A COMPARISON OF EARLY HOLOCENE AND LATE HOLOCENE VEGETATION STRUCTURE AND FIRE FREQUENCY IN THE PUGET LOWLAND

by

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THESIS ABSTRACT

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The Puget Lowland of the Pacific Northwest (PNW) has a dynamic post-glacial vegetation and climate history. Vegetation structure and fire frequency may be affected by a variety of factors such as large-scale climatic change, as well as more local factors like changing natural and human ignition sources. This study examines forest dynamics and fire disturbance events in the Puget Lowland throughout the Holocene through the use of a new lake sediment record. It was found that vegetation structure in the early and late Holocene did not react to fire disturbance events in the same way. Even further, increasing human presence and modification of land during the late Holocene lead to marked changes within the pollen and charcoal records and lake productivity. It is important to recognize that the relationship among vegetation, fire frequency, climate, and human influence is constantly changing and may not reflect patterns that have been observed in the past.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

CHAPTER I

INTRODUCTION

The Puget Lowland of the Pacific Northwest (PNW) has a particularly dynamic post-glacial vegetation and climate history. The historical dominance of extensive old growth forest is relatively new on a geologic time scale, appearing in the mid-Holocene (Brubaker, 1991). This area has also experienced pronounced transformations due to changes in climate through the late Pleistocene and the onset of the Holocene (Brubaker, 1991; Whitlock, 1992; Whitlock et al., 2003), as well as from indigenous land use and the increasing presence of European development in the more recent past (Leopold & Boyd, 1999; Shadow Lake IAVMP, 2016). After the Last Glacial Maximum (LGM) approximately 24-19 ka (thousands of years before present), the Puget Lobe of the Cordilleran ice sheet reached its southernmost extent (~16 ka) during the Vashon Stade of the Fraser glaciation (Porter & Swanson, 1998; Haugerud, 2020). The presence of the ice sheet caused a cooler and drier climate in the region due to the location of the North American jet stream (COHMAP members, 1988; Whitlock, 1992). Segments of the Puget Lobe retreated rapidly and irregularly, resulting in landforms such as drumlins and proglacial lakes (Porter & Swanson, 1998). After the retreat of the Puget Lobe, lake basins and other localized depressions began preserving the area's ecological history (Crausbay et al., 2017). This area is a particularly significant region to study due to its abundant biodiversity but continuing rapid settlement. This urbanization results in increasingly fragmented habitat and loss of biodiversity.

The Puget Lowland region was occupied by the Lushootseed speaking Coast Salish after the LGM, with the earliest evidence of humans dating to the transition from the late Pleistocene to the Holocene beginning around 14.5 ka (Ames & Hodges, 2015). Long before Euro-American settlement, these peoples were modifying the landscape through the use of fire to produce more favorable conditions for their desired food types (LeCompte-Mastenbrook, 2015). The Coast Salish maintained mobile lifestyles until around 6-4 ka (Quinn, 2010), and then transitioned into sedentism and increased social complexity from 4-3 ka (Ames, 2001; Lepofsky, 2003). When reconstructing past landscapes, it's important to recognize that humans have potentially played a role in the formation of a landscape for thousands of years.

Using paleoecological records from small lakes, it is possible to reconstruct the vegetation and fire history at a decadal and local (km-scale) resolution. Following the LGM, tundra and subalpine vegetation types existed throughout the Puget Lowland region of the PNW (Whitlock, 1992) with vegetation consisting of mountain hemlock, lodgepole pine, and Engelmann spruce (Brubaker, 1991). The early Holocene (11.6-9 ka) is characterized by dry and warm conditions with increased fire activity (Gavin et al., 2013; Walsh et al., 2015). Vegetation eventually transitioned to a cool conifer forest ecosystem type (Thompson & Anderson, 2000), and climate became cooler and wetter 8-4 ka with decreased fire disturbance (Gavin et al., 2013; Walsh et al., 2015). Old-growth forest types consisting of Douglas-fir, alder, and western hemlock tree species in this area came into existence about 6,000 years ago (Brubaker, 1991). Following the establishment of old-growth forest, climate variability and indigenous burning lead to an increase in fire frequency in this area (Walsh et al., 2015).

The old-growth forests that exist in the PNW today formed under middle to late Holocene conditions that no longer exist (Whitlock et al., 2003). Despite increasingly unsuitable conditions, these tree species continue to exist in this region today due to their slow response to a changing climate and ability to remain established in the area (Crausbay et al., 2017). Considering the inertia present in vegetation structure, we may slowly start to see a delayed change in forest composition. Even further, recent climate change in the context of the Holocene climate and vegetation changes may lead to the vegetation in this area experiencing significant shifts in composition.

Vegetation structure and fire frequency may be affected by a variety of factors such as large-scale climatic change, as well as more local factors such as changing natural and human ignition sources. Because of this complicated relationship, it is important to consider local history in the reconstruction of vegetations histories at the landscape scale. Taking this into consideration, I focus on three questions throughout my research:

1. How has lake productivity at Shadow Lake changed through time and in what way have humans influenced these processes?
2. How is the changing climate during the early-Holocene and the late-Holocene represented in vegetation structure and fire disturbance in the Puget Lowland?
3. How does vegetation successional change (inferred from pollen data) immediately following a fire event differ between the early and late Holocene?

This study examines forest dynamics and fire disturbance events in the Puget Lowland through the Holocene using of a new lake sediment record. A multi-proxy approach allows us to determine the timing and causes of these reconstructed changes. Pollen assemblages and charcoal analysis are two commonly used proxies that make it possible to look at changes in vegetation structure and fire frequency, while relating them back to large-scale climate trends (Whitlock et al., 2015).

