, T., Telford, R. J., Finsinger, W., Guiot, J., Kühl, N., Maezumi, S. Y., Tipton, J. R., Carter, V. A., Brussel, T., Phelps, L. N., Dawson, A., Zanon, M., Vallé, F., Nolan, C., Mauri, A., Vernal, A., Izumi, K., Holmström, L., Marsicek, J., Goring, S., Sommer, P. S., Chaput, M., and Kupriyanov, D.: Pollen-based climate reconstruction techniques for late Quaternary studies, *Earth-Science Reviews*, 210, 103384, <https://doi.org/10.1016/j.earscirev.2020.103384>, 2020.

Clarke, H., Cirulis, B., Borchers-Arriagada, N., Bradstock, R., Price, O., and Penman, T.: Health costs of wildfire smoke to rise under climate change, *npj Clim. Atmos. Sci.*, 6, 102, <https://doi.org/10.1038/s41612-023-00432-0>, 2023.

COHMAP: Climatic Changes of the Last 18,000 years: Observations and Model Simulations, *Science*, 241, 1043-1052, DOI: 10.1126/science.241.4869.1043, 1988.

Clark-Wolf, K. D., Higuera, P. E., McLauchlan, K. K., Shuman, B. N., and Parish, M. C.: Fire-regime variability and ecosystem resilience over four millennia in a Rocky Mountain subalpine watershed, *Journal of Ecology*, 111, 2643-2661. <https://doi.org/10.1111/1365-2745.14201>, 2023.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A. F., and Krebs, P.: Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation, *Quaternary Sci. Rev.*, 28, 555-576, <https://doi.org/10.1016/j.quascirev.2008.11.005>, 2009.

Crane, M. F.: *Pteridium Aquilinum*. USDA Forest Service Index of Species Information: <https://www.fs.fed.us/database/feis/plants/fern/pteaqu/all.html>, last access: 12 October 2024, 1990.

CRD: Service Plan for Watershed Protection: 2016-2019, Capital Regional District, Victoria, British Columbia, Canada, 2015.

CRD: Regional Water Supply: 201~~27~~ Strategic Plan, Capital Regional District, Victoria, British Columbia, Canada, 202.

Cunningham, C. X., Williamson, G. J., and Bowman, D. M.: Increasing frequency and intensity of the most extreme wildfires on Earth, *Nat. Ecol. Evol.*, 8, 1420-1425, <https://doi.org/10.1038/s41559-024-02452-2>, 2024.

Cwynar, L. C.: Fire and the forest history of the North Cascade Range, *Ecology*, 68, 791-802, <https://doi.org/10.2307/1938350>, 1987.

## UNCLASSIFIED - NON CLASSIFIÉ

Daly, C., Neilson, R. P., and Phillips, D. L.: A statistical-topographic model for mapping climatological precipitation over mountainous terrain, *J. of Appl. Meteorol. Clim.*, 33, 140-158, [https://doi.org/10.1175/1520-0450\(1994\)033<0140:ASTMFM>2.0.CO;2](https://doi.org/10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2), 1994.

1020 DeLuca, T. H., MacKenzie, M. D., Gundale, M. J., and Holben, W. E.: Wildfire-produced charcoal directly influences nitrogen cycling in ponderosa pine forests. *Soil Science Society of America Journal*, 70, 448-453, <https://doi.org/10.2136/sssaj2005.0096>, 2006.

Douglas, G. W., Meidinger, D. V., and Pojar, J. (Eds.): *Illustrated Flora of British Columbia. Volume 4: Dicotyledons (Orobanchaceae Through Rubiaceae)*, B.C. Ministry of Environment, Lands & Parks and B.C. Ministry of Forests. Victoria. 427 p., ISBN:978-0-7726-3685-0, 1999.

1025

Dunnette, P. V., Higuera, P. E., McLauchlan, K. K., Derr, K. M., Briles, C. E., and Keefe, M. H.: Biogeochemical impacts of wildfires over four millennia in a Rocky Mountain subalpine watershed. *New Phytologist*, 203, 900-912, <https://doi.org/10.1111/nph.12828>, 2014.

Dye, A. W., Reilly, M. J., McEvoy, A., Lemons, R., Riley, K. L., Kim, J. B., and Kerns, B. K.: Simulated future shifts in wildfire regimes in moist forests of Pacific Northwest, USA, *J. Geophys. Res-Bioge.*, 129, e2023JG007722, <https://doi.org/10.1029/2023JG007722>, 2024.

1030

Egan, J., Staff, R., and Blackford, J.: A high-precision age estimate of the Holocene Plinian eruption of Mount Mazama, Oregon, USA. *The Holocene*, 25, 1054-1067, <https://doi.org/10.1177/0959683615576230>, 2015.

