THE ROLES OF HUMANS AND CLIMATIC VARIATION ON THE FIRE HISTORY OF SUBALPINE MEADOWS - MOUNT RAINIER NATIONAL PARK (WASHINGTON)

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ABSTRACT

THE ROLES OF HUMANS AND CLIMATIC VARIATION ON THE FIRE HISTORY OF SUBALPINE MEADOWS - MOUNT RAINIER NATIONAL PARK (WASHINGTON)

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With the creation of Mount Rainier National Park (MORA) in 1899 came the active management of the park's landscapes and a heavy emphasis on fire suppression. Today managers at MORA have made returning fire to the park's landscapes a top priority. In order to achieve this goal, and to make more informed decisions in regard to the application of fire, land managers at MORA need to better understand past fire occurrences and the drivers of fire activity on the mountain. To address this problem, analysis of macroscopic charcoal preserved in lake sediments was used to reconstruct the fire history for Shadow, Sunrise, and Little Sunrise Lakes along the Sunrise Ridge of MORA. Reconstructions for these sites show that during the late Pleistocene fire activity on the Sunrise Ridge was low. Transitioning into the early Holocene, fire activity increased and remained high from the start of the mid-Holocene through ca. 6,000 cal yr BP and then declined through ca. 4,500 cal yr BP. From the start of the late Holocene, fire activity increased substantially through ca. 2,000 cal yr BP,

decreased through ca. 1,000 cal yr BP, and then increased to present. The similarity between the Sunrise Ridge records and other sites in the Pacific Northwest suggests that broad-scale climatic variability, such as changes in annual insolation and the El Niño–Southern Oscillation, were likely the primary driver of fire activity on Mount Rainier during the Holocene. While it is possible that human-set fires also influenced the fire reconstructions, results from the lakes along the Sunrise Ridge do not show clear evidence of anthropogenic burning. In terms of future fire activity, projected increases in summer temperature and decreases in summer precipitation will most likely lead to a higher occurrence of drought and subsequent fire at MORA.

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CHAPTER I

INTRODUCTION

Mount Rainier National Park (MORA) was created by Congress on March 2, 1899, with the intent of setting aside areas of outstanding scenic and scientific value for the enjoyment of present and future generations (Mount Rainier National Park, 2013). Today, 1.5-2 million people visit MORA each year, many of whom travel to the park to specifically see the subalpine meadows like those at Sunrise and Paradise (Mount Rainier National Park, 2013) (Figure 1).

Figure 1. Paradise Meadows. Photo Courtesy of MORA

With the creation of MORA in 1899 came the active management of the park's landscapes and a heavy emphasis on fire suppression. Throughout the 20th century, park staff actively sought to extinguish all forest fires within the boundaries of MORA (Dombeck, Williams, & Wood, 2004). Up until 1988, land managers at MORA focused only on the suppression of wildfires and ensuring reasonable protection of park structures and facilities (MORA Fire Control Plan, 1979; MORA Fire Management

Plan (FMP), 1988). Park managers recently concluded that these activities have led to a loss of biodiversity and vigor in vegetation and wildlife (MORA FMP, 2005). To combat this loss, managers at MORA have made returning fire to the parks landscapes a top priority. (MORA FMP, 2005). In order to achieve this goal, and to make more informed decisions in regard to the application of fire, land managers at MORA need to better understand the fire history of the mountain.

Today, very little is known about the long-term fire history of MORA. Only a handful of individual fire records have been developed that examine changes in fire activity in response to climatic and anthropogenic influences. Dunwiddie (1986) reconstructed fire activity for the Paradise area of MORA and Tweiten (2007) reconstructed fire from a record obtained from Buck Lake in the northeast quadrant of the park. Tweiten (2007) found an increase in fire occurrence during the late Holocene. This increase was not noted by Dunwiddie (1986) at Paradise and is somewhat perplexing because it occurred during a period thought to be marked by a wetter, cooler climate (Dunwiddie, 1986; Graumlich & Brubaker, 1986; Tweiten, 2007). Tweiten (2007) hypothesized that the spike in fire at Buck Lake during the late Holocene could be attributed to anthropogenic burning. However, it is also possible that greater climate variability is the cause of increased fire during the late Holocene in the Buck Lake record. It is apparent that further research is needed in order to better understand the long-term fire history at MORA and the impacts of climate and human land use on that history.

Purpose and Objectives

The purpose of this research was to use fossil charcoal preserved in lake sediments to reconstruct the Holocene (past ~11,000 years) fire history for the Sunrise Ridge area of MORA. From these records, shifts in fire frequency, mean fire intervals (MFI), charcoal accumulation rates (CHAR), significant fire events and fire event magnitude were determined. Once reconstructed, these fire histories were used to address the following research questions:

1) How did fire activity change during the Holocene on the Sunrise Ridge of MORA?

2) What factors influenced this past fire activity (e.g., climate variability, human land use, etc)?

Given the above research questions, the objectives for this thesis were:

1) to use macroscopic charcoal analysis of lake sediment cores to reconstruct the fire history of the Sunrise Ridge area of MORA and

2) to compare the reconstructed fire history of the Sunrise Ridge area of MORA to existing local and regional climatic and archaeological records in order to assess their relative influence on those histories.

Significance

This research is significant for several reasons. First, this research will add to the body of knowledge of past fire activity in the southern Cascade Range. Currently, only a handful of long-term fire records exist. This research will help to fill that gap. Second, results from this research will help in better understanding drivers of past fire activity in the Cascades. Our current knowledge is limited by the number of reconstructed records and the ability to compare these records to possible drivers such as anthropogenic burning and climatic variability. Finally, results from this research will aid land manager at MORA in making long-term fire management decisions. The current fire management plan for MORA is based upon records that only span the past 2,000 years (MORA FMP, 2005). This thesis provides a much longer record of fire activity for the mountain.

CHAPTER II

LITERATURE REVIEW

Fire-History Reconstruction

The goal of fire history reconstruction is to develop long-term records of fire activity for a specific geographic area. These records make it potentially possible to examine how past climatic variability, reorganization of vegetation, and human use of fire possibly affected prehistoric fire regimes. Such insights are critical for understanding the legacy of past fires in present ecosystems, as well as shifts in fire that may accompany projected climate changes as a result of increased atmospheric greenhouse gas concentration (Bartlein et al., 1998; Overpeck et al., 1997).

Long-term fire history information is derived primarily from two types of data: (1) fire-scarred tree-rings and stand-age data, and (2) charcoal data from sediment records (Agee, 1993; Patterson, Edwards, & Maguire, 1987; Whitlock & Larsen, 2001). Tree-ring data and stand-age information provide short-term reconstructions of fire events, usually spanning the last 400 years or less (Agee, 1993). Fire-scars on tree-rings register fire-events that were not lethal to the tree, whereas stand establishment dates identify the minimum age of the last stand-replacing fire (Whitlock & Larsen, 2001).

The second method of fire history reconstruction, and the primary focus of this thesis, involves the examination of paleoenvironmental data preserved in sediments, focusing specifically on lake sediments. Lake sediments serve as repositories of proxy data recording past environmental conditions within a watershed. Charcoal is introduced into a lake through air transport and inwash from streams and drainages

(Whitlock & Larsen, 2001). Intervals in sediment cores for which charcoal abundance exceeds a prescribed background level are considered evidence of a fire episode (Whitlock & Larsen, 2001). The time series of charcoal peaks from lake-sediment records provide information on long-term variations in fire frequency. In recent studies, charcoal analysis has proven to be reliable, relatively simple, and cost effective (Gavin, McLachlan, Brubaker, & Young, 2001; Long, Power, & Bartlein, 2011; Long, Whitlock, Bartlein, & Millspaugh, 1998; Walsh, Whitlock, & Bartlein, 2008).

Both tree-ring and lake-sediment records of past fire activity have strengths and weaknesses. Tree-ring records offer a high level of spatial resolution in fire reconstructions. Tree-ring records are also useful to distinguish between locations that experienced high-severity and low-severity fires (Agee, 1993). Although tree-ring methods extend back to the age of the oldest living tree, this time span is not long enough to capture major changes in vegetation and climate. Tree-ring records are also biased toward low-severity fire events that scar trees but do not kill them (Agee, 1993).

Charcoal records from lake sediments reconstruct past fires with less temporal and spatial precision than tree-ring records but are able to extend the fire record much farther into the past (Millspaugh & Whitlock, 1995). Modern studies have shown that charcoal accumulation into a lake continues for a few years after a fire because of transportation and redeposition of secondary charcoal within the watershed and the lake (Millspaugh & Whitlock, 1995). This process tends to blur the exact age of a fire. Additionally, the charcoal deposited in a lake may represent more than one fire within the watershed or fires from more than one year (Millspaugh & Whitlock, 1995). As a result, lake sediment researchers refer to a fire episode as one or more fires occurring in the time interval of interest, rather than an individual fire (Clark, Lynch, Stocks, & Goldammer, 1998; Gardner & Whitlock, 2001; Long, Whitlock, Bartlein, & Millspaugh,1998; Millspaugh & Whitlock, 1995).

Fire reconstructions based on charcoal records lack the spatial specificity of dendrochronologic records, but they offer an opportunity to examine the role of fire over several millennia and during periods of major vegetation and climatic change (Long et al., 1998). Records of macroscopic charcoal particles (>125mm) are interpreted as resulting from a fire within the lake’s watershed, based on empirical evidence that particles of this size do not travel far from their source (Clark et al., 1998; Gardner & Whitlock, 2001; Long et al., 1998; Millspaugh & Whitlock, 1995). In addition, local fires upwind of the lake are better recorded than those downwind (Gardner & Whitlock, 2001; Millspaugh & Whitlock, 1995). Overall, macroscopic charcoal analysis is relatively simple, cost effective, and is currently the best suited method for reconstructing long-term fire records (Ali, Higuera, Bergeron, & Carcaillet, 2009).

Tephra

Tephra layers (i.e., volcanic ash deposits) play a critical role in dating and creating age models for lake sediment cores (Eden & Froggatt, 1996). Dates for each deposit are typically established via radiocarbon dating or tree-rings and can then be used to assign specific dates for tephra. These dates are then used along with radiocarbon dates from plant macrofossils to create an age model for each lake core. On

Mount Rainier, there are 22 known tephra layers with associated radiocarbon or dendrochronological-based dates deposited from distinct volcanic eruptions across the Cascades. Each layer has a unique chemical fingerprint that allows the deposit to be identified across the area affected by fallout (Sisson & Vallence, 2009).

Mullineaux (1974) identified, dated, and named the tephra deposits present on Mount Rainier. Of those 22 layers, 12 originated from Mount Rainier, 10 from Mount St. Helens and 1 from Mount Mazama (currently Crater Lake) (Mullineaux, 1974). Sisson and Vallance (2007), through microprobe analysis, were able to identify an additional 10 - 12 tephra layers, all originating from Mount Rainier. Furthermore, they were able to greatly refine dates associated with tephra layers described by Mullineaux (1974). In the Sunrise Ridge area, the following tephra layers are present and easily discernible: Mount St. Helens-W, Mount Rainier-C, Mount Rainier-P set, Mount St. Helens-Yn, Mount Rainier-F, Mount Rainier-D, Mount Rainier-A, Mount Mazama-O, and Mount Rainier-R (Figure 2).

The rapid deposition of tephra on a landscape can have detremental affects to forest communities (Zoble & Antos, 1997). Increased fuel as a result of vegetation kill by tephra deposits can lead to high-magnitude fire episodes (McGlone, 1981). Research by Giles, Newnham, Lowe, and Munro (1999) found that changes in vegetation occurred immediately following the deposition of a major tephra layer in New Zealand.

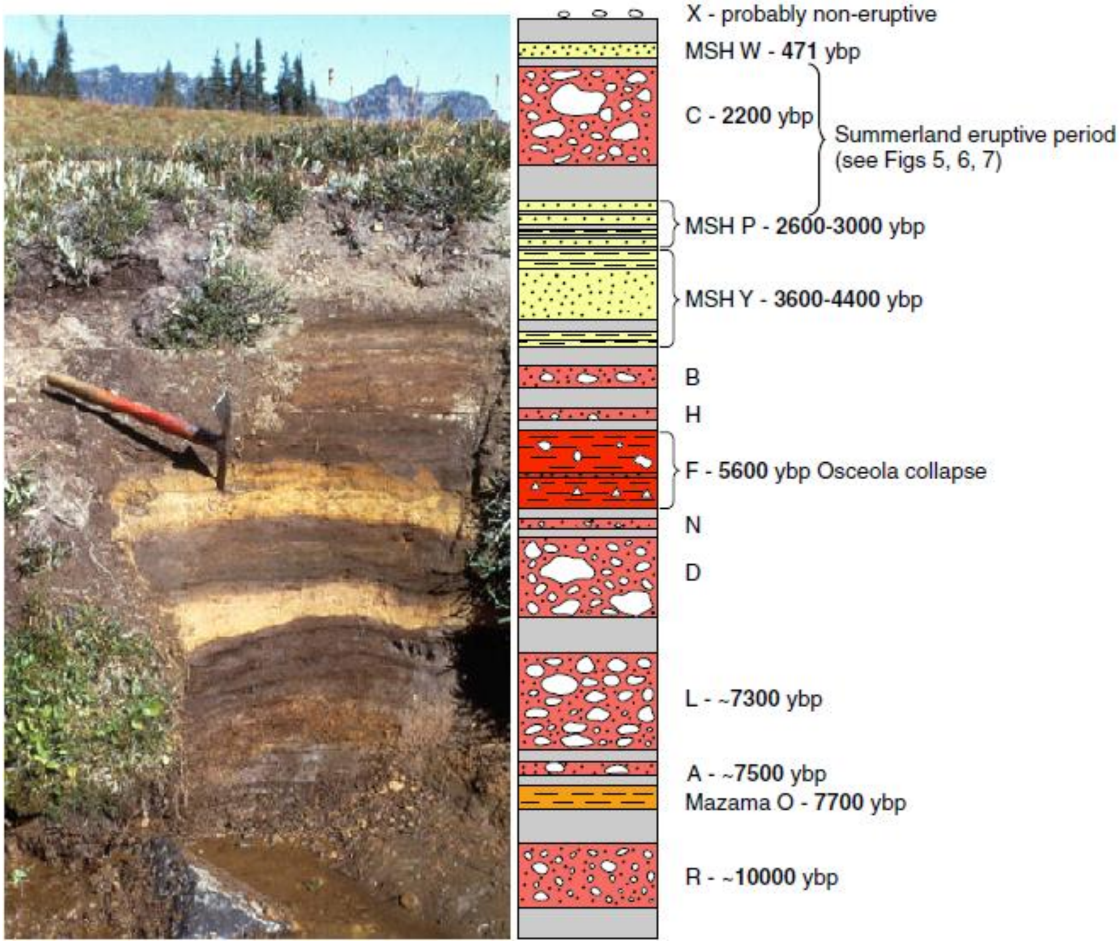

Figure 2. Tephra Layers on Mount Rainier. Average calibrated ages based on several radiocarbon dates. Images from Mullineaux (1974) and Sisson and Vallance (2007).