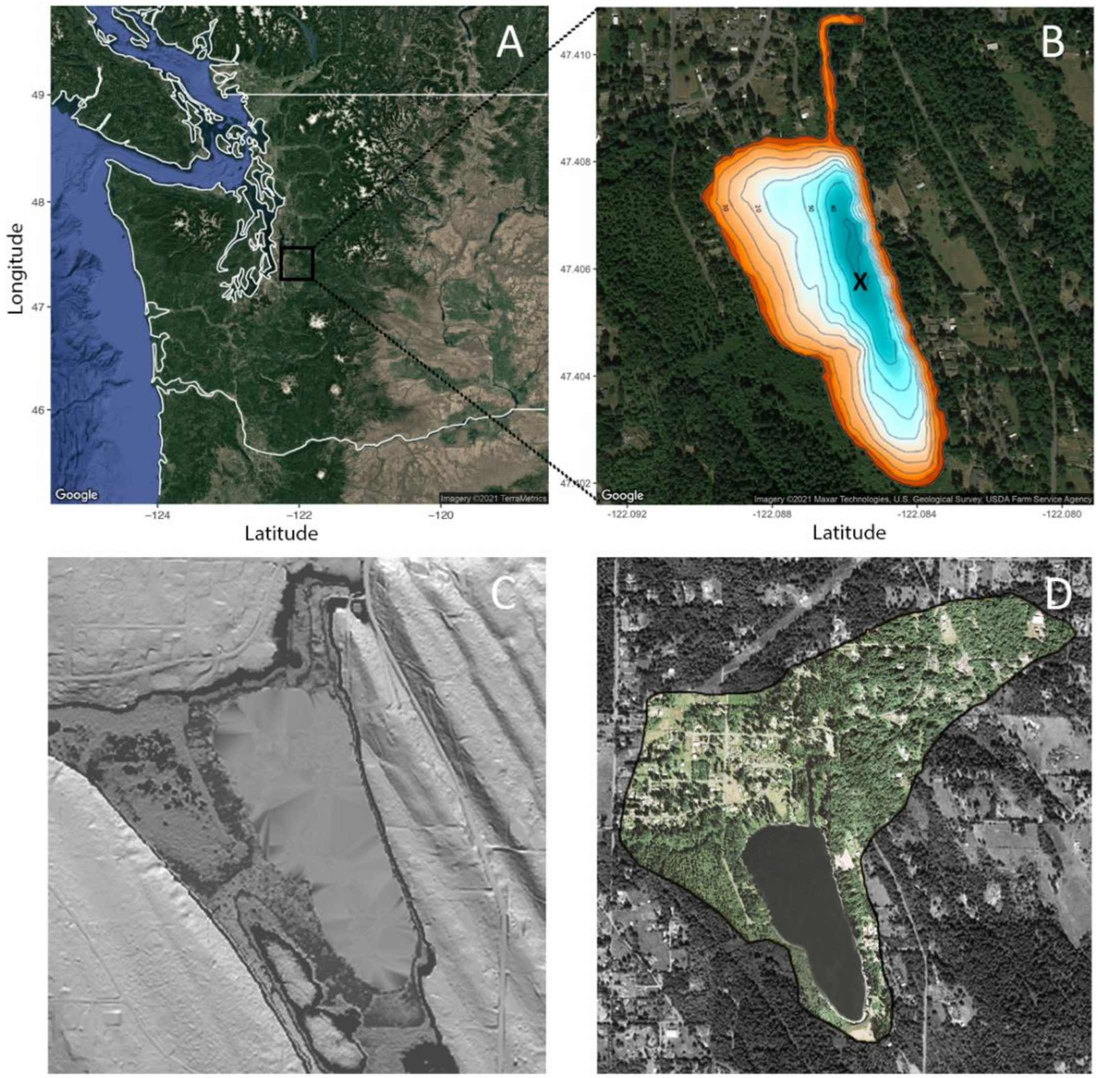

Figure 1. A) Location of Shadow Lake in Renton, WA, USA. B) Lake bathymetry of Shadow Lake. Lake depth is shown at 5 ft intervals ranging from 0-45 ft. The location of the extracted core is designated by the black "X". C) LIDAR of Shadow Lake and its surrounding area. D) Watershed of Shadow Lake, which is shown in color and outlined in black.

CHAPTER II

SITE DESCRIPTION

Shadow Lake is located in King County, Washington (47°24'6" N 122°4'10" W) and is 515 ft above sea level (Figure 1A). Shadow Lake has a surface area of 20.2 ha and a watershed of 208.8 ha (Figure 1D) (Shadow Lake IAVMP, 2016). Located in an area of glacial striations, its narrow shape is due to it being situated between ridges of drumlinized glacial drift and formed from the advance of the Puget Lobe (Figure 1C) (Porter & Swanson, 1998; Haugerud, 2020). The deepest location in the northeastern corner of the lake reaches 13.5 m (Figure 1B). Dissolved oxygen decreases rapidly 4 m below the lake surface; water became anoxic 10 m below surface (conditions in September of 2019). The lakebed is gently sloping on the western and southern edges of the lake but is much steeper on the eastern side. A peat bog is located on the southern and western edges of the lake.

Shadow Lake is located in the Tsuga heterophylla Zone characteristic of western Washington (Franklin & Dyrness, 1988). Forest composition consists of *Tsuga heterophylla* (western hemlock), *Pseudotsuga menziesii* (Douglas fir), and *Thuja plicata* (western red cedar). It is important to note that this area has been subject to logging and fire suppression, resulting in changes to vegetation structure that may not be directly characteristic of the Tsuga heterophylla zone. Because of this, there are greater abundances of species such as *Alnus rubra* (red alder) and *Pseudotsuga menziesii*, as well as the Pinus (pine) and Quercus (oak) genera (Franklin & Dyrness, 1988). Observations made in the field show that current common species around the perimeter of the lake include red alder, Douglas fir, western red cedar, western hemlock, black cottonwood, Sitka spruce, and sword fern.

The Puget Lowland has a wet, maritime climate (Franklin & Dyrness, 1988). The region has a winter (December, January, and February average) temperature normal of 5°C and precipitation of 36.9 cm and summer (June, July, and August average) temperature normal of 17.4°C and precipitation of 10.4 cm; more specific to the study site, Renton, WA has a winter temperature normal of 5.6°C and precipitation of 39.2 cm and summer temperature normal of 18.4°C and precipitation of 8.8 cm (NOAA Climate Data Online).

The land surrounding Shadow Lake was not utilized by Native American populations for agricultural purposes due to the presence of boggy, inhospitable land for crops, but they were able to harvest bog cranberry in the habitat bordering the lake (Shadow Lake IAVMP, 2016). Following Euro-American settlement in the late 1800s, alteration to the land surrounding Shadow Lake did not start until 1910, when the land started being harvested for timber, which continued until the late 1940s (Shadow Lake IAVMP, 2016). Logging in this area focused on Douglas-fir and western red cedar (Davis, 1973). The first recorded county roads are estimated to have been built around 1921 (Shadow Lake IAVMP, 2016). Shadow Lake itself was not altered until approximately the late 1950s, when a channel was dug on the northern shore of the lake to provide boat access from public land. Residential land use surrounding the lake increased in the 1960s (Shadow Lake IAVMP, 2016).