Eldridge, M., and Seip, L.: Sooke Reservoir Expansion: An Archaeological Impact Assessment (Permit 2002-121), Rep., on file at the BC Archaeology Branch, Victoria, BC, 2002.

1035

Enache, M. D., and Cumming, B. F.: Tracking recorded fires using charcoal morphology from sedimentary sequence of Prosser Lake, British Columbia (Canada). *Quaternary Res.*, 65, 282-292, <https://doi.org/10.1016/j.yqres.2005.09.003>, 2006.

Feurdean, A.: Experimental production of charcoal morphologies to discriminate fuel source and fire type: an example from Siberian taiga. *Biogeosciences*, 18, 3805-3821, <https://doi.org/10.5194/bg-18-3805-2021>, 2021.

1040 [Fischer, H., Schüpbach, Gideon, G., Bigler, M., Röthlisberger, R., Erhardt E., Stocker, T. F., Mulvaney, R., Wolff, E. W.: Millennial changes in North American wildfire and soil activity over the last glacial cycle. \*Nature Geoscience\*, 8, 723-727, <https://doi.org/10.1038/ngeo2495>, 2015.](https://doi.org/10.1038/ngeo2495)

**Commented [RH57]:** From Referee#1: P2. L38. "Fischer et 2015" is not in the Reference list.  
**Response: A reference has been added.**

Flannigan, M. D., Logan, K. A., Amiro, B. D., Skinner, W. R., and Stocks, B. J.: Future Area Burned in Canada. *Climatic Change*, 72, 1-16, <https://doi.org/10.1007/s10584-005-5935-y>, 2005.

1045 Gavin, D.G., Brubaker, L.B., Lertzman, K.P.: An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island. *Can. J. Forest Res.*, 33, 573–586, <https://doi.org/10.1139/x02-196>, 2003a.

Gavin, D. G., Brubaker, L. B., Lertzman, K. P.: Holocene Fire History of a Coastal Temperate Rain Forest Based on Soil Charcoal Radiocarbon Dates. *Ecology*, 84, 186–201, [https://doi.org/10.1890/0012-9658\(2003\)084\[0186:HFHOAC\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2003)084[0186:HFHOAC]2.0.CO;2) 2003b.

1050 Gavin, D. G., Hallett, D. J., Hu, F. S., Lertzman, K. P., Prichard, S. J., Brown, K. J., Lynch, J. A., Bartlein, P., and Peterson, D. L.: Forest fire and climate change in western North America: insights from sediment charcoal records. *Front. Ecol. Environ.*, 5, 499-506, <https://doi.org/10.1890/060161> , 2007.

Gedye S. J., Jones, R. T., Tinner, W., Ammann, B., Oldfield, F. (2000). The use of mineral magnetism in the reconstruction of fire history: A case study from Lago di Origlio, Swiss Alps. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164(1-4): 101–110.

1055

Giuliano, C., and Lacourse, T.: Holocene fire regimes, fire-related plant functional types, and climate in south-coastal British Columbia forests. *Ecosphere*, 14, e4416, <https://doi.org/10.1002/ecs2.4416>, 2023.

Goring, S., Williams, J. W., Blois, J. L., Jackson, S. T., Paciorek, C. J., Booth, R. K., Marlon, J. R., Blaauw, M., and Christen, J. A. (2012). Deposition times in the northeastern United States during the Holocene: establishing valid priors for Bayesian

1060 age models. *Quaternary Sci. Rev.*, 48, 54-60, <https://doi.org/10.1016/j.quascirev.2012.05.019>, 2012.

Hai, J., Zhang, L., Gao, C., Wang, H., and Wu, J.: How does fire suppression alter the wildfire regime? A systematic review. *Fire*, 6, 424, <https://doi.org/10.3390/fire6110424>, 2023.

Hallett, D. J., Lepofsky, D. S., Mathewes, R. W., and Lertzman, K. P.: 11 000 years of fire history and climate in the mountain hemlock rain forests of southwestern British Columbia based on sedimentary charcoal. *Can. J. Forest Res.*, 33, 292–312,

1065 <https://doi.org/10.1139/x02-177>, 2003.

Halofsky, J. S., Donato, D. C., Franklin, J. F., Halofsky, J. E., Peterson, D. L., and Harvey, B. J.: The nature of the beast: examining climate adaptation options in forests with stand-replacing fire regimes. *Ecosphere*, 9(3), e02140, <https://doi.org/10.1002/ecs2.2140>, 2018.