As a result of the eruption, some taxa became at least temporarily extinct. Antos and Zobel (1986) examined vegetation response in tephra-fall zones of varying depth at Mount St. Helens. They found that the initial impact of ash fall on herb and shrub communities were significant, and vegetation recovery to pre-eruption conditions required more than 20 years. Long, Power, and Bartlein (2011) found in the Central Cascades of Oregon a decrease in nonarboreal vegetation immediately after tephra deposition. The authors suggest that a high-magnitude fire episode may have been triggered by increased fuel as a result of vegetation killed by the Rock Mesa tephra deposition. They concluded that fire episodes, possibly in conjunction with tephra fall events, provided a catalyst for short-term changes in forest composition.

PNW and MORA Fire Records

Cascade Mountains

Studies that use macroscopic charcoal from lake sediments to reconstruct long-term fire histories have been conducted in limited numbers from areas across the PNW, and even fewer from the Cascade Mountains. However, many of these studies provide valuable insight into the way in which fire activity varied during the late Pleistocene and Holocene in the PNW, as well as possible reasons for those changes.

Hallet, Lepofsky, Mathewes, and Lertzman (2003) reconstructed an 11,000 year record for Frozen Lake and Mount Barr Cirque Lake in the North Cascades of British Columbia. They found that fires were frequent between ca. 11,000 and 8,800 calibrated year before present (cal yr BP), but fire frequency then decreased throughout the remainder of the early Holocene. During the mid-Holocene, fire frequency continued to decline reaching its minimum value of 2 episodes/1,000 yr around ca. 6,000 cal yr BP. Fire frequency then increased through ca. 4,200 cal yr BP with a peak of 6.9 fire episodes/1,000 yr, decreased between ca. 3,500 to 2,400 cal years BP (low of 4.8 episodes/1,000 yr), and then increased between ca. 2,400 and 1,300 cal yr BP with a high of 6.4 episodes/1,000yr. A sharp decline in fire frequency occurred from ca. 1,300 cal yr BP to present day.

Pritchard, Gedalof, Oswald, and Peterson (2009) reconstructed a 10,500 year record for Panther Potholes in the heart of North Cascades National Park. They found that fire frequency varied there throughout the Holocene, with frequent fires in the early Holocene. The highest fire frequency for their record (9 fires episodes/1,000 yr) occurred at ca. 8,500 cal yr BP. After ca. 8,000 cal yr BP, fire frequency markedly declined. During the mid-Holocene, fire frequency remained low and in the late Holocene, fires again became more frequent with higher fire frequency between ca. 3,000 and 2,000 cal yr BP and ca. 1,000 and 500 cal yr BP.

Spooner, Brubaker, and Foit (2008) working in North Cascades National Park reconstructed a 14,000 year record from Ridley Lake. They found that charcoal accumulation rates (CHAR) were low from ca. 14,000 to 8,500 cal yr BP. After that time, CHAR values increased slightly but remained low for the mid-Holocene. During the late Holocene, charcoal input remained relatively low and steady except for peaks in CHAR at ca. 3,000 cal yr BP and 500 cal yr BP.

Cwynar (1987) reconstructed a 14,000-year old record for Kirk Lake in the foothills of the Washington North Cascades. He found high charcoal concentration rates from ca. 14,000 through 9,400 cal yr BP, with a gradual decrease in charcoal concentration throughout the early Holocene. A continued decrease in charcoal concentration occurred until ca. 7,500 cal yr BP. During the mid-Holocene, charcoal concentration slowly rose through ca. 6,000 cal yr BP. After that time, charcoal concentration was not reconstructed for Kirk Lake.

Long, Power, and Bartlein (2011) reconstructed a 12,000-year-old fire record for Tumalo Lake on the eastern flank of the Cascade Range in Oregon. From ca. 12,000 to 9,200 cal yr BP, fire episodes occurred on average every 160 years. Beginning ca. 9,200 cal yr BP, fire fire-episode frequency declined. During the mid-Holocene, a shift to longer fire-episode intervals, averaging around 210 years, was recorded. During the late Holocene, fire frequency increased starting ca. 3,000 cal yr BP. A peak of 8 fire episodes/1,000 yr occurred ca. 1,400 cal yr BP, and then declined to present day values of 3 fire episodes/1,000 yr.

Taken together, these high-elevation records for the Cascades show remarkably similar trends in terms of past fire activity and timing of increases and decreases in fire activity. These findings suggest that broad scale driver's heavily influenced fire activity in the PNW (Gavin, Hu, Lertzman, & Corbett, 2006; Whitlock, Higuera, McWethy, & Briles, 2010). These records along with those from past research on MORA will be further examined and compared to results for the Sunrise Ridge in the discussion section.

MORA

At MORA, prior to this research, only three studies utilizing macroscopic charcoal analysis to reconstruct long-term fire histories had been conducted (Dunwiddie, 1986; Sugita, 1990; Tweiten, 2007). Dunwiddie (1986) reconstructed a 6,000 year fire history for the Paradise area of MORA. Lake sediment cores from Jay Bath, Log Wallow, and Reflection Pond 1 were used for this reconstruction (Figure 3).

These three lakes are located close to the boundary between the Pacific silver fir (*Abies amabilis)* and mountain hemlock *(Tsuga mertensiana)* zones.

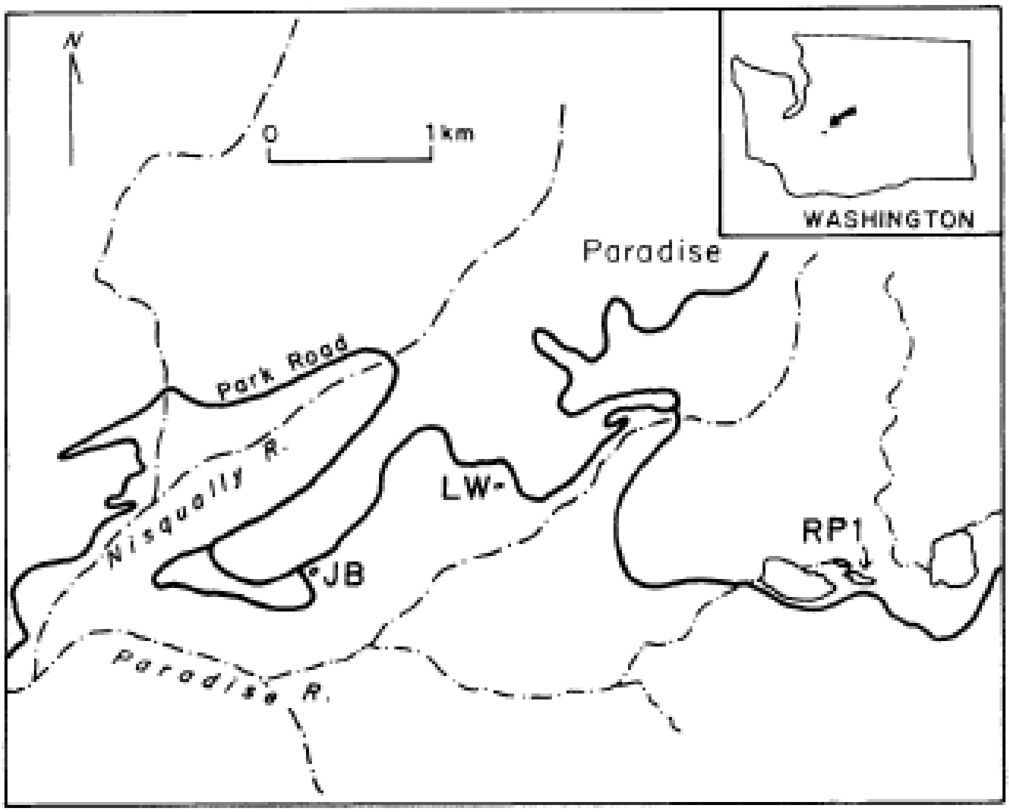

Figure 3. Location of lakes cored by Dunwiddie on Mount Rainier. Jay Bath (JB), Log Wallow (LW), and Reflection Pond 1 (RP1) (Dunwiddie, 1986).

Elevations for the sites range between 1,310 to 1,480 m. For Jay Bath, charcoal concentrations were highest during the mid-Holocene, peaked ca. 5,000 cal yr BP, and then declined after that. In the late Holocene, fire activity was almost nonexistent. For Log Wallow, charcoal concentrations were low and variable (several peaks of 1 and 2 fragments/ml) during the mid-Holocene, but then increased substantially starting ca. 4,900 cal yr BP. Charcoal concentration peaked 4-6 cm below the MSH-Yn tephra (ca.

3,600 cal yr BP). On top of the MSH-Yn layer, charcoal concentration rapidly decreased and remained generally low throughout the late Holocene. At Reflection Pond 1, charcoal concentration was low and variable during the mid-Holocene and peaked several centimeters below MSH-Yn. On top of MSH-Yn, charcoal concentration remained low and variable until a peak at ca. 500 cal yr BP; charcoal concentration then decreased until the present. These peaks in charcoal concentration in the Log Wallow and Reflection Pond 1 cores below the MSH-Yn layer probably represent one or more fires that occurred roughly 200 years prior to the MSH-Yn eruption (Dunwiddie, 1986).

Sugita (1990) reconstructed the fire history for the northwest portion of MORA for the past 830 years. Charcoal particles from sediments obtained from alpine bogs in close proximity to Mowich Lake were examined. Sugita determined that major fire events occurred in AD 1188, 1300, 1630 and 1857 due to peaks in charcoal concentration and associated radiocarbon dates (Sugita, 1990). These results provide data on fire episodes over the past 1,000 years, but do not address fire severity or magnitude. They also do not provide a long enough record to adequately examine long-term changes in fire activity at MORA.

Tweiten (2007) reconstructed a 7,000-year long record of fire activity at Buck Lake, located in the Sunrise area of MORA along the boundary between subalpine forest and meadow. His results show that fire frequency remained low from ca.7,000 to 6,500 cal yr BP. Fire frequency increased significantly between ca. 6,500 and 6,700 cal yr BP, but then remained low throughout the rest of the mid-Holocene. During the late Holocene, fire frequency increased, with the highest fire-return interval occurring ca.

2,800 cal yr BP, and more regular fire events since that time. For the past 1,000 years, three fire episodes occurred at Buck Lake, giving an average fire-return interval of 430 years for the time period.

Tweiten's study is of particular importance because the charcoal record for Buck Lake shows a dramatic increase in fire episodes after ca. 2,800 cal yr BP which in terms of past climate reconstruction, seems to be opposite of expected results. Unlike Tweiten (2007), Dunwiddie (1986) found no significant increase in fire activity during the late Holocene on Mount Rainier. Dissimilarities in the two reconstructions could be due to difference in methods and techniques utilized in both studies or they could be due to higher fire activity near Buck Lake. Buck Lake is located near an excavated archaeological sites with dated stratigraphy. Tweiten (2007) suggested that the timing of the fire frequency increase in the Buck Lake record may indicate that Native Americans were the primary ignition sources for the drainage during the last several thousand years. While one charcoal record is not enough to confirm the impacts of potential drivers of fire activity (including human impacts) on the fire history of subalpine meadows at MORA, it does provide an opportunity to compare nearby sites to see if similar results as for Buck Lake are found. This comparison will provide better insight into past fire activity as a whole for the mountain.

Natural Controls of Fire Activity

Climate Impacts on Fire

Climate is an important variable that impacts the frequency and magnitude of fires in the PNW (Hessl, McKenzie, & Schellhaas, 2004). Historically, annual variation in climate (e.g., hotter/drier) appears to have been an important driver of fire activity (Heyerdahl, Brubaker, & Agee, 2002). Climate variability has been shown to considerably impact snow accumulation, rainfall, and drought (including both long and short-term), as well as the occurrence of large outbreaks of forest disease, insect infestations, large areas of wind-thrown timber, large areas of ice damaged trees, and the persistence of fire weather (MORA FMP, 2005).

Of these conditions, summer drought is most closely linked with the occurrence of major fire years in the PNW (Hessl et al., 2004). Summer drought conditions are important in the PNW because the fire season occurs in late summer (August – September and even into October) rather than spring or early summer, and there is ample time for high temperatures to deplete moisture generated by winter or spring conditions, even in large-diameter fuels (Hessl et al., 2004). Severe summer droughts have occurred in the PNW in the past and more recently have been tied to the occurrence of El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) events (Cayan et al., 1999; Graumlich, 1987; Hamlet & Lettenmaier, 1999). Specifically, drought has been tied to El Niño years in the PNW (Hamlet & Lettenmaier, 1999).

Spring snow pack tends to be shallow in the PNW during El Niño years due to lower than average winter/spring precipitation and warmer than average spring temperatures (Cayan, Redmond, & Riddle, 1999). Shallow snow packs are likely to melt earlier, resulting in drought and in longer periods when fires could ignite and spread compared to years with deeper snow packs. During La Niña years in the PNW, snow pack is deeper than average and fire activity is suppressed (Heyerdahl et al., 2002).

The influence of the Pacific Decadal Oscillation (PDO) on precipitation in the PNW is similar to that of ENSO and is evident in modern records of snow pack and stream flow (Cayan et al., 1999; Hamlet & Lettenmaier, 1999) and in historical reconstructions of temperature (Minobe, 1997). Furthermore, there is evidence to suggest that despite effective fire suppression, decadal variation in 20th-century fire extent in the PNW may have been influenced by variation in the PDO (Mote, Keeton, & Franklin, 1999).

PNW Climate Variability

Climatic shifts in the PNW are relatively well known for the last 20,000 years. Large-scale controls of climate variability in the region include the size and position of the Laurentide and Cordilleran ice sheets and variations in the amplitude of the seasonal cycle of insolation (Bartlein et al., 1998; Thompson, Whitlock, Bartlein, Harrison, & Spaulding, 1993). The late Pleistocene was marked by the retreat of the Cordilleran ice sheet and establishment of the current interglacial period (Booth, Troost, Clague, & Waitt, 2003). With the retreat of the Cordilleran ice due to a warming climate during the

Bølling-Allerød interstadial, lower elevation passes in the Cascades, such as Snoqualmie, opened (Burtchard & Swinney 2004). Starting around ca. 13,500 cal yr BP, with increasing insolation, ice sheets in the PNW re-advanced (the Sumas stade of the Fraser Glaciation). This cold period, known as the Younger Dryas, lowered permanent snow levels in the PNW (Broecker et al., 2010).