CHAPTER III

METHODS

Field and laboratory methods

Sediment was collected in September 2019 using a 5-cm diameter Livingstone piston corer on an anchored raft floating over the deepest part of Shadow Lake (Wright et al., 1984). The sediment and corer were brought up through metal casing then extruded into PVC core holders wrapped in plastic wrap to prevent moisture loss. Two parallel cores with overlapping drives (core 1 and core 2) were obtained and sections of each were used during analysis. A core of the surface sediments was collected using a clear tube fitted with a piston and subsampled the next day into plastic bags by 0.5 cm for samples 0-26 cm and 1 cm for samples 26-38 cm. Core 1 overlaps with the surface core at 16 cm below sediment surface; core 2 (parallel core) aligns with core 1 at 69 cm below sediment surface. All samples were stored at 4°C in the lab core correlation between surface and drive A, and between cores 1 and 2 and the sediment cores were subsampled into bags at 1-cm intervals for future use.

Radiocarbon dates (^{14}C yr BP) were acquired at seven depths. Six dates were obtained on plant or wood macrofossils and one date was obtained from bulk sediment > 150 µm. Macrofossil samples were pretreated with 10% HCl and 10% KOH rinses. Additional age controls were provided by tephra from Mt. Mazama and an abrupt increase in *Alnus rubra* pollen coinciding with the general time period of widespread logging in the Puget Lowland (~1910 CE). The radiocarbon dates were converted to calendar years (cal yr BP) using INTCAL20 (Reimer et al., 2020). An age-depth relationship was developed using the CLAM program (Blaauw, 2010) modified to use a spline curve with monotonically increasing age with depth (Schworer et al., 2017).

Magnetic susceptibility was measured at 1-cm intervals. Loss on ignition (LOI) at 550° and bulk density were calculated on 1 cm^3 every 10 cm. To measure organic carbon and nitrogen stable isotopes, samples at 5-cm intervals were acid rinsed followed by two rinses of dH_2O to remove inorganic carbon (1 M HCl), dried, and ground. Measurement of total nitrogen, total organic carbon, $\delta^{15}N$ and $\delta^{13}C_{org}$ were made using an isotope ratio mass spectrometer at the University of California Stable Isotope Facility, with a reported mean absolute accuracy on calibrated reference material of 0.05‰ for both ^{13}C and ^{15}N.

Charcoal and pollen analysis

Charcoal analysis was completed using 1 cm^3 of sediment over 1-cm increments. Samples were soaked in 10% sodium hexametaphosphate (Na-HMP) overnight and sieved for 250 µm and 125 µm fractions. The 125-250 µm size fraction was then treated with 3% hydrogen peroxide for approximately 12 hours and sieved at 125 µm fractions. Each sample was counted for charcoal fragment abundance using a stereoscope at 3.5-5×.

Local fire history and peaks in the charcoal record were determined using CharAnalysis (Higuera et al., 2009). Charcoal accumulation rate (pieces cm^{-2} yr^{-1}), or CHAR, was calculated. CHAR was interpolated to 15-year intervals. Varying widths of the loess (“background”) smoothing window and thresholds of peak height were applied for detecting increases in CHAR above background levels. A window width of 500 years was chosen using the signal-to-noise ratio as a criterion.

Pollen analysis was performed on 60 samples processed from 1 cm^3 of sediment using the methods of Faegri & Iversen (2000). Pollen percentages were calculated using a minimum of 300 pollen grains counted per sample. Most pollen grains were identified to the genus level with the exception of a few species known to exist in the area, such as *Tsuga heterophylla* and *Alnus rubra*. While Cupressaceae cannot be broken down to the species level, it is recognized that the pollen located in this site likely comes from *Thuja plicata* due to its presence in low elevation forests (Leopold et al., 2016). *Pseudotsuga* pollen is recognized as *Pseudotsuga menziesii*.

Stratigraphic zones in the pollen record were determined to be statistically significant using the broken stick method (Grimm, 1987). Arboreal pollen types were separated into two groups: early successional species (ES) and late successional species (LS). Early successional species included *Pseudotsuga* sp., *Pinus* sp., and *Alnus rubra*. Although *Alnus rubra* can persist in wetlands as a climax community (Worthington et al., 1962), such wetlands are rare on the landscape. Additionally, it is an indicator of recent fire, which is why it is included within the ES species (Hansen, 1947). Late successional taxa included *Tsuga heterophylla* and Cupressaceae sp.

Further analysis was made by examining how pollen abundance changed following a fire event (peaks in CHAR). Two time periods were used: a segment of the early Holocene (10,700-9,000 yr BP) and of the late Holocene (4,000 yr BP-present). CHAR peaks during these time periods were identified; the age of each peak was then compared to the pollen samples closest in age. Pollen samples that were within 200 years after a fire event were included in the analysis. Pollen abundance for these samples was plotted against time since fire event to examine how vegetation structure changes after fire.

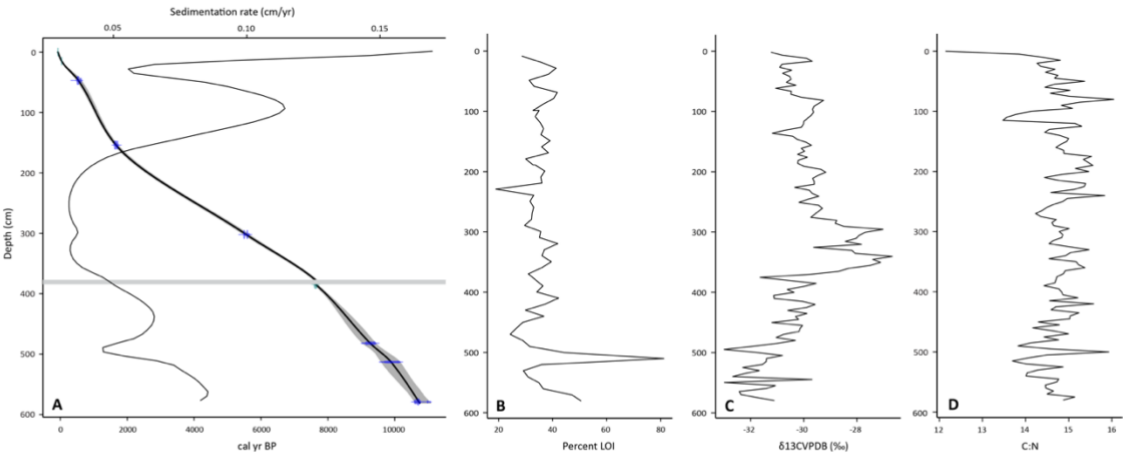

Figure 2. A) Age-depth model for Shadow Lake, which was determined using CLAM (Blaauw, 2010). Mt. Mazama tephra is shown by the horizontal gray bar at ~380 cm. The resulting sedimentation rate is plotted over the age-depth model. B) Loss on ignition (LOI) expressed as a percentage. C) $\delta^{13}C$ expressed as ‰ VPDB. D) C:N molar ratio calculated from the total carbon and total nitrogen measurements.