- Hamann, A., and Wang, T. L.: Models of climatic normals for genecology and climate change studies in British Columbia, *Agr. Forest Meteorol.*, 128, 211-221, <https://doi.org/10.1016/j.agrformet.2004.10.004>, 2005.
- 1070 Hanes, C. C., Wang, X., Jain, P., Parisien, M-A., Little, J. M., and Flannigan, M. D.: Fire-regime changes in Canada over the last half century. *Can. J. Forest Res.*, 49, 256-269, <https://doi.org/10.1139/cjfr-2018-0293>, 2019.
- Hebda, R. J.: British Columbia Vegetation and Climate History with Focus on 6 ka BP. *Géogr. Phys. Quatern.*, 49, 55–79, <https://doi.org/10.7202/033030arCopiedA>, 1995.
- 1075 Hebda, N. J., Brown, K. J., Conder, N., Walker, I. R., and Hebda, R. J.: Past wildfire effects on terrestrial vegetation and biogeochemistry in a drinking water supply catchment. *Quaternary Science Reviews*, 340, <https://doi.org/10.1016/j.quascirev.2024.108663>, 2024.
- Hebda, N. J. R.: Assessing wildfire risk to municipal drinking water using paleoecology, PhD dissertation, University of British Columbia, Canada. pp. 204. <https://open.library.ubc.ca/collections/ubctheses/24/items/1.0421622>, 2022.
- 1080 Hessburg P. F., Miller, C. L., Parks, S. A., Povak N. A., Taylor, A. H., Higuera, P. E., Prichard, S. J., North, M. P., Collins, B. M., Hurreau, M. D., Larson, A. J., Allen, C. D., Stephens, S. L., Rivera-Huerta, H., Stevens-Rumann, C. S., Daniels, L. D., Gedalof, Z., Gray, R. W., Kane, V. R., Churchill, D. J., Haggmann, R. K., Spies, T. A., Cansler, C. A., Belote, R. T., Veblen, T. T., Battaglia, M. A., Hoffman, C., Skinner, C. N., Safford, H D., and Salter, R. B.: Climate, Environment, and Disturbance History Govern Resilience of Western North American Forests. *Front. Ecol. Evolution*, 7, 239, <https://doi.org/10.3389/fevo.2019.00239>, 2019.
- 1085 Higuera, P. E., Peters, M. E., Brubaker, L. B., and Gavin, D. G.: Understanding the origin and analysis of sediment-charcoal records with a simulation model, *Quaternary Sci. Rev.*, 26, 1790-1809, <https://doi.org/10.1016/j.quascirev.2007.03.010>, 2007.
- Higuera, P.: CharAnalysis 0.9: Diagnostic and analytical tools for sediment-charcoal analysis, User's Guide, Montana State University, University of Illinois, URL: <http://CharAnalysis.googlepages.com>, 2009.
- 1090 Higuera, P. E., Gavin, D. G., Bartlein, P. J., Hallett, D. J. (2011). Peak detection in sediment–charcoal records: impacts of alternative data analysis methods on fire-history interpretations. *International Journal of Wildland Fire*, 19(8), 996-1014.
- Hoffman, K. M., Wickham, S. B., McInnes, W. S., & Starzomski, B. M. (2019). Fire exclusion destroys habitats for at-risk species in a British Columbia protected area. *Fire*, 2(3), 48.