During the early Holocene (11,000 – 7,000 cal year BP), glacial ice retreated rapidly after ca. 10,000 cal yr BP and alpine glaciers across the Cascades were within present glacial limits by the start of the period (Heine, 1998; Samolczyk et al., 2010). Summer insolation during the period was 8% higher and winter insolation was 8% lower than at present at 45°N latitude (Figure 4) (Berger & Loutre, 1991). Increased seasonality led to higher summer temperatures and decreased effective moisture, presumably causing more summer drought and colder winters than at present (Thompson et al., 1993; Whitlock & Bartlein, 1993). Expansion of xerophytic (dry-adapted) communities, higher alpine treeline, and lower lake levels and stream activity support this shift (Mann & Hamilton, 1999; Whitlock, Shafer, & Marlon, 2000).

During the mid-Holocene (7,000-4,000 cal years BP), summer insolation continued to decrease and winter insolation continued to increase to present day values. Cooler and effectively wetter conditions than before were established in the PNW during the mid-Holocene as evidenced by increased mesophytic (wet adapted) vegetation and downslope shifts in alpine treeline (Thompson et al., 1993). For the North Cascades, moist subalpine forest began to establish around ca. 5,500 cal yr BP (Pellatt, Smith, Mathewes, & Walker, 1998).

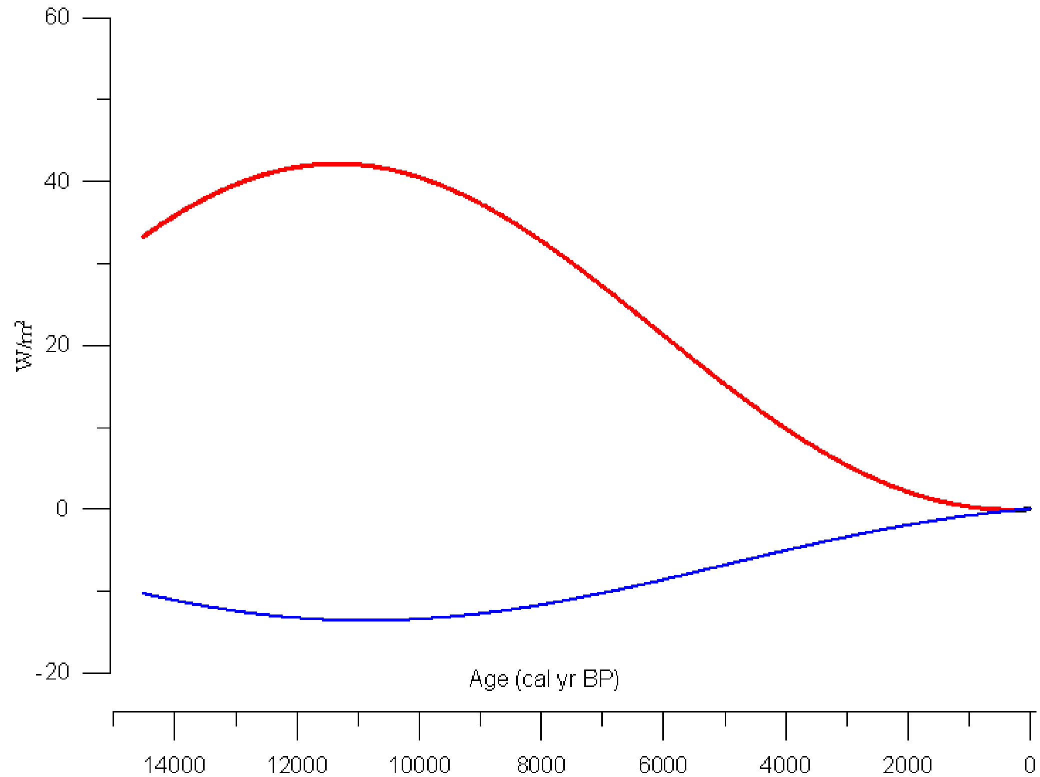

Figure 4. Northern hemisphere summer (red) and winter (blue) insolation anomoly at 45°N. Data from Berger and Loutre (1991).

During the late Holocene (ca. 4,000 cal yr BP- present), precipitation increased and temperatures gradually declined with minimum temperatures and maximum precipitation between ca. 2,500 and 1,600 cal yr BP (Pellatt et al., 1998). Cooler and wetter conditions accompanied widespread neoglaciation which reached full development after ca. 3,000 cal yr BP (Mann, Bradley, & Hughes, 1999). The end of the late Holocene in the PNW saw several periods of short-term variations in climate. Between ca. 900-600 cal yr BP, the Medieval Warm Anomaly (MWA) was marked by a warmer and dryer climate (Gates, 1993). The Little Ice Age (LIA) ca. 550–150 cal yr BP saw the return of cooler temperatures and glacial activity in the PNW and was the coldest of a series of cool oscillations in the late Holocene (Davis, 1988; Gates, 1993; Luckman, 1994). During the LIA, glaciers in the Spearhead and Fitzsimmons ranges in southwest British Columbia expanded to their maximum extents (Osborn et al., 2007). Across the rest of the Cascades, there was also relatively extensive glacier cover (Samolczyk et al., 2010). Both the MWA and LIA are depicted in tree-ring records from the PNW (Graumlich & Brubaker, 1986). The exact causes for both are not well known, but reduced solar output and increased global volcanic activity have been suggested as possible causes (Samolczyk et al., 2010).

MORA Climate Variability

The climate history of MORA is known from tree-ring records, alpine-glacial ice cores, pollen records, and geological evidence of glacial retreat and expansion. With the retreat of the Cordilleran ice sheet ca. 14,000 cal yr BP, open forest-tundra habitats became established on the lower to mid-elevation slopes of Mount Rainier (Heine, 1998). Following these relatively warmer conditions, ice readvanced down the major river valleys ca. 13,500 cal yr BP, a period known as the McNeely drift (Sumas Stade in the Puget Trough). This lowered snowline to about 1,800 m (Heine, 1998). Above 1,800 m most of Mount Rainier’s major landforms were under perpetual snowpack or were subjected to a loss of vegetation due to extended snowpack and frost heaving (Crandell & Miller, 1974). The Younger Dryas (ca. 12,900-11,600 cal yr BP), a period of cold climatic conditions and drought, did not produce glacial advances on Mount Rainier and is most likely due to lack of available moisture, and cold conditions on the mountain at the time (Davis, Menounos, & Osborn, 2009; Menounos, Osborn, Clague, & Luckman, 2009). Instead, glaciers retreated (Heine, 1998). Following the Younger Dryas, subsequent warmer, moist, conditions led to glacial advances ca. 10,900 – 9,950 cal yr BP (Heine, 1998). As the ice retreated ca.10,000 cal yr BP, the open forest-tundra habitats that retreated downslope during glacial advances again moved upslope (Heine, 1998).

Climate reconstructions for Mount Rainier show that the mid-Holocene was marked by a warm period referred to as the Holocene Climate Optimum (HCO) (Burtchard, 1998) (Figure 5). Sources for this climate reconstruction include plant macrofossil and pollen data, interpretive summaries from Mount Rainier, the Cascades and the surrounding region, and synchronous North Cascade and Mount Rainier glacial advance-retreat patterns. Starting around ca. 6,000 cal yr BP, the HCO gave way to a period of generally cooler and moister conditions. On Mount Rainier, as well as the rest of the Cascades, upper elevation forest cover retreated downslope to approximately present elevations with an increase in the expanse of alpine tundra, and subalpine parklands (Burtchard & Swinney, 2004).

During the late Holocene, oscillating but generally cooler and moister climatic conditions set in (Crandell & Miller, 1974). The Burroughs Mountain glacial advance started ca. 3,400 cal yr. B.P and was the largest glacial advance of the late-Holocene. The end of the advance occurred ca. 2,200 cal yr B.P. (Crandell & Miller, 1974). Dunwiddie (1986) found that neoglacial moraines from Mount Rainier dating from ca. 2,800-2,600 cal yr BP supported Crandell and Miller’s (1974) findings. He estimated that the Burroughs Mountain advance would have resulted in a shorter growing seasons and a reduced fire frequency. Forest density in the lowlands and western foothills, if not modified by fire, advanced to higher seral stages with a reduction in low seral stage species (i.e. a reduction in open grasslands) (Brutchard, 2007).

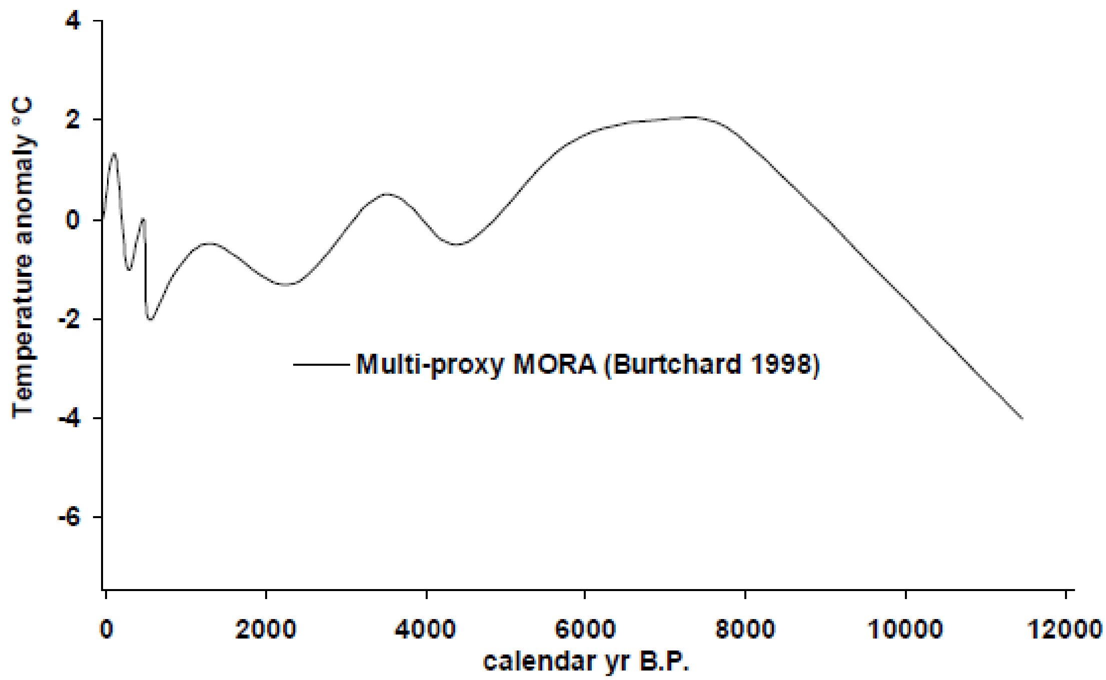

Figure 5. Mulit-proxy based temperature record for MORA. Figure from Hekkers (2010).

On Mount Rainier, toward the end of the late Holocene, climatic conditions remained relatively cool and included an acute glacial advance between about ca. 600 and 150 years ago (i.e., the Little Ice Age) (Crandell & Miller, 1974). Crandell and Miller (1974) believed the interval between the Burroughs Mountain and Little Ice Age advances to be as short as 1,200 years. Graumlich and Brubaker (1986) using tree-ring based reconstructions found temperatures between ca. 360 to 110 cal yr BP (1590 and 1900 AD) to be approximately 1 °C lower than those of the 20th century. According to their research, cool episodes occurred from ca. 350 to 300 cal yr BP (1600 to 1650 AD), from ca. 250 to 190 cal yr BP (1700 to 1760 AD) and from ca. 90 to 50 cal yr BP (1860 to 1900 AD). The end of the Little Ice Age in the PNW began with an increase in temperatures starting around ca. 110 cal yr BP (1840 AD).

Human Controls of Fire Activity

Use of fire by People

Holocene Land Use Patterns at MORA

Land use patterns for Mount Rainier and the PNW are based upon a modified forager to collector continuum model as described by Burtchard (2007). This model anticipates a change in land use and subsistence patterns in response to climate and population changes throughout the late Pleistocene and Holocene. Burtchard's model is based upon the work of Lewis Binford (1980) and is modified to fit the Washington Cascades. The following information is from Burtchard (2007) and is based upon this model.

The first colonizing populations in North America probably arrived in the PNW ca. 16,500 to 13,500 cal yr BP following the movement of Pleistocene megafauna south through an ice-free corridor between the Cordilleran and Laurentide ice sheets (Ames, 2003). For the Washington Cascades, the earliest plausible, culturally-related radiocarbon age comes from archaeological deposits found near the Cedar River north of MORA, and dates to ca. 9,500 cal yr BP (Samuels, 1993). Mierendorf and Foit (2008) report an essentially identical age from stratified cultural deposit in the North Cascades. During the early Holocene, with the extinction of many late Pleistocene fauna, humans likely placed an increased focus on surviving ungulates (e.g., elk and deer) (Ames, 2003). During the early Holocene, on Mount Rainier, recent evidence from stratified deposits on Sunrise Ridge indicate that near-modern floral and probably faunal associations established ca. 9,000 cal yr BP (Burtchard 2001). Some level of human use of resources occurred within the present day limits of MORA at this time. In terms of the archaeological record, the lowest number of dated artifacts from the mountain comes between ca. 10,000 - 7,000 cal yr BP (Burtchard, 2007). This makes sense given that forage was likely abundant at lower elevations, negating the necessity to travel to the mountains for subsistence reasons.

Radiocarbon-dated cultural deposits are more common from the mid-Holocene (ca. 6000 – 7000 cal yr BP), and firmly establish human presence in the Washington Cascades by this time (McClure, 1998). According to Burtchard's model, an increase in expanses of alpine tundra and subalpine parklands ca. 6,000 cal yr BP on Mount Rainier would have attracted increased numbers of elk, deer and other game during the late summer months. At the same time, loss of forage in the lowlands due to forest encroachment along with increasing regional population density contributed to an increase in human use at higher elevations. This hypothesis is reflected in the archeological record for the mountain, which shows an increase in artifacts between ca. 7,500 and 6,300 cal yr BP.

During the mid to late Holocene higher population density and declining ungulate habitat reached a point at which competition for available resources was too great to reliably sustain previous foraging practices. Food collection in the uplands would have shifted focus from ungulates to alternative high-value resources such as mountain goats, mountain beaver, marmots, and huckleberries. These resources were comparably not available in high abundance in the lowlands. A shift to winter reliance on mass-harvested and stored anadromous fish (i.e., salmon) would have also occurred. Along with this shift came a presumed focus on fire-based forest management to promote more productive early seral-stage communities in both lowland and upland settings. The archaeological record for MORA, for this time, shows an increase in artifacts from the Buck Lake site (45PI438), which supports Burtchard's model of a heightened use of Mount Rainier's subalpine zone relative to the early Holocene.