CHAPTER IV

RESULTS

Lithology and paleoenvironment

I collected 581 cm of sediment from Shadow Lake. A combination of dense sediments and faulty coring equipment prevent further coring; basal sediments were not reached. Sediment color and texture is fairly uniform downcore, with the exception of the presence of 7 cm of Mt. Mazama tephra. LOI remained within the range of 30-45%, except for a drop to ~19% at 230 cm and a spike to ~81% at 510 cm (Figure 2B). $\delta^{13}C_{org}$ stayed within the range of -32 to -27‰ (Figure 2C). There is a distinct increase in $\delta^{13}C$ around 350 cm, which occurs directly following the eruption of Mt. Mazama. The C:N ratio fluctuated between approximately 12 to 14, with a notable dip to ~10 at the sediment surface (0.5 cm) (Figure 2D).

^{14}C Sample Number	Depth (cm)	Type	Radiocarbon age (^{14}C yr BP)	Calibrated age (cal yr BP)
–	0	–	–	-69
170039	47 - 48	Deciduous leaf	510 ± 45	530 (630 - 490)
41112	154-155	Needle fragments	1788 ± 22	1660 (1730 - 1620)
170036	294 - 295	Western red cedar needle	3830 ± 25	4220 (4400 - 4330)*
41113	302-303	Cone bracts, seed wing, needle	4846 ± 28	5590 (5650 - 5570)
Mazama	377-384.5	Tephra	–	7633 ± 25
170037	482 - 483	Charred conifer needle	8280 ± 55	9280 (9440 - 9090)
170038	513 - 514	Conifer needle	8820 ± 65	9880 (10170 - 9630)
41114	579 - 580	Bulk sediment > 150 µ	9465 ± 34	10700 (11060 - 10970)

Table 1. Radiocarbon dates collected from the Shadow Lake sediment core and other time constraints used in the development of the age-depth model.
**Date was excluded from age-depth model due to a larger difference in age (~1,200 yrs) with nearby sample at 302 cm.*

Chronology

Six of the seven radiocarbon dates were used to develop the age depth model for Shadow Lake (Table 1). A *Thuja plicata* needle dated at 294 cm was also excluded due to a large difference in age (~1,000 years) with the sample dated at 302 cm. The resulting age-depth model is relatively linear (Figure 2A). Relatively high sedimentation rate occurred 2,000 yr-present (0.05-0.15 cm/yr) and 10,000-10,700 cal yr BP (~0.075 cm/yr).

The base of the core is dated at ~10,700 cal yr BP.

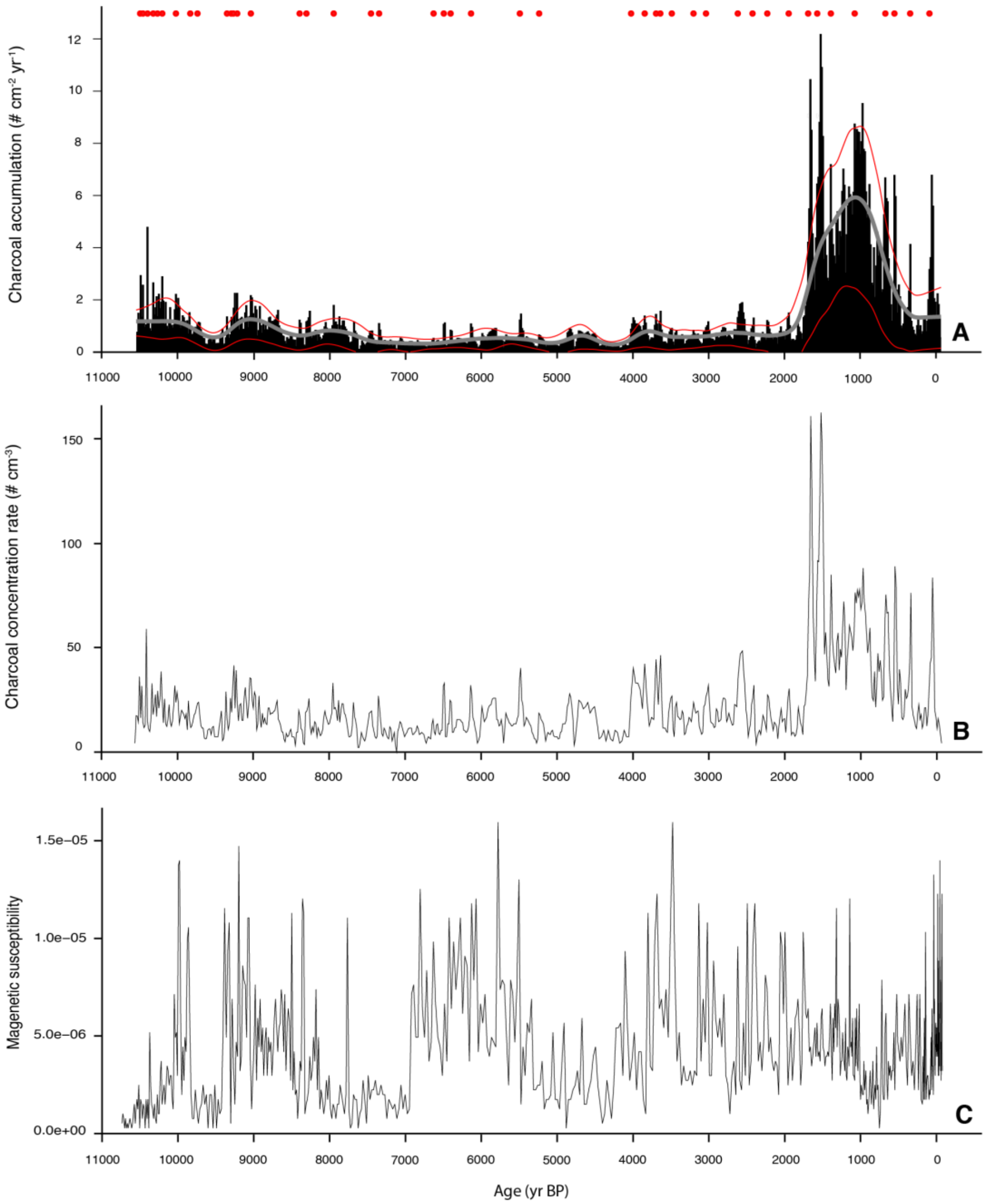

Figure 3. A) The charcoal accumulation rate (CHAR) at Shadow Lake is shown by the black plot. Peaks in CHAR are shown by the red points located at the top of the plot. The lines plotted over CHAR demonstrate varying thresholds in background charcoal to determine when peaks in CHAR occurred using a 500-year smoothing window. B) The charcoal concentration rate as it changes through time. C) Magnetic susceptibility record for Shadow Lake.