## UNCLASSIFIED - NON CLASSIFIÉ

- Hoffman, K. M., Davis, E. L., Wickham, S. B., Schang, K., Johnson, A., Larking, T., Lauriault, P. N., Le, N. Q., Swerdfager, E., and Trant, A. J.: Conservation of Earth's biodiversity is embedded in Indigenous fire stewardship, *P. Natl. A. Sci. U.S.A.*, 118, e2105073118, <https://doi.org/10.1073/pnas.2105073118>, 2021.
- Jensen, K., Lynch, E. A., Calcote, R., and Hotchkiss, S. C.: Interpretation of charcoal morphotypes in sediments from Ferry Lake, Wisconsin, USA: do different plant fuel sources produce distinctive charcoal morphotypes? *The Holocene*, 17, 907-915, <https://doi.org/10.1177/0959683607082>, 2007.
- Juggins, S.: riojaPlot: Stratigraphic diagrams in R, package version 0.1-20, R [code], <https://github.com/nsj3/riojaPlot>, 2023.
- Kajak, Z., Kacprzak, K., and Polkowski, R.: Tubular bottom sampler. *Ekologia Polska B*, 11, 159–165, 1965.
- Kapp, R.O.: How To Know Pollen and Spores. W. C. Brown Co. Iowa, Dubuque, ISBN 0-697-04849-7, 1971.
- Kassambara, A.: rstatix: Pipe-Friendly Framework for Basic Statistical Tests. R package version 0.7.2, r [code], <https://rpkgs.datanovia.com/rstatix/>, 2023.
- Kelly, R. F., Higuera, P. E., Barrett, C. M., and Hu, F. S.: A signal-to-noise index to quantify the potential for peak detection in sediment–charcoal records. *Quaternary Res.*, 75, 11-17, <https://doi.org/10.1016/j.yqres.2010.07.011>, 2011.
- Knutti, R., and Sedláček, J.: Robustness and uncertainties in the new CMIP5 climate model projections. *Nat. Clim. Change*, 3, 369-373, <https://doi.org/10.1038/nclimate1716>, 2013.
- Lemmen, J., and Lacourse, T.: Fossil chironomid assemblages and inferred summer temperatures for the past 14,000 years from a low-elevation lake in Pacific Canada. *J. Paleolimnol.*, 59, 427-442, <https://doi.org/10.1007/s10933-017-9998-3>, 2018.
- Leonardi, M., Hallett, E. Y., Beyer, R., Krapp, M., and Manica, A.: pastclim 1.2: an R package to easily access and use paleoclimatic reconstructions. *Ecography*, 3, e06481, <https://doi.org/10.1111/ecog.06481>, 2023.
- Littell, J. S.: Drought and fire in the western USA: is climate attribution enough? *Curr. Clim. Change Rep.*, 4, 396-406, <https://doi.org/10.1007/s40641-018-0109-y>, 2018.
- Livingstone, D. A.: A lightweight piston sampler for lake deposits. *Ecology* 36: 137-139, <https://doi.org/10.2307/1931439>, 1955.
- Liu, Y., Stanturf, J., and Goodrick, S.: Trends in global wildfire potential in a changing climate. *Forest Ecol. Manag.*, 259, 685-697, <https://doi.org/10.1016/j.foreco.2009.09.002>, 2010.

- Loader C.: locfit: Local regression, likelihood and density estimation. R package version 1,5 r [code], <https://cran.r-project.org/web/packages/locfit/index.html>, 2023.
- 1120 <https://doi.org/10.1016/j.yqres.2013.03.001>, 2013.
- Lucas, J. D., and Lacourse, T.: Holocene vegetation history and fire regimes of *Pseudotsuga menziesii* forests in the Gulf Islands National Park Reserve, southwestern British Columbia, Canada. *Quaternary Res.*, 79, 366-376, <https://doi.org/10.1016/j.yqres.2013.03.001>, 2013.
- MacCarthy, J., Tyukavina, A., Weisse, M. J., Harris, N., and Glen, E.: Extreme wildfires in Canada and their contribution to global loss in tree cover and carbon emissions in 2023, *Glob. Change Biol.*, 30, <https://doi.org/10.1111/gcb.17392>, 2024.
- 1125 <https://doi.org/10.1016/j.ecolind.2019.105518>, 2019.
- Magiera, T., Łukasik, A., Zawadzki, J., and Rösler, W.: Magnetic susceptibility as indicator of anthropogenic disturbances in forest topsoil: A review of magnetic studies carried out in Central European forests, *Ecol. Indic.*, 106, <https://doi.org/10.1016/j.ecolind.2019.105518>, 2019.
- Marlon, J. R., Bartlein, P. J., Walsh, M. K., Harrison, S. P., Brown, K. J., Edwards, M. E., Higuera, P. E., Power, M. J., Anderson, R. S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F. S., Lavoie, M., Long, C., Minckley T., Richard, P. J. H., Scott, A. C., Shafer, D. S., Tinner, W., Umbanhowar, C. E., and Whitlock, C.: Wildfire responses to abrupt climate change in North America. *P. Natl. Acad. Sci. U.S.A.*, 106, 2519-2524, <https://doi.org/10.1073/pnas.0808212106>, 2009.
- 1130 <https://doi.org/10.1073/pnas.1112839109>, 2012.
- Marlon, J. R., Bartlein, P. J., Gavin, D. G., Long, C. J., Anderson, R. S., Briles, C. E., Brown, K. J., Colombaroli, D., Hallet, D. J., Power, M. J., Scharf, E. A., and Walsh, M. K.: Long-term perspective on wildfires in the western USA. *P. Natl. Acad. Sci. U.S.A.*, 109, E535-E543, <https://doi.org/10.1073/pnas.1112839109>, 2012.
- 1135 <https://doi.org/10.1016/j.quascirev.2012.11.029>, 2013.
- Marlon, J. R., Bartlein, P. J., Daniiau, A. L., Harrison, S. P., Maezumi, S. Y., Power, M. J., Tinner, W., and Vanniére, B.: Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. *Quaternary Sci. Rev.*, 65, 5-25, <https://doi.org/10.1016/j.quascirev.2012.11.029>, 2013.
- Marlon, J. R., Kelly, R., Daniiau, A. L., Vanniére, B., Power, M. J., Bartlein, P., Higuera, P., Blarquez, O., Brewer, S., Brücher, Feurdean, A., Romera, G. G., Iglesias, S., Maezumi, Y., Magi, B., Mustaphi, C. J., and Zhihai, T.: Reconstructions of biomass burning from sediment-charcoal records to improve data-model comparisons. *Biogeosciences*, 13, 3225-3244, <https://doi.org/10.5194/bg-13-3225-2016>, 2016.
- 1140 <https://doi.org/10.1017/qua.2020.48>, 2020.
- Marlon, J. R.: What the past can say about the present and future of fire. *Quaternary Res.*, 96, 66-87, [doi:10.1017/qua.2020.48](https://doi.org/10.1017/qua.2020.48), 2020.