During the late Holocene, population density in the PNW reached its peak (Ames & Maschner, 2000). On Mount Rainier, late Holocene climatic conditions remained relatively cool and high-elevation ungulate forage improved, while low-elevation forests expanded in response to increased overall moisture (Brutchard, 2007; Dunwiddie, 1986; Franklin, Moir, Hemstrom, Greene, & Smith, 1988; Moir, 1989). In the lowlands, cool and moist conditions further increased forest cover and reduced ungulate habitat. These changes further increased the usefulness of fire to combat forest encroachment and to enhance ungulate forage. According to Burtchard's model, during this time, human use of subalpine and alpine zones at MORA involved increasingly regular trips by small groups to protect summer ungulate herds and a continued emphasis on harvesting high-value resources. The archaeological record supports this hypothesis and records a high density and relatively high diversity of artifacts recovered from ca. 3,600-2,200 cal yr BP at the Sunrise Ridge Borrow Pit site (45PI408)

(McCutcheon, 1999). This is evidenced by a marked increase in artifact diversity and density immediately atop the MSH-Yn tephra deposit (ca. 3,650 cal yr BP) compared with earlier deposits at the Buck Lake site (45PI438) (Burtchard, 1998; McCutcheon, 1999).

From 400 cal yr BP until the early 20th century, introduced disease and encroachment by euro-Americans greatly altered the life ways and social organization of Native People in the PNW. The impact of rapid population loss due primarily to small pox and malaria on Northwest settlement and subsistence strategies were almost certainly catastrophic (Boyd, 1999). By the start of the 20th century, the decline in indigenous populations was a minimum of 80% of precontact populations (Boyd, 1999). This rapid decline greatly impacted the social hierarchy and subsistent strategies in the PNW tribes. The signing of treaties and establishment of reservations during the mid 1800's forced the relocation of most Native People and severely limited their ability to continue traditional gathering practices (Wilkinson, 2006).

On Mount Rainer, during the 20th century, human use shifted from the collection of berries and limited hunting activities to primary use as a recreation and wilderness destination culmination with the creation of MORA (Brutchard, 2007). With the creation of MORA and forest reserves, an almost immediate suppression of fire on the mountain occurred. In terms of the archaeological record, there are minimal sites recorded for this time (Brutchard, 2007).

Oral Histories and Written Records of Anthropogenic Burning

Oral histories are straightforward in terms of the use of fire and land use by Native People in the PNW prior to Euro-American contact and up until recent time. In the subalpine zone of the Cascades, fire was used to enhance black mountain huckleberry (*Vaccinium membranaceum*) production and aided in drying berries (Mack & McClure, 2002). Fire was also used to prevent the invasion of shrubs and trees into meadows and camp sites (Gottesfeld, 1994). These practices continued into the early 20th century, well within the living memory of tribal elders (French, 1999). In British Columbia, the Gitksan and Wet'suwet'en people continue to this day to manage huckleberry through fire (Gottesfeld, 1994). Additionally, according to Norton and Hunn (1999), many of the meadows in the Southern Cascades were along the Klikitat trade network and were regularly burned. These purposely set fires were used to maintain clearings and trail networks essential to trade and travel.

Historic records are also key in understanding past fire use. Fire reports from Mount Rainier Forest Reserve from 1904 and 1905 recorded that 16 of 32 fires were caused by Native People (Allen 1904, 1905). All of these fires were in the southeastern portion of the reserve, an area known for huckleberry gathering (Allen, 1905). In 1900, Fred Plummer, who was the geographer for the reserve, noted that Indian set fires near Steam Boat Mountain occurred periodically from 1880 to 1900 and that the last and most extensive fire being in 1897 (Plummer, 1900). This observation of small intensity repeated burns suggests a well established pattern of management through fire. This is very different from today. Fire suppression and the exclusion of human-set fires at

MORA and on the Sunrise Ridge (the study area for this thesis) have most certainly impacted the fire activity on the mountain and vegetation assemblages that are present today.

CHAPTER III

RESEARCH AREA

The study area for this research is located in the northeast quadrant of MORA, along the Sunrise Ridge near the prehistoric Sunrise Ridge Borrow Pit site (45PI408), a stratified archaeological deposit dating to the last ca. 4000 years (Dampf, 2002; Mullineaux, 1974).The Sunrise Ridge is a distinct glacially carved feature that extends 10-12 km in a northeast direction. The Sunrise ridge drops significantly on either side of its ridgeline and is bounded by the White River to the south and Sunrise Creek to the north. Glacier runoff and snowmelt from the area feed these two drainages, with Sunrise Creek eventually feeding into the White River near the park boundary and Highway 410 (Figure 6 & 7). The Sunrise Ridge became ice free sometime prior to ca. 14,000 cal yr BP with the retreat of glaciers after the glacial maximum. (Crandell & Miller, 1974; Heine, 1998; Hekkers, 2010)

The research area sits near the upper limit of the Subalpine Fir (*Abies lasiocarpa*) Zone. This zone is characterized by rugged mountainous terrain above 1400 m and is defined at the upper limits as the treeline and at the lower limit as the closed canopy forests. Subalpine meadows are perhaps the most striking feature of this zone. The Cascade Range in Washington supports subalpine meadows that span elevation gradients larger than any other mountain range in North America (Franklin et al., 1988).

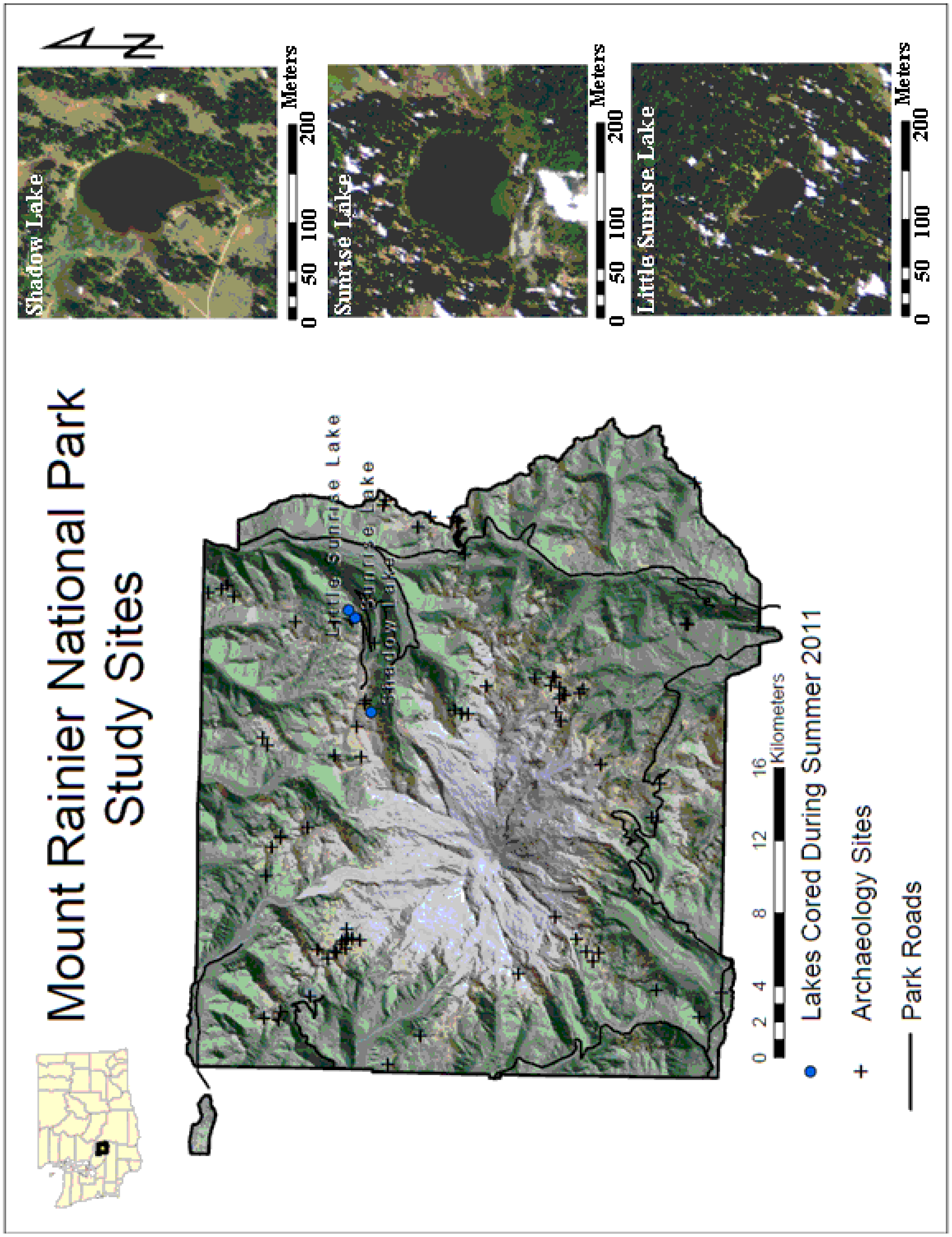

Figure 6. Map of studies sites at Mount Rainier National Park. Map generated in ArcMap with data obtained from WA DNR, USDA and MORA. Known archaeological sites shown are as of 2007.

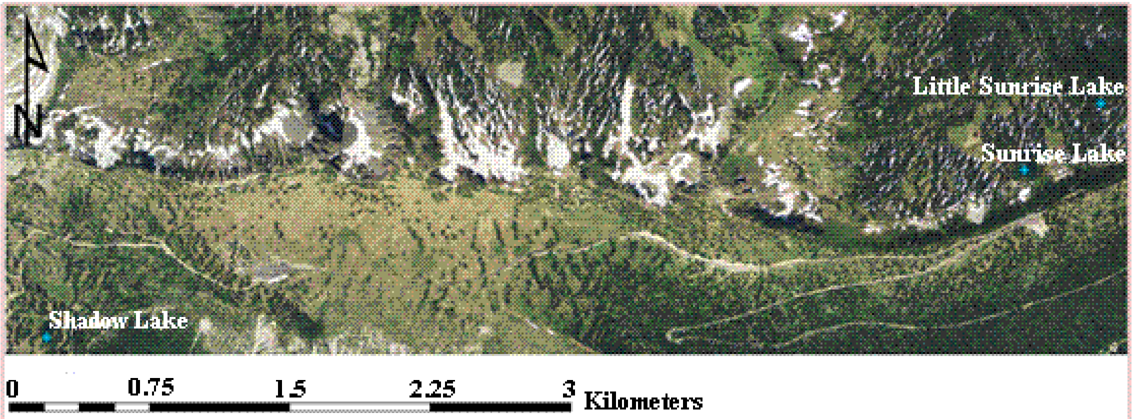

Figure 7. Map of the Sunrise Ridge study area. Map Generated in ArcMap with data obtained from WA DNR, USDA and MORA.

Tree taxa within this zone include mountain hemlock (*Tsuga mertensiana*), subalpine fir, Alaska yellow cedar (*Chamaecyparis nootkatensis*), western white pine (*Pinus monticola*), Engelmann spruce (*Picea engelmannii*), Pacific silver fir (*Abies amabilis*), and Alaska yellow cedar (*Chamaecyparis nootkatensis)* (Franklin et al., 1988; MORA FMP, 2005). The two dominant tree species within this zone are mountain hemlock, found in cold, moist locations and subalpine fir, found in cold, dry locations (Franklin et al., 1988; MORA FMP, 2005).

Commonly associated shrub species within this zone include big huckleberry (*Vaccinium membranaceum*), black mountain huckleberry (*Vaccinium membranaceum*), dwarf bramble (*Rubus lasiococcus*), fool's huckleberry (*Menziesia ferruginea*), and rhododendron (*Rhododendron albiflorum*) (Franklin et al., 1988; MORA FMP, 2005). The forest fauna includes a wide array of small mammals and birds. Large mammals include mule deer (*Odocoileus hemionus*), elk (*Cervus elaphus*), black bear (*Ursus americanus*), and mountain goat (*Oreamnos americanus*) (Franklin et al., 1988).

Study Sites

Three study sites were chosen based on their close proximity to the Sunrise Ridge Borrow Pit site (45PI408), alpine meadows, and proximity to roads and trails for ease of access. A query was completed in ArcGIS based upon these three parameters and the sites listed in Table 1 were determined.

Table 1

Elevation and Location of Study Sites

Lake	UTM Coordinate (NAD83)			Elevation (m)
Sunrise Lake	Zone 10	607488E	5196902N	1768
Little Sunrise Lake	Zone 10	607836E	5197587N	1707
Shadow Lake	Zone 10	602317E	5196163N	1890

Shadow Lake

Shadow Lake is located at an elevation of 1890 m and is in close proximity to the Sunrise Visitor Center (<1 km) (Figure 8). Shadow Lake at its deepest point is 4.5 m and covers approximately 0.48 hectares (Lakes of WA, Water Supply Bulletin 14, 2012). The average annual temperature at Shadow Lake is approximately 1.7°C, with an average high of approximately 18.6°C in the summer and an average low of approximately -8.3°C in the winter (NRCS, 2012). On average, the site recieves approximately 1960 mm of precipitiation annually (NRCS, 2012).

Figure 8. Photographs of Shadow Lake. Left, Aerial Photo. Right, photo taken by the author in August 2011 looking northeast.

The forest surrounding the lake is composed of mostly subalpine fir. Also present are Engelmann spruce, Alaska yellow cedar, whitebark pine (*Pinus albicaulis*) and mountain hemlock. Shrubs surrounding the lake include patches of fool's huckleberry and black mountain huckleberry. A variety of perennial grasses and subalpine wildflowers, such as subalpine lupine (*Lupinuslatifolius var. subalpinus*), broad leafed arnica (*Arnica latifolia*) and pasque flower *(Anemone occidentalis)* are present in the open meadow around the lake.

First built in 1934 by the CCC, the shores of Shadow Lake were once utilized as a public campground and picnic area. Due to the impacts of over-use and over-crowding, the campground and picnic area were removed over several summers in the early 1960s (Catton, 1996) (Figure 9). While the area has been rehabilitated, some of the campground's infrastructure is still present (i.e. sewer lines).