Fire history

The number of charcoal pieces counted per sample was as low as 0 and reached up to 174. Charcoal accumulation rates were moderately high during the early Holocene (1-5 pieces cm^{-2} yr^{-1} and then remained low for the duration of the middle Holocene and into the late Holocene (Figure 3B). Around 1,800 yr BP there is a large increase in CHAR (up to 6-12 pieces cm^{-2} yr^{-1}). CHAR remains relatively high up until the present.

CharAnalysis separated peaks in CHAR from background levels of charcoal using a signal-to-noise (SNI) index of 2-7, except for three time periods (7,050-6,850 yr BP, 5,000-4,450 yr BP, and 1,050-850 yr BP) when SNI ranged from 0-2. The charcoal record shows three time periods of fire frequency (Figure 3A). High fire frequency exists from 10,7000-9,000 yr BP (13 peaks). The period from 9,000-4,000 yr BP consists of a low overall charcoal concentration and accumulation rate with 12 peaks in charcoal and fires occurring at unequal intervals. From 4,000 yr BP-present, there are more abundant fire events (19 peaks) that are evenly distributed, indicating frequent persistent fire. A distinct increase in charcoal accumulation and concentration occurs around 2,000 yr BP but does not impact the number of peaks shown in the charcoal record.

Magnetic susceptibility fluctuated consistently between ~2×10^{-7} and 1.5×10^{-5} cgs (Figure 3C). There are notable periods of reduced magnetic susceptibility in the following periods: 10,700-10,000, 8,500-7,000, and 5,500-4,000 yr BP. There was no cross-correlation between magnetic susceptibility and the charcoal record at any lag (±100 years).

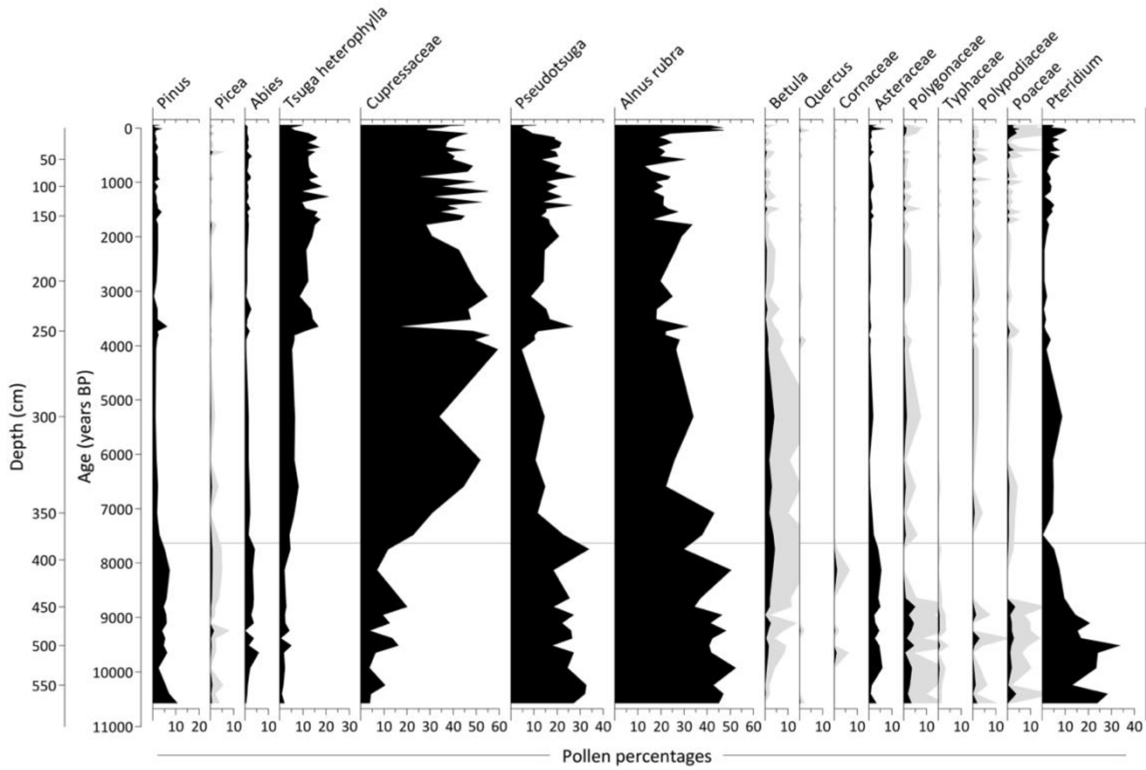

Figure 4. Pollen diagram of common pollen and spore taxa from Shadow Lake, Washington. The location of tephra from Mt. Mazama within the core is shown in light gray (~7,633 ± 25 yr BP).

Pollen record

Abundant pollen types at Shadow Lake include *Pinus*, *Tsuga heterophylla*, *Abies*, *Pseudotsuga*, Cupressaceae, *Alnus rubra*, and Pteridium (Figure 4). Based on a stratigraphically- constrained cluster analysis, the pollen record is separated into two statistically significant zones: 10,700-the eruption of Mt. Mazama (7,633 yr BP) and 7,633 yr-present (Figure 5). Zones 1 and 2 mark the transition between the dominance of early successional to late successional pollen types. Zone 1 was dominated by *Pseudotsuga* (20-35%), *Alnus rubra* (35-50%), *Pteridium* (15-35%), and *Asteraceae* (~5%). Other pollen types present at this time include *Poaceae* and *Polygonaceae*.

Cupressaceae begins to increase around 8,000 yr BP, occurring just before the eruption of Mt. Mazama (7,633 yr BP). Zone 2, after the eruption of Mt. Mazama, is characterized by the persistent presence of Cupressaceae (20-60%). Other abundant pollen types include *Tsuga heterophylla* (5-15%) and *Alnus rubra* (15-40%). Starting around 2,000 yr BP, there is a high turnover rate among Cupressaceae, *Pseudotsuga*, and *Tsuga heterophylla*. Cluster analysis further breaks Zones 1 and 2 into two and three sub-zones, respectively, that while not supported statistically by the broken-stick method are used here for discussion of the vegetation and fire history.