- 1145 Mathewes, R. W., and Heusser, L. E.: A 12,000 year palynological record of temperature and precipitation trends in southwestern British Columbia. *Can. J. Botany*, 59, 707-710, <https://doi.org/10.1139/b81-100>, 1981.
- Mattioli, W., Ferrara, C., Lombardo, E., Barbati, A., Salvati, L., and Tomao, A.: Estimating wildfire suppression costs: a systematic review. *Int. For. Rev.*, 24, 15-29, <https://doi.org/10.1505/146554822835224801>, 2022.
- McAndrews, J. H., and Power, D. M.: Palynology of the Great Lakes: the surface sediments of Lake Ontario. *Can. J. Earth Sci.*, 10, 777-792, <https://doi.org/10.1139/e73-071>, 1973.
- 1150 McDadi, O., and Hebda, R. J.: Change in historic fire disturbance in a Garry oak (*Quercus garryana*) meadow and Douglas-fir (*Pseudotsuga menziesii*) mosaic, University of Victoria, British Columbia, Canada: A possible link with First Nations and Europeans. *Forest Ecol. Manag.*, 256, 1704–1710, <https://doi.org/10.1016/j.foreco.2008.03.012>, 2008.
- Meidinger, D., and Pojar, J.: *Ecosystems of British Columbia*, BC Min. of For., Victoria, Special Rep. Series No. 6, pp. 330, 1155 ISSN 0843-6452, 1991.
- Moore, P. D., Webb, J. A., and Collison, M. E.: *Pollen analysis*, viii, PP. 216, ISSN 978-0-632-02176-5, 1991.
- Moritz, M. A., Parisien, M. A., Batllori, E., Krawchuk, M. A., Van Dorn, J., Ganz, D. J., and Hayhoe, K.: Climate change and disruptions to global fire activity. *Ecosphere*, 3, 1-22, <https://doi.org/10.1890/ES11-00345.1>, 2012.
- Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., Leonard, J., McCaffrey, S., Odion, D., 1160 C., Schoennagel, T., and Syphard, A. D.: Learning to coexist with wildfire. *Nature*, 51, 58-66, <https://doi.org/10.1038/nature13946>, 2014.
- Mustaphi, C. J. C., and Pisaric, M. F. J.: A classification for macroscopic charcoal morphologies found in Holocene lacustrine sediments. *Prog. Phys. Geog.*, 38, 734-754, <https://doi.org/10.1177/0309133314548886>, 2014.
- Oksanen, J., Simpson, G., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P., O'hara, R. B., Solymos, P., Stevens, H. M., 1165 H., Szöcs, E., Wagner, H. H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., Caceres, M., Durand, S., Evangelista, H., Fitzjohn, R., Friendly, M., Furneaux, B. R., Hannigan, G., Hill, M. O., Lahti, L., McGlinn, D., Oulette, M-H., Cunha, E. R., Smith, T. W., Stier, A., ter Braak, C., and Weedon, J.: *vegan community ecology package version 2.6-2* April 2022, R [code], [://cran.r-project.org](https://cran.r-project.org), 2022.
- Nakagawa, T., Tarasov, P., Staff, R., Ramsey, C. B., Marshall, M., Schlolaut, G., Bryant, C., Brauer, A., Lamb, H., 1170 Haraguchi, T., Gotanda, K., Kitaba, I., Kitagawa, H., van der Plicht, J., Yonenobu, H., Omori, T., Yokoyama, Y., Tada, R., & Yasuda, Y.: The spatio-temporal structure of the Lateglacial to early Holocene transition reconstructed from the pollen record

UNCLASSIFIED - NON CLASSIFIÉ

of Lake Suigetsu and its precise correlation with other key global archives: Implications for palaeoclimatology and archaeology, *Global and Planetary Change*, 202, 103493, <https://doi.org/10.1016/j.gloplacha.2021.103493>, 2012.

1175 Overpeck, J. T., Rind, D., and Goldberg, R.: Climate-induced changes in forest disturbance and vegetation. *Nature*, 343, 51-53, <https://doi.org/10.1038/343051a0>, 1990.