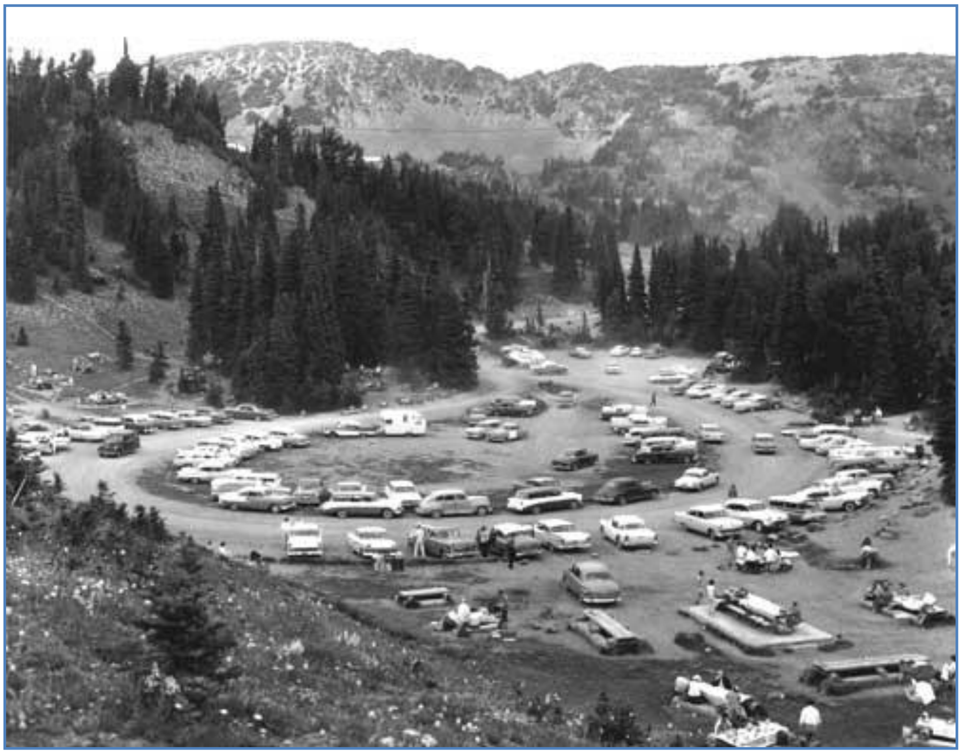

Figure 9. Campground and picnic area at Shadow Lake, July 1960. Mission 66 called for the development of 1,200 new camping and picnicking sites mostly at lower elevations in order to disperse visitor use and alleviate crowded conditions such as seen here. Photo Courtesy of MORA.

Sunrise Lake

Sunrise Lake is located at an elevation of 1768 m, is 4.6 m at its deepest point and covers roughly 1.6 hectares (Figure 10) (Lakes of WA, 2012). Sunrise Lake is located 5.25 km to the northeast of Shadow Lake and lies on the north side of the ridge proper. The lake itself sits in a basin surrounded on three sides by steep rock and scree fields. The average annual temperature at the site is approximately 2.8°C, with an average high of approximately 17.2°C in the summer and an average low of approximately -7.2°C in the winter (NRCS, 2012). On average, the site recieves 1900 mm of precipitation annually (NRCS, 2012).

Figure 10. Photogrpahs of Sunrise Lake. Left, Airphoto of Sunrise Lake. Right**,** coring Sunrise Lake. Photo courtesy of CWU.

The forest surrounding Sunrise Lake consists predominetly of subalpine fir, with lesser numbers of whitebark pine, Pacific silver fir, Engelmann spruce, Alaska yellow cedar, and mountain hemlock. Shrubs surrounding the lake include black mountain huckleberry, pink mountain heather (*Phyllodoce empetriformis*), and White Mountain heather (*Cassiope mertensiana*). Forbs in the immediate area include glacier lily (*Erythronium grandiflorum*), pasque flower and yellow violet (*Viola pubescens*).

Little Sunrise Lake

Little Sunrise Lake is located at an elevation of 1707 m, is 3.6 m at its deepest point and covers roughly 0.4 hectares (Figure 11) (Lakes of WA, 2012). Little sunrise is 440 m to the north- northeast of Sunrise Lake. Annual average temperature and precipitation are the same as for Sunrise Lake.

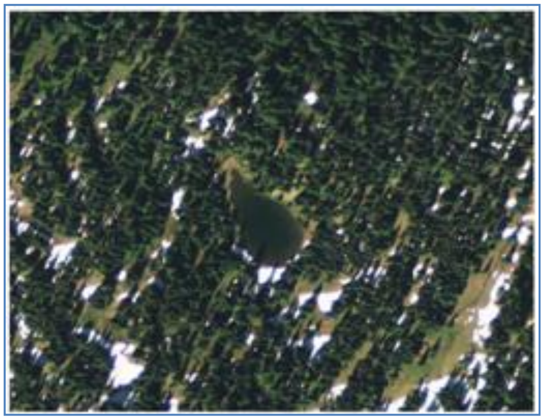

Figure 11. Photographs of Little Sunrise Lake. Right, Airphoto. Left, photo taken by author August 2011.

The forest surrounding the lake is predominetly subalpine fir with some whitebark pine and Engelmann spruce. Shrubs surrounding the lake include black mountain huckleberry and pink mountain heather. Forbs in close vicinity to the lake include glacier lily, lesser spearwort (*Ranunculus flammula*), hellebore (*Helleborus niger*), white marsh marigold (*Caltha leptosepala*), Subalpine lupine and yellow violet.

CHAPTER IV

METHODS

Field

Sediment cores were obtained from Shadow, Sunrise, and Little Sunrise lakes during the summer of 2011. Long sediment cores were retrieved using a hand-operated modified Livingstone piston corer lowered from a floating platform (Wright et al., 1984) (Figure 12). Cores were taken from the deepest part of each lake to avoid possible slumping of sediments and sunken logs along the shoreline. Once obtained, the cores were described, wrapped in cellophane and aluminum foil, and transported to the Paleoecology Lab at Central Washington University. Short sediment cores were collected using a Bolivia piston corer, which recovered the top sediments from the lake, including the sediment-water interface (Figure 12b). The short core was subsampled in the field at 0.5-cm intervals and samples were placed in labeled Whirl-pak bags.

Figure 12. a) Livingstone piston corer (photo: D. Gavin) b) Bolivia piston corer with the short core inside (photo: M. Walsh); c) long sediment core from Shadow Lake (numerous volcanic tephra layers are visible) (photo: M. Walsh).

Lab

The chronology of the sediment cores was determined using Accelerator Mass Spectrometry (AMS) radiocarbon dating and the identification of dated tephra layers. Plant macrofossils such as needles and twigs were identified and used to provide material for AMS dating. AMS dates were determined by Beta Analytic, Inc. (Miami) and DirectAMS (Seattle). ^{14}C dates were converted to calendar years before present (cal yr BP; present = 1950 AD) using Calib 6.0 html (Reimer & Stuiver, 2013). The Calib program output provided a medium age and age range determined to have the highest probability within the first sigma. The median age was used in most cases and was compared against a radiocarbon age vs. calibrated age plot. If the median age did not fit within the highest peak from the plot, the immediate highest peak to the medium age was selected and rounded to the nearest decade. The radiocarbon age vs. calibrated age plot created by the Calib program takes into account the IntCal04 calibration dataset for past atmospheric ^{14}C fluctuations.

Tephra layers were identified visually by James Vallance at the USGS Cascade Volcano Observatory in Vancouver, Washington. Tephra ages based on ^{14}C age determinations were also converted to cal yr BP using Calib 6.0 and median ages were determined in the same manner as those for AMS-^{14}C samples. In most cases, the deposition of tephra is a rapid event (Mullineaux, 1974); therefore, the thickness of individual tephra layers was subtracted from the true core depth to create an adjusted depth. The long and short cores from each lake were correlated based on tephra layers present in both cores. Once correlated, the long core and short core were combined to create a continuous record for each lake.

Once ^{14}C ages were converted to cal yr BP, an age model with specific assigned dates to depths was created and plotted using a constrained cubic spline interpolation. Using a constrained cubic spline prevents overshooting of points compared to a natural cubic spline, however, it sacrifices some smoothness for a more stable shape (Elfving & Andersson, 1987).

Magnetic susceptibility readings were conducted on each lake core in order to help identify tephra layers. Magnetic susceptibility was measured at contiguous 1-cm intervals on the intact cores using a Sapphire Instruments magnetic coil. Loss on ignition (LOI) was used to determine the organic content of the cores and followed procedures outlined in Dean (1974). Sediment samples of one cubic centimeter were taken at 5-cm intervals from each respective core. The samples were first placed in dry crucibles and weighed. The samples were then placed in a drying oven overnight at 95°C to remove all water. After the samples were cooled in a dessication tank and weighed, they were fired in a muffle furnace at 550°C for 2 hours. The samples were then cooled again in a dessication tank and weighed. The following calculation was used to determine the percent organic content in each sample.

$$\frac{(\text{dry weight before ignition} - \text{dry weight after ignition})}{\text{dry weight before ignition}} \quad \text{X } 100$$

Charcoal analysis procedures followed well-established methods outlined in Whitlock and Larsen (2001) and modified by Walsh et al. (2008). For each long core, contiguous samples of 2 cc were taken at 1-cm intervals and placed in a plastic vial. Charcoal samples were soaked in a solution of 5% sodium hexametaphosphate for >24 hours and a weak bleach solution for 1 hour to disaggregate the sediment. Samples were then washed through nested sieves of 250 and 125 μm mesh size and the residue was transferred into gridded petri dishes and counted. Only charcoal particles >125 μm in diameter were counted and each particle was recorded as either woody or herbaceous charcoal (Figure 13) (Jensen, Lynch, Calcote, & Hotchkiss, 2007; Walsh et al., 2008, 2010). Charcoal counts were converted to charcoal concentration (particles/cm^3) by dividing by the volume of each sample.

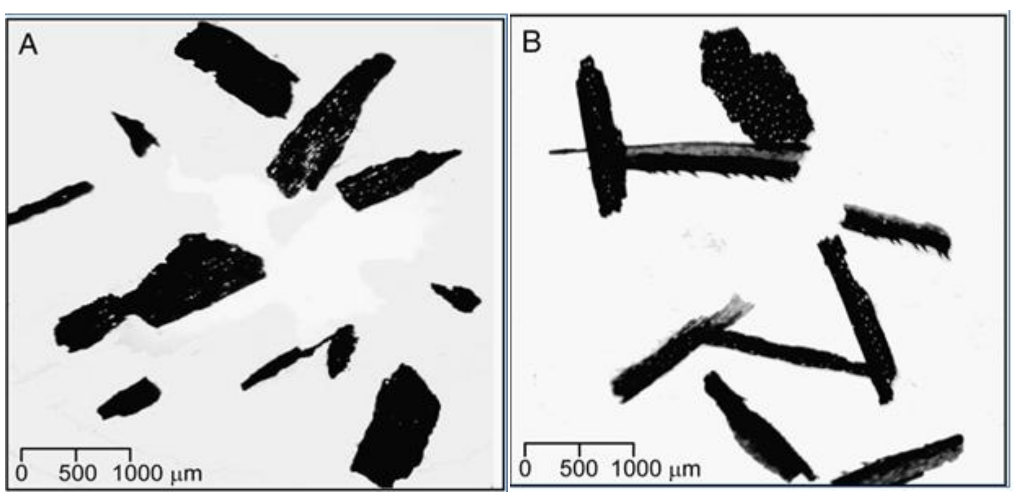

Figure 13. Photos of charcoal particles. (A) woody charcoal particles and (B) herbaceous (i.e., grass) charcoal particles. Images from Walsh et al. (2008).

Charcoal data analysis methods followed Higuera et al. (2008). The program CharAnalysis was used to identify individual fire episodes within the charcoal record, to calculate fire frequency (total number of fires within a 1,000-year period), and to calculate mean fire-return intervals (average years between fires). The program output also provided useful indications of fire magnitude (the total charcoal influx in a peak which is related to fire size, severity, and taphonomic processes) (Whitlock et al., 2006; Higuera et al., 2008).

The CharAnalysis program determines fire history by first calculating charcoal accumulation rates (CHAR) or influx values (particles/cm^2/yr). These were obtained by interpolating the charcoal data to constant time steps, which varied for each lake, and represented the median temporal resolution (MTR) in the core; the data were not log-transformed. The CHAR data series was then decomposed into a “background” and “peaks” component. The background component is attributed to slow changes in charcoal production associated with changing fuel types (Marlon, Bartlein, & Whitlock, 2006). The peaks component represents inferred “fire episodes” (i.e., one or more fires occurring in the duration of a peak) (Long et al., 1998).

The CHAR background component was described using a robust (Lowess) smoother with a 400-yr window width, and the CHAR peaks component was taken as the residuals after background was subtracted from the interpolated time series. The threshold value separating fire-related from non-fire related variability in the peaks component was set at the 95th percentile of a Gaussian distribution modeling noise in the CHAR peaks time series. Sensitivity analysis of window widths between 300 and

1,000 years showed that the signal-to-noise ratio (i.e., the measure of the separation between peaks and non-peak values) was maximized at 400 years for each lake. All CHAR peaks were screened to eliminate those that resulted from statistically insignificant variations in charcoal counts (Gavin, Hu, Lertzman, & Corbett, 2006). If the maximum charcoal count from a peak had a >5% chance of coming from the same Poisson-distributed population as the minimum count within the preceding 75 years, it was identified as not significant (Higuera, Peters, Brubaker, & Gavin, 2007).

The CHAR time series was plotted on a log-transformed scale in order to facilitate comparison between different sections of the core. The significant peaks (i.e., fire episodes) were also plotted and used to calculate smoothed fire frequency, mean fire-return interval, and fire-episode magnitude. Fire frequency (episodes/1,000 yr) is the sum of the total number of fires within a 1,000-yr period, smoothed with a Lowess filter. Mean fire-return interval (mFRI) is the average years between fire episodes.

CHAPTER V

RESULTS

Shadow Lake

Chronology

After comparing the short core (SL11A) and long core (SL11C) for Shadow Lake, it was determined, based on the position of the MSH-W tephra layer (14 cm deep in both cores), that the short core did not capture any more sediment than the long core and therefore was not used. The total length of the long core (SL11C) for Shadow Lake was 276 cm. Once tephra layers were extracted, the total adjusted depth for the core was 162 cm. The age model for the SL11C core was developed using three AMS-^{14}C age determinations and the identification of five dated tephra layers (Figure 14 &Table 2). The long core contained nine tephra of known age, but only five had reliable enough dates to include in the age model. The resulting age model for SL11C suggests a basal date of 10180 cal yr BP with a median resolution of 47 years per centimeter.

The sedimentation rate for SL11C remained relatively constant from ca. 10,180 through 3,650 cal yr BP with a rate of 0.009 cm/yr. From ca. 3,650 to 2,340 cal yr BP the sedimentation rate increased substantially to 0.027 cm/yr. From ca. 2,340 cal yr BP until present day, the sedimentation rate slowed to 0.025 cm/yr.