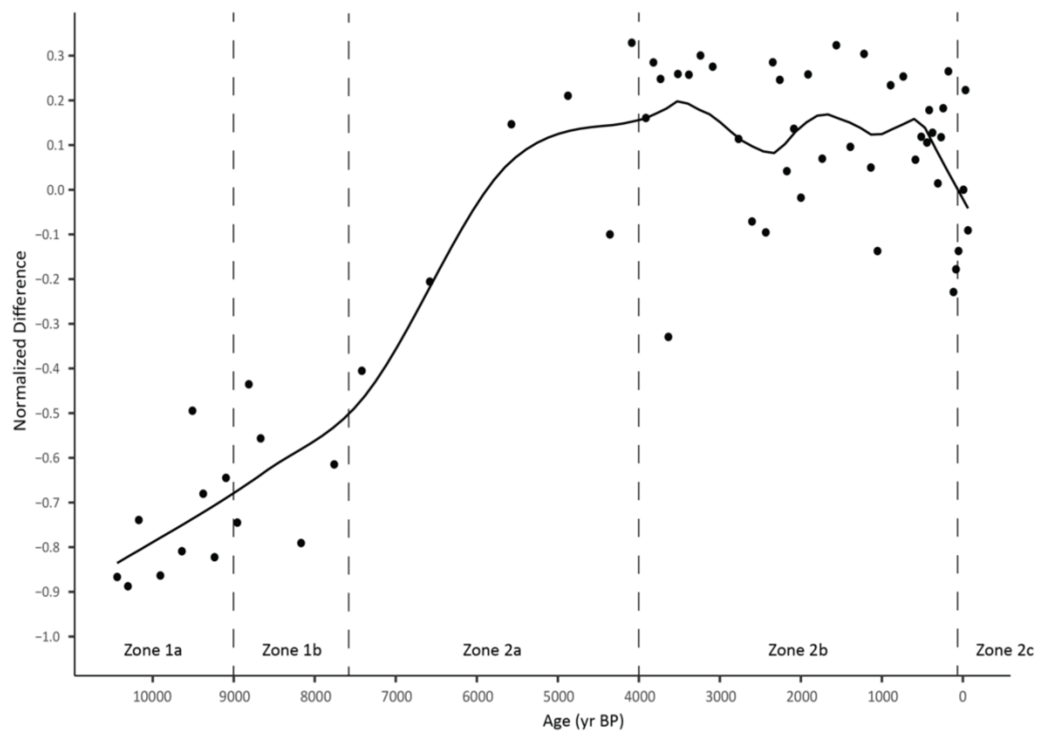

Figure 5. The normalized difference between early successional (state species) and late successional (state species) pollen percentages, calculated as (LS-ES)/(LS+ES). Stratigraphic subzones are overlayed to show how the zones correspond with change in vegetation structure. Zones 1a and 1b are characterized by early successional pollen types, while Zones 2a, 2b, and 2c have slightly more late successional than early successional pollen types. The line is a loess regression fitted to 60 pollen samples.

Pollen/CHAR correlation

Five pollen taxa were used in the correlation analysis between time after a peak in CHAR and pollen abundance (*Alnus rubra*, Cupressaceae sp. (corresponding to western red cedar), *Pseudotsuga sp.*, Pteridium, and *Tsuga heterophylla*) due to their relative abundance in the Shadow Lake pollen record, as well as their roles in successional vegetation structure (Figure 6). Due to the temporal distribution in samples counted for this core, and the focus on change over the past 2,000 years, there is a lower resolution for the early Holocene correlation analysis.

In the early Holocene, *Alnus rubra* is highest in abundance immediately following a fire (~47%) and 100 years after a fire event (~52%) and is lowest around 50 years after a fire event and begins to gradually decrease 100 years after a fire event. Cupressaceae sp. gradually increases following a peak in CHAR but remains relatively low (below 20%) for the early Holocene. *Pseudotsuga sp.* reaches its highest abundance (~32%) within the first 50 years following a fire, and then decreases in abundance slightly over the next 150 years. Pteridium is highest in abundance 100 years after a peak in CHAR. *Tsuga heterophylla* remains low in abundance for all of the early Holocene, staying around 5%.

During the late Holocene, *Alnus rubra* reaches its highest abundance (~48%) 50 years after a fire event and remains high until around 125 years post-fire. Cupressaceae sp. also remains high (~17-55%) for much of the 200 years after a CHAR peak; there is a slight decrease around 100 years. *Pseudotsuga sp.* is highest in abundance directly following a fire event, slightly decreases from 50-100 years post-fire, and then gradually increases over the next 100 years. *Pteridium* remains low for most of the late Holocene

(~1-11%). *Tsuga heterophylla* decreases slightly directly following a post-fire and then increases slightly and remains constant around 15-20% abundance.