PCIC: Plan2Adapt: Summary, Pacific Climate Impacts Consortium, <https://services.pacificclimate.org/plan2adapt/app/>, last access: 29 October 2024.

Parisien, M.-A., Dawe, D. A., Miller, C., Stockdale, C. A., and Armitage, O. B.: Applications of simulation-based burn probability modelling: a review. *Int. J. Wildland Fire*, 28: 913-926, 10.1071/WF19069, 2019.

1180 Parisien, M. A., Barber, Q. E., Bourbonnais, M. L., Daniels, L. D., Flannigan, M. D., Gray, R. W., Hoffman, K. M., Jain, P., Stephens, S. L., Taylor, S. W., and Whitman, E.: Abrupt, climate-induced increase in wildfires in British Columbia since the mid-2000s, *Nature Commun. Earth & Environment*, 4, 309, <https://doi.org/10.1038/s43247-023-00977-1>, 2023.

Pausas, J. G., and Keeley, J. E.: Wildfires as an ecosystem service, *Front. Ecol. Environ.*, 17, 289-295, <https://doi.org/10.1002/fee.2044>, 2019.

1185 Pellatt, M. G., Smith, M. J., Mathewes, R. W., Walker, I. R., and Palmer, S. L.: Holocene treeline and climate change in the subalpine zone near Stoyoma Mountain, Cascade Mountains, southwestern British Columbia, Canada, *Arct. Antarct. Alp. Res.*, 32, 73-83, <https://doi.org/10.1080/15230430.2000.12003341>, 2000.

Pellatt, M. G., Hebda, R. J., Mathewes, R. W.: High-resolution Holocene vegetation history and climate from Hole 1034B, ODP leg 169S, Saanich Inlet, Canada, *Mar. Geol.*, 174, 211-226, [https://doi.org/10.1016/S0025-3227\(00\)00151-1](https://doi.org/10.1016/S0025-3227(00)00151-1), 2001.

1190 Pellatt, M. G., and Gedalof, Z. E.: Environmental change in Garry oak (*Quercus garryana*) ecosystems: the evolution of an eco-cultural landscape. *Biodivers. Conserv.*, 23, 2053-2067, <https://doi.org/10.1007/s10531-014-0703-9>, 2014.

Pellatt, M. G., McCoy, M. M., and Mathewes, R. W.: Paleoecology and fire history of Garry oak ecosystems in Canada: implications for conservation and environmental management. *Biodivers. Conserv.*, 24, 1621-1639, <https://doi.org/10.1007/s10531-015-0880-1>, 2015.

1195 [Perrakis, D.P., Brown, K.J., Morrison, K., Taylor, S.W., and Horrelt, D.R. Assessing wildfire potential in a coastal forest watershed, British Columbia, Canada. \*Forest Ecology and Management\*, 590: 122796. doi.org/10.1016/j.foreco.2025.122796, 2025.](#)

Formatted: Font: Not Bold

- Perera, A. H., and Buse, L. J.: Ecology of Wildfire Residuals in Boreal Forests (1st ed.), John Wiley & Sons, Ltd, ISBN 978-1200 1-4443-3653-5, 2014.
- Pojar, J., Klinka, K., and Demarchi, D. A.: Mountain hemlock zone, Ecosystems of British Columbia, Special Report Series 6, BC Min. For., 113-124, ISSN 0843-6452, 1991.
- Pojar, J., and MacKinnon, A. (Eds.): Plants of the Pacific Northwest coast: Washington, Oregon, British Columbia and Alaska, Lone Pine Publishing, Redmond, WA., 526 pp., 1994.
- 1205 Power, M. J., Marlon, J., Ortiz, N., Bartlein, P. J., Harrison, S. P., Mayle, F. E., Ballouche, A., Bradshaw, R. H. W., Caracaillet, C., Cordova, C., Mooney, S., Moreno, P. I., Prentice, I. C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A. A., Anderson R. S., Beer, R., Behling, H., Briles, C., Brown, K. J., Brunelle, A., Bush, M., Camill, P., Chu, G. Q., Clark, J., Colombaroli, D., Connor, S., Daniau, A-L., Daniels, M., Dodson, J., Doughty, E., Edwards, M. E., Finsinger, W., Foster, D., Frechette, J., Gaillard, M-J., Gavin, D. G., Gobet, E., Haberle, S., Hallett, D. J., Higuera, P., Hope, G., Horn, S., Inoue, J., Kaltenrieder, P., Kennedy, L., Kong, Z. C., Larsen, C., Long, C. J., Lynch, J., McGlone, M., Meeks, S., 1210 Mensing, S., Meyer, G., Minckley, T., Mohr, J., Nelson, D. M., New, J., Newnham, R., Noti, R., Oswald, W., Pierce, J., Richard, P. J. H., Rowe, C., Sanchez Goni, M. F., Schuman, B. N., Takahara, H., Toney, J., Turney, C., Urrego-Sanchez, D. H., Umbanhowar, C., Vandergoes, M., Vanniere, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., and Zhang, J. H.: Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and 1215 analysis of charcoal data. *Climate dynamics*, 30, 887-907, <https://doi.org/10.1007/s00382-007-0334-x>, 2008.
- Ramsey, C. B.: Bayesian analysis of radiocarbon dates, *Radiocarbon*, 51, 337-360, doi:10.1017/S003822200033865, 2009.
- Reimer, P. J., Austin, W. E., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B., Butzin, M., Cheng, H., Edwards, R., Friedrich, L. M., Grootes, P. M., Guilderson, T P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kromer, B., Manning, S. W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R. W., Richards, D. A., Scott, E. M., 1220 Southon, J. R., Turney, C. S. M., Wacker, L., Adolphi, F., Buntgen, U., Capano, M., Fahrni, S M., Fogtmann-Schulz, A., Friedrich, R., Kohler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A. and Talamo, S.: The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP), *Radiocarbon*, 62, 725-757, doi:10.1017/RDC.2020.41, 2020.
- Renssen, H., Seppä, H., Crosta, X., Goosse, H., & Roche, D. M.: Global characterization of the Holocene thermal 1225 maximum. *Quat. Sci. Rev.*, 48, 7-19, <https://doi.org/10.1016/j.quascirev.2012.05.022>, 2012.