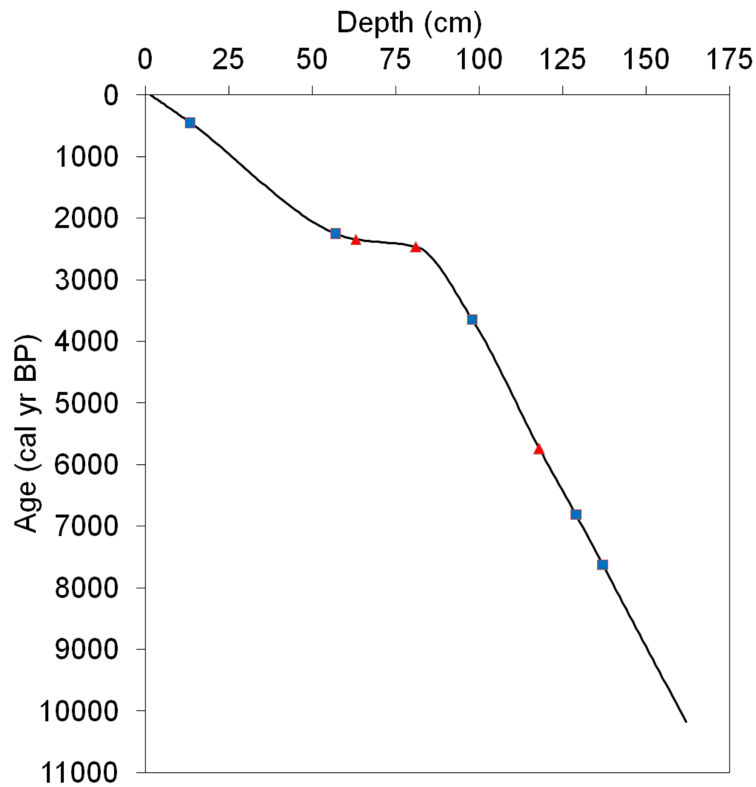

Figure 14. Shadow Lake age model. Red triangles are dates obtained from AMS-14C age determinations. Blue squares are dates from known tephra layers.

Table 2

Age–Depth Relations for the Shadow Lake Core

Depth(cm)	Lab Code	Source Material	Age (Cal yr BP)
14		MSH –W	470[a]
57		MR-C	2250[a]
64	SL11C582	Twig	2342[b]
81	SL11C604	Twig	2460[c]
98		MSH-Yn	3650[a]
118	SL11C660	Twig	5740[c]
129		MR-D	6810[a]
137		Mazama-O	7627[d]

[a] Ages as reported in Mullineaux (1974, 1996), Clynne et al. (2004), Donogue et al. (2007) and Sisson and Vallence (2009).

[b] ^{14}C age determinations completed at Beta Analytics AMS Facility (Miami).

[c] ^{14}C age determination completed at DirectAMS Facility (Seattle).

[d] Age as reported in Zdanowicz et al. (1999).

Lithology

The SL11C core ended at the Mount Rainier (MR)-R tephra layer, which made up the bottom 1 cm of the core (Figure 15). From 261-252 cm, the core consisted of light brown to brown gyjtta (lake sediment). Between 251- 237 cm was the Mazama-O tephra layer. Above that from 236-234 cm, the core consisted of dark brown gyttja. At a depth of 233-234 cm was the MR-A tephra, and from 232-228 cm the core consisted of dark brown gyttja. At a depth of 227-225 cm was the MR-D tephra layer. Between 225-215 cm, the core was composed of dark brown gyttja. Starting at 214 cm, the MR-F tephra extended for 64 cm. From 150-144 cm, the core was dark brown gyjtta. At a depth of 143-142 cm was the MR-B tephra. From 142-130 cm, the core consisted of dark brown gyttja. At a depth of 129-121 cm was the Mount St. Helens (MSH)-Yn tephra layer. Between 121-103 cm, the core was composed of light brown to brown gyjtta. At 102-100 cm was the MSH-Pm tephra layer. Between 100-90 cm, the core consisted of brown gyjtta. At a depth of 89-87 cm was the MR-Pu tephra. From 87-77 cm the core consisted of dark brown gyttja. Starting at a depth of 76 cm, the MR-C tephra layer extended for 20 cm. From 58-17 cm, the core consisted of brown to greenish brown gyttja. The MSH-W layer was found at a depth of 16-14 cm in the core. From 14 cm to the top, the core consisted of brown gyjtta.

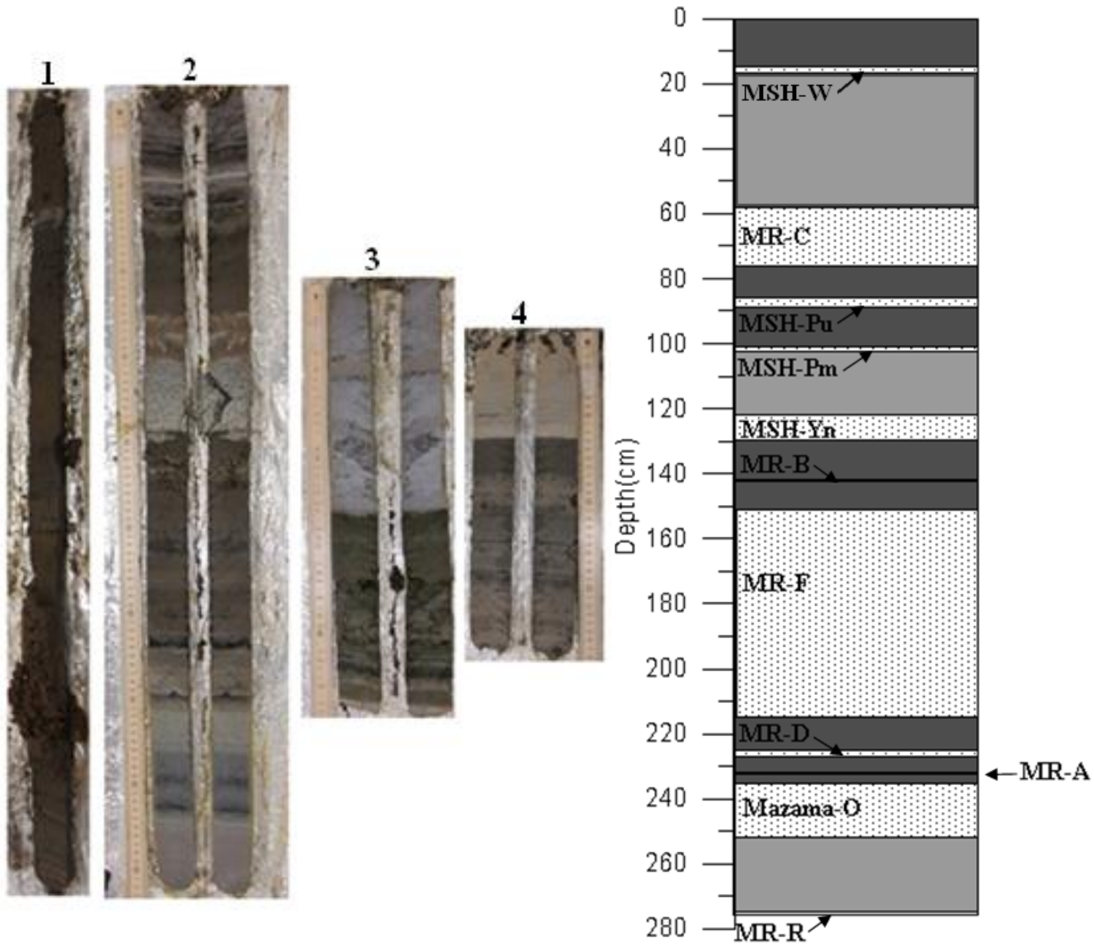

Figure 15. Shadow Lake core drives and lithology**.** Left, SL11C drives 1, 2, 3, & 4. Right**,** lithology.

Percent organic values were low overall for the core with the highest value being 21% at a depth of 253 cm in the core (Figure 16). From the base of the core until a depth of 253 cm, the organic content varied widely between 0 and 21%. From 252-228 cm, percent organic content was low (2%-6%) corresponding with the Mazama- O tephra layer. From 228-218 cm, percent organic content was increased to 16%. Between 217 and 153 cm organic content was low and ranged from 1-5%, corresponding with the MR-F tephra layer. From 152 to 108, LOI varied between 1-16%. Between 107 and

103, LOI dropped significantly to 0.85%. Starting at a depth of 98 cm, percent organic values increased, with the top 53 cm of the core having the highest average organic values. Most likely this indicates a more productive lake system during this time period.

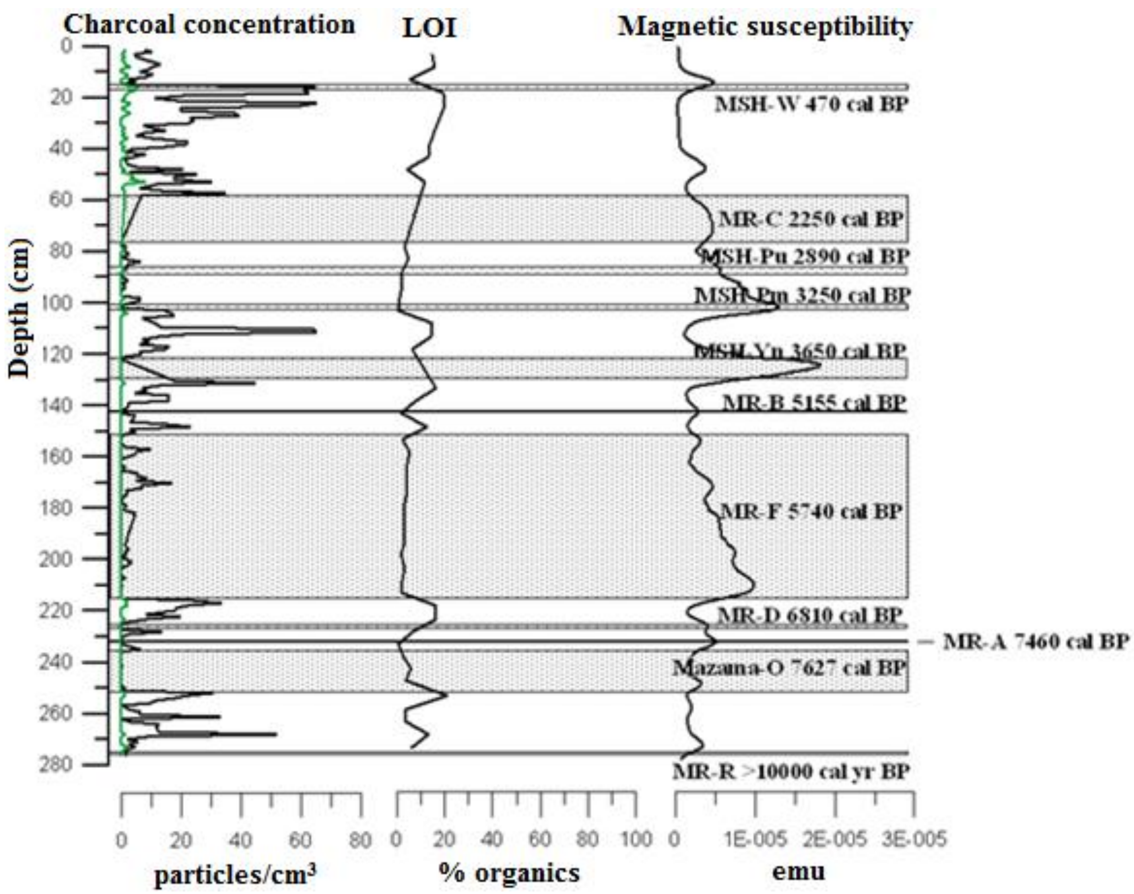

Figure 16. Shadow Lake charcoal concentration, magnetic susceptibility, and organic content plotted against tephra layers by depth. Green line is herbaceous (grass) charcoal.

Magnetic susceptibility readings for SL11C show higher values for depths associated with tephra layers within the core (Figure 16). Values spiked through the Mazama-O, MR-D, MR-F, MSH-Yn, MSH-P, MR-C and MSH-W tephra layers. These spikes in magnetic susceptibility associated with tephra layers also correlated with a drop in organic content in the core.

Charcoal Record

Early Holocene (10,000-7,000 cal yr BP, 162-131 cm): Charcoal concentrations during the early Holocene were relatively high (Figure 17). CHAR values ranged between 0-0.5 particles/cm^2/yr with an average of 0.09 particles/cm^2/yr. Fire frequency increased from no fire episodes at the beginning of the record to 2.8 fire episodes/1,000 yr by the end of the early Holocene. Average fire frequency for the period was 1.68 fire episodes/1,000 yr with a mean fire-return interval of 505 years. Five significant fire episodes were registered and occurred ca. 9,290, 8,590, 8,070, 7,690, and 7,410 ca yr BP. The largest of these occurred ca. 8,590 cal yr BP, with a fire-episode magnitude of 11.05 particles/cm^3.

Middle Holocene (7,000-4,000 cal yr BP, 131-102 cm): Charcoal concentrations during the mid-Holocene were lower compared to the early Holocene. Charcoal concentrations dropped toward the start of the period and increased significantly toward the end. CHAR values ranged between 0.01-0.34 particles/cm^2/yr with an average of 0.10 particles/cm^2/yr. Fire frequency increased from 2.8 fire episodes/1,000 yr at the beginning of the mid-Holocene to 4.3 fire episodes/1,000 yr ca. 6,380 cal yr BP (Figure 4). It then decreased to 1 fire episode/1,000 yr ca. 5,060 cal yr BP and slowly increased to 1.9 fire episodes/1,000 yr by the end of the time period. Average fire frequency for the mid-Holocene was 2.3 fire episodes/1,000 yr with a mean fire-return interval of 434 years. Seven significant fire episodes occurred during the mid-Holocene, ca. 6,850, 6,570, 6,470, 6,280, 6,000, 5,490, and 4,500 cal yr BP. The largest peak occurred ca. 6,470 cal yr BP, with a fire-episode magnitude of 4.72 particles/cm^3.