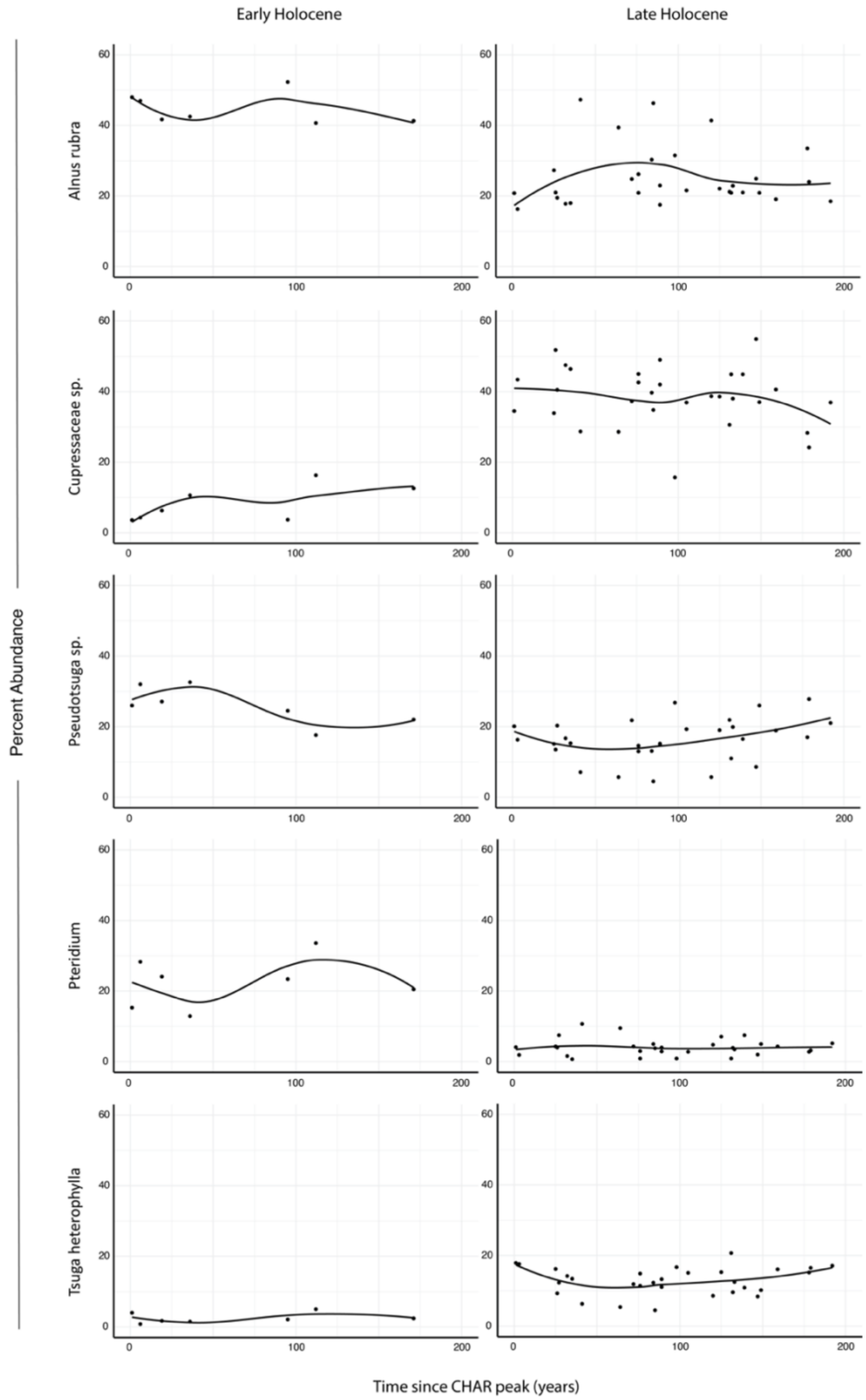

Figure 6. Loess regression of pollen abundances through time after a peak in CHAR. Time periods from the early Holocene (10,700-9,000 yr BP) and late Holocene (4,000 yr BP- present) were used for the comparison. The five pollen types examined were Alnus rubra*, Cupressaceae sp.,* Pseudotsuga sp.*, Pteridium, and* Tsuga heterophylla

CHAPTER V

DISCUSSION

This study encompasses the majority of the Holocene, providing an analysis of how vegetation structure and disturbance regime during the early Holocene compares to the late Holocene and into the present in central Puget Lowland. These data demonstrate the existence of similar disturbance regimes during the two time periods of interest, yet different successional states and paleoenvironmental conditions.

Early successional vegetation (10,700 yr BP-eruption of Mt. Mazama)

Zone 1a occurs from 10,700-9,000 yr BP, which aligns with a period of high fire frequency during the Early Holocene. There is a period of increased C:N and LOI around 9,700 years BP, indicating a high terrestrial organic matter input. Despite this, $\delta^{13}C_{org}$ remains relatively low (often less than -30‰) for the entirety of the Holocene, indicating low productivity within the lake and organic matter sources of lake-water CO_2 (Meyers and Teranes, 2001). This may be a result of low photosynthesis rates from low light penetration through the water column due to the tannin-rich lake water (form the neighboring bog) or the result of a N- or P-limited system.

Vegetation structure is in an early successional state for the entirety of this time period. More specifically, this period has high abundance of *Pseudotsuga sp.* and *Alnus rubra*, as well as grassy and weedy pollen types. The vegetation structure likely consisted of open stands of *Alnus rubra* and *Pseudotsuga sp.* due to the lack of diversity of other pollen types. Open forest stands allowed for terrestrial organic matter to be transported into the lake around 9,700 years BP.

Zone 1b (9,000-7,7633 yr BP) is a period of decreased fire frequency, but pollen types remain relatively similar to earlier years. Despite this decrease in fire events, vegetation structure remains in an early successional state. *Alnus rubra*, *Pseudotsuga sp.*, and Pteridium either persist through or establish soon after a fire event. Eventual increases (~50 years after a fire event) in Cupressaceae sp. show a complex forest stand and potential entrance into a late-successional type.

Despite this slight increase in a more diverse forest stand, Cupressaceae sp. (western redcedar) does not become abundant until just prior to the eruption of Mt. Mazama. The relatively low abundance of Cupressaceae and *Tsuga heterophylla* throughout this time period shows that vegetation structure in this region did not progress into later, closed successional types despite the decrease in fire disturbance events around 9,000 yr BP.

Other studies in the Puget Lowland area also have pollen records of early successional vegetation during this time period, particularly from 10,700-9,000 yr BP (Leopold et al., 1982; Cwynar, 1987; Crausbay et al., 2017). As found in this research, these nearby studies are typically abundant in *Pseudotsuga sp.*, *Alnus rubra*, and weedy pollen types (Tsukada & Sugita, 1982). The distinct increase in *Cupressaceae sp.* shown in this study is well-supported in studies from throughout the Puget Lowland (Leopold et al., 1982; Cwynar, 1987; Brubaker, 1991; Crausbay et al., 2017).

Steady-state forest and fire dynamics (7,633-4,000 yr BP)

Zone 2a begins after the eruption of Mt. Mazama and extends until ~4,000 yr BP. This period coincides with a period of low charcoal accumulation and concentration, and low fire frequency, likely due to an initial decrease in biomass following the eruption of Mt. Mazama. The increase in $\delta^{13}C_{org}$ at this time is attributed to a decreased input of dissolved organic carbon (DOC) into the lake. The Mazama tephra may have blanketed the soil and bog surrounding the lake, cutting off that supply of DOC, leading to a transition to increased use of atmospheric CO_2, ultimately increasing $\delta^{13}C_{org}$ values up to values of -25‰. At this time, $\delta^{15}N$ also decreased due to the tephra restricting nitrogen cycling. An alternate explanation, that $\delta^{13}C_{org}$ increased due to CO_2 limitation during a period of high productivity, is not supported by higher organic matter accumulation, lower C:N, or higher biogenic silica (inferred from an associated loss-on-ignition).

With less biomass to burn and therefore decreased fire frequency, forest stands began to increase in complexity, which is supported by an increase in *Cupressaceae sp.* and *Tsuga heterophylla*. This provides evidence for the transition into a late successional forest-type. Following the transition from early to late successional types, vegetation structure at the Shadow Lake study area remains relatively stable for the remainder of Zone 2a, allowing for the establishment of the old-growth forest types known today (Brubaker, 1991).