Ripley B.: MASS: Modern applied statistics with S., R package version 7.3 r [code], <https://cran.r-project.org/web/packages/MASS/index.html> 2023.

Rosenberg, S. M., Walker, I. R., Mathewes, R. W., and Hallett, D. J.: Midge-inferred Holocene climate history of two subalpine lakes in southern British Columbia, Canada, *The Holocene*, 14, 258-271,

1230 <https://doi.org/10.1191/0959683604hl703rp>, 2004.

Rowe, J. S.: Concepts of Fire Effects on Plant Individuals and Species, in: *The Role of Fire in Northern Circumpolar Ecosystems*, edited by: R. W. Wein and D. A. MacLean, John Wiley and Sons, New York, 135–155, ISBN 0 471 10222 9, 1983.

Rummery, A. T.: The effects of fire on soil and sediment magnetism, Doctoral dissertation, University of Liverpool, 1981.

1235 Scott, S.: Post Wildfire Natural Hazards and Risk Analysis of the Mt Healey and Rithet Wildfires, Technical Report File # SS2020006, Integrated Water Services, Capital Regional District, Victoria, British Columbia, Canada, pp 37, 2020.

Senande-Rivera, M., Insua-Costa, D., and Míguez-Macho, G.: Spatial and temporal expansion of global wildland fire activity in response to climate change, *Nat. Commun.*, 13, 1208, <https://doi.org/10.1038/s41467-022-28835-2>, 2022.

Sheehan, T., Bachelet, D., and Ferschweiler, K.: Projected major fire and vegetation changes in the Pacific Northwest of the conterminous United States under selected CMIP5 climate futures, *Ecol. Model.*, 317, 16-29,

1240 <https://doi.org/10.1016/j.ecolmodel.2015.08.023>, 2015.

Stephens, S. L., Burrows, N., Buyantuyev, A., Gray, R. W., Keane, R. E., Kubian, R., Liu, S., Seijo, F., Tolhurst, K. G., and Van Wagtenonk, J. W.: Temperate and boreal forest mega-fires: Characteristics and challenges, *Frontiers in Ecology and the Environment*, 12, 115-122, <https://doi.org/10.1890/120332>, 2014.

1245 Uchytel, R. J.: *Pseudotsuga menziesii* var. *Menziesii*, in: *Fire Effects Information System*, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, <https://www.fs.usda.gov/database/feis/plants/tree/psemenm/all.html>, last access: 3 November 2024, 1991.

Vincent, R., Mathews, D., and Eldridge, M.: Sooke Lake Reservoir Expansion Phase II: An Archeological Impact Assessment, Permit 2202-336, Victoria, Capital Regional District, 2002.

1250 Walker, I. R., and Mathewes, R. W.: Chironomidae (Diptera) and postglacial climate at Marion Lake, British Columbia, Canada, *Quaternary Res.*, 27, 89-102, doi:10.1016/0033-5894(87)90052-4, 1987.

## UNCLASSIFIED - NON CLASSIFIÉ

Walker, I. R., Pellatt, M. G.: Climate Change in Coastal British Columbia - A Palaeoenvironmental Perspective, *Can. Water Resour. J.*, 28, 531-566, <https://doi.org/10.4296/cwrj2804531>, 2003.