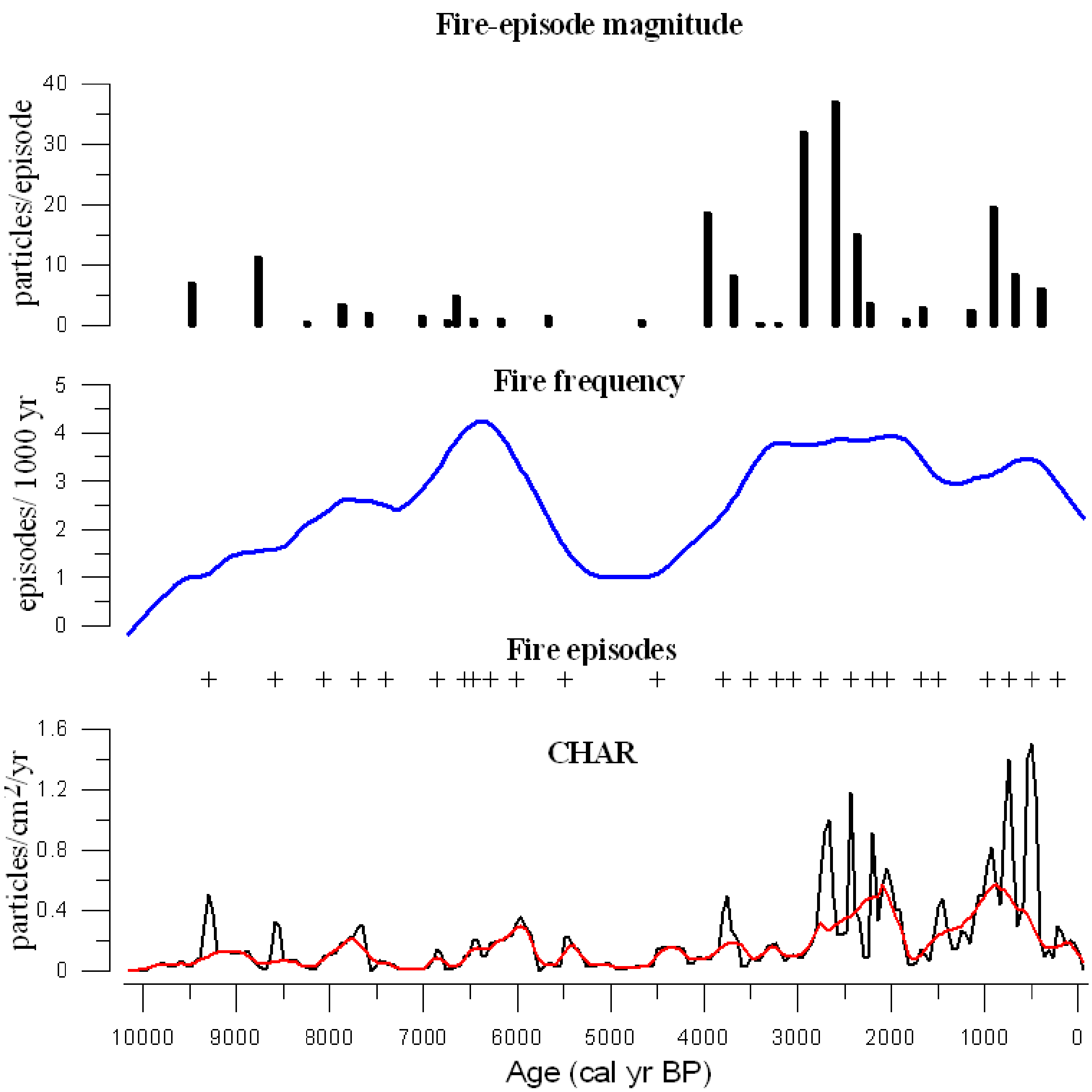

Figure 17. Shadow Lake CHAR, fire episodes, fire frequency, and fire-episode magnitude.

Late Holocene (4000 cal yr BP - present, 102-0 cm): Charcoal concentrations during the late Holocene increased significantly from the mid-Holocene. Charcoal concentrations for the entire record were highest during this time period. CHAR values ranged between 0.01-1.4 particles/cm^2/yr with an average of 0.34 particles/cm^2/yr. The highest CHAR value (1.5 particles/cm^2/yr) of the record occurred ca. 500 cal yr BP. Fire frequency increased from 1.9 fire episodes/1,000 yr at the beginning of the late Holocene to 3.9 fire episodes /1,000 yr ca. 2,000 cal yr BP. It then decreased to 2.9 fire episodes/1,000 yr ca. 1350 cal yr BP, increased to 3.5 fire episodes /1,000 yr ca. 550 cal yr BP and decreased to 2.2 fire episodes /1,000 yr at present. Average fire frequency for the late Holocene was 3.3 fire episodes/1,000 yr with a mean fire-return interval of 303 years. Fourteen significant fire episodes were registered during the late Holocene and occurred ca. 3,790, 3,510, 3,230, 3,040, 2,760, 2,430, 2,200, 2,050, 1,680, 1,490, 970, 740, 500, and 220 cal yr BP. The two largest peaks occurred ca. 2,760 and ca. 2,430 cal yr BP, with fire-episode magnitudes of 31.8 and 36.8 particles/cm^3. Fourteen of the 25 significant fire peaks for the entire record for Shadow Lake occurred during the late Holocene.

In the SL11C core, a significant fire episode (ca. 2,200 cal yr BP) occurred shortly after the MR-C tephra layer. This fire episode had a peak magnitude of 14.9 particles/cm^3 and according to the age model occurred approximately 50 years after the deposition of the MR-C tephra layer (Figure 18). The MR-C tephra layer was substantial and spanned 20 of the 276 cm core. By depth, charcoal concentration (raw charcoal count) peaked at 34.5 particles/cm^3 in the centimeter following the MR-C tephra deposit, suggesting that the fire event may have actually occurred immediately following the eruption.

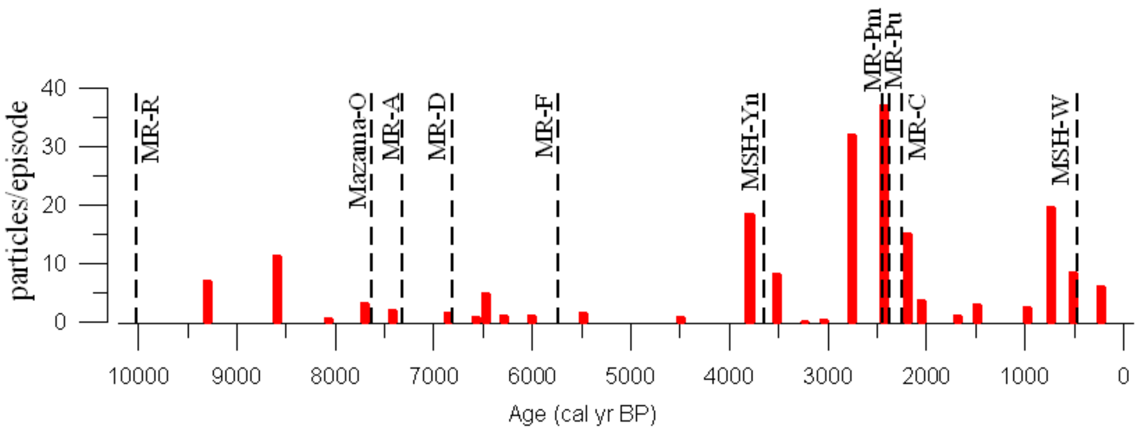

Figure 18. Shadow Lake fire episodes and peak magnitude plotted with identified tephra layers against age (cal yr BP). Note: the MR-Pm and MR-Pu tephra layers were deposited after the fire event ca. 2430 cal yr BP.

Sunrise Lake

Chronology

The top 14 cm of the short core (UL11C) from Sunrise Lake were combined with drive 1 of the UL11C core and drives 2 and 3 of the UL11B core to form a combined core (referred to hereafter as UL11D). This was done by correlating the cores based on common tephra layers. This combined core was 274 cm in length, but once the tephra layers were removed, the total adjusted depth for the combined core was 230 cm. The age model for the UL11D core was developed using four AMS-^{14}C age determinations and the identification of five dated tephra layers (Figure 19 and Table 3). The long core contained eight tephra of known age, but only five had reliable enough dates to include in the age model. The resulting age model for the Sunrise Lake core suggests a basal date of 14,508 cal yr BP with a median resolution of 48 years per centimeter.

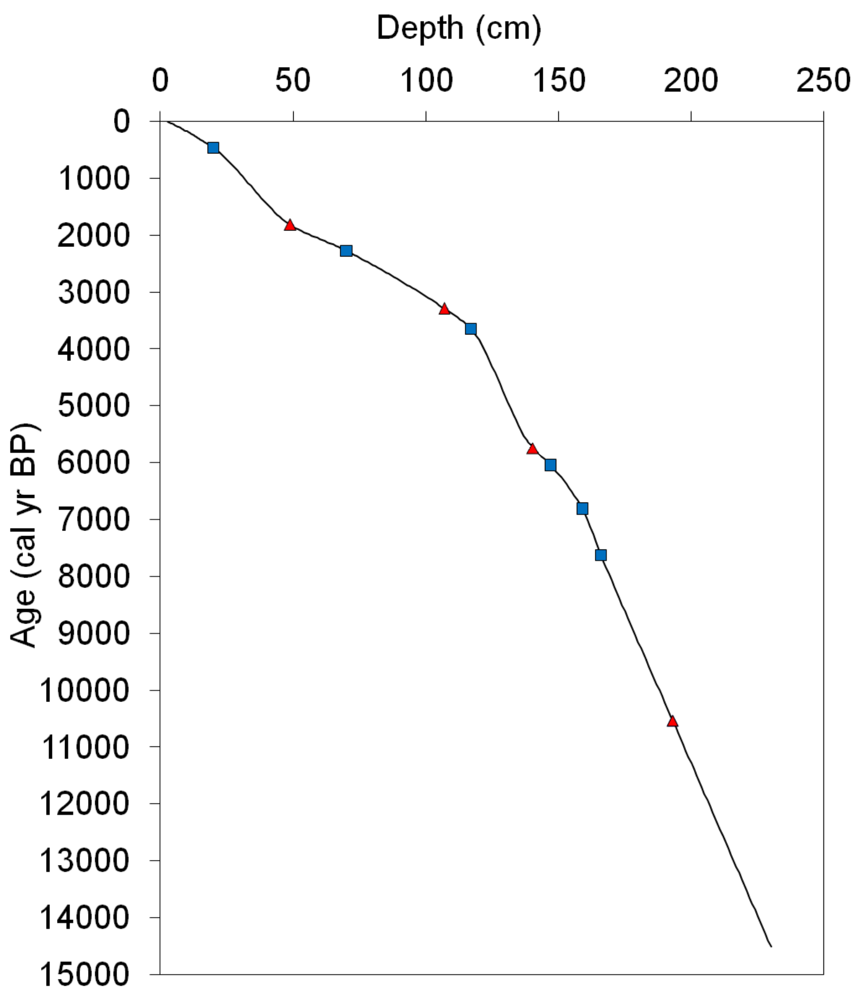

Figure 19. Sunrise Lake age model. Red triangles are dates obtained from AMS-14C age determinations. Blue squares are dates from known tephra layers.

Table 3

Age–Depth Relations for the Sunrise Lake Core

Depth(cm)	**Lab Code**	**Source Material**	**Age (Cal yr BP)**
20		MSH-W	470 [a]
49	UL11C685	Wood	1820 [b]
69		MR-C	2250 [a]
93	UL11C747	Wood	3290 [b]
117		MSH-Yn	3650 [a]
140		MR-F	5740 [a]
145	UL11B773	Plant Material	5990 [b]
159		MR-D	6810 [a]
166		Mazama-O	7627 [c]
179	UL11B837	Twig	10530 [b]

[a] Ages as reported in Mullineaux (1974, 1996), Clynne et al. (2004), Donogue et al. (2007) and Sisson and Vallence (2009).
[b] ^{14}C age determinations completed at Beta Analytics AMS Facility (Miami).
[c] Age as reported in Zdanowicz et al. (1999).

The sedimentation rate for the UL11D core remained relatively constant from the base of the core through ca. 6,810 cal yr BP, with an average of 0.005cm/yr. From ca. 6,810 to 5,740 cal yr BP the sedimentation rate increased to 0.018 cm/yr. From ca. 5,740 to 3,650 cal yr BP the sedimentation rate slowed to 0.016 cm/yr. From ca. 3,650 to 1,820 cal yr BP the sedimentation rate increased substantially to 0.037 cm/yr. From ca. 1,820 cal yr BP until present day, the sedimentation rate slowed to 0.026 cm/yr.

Lithology

The UL11D core ended at an unidentified tephra layer which made up the bottom 4 cm of the core. From 270-246 cm, the core consisted of tan to light brown gyjtta, except at a depth of 265-264 cm, where there was an unknown tephra layer. At a depth of 256 another unknown tephra was 2 cm thick. From 245-238 cm was the MR-R tephra layer. From 238-205cm, the core consisted of dark brown to brown gyttja. At a depth of 204-194 cm was another unidentified tephra layer. Between 194 and 150 cm, the core was composed of dark brown gyttja. From 186-178 cm was the Mazama-O tephra. Above that, from 150-131 cm, the core consisted of dark brown gyjtta. At a depth of 131-119 cm was the MSH-Yn tephra layer. Above that from 179-175 cm, the core was dark brown gyjtta. The MR-D tephra layer was found from a depth of 174-168 cm. Between 168-155 cm, the core consisted of brown to dark brown gyjtta. At a depth of 154 cm, the MR-F tephra layer comprised 1 cm of the core. From 153-130 cm, the core consisted of dark brown gyttja. The MSH-Yn layer extended from a depth of 130-119 cm in the core. From 119-85 cm, the core consisted of brown gyjtta. Starting at 84 cm, the MR-P tephra layer was 4 cm thick and above that, from 80-70 cm, the core consisted of brown to light brown gyttja. At a depth of 69 cm, the MR-C tephra layer comprised 11 cm of the core. From 58-21 cm, the core consisted of brown gyttja. From 20-16 cm was the MSH-W tephra, and from 16 cm to the top of the core was brown gyttja (Figure 20).

The organic content of the core was low at the bottom and increased substantially toward the top, with the overall highest value of 37.9% occurring at a depth of 32 cm. From the base of the core until a depth of 194 cm, the organic content steadily increased from 4.7% to 13.2%. From 194-189 cm the organic content decreased to 6.4%. From 189-119 cm, percent organic values remained low and variable (5.3-8.6%). From 119-107 cm, the organic content increased to 16.7% and then decreased through a depth of 97 cm. From 97-52 cm, the organic content rose from 1.4% to

33.9%. From 52-47 cm organic content dropped to 5.01%. From 52-32 cm the organic content steadily rose to a high of 37.9% and then decreased to 1.7% at the top of the core. The organic content was highest for the core between 42 and 22 cm.