Other studies in this area do not show as marked of a decrease in both CHAR and fire frequency yet support the idea of the development of late successional forest types (Leopold, 1982; Tsukada & Sugita, 1982; Cwynar, 1987; Crausbay et al., 2017). Unlike other studies from the Puget Lowland, *Alnus rubra* remains relatively high in abundance at Shadow Lake throughout the Holocene.

Regional burning and rapid species turnover (4,000 yr BP-present)

Zone 2b occurs from 4,000 yr BP-1910 CE, or the start of widespread logging in the study area. This time period is characterized by an increase in fire frequency and charcoal accumulation, yet there is no lasting visible change in the pollen record. A distinct decrease in late successional pollen types and increase in early successional pollen types around 4,000 years BP indicates that the change in fire regime was reflected in the vegetation structure, but late successional types recover and persist for ~2,000 years, despite frequent fire occurring in the area.

Around 2,000 years BP, there is a marked increase in turnover rate between species (Cupressaceae sp., *Pseudotsuga sp.*, *Alnus rubra*, and *Tsuga heterophylla*). This supports the idea that the vegetation around Shadow Lake was largely impacted by individual fires within the source areas of pollen dispersed to the lake. Additionally, because there is no increase in fire frequency coinciding with the distinct increase in CHAR ~2,000 yr BP, it is likely that there was also an increase in regional fires that did not directly impact the Shadow Lake site.

The lack of an increase in magnetic susceptibility and C:N (Meyers & Teranes, 2001) indicates that the increase in CHAR is not due to an increase in soil erosion from the slope proximal to the core site. In addition, the increase in CHAR is unlikely due to a regional climate change, as prior studies have not identified a change to warmer and drier conditions at this time (Gavin & Brubaker, 2015). Thus, we conclude that increased CHAR is likely from indigenous fire management, burning at frequencies higher than can be detected at the sample resolution analyzed (a mean of 10.5 yr/cm after 2000 cal yr BP). While the soil in the area was not directly impacted, the high turnover rate in pollen types also supports the idea of changing forest stands and fire playing a prominent role in indigenous land management.

Studies show that the Coast Salish transitioned to a sedentary lifestyle beginning around 4,000 yr BP (Lepofsky et al., 2003). Increased regional burning can be attributed to the Coast Salish people's efforts of decreased conifer encroachment through the use of burning in order to promote huckleberry growth, a key food for both them and wildlife in the area (LeCompte-Mastenbrook, 2015). Conifer encroachment was prevented through the burning of other herbaceous types, such as *Pteridium* (LeCompte-Mastenbrook, 2015), which helps explain why Pteridium abundance was low (but increased slightly in Zone 2b) at this time despite more favorable conditions with an increase in fire frequency.

Zone 2c (~1910 CE-present) is described by a sharp increase in *Alnus rubra*, along with decreases in *Pseudotsuga sp.* and *Tsuga heterophylla*. Coinciding with this increase in certain pollen types, there were also decreases in abundance of Cupressaceae sp., *Pseudotsuga sp.*, and *Tsuga heterophylla*. The changes in pollen abundances coincide with the onset of widespread logging in the study site area (Shadow Lake IAVMP, 2016). The increasing presence of human influence is also shown in the C:N record, which rapidly drops to ~12 in the most recent sample, indicating an increase in nitrogen within the system. This is attributed to an increase in the amount of human and animal waste being deposited within the watershed.

Summary of vegetation and fire

The late Holocene is characterized by frequent fires similar to the early Holocene yet has a more diverse and rapidly changing forest type. Some early successional pollen types are either high in abundance immediately after a fire event (*Pseudotsuga*) or increase in abundance within 100 years after a peak in CHAR (*Alnus rubra*). Unlike the early Holocene, late successional pollen types do not decrease substantially during this time and become re-established in relatively high abundance around 100 years after a fire event.

The observed increase in CHAR around 2,000 yr BP is attributed to an increase in regional fires and indigenous land management. Increased regional burning is supported by other studies from the area that show increases in both Western US and PNW biomass burning (Walsh et al., 2015; Crausbay et al., 2017). The concept of increased pollen species turnover rate due to indigenous burning is also shown in prior studies from the Puget Lowland (Crausbay et al., 2017). While there is no direct impact of this increased fire period on the sediment characteristics at Shadow Lake, it is well-supported that the Puget Lowland underwent notable changes in biomass burning rates and vegetation structure starting around 2,000 yr BP (Walsh et al., 2015; Crausbay et al., 2017).

Another distinct time of vegetation change observed in the greater Puget Lowland region is the start widespread logging (~1910 CE). Like Shadow Lake, other studies from the area show sharp increases in *Alnus rubra* (Davis, 1973; Tsukada & Sukita, 1982; Crausbay et al., 2017). With the start of logging, vegetation structure began returning into an early successional state (Figure 5) due to an increase in disturbance frequency and therefore decline in stand diversity.

CHAPTER VI

CONCLUSIONS

In this study, it was found that during the early Holocene, the Shadow Lake area experienced high fire frequency and was characterized by vegetation structure that remained in an early successional state despite a decrease in fire frequency in the latter part of the early Holocene. Following the eruption of Mt. Mazama and throughout the mid Holocene, there were infrequent fire events and vegetation began to increase in complexity. These events coincide with the establishment of old-growth forest in the region. Beginning in the late Holocene, fire frequency increased once again, followed by an increase in charcoal accumulation, indicative of an increase in regional burning. Despite this increase in fire frequency, vegetation progressed into a late successional state, with stand complexity continuing to become more complex with more taxonomic evenness. This time period aligns with a period of cultural transition of the Coast Salish people and a more sedentary lifestyle. Widespread logging and increase human land modification (1910-1950 CE) are supported by an increase in the abundance of *Alnus rubra* and increased nitrogen within the lake watershed. Many of these findings are well-supported in other studies done within the central Puget Lowland region (Leopold, 1982; Tsukada & Sukita, 1982; Cwynar, 1987; Crausbay et al., 2017).

Due to the contrasting vegetation structure in the early and late Holocene, it can be said that vegetation did not react to frequent fire disturbance similarly between the two time periods. The regional climate likely influenced post-fire successional trajectories, limiting the return of the early-Holocene vegetation type during the increase in fire during the late Holocene. Even further, increasing human presence and modification of land lead to marked changes within the pollen and charcoal records and lake productivity. The relationship among vegetation, fire frequency, climate, and human influence is nuanced and location dependent. Because of this, it is important to recognize that these relationships are constantly changing and may not reflect patterns observed in the past as we progress into the future.

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