1255 Walsh, M. K., Marlon, J. R., Goring, S.J., Brown, K. J., and Gavin, D. G.: A regional perspective on Holocene fire-climate-human interactions in the Pacific Northwest of North America. *Ann. Assoc. Am. Geogr.*, 105: 1135–1157, <https://doi.org/10.1080/00045608.2015.1064457>, 2015.

Wang, T., Campbell, E. M., O'Neill, G. A., and Aitken, S. N.: Projecting future distributions of ecosystem climate niches: Uncertainties and management applications, *Forest Ecol. Manag.*, 279, 128–140, <https://doi.org/10.1016/j.foreco.2012.05.034>, 2012.

1260 Wang, T., Hamann, A., Spittlehouse, D., and Carroll, C.: Locally downscaled and spatially customizable climate data for historical and future periods for North America, *PLoS one*, 11, e0156720, <https://doi.org/10.1371/journal.pone.0156720>, 2016.

1265 Wang, X., Thompson, D. K., Marshall, G. A., Tymstra, C., Carr, R., and Flannigan, M. D.: Increasing frequency of extreme fire weather in Canada with climate change, *Climatic Change*, 130, 573–586, <https://doi.org/10.1007/s10584-015-1375-5>, 2015.

Wang, X., Parisien, M. A., Taylor, S. W., Perrakis, D. D., Little, J., and Flannigan, M. D.: Future burn probability in south-central British Columbia, *Int. J. Wildland Fire*, 25, 200-212, <https://doi.org/10.1071/WF15091>, 2016.

1270 Wang, X., Parisien, M. A., Taylor, S. W., Candau, J. N., Stralberg, D., Marshall, G. A., Little, J. M., and Flannigan, M. D.: Projected changes in daily fire spread across Canada over the next century, *Environ. Res. Lett.*, 12, 025005, [10.1088/1748-9326/aa5835](https://doi.org/10.1088/1748-9326/aa5835), 2017

Wang, Z., Wang, Z., Zou, Z., Chen, X., Wu, H., Wang, W., Su, H., Li, F., Xu, W., Liu, Z. and Zhu, J.: Severe global environmental issues caused by Canada's record-breaking wildfires in 2023, *Adv. Atmos. Sci.*, 565-571, <https://doi.org/10.1007/s00376-023-3241-0>, 2024.

1275 Wanner, H., Beer, J., Bütikofer, J., Crowley, T. J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean M., Joos, F., Kaplan, J. O., Küttel, M., Müller, S. A., Prentice, I. J., Solomina, O., Stocker, T. F., Pavel, T., Wagner, M., and Widmann, M.: Mid-to Late Holocene climate change: an overview, *Quaternary Sci. Rev.*, 27, 1791-1828, <https://doi.org/10.1016/j.quascirev.2008.06.013>, 2008.

UNCLASSIFIED - NON CLASSIFIÉ

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., and Swetnam, T. W.: Warming and earlier spring increase western U.S. Forest Wildfire Activity, *Science; Research Articles*, 313, 940-943, 10.1126/science.1128834, 2006.

1280 Whitlock, C., Shafer, S. L., and Marlon, J.: The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management, *Forest Ecol. Manag.*, 178, 5-21, [https://doi.org/10.1016/S0378-1127\(03\)00051-3](https://doi.org/10.1016/S0378-1127(03)00051-3), 2003.

Wirth, C.: Fire regime and tree diversity in boreal forests: implications for the carbon cycle, in: *Forest diversity and function: temperate and boreal systems*, edited by: Scherer-Lorenzen, M., Körner, C., and Schulze, E-D., Springer, Berlin Heidelberg,

1285 309-344, <https://doi.org/10.1007/b137862>, 2005.

Wong, C., Sandmann, H., Dörner, B.: Historical variability of natural disturbances in British Columbia: A literature review. FORREX—Forest Research Extension Partnership, Kamloops, B.C. FORREX Series 12, ISBN: 1-894822-13-7, 2004.

Wright, H.E.: A square-rod piston sampler for lake sediments, *J. Sediment. Res.*, 37, 975–976, <https://doi.org/10.1306/74D71807-2B21-11D7-8648000102C1865D>, 1967.

1290 Wu, D., Zhou, A., Liu, J., Chen, X., Wei, H., Sun, H., Yu, J., Bloemendal, J., and Chen, F.: Changing intensity of human activity over the last 2,000 years recorded by the magnetic characteristics of sediments from Xingyun Lake, Yunnan, China, *J. Paleolimnol.*, 53, 47-60, <https://doi.org/10.1007/s10933-014-9806-2>, 2015.

1295