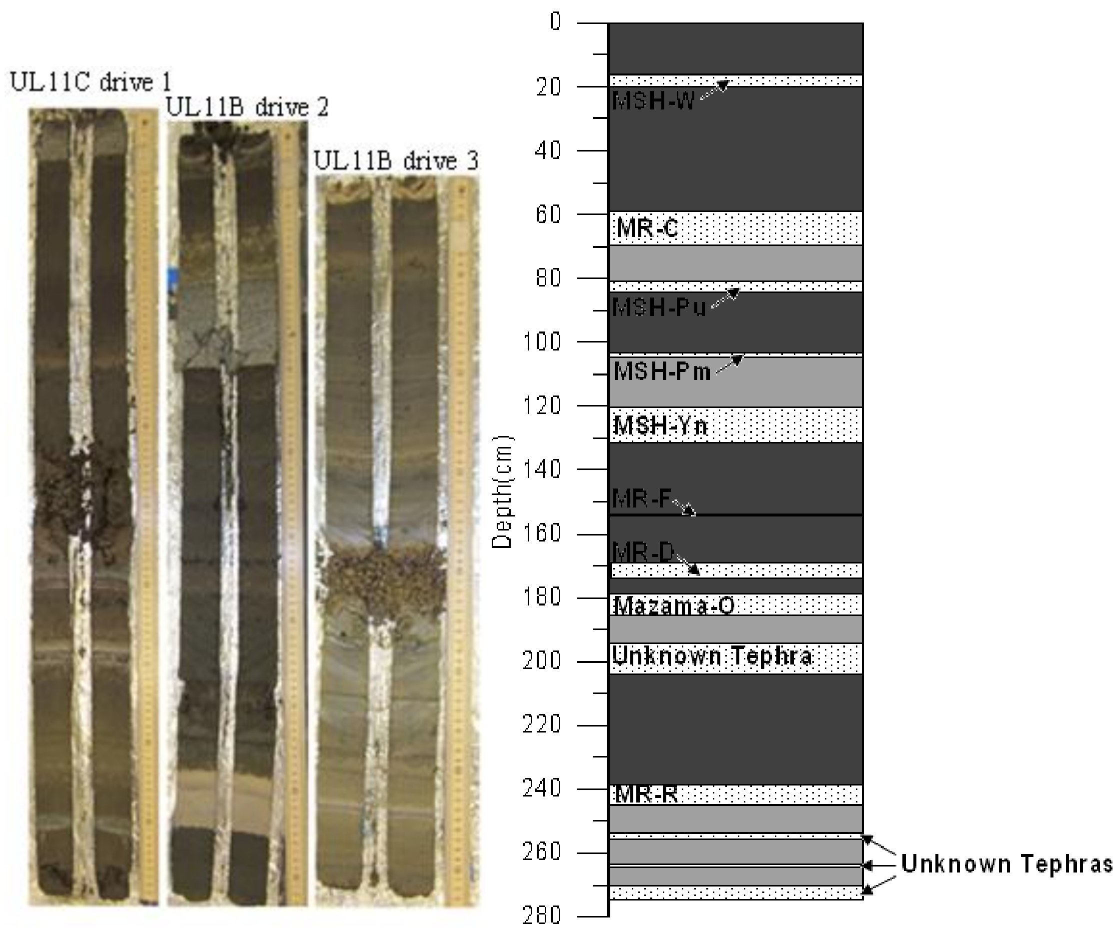

Figure 20. Sunrise Lake core drives and lithology. Left, UL11C drive 1 and UL11B drives 2 and 3. Right**,** lithology.

Magnetic susceptibility readings for the UL11D core showed high values for depths associated with tephra layers within the core. Values spiked in association with the MR-R, Mazama-O, MR-D, MR-F, MSH-Yn, MSH-P, MR-C, MSH-W, and two unknown tephra layers. These spikes in magnetic susceptibility associated with tephra layers also correlated with a drop in organic content in the core (Figure 21).

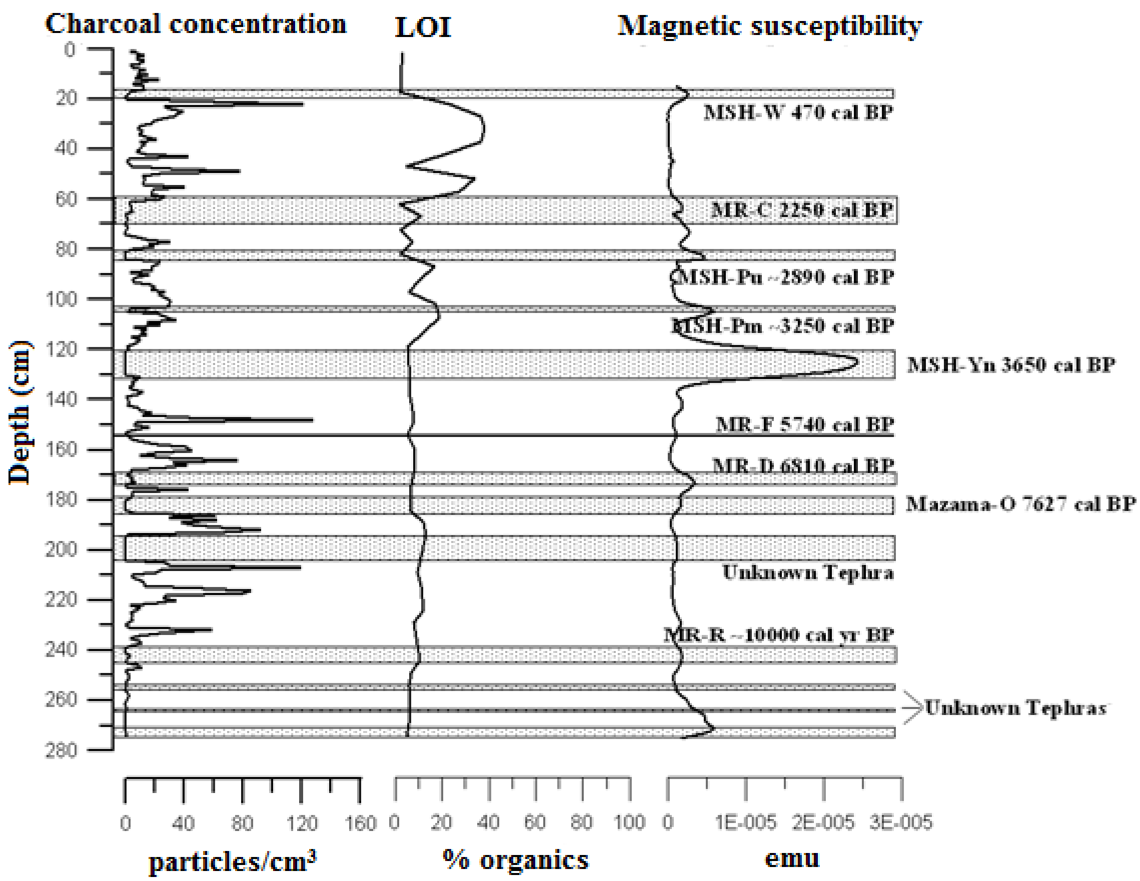

Figure 21. Sunrise Lake charcoal concentration, magnetic susceptibility, and organic content plotted against tephra layers by depth.

Charcoal Record

Late Pleistocene (14,500-11,000 cal yr BP, 230-198 cm): Charcoal concentrations during the Late Pleistocene were low to nonexistent (Figure 22). CHAR values ranged between 0-0.54 particles/cm^2/yr with an average of 0.04 particles/cm^2/yr.

Fire frequency increased from no fire episodes at the beginning of the record to 2.4 fire episodes/1,000 yr ca. 11,700 cal yr BP (Figure 8). Five significant fire episodes occurred during the Late Pleistocene, ca. 13,380, 12,320, 11,990, and 11,120 cal yr BP. The largest of these occurred ca. 11,460 cal yr BP with a fire-episode magnitude of 17.5 particles/cm^3. Average fire frequency for the time period was 1.3/1,000 yr with a mean fire-return interval of 769 years.

Early Holocene (11,000-7,000 cal yr BP, 198-160 cm): During the early Holocene, charcoal concentrations increased significantly compared to the late Pleistocene. CHAR values ranged between 0-1.1 particles/cm^2/yr with an average of 0.27 particles/cm^2/yr. Fire frequency remained relatively high through ca. 10,000 cal yr BP, decreased to 1 fire episode/1,000 yr ca. 9,200 cal yr BP, increased to 2.4 fire episodes/1,000 yr ca. 7900 cal yr BP, and then decreased to 1.6 fire episodes/1,000 yr at the end of the late Holocene. Average fire frequency for the period was 1.9 fire episodes/1,000 yr with a mean fire-return interval of 526 years. Seven significant fire episodes were registered during the early Holocene and occurred ca. 10,600, 10,160, 9,830, 8,820, 8,340, 7,810, and 7,570 cal yr BP. The largest of these occurred ca. 8,820 cal yr BP with a fire-episode magnitude of 64.4 particles/cm^3. The second largest occurred ca. 8,340 with a fire-episode magnitude of 54.1 particles/cm^3.

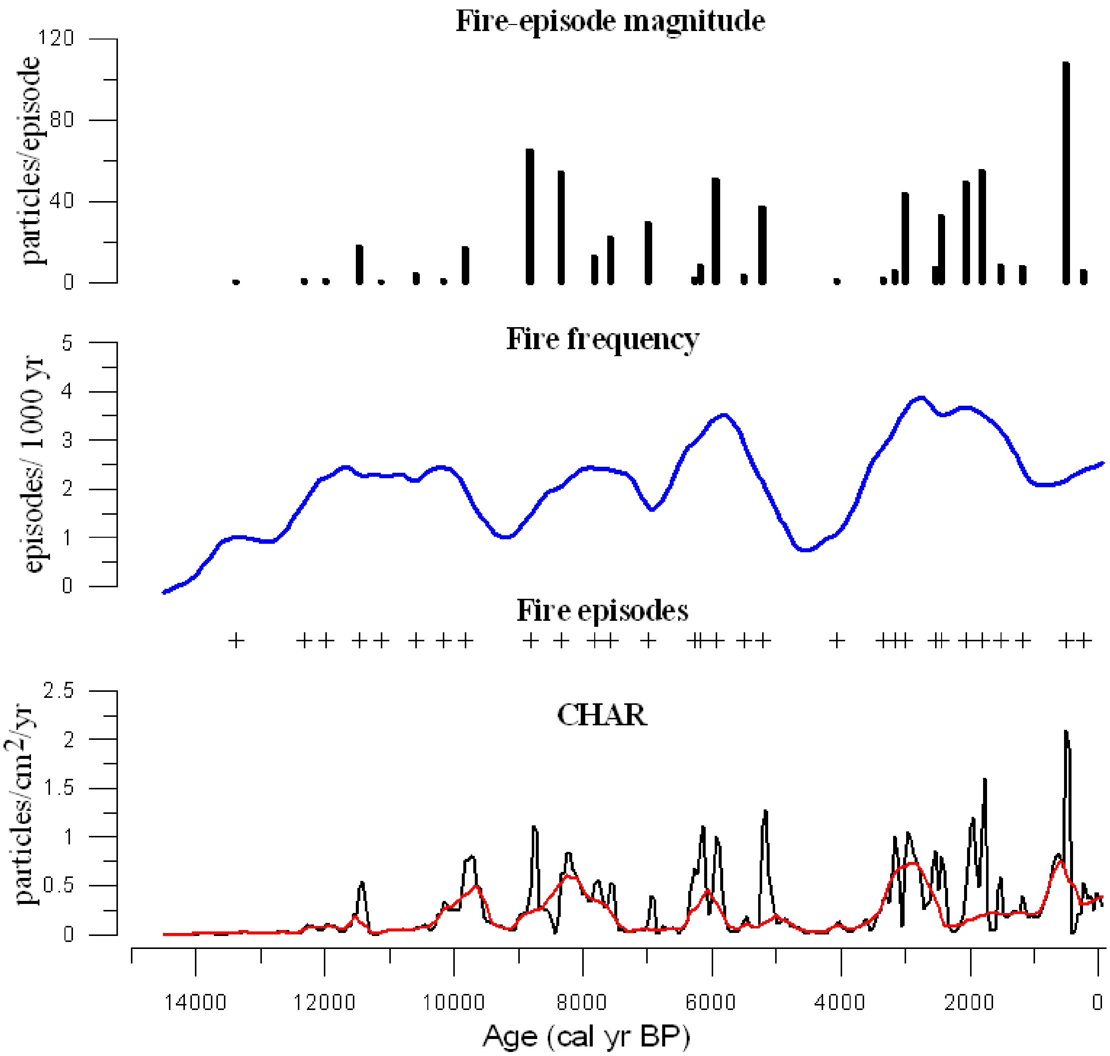

Figure 22. Sunrise Lake CHAR, fire episodes, fire frequency, and fire-episode magnitude plotted against age (cal yr BP).

Middle Holocene (7,000-4,000 cal yr BP, 160-122 cm): Charcoal concentrations during the mid-Holocene started low and increased significantly through ca. 5,259 cal yr BP. After that, charcoal concentrations decreased and remained low through the remainder of the period. CHAR values ranged between .01-1.3 particles/cm^2/yr with an average of 0.23 particles/cm^2/yr. Fire frequency increased from 1.6 fire episodes/1,000 yr at the beginning of the mid-Holocene to 3.5 fire episodes/1,000 yr ca. 5,840 cal yr BP. Fire frequency then decreased to 0.7 fire episodes/1,000 yr ca. 4,550 cal yr BP, and slowly increased to 1.4 fire episodes/1,000 yr by the end of the mid-Holocene. Average fire frequency for the mid-Holocene was 2 fire episodes/1,000 yr with a mean fire-return interval of 500 years. Seven significant fire episodes occurred during the mid-Holocene ca. 7,000, 6,280, 6,180, 5,940, 5,510, 5,220, and 4,070 cal yr BP. The largest peak occurred ca. 5,940 cal yr BP with a fire-episode magnitude of 50.5 particles/cm^3.

Late Holocene (4,000 cal yr BP - present, 122-0 cm): Charcoal concentrations during the late Holocene started low and steadily increased through the MSH-Pm tephra, ca. 3,250 cal yr BP. After that, charcoal concentrations slowly decreased until the MR-C tephra layer, ca. 2,250 cal yr BP. Immediately after the MR-C tephra, charcoal concentration increased significantly and peaked at 120.5 particles/cm^3 ca. 540 cal yr BP. Charcoal concentration then decreased substantially until the present. CHAR values ranged between 0.02-2.1 particles/cm^2/yr for the period with an average of 0.44 particles/cm^2/yr. The highest CHAR value (2.1 particles/cm^2/yr) of the record occurred ca. 520 cal yr BP. Fire frequency increased from 1.2 fire episodes/1,000 yr at the beginning of the late Holocene to 3.8 fire episodes/1,000 yr ca. 2770 cal yr BP. It then slowly decreased to 2.7 fire episodes/1,000 yr ca. 900 cal yr BP and increased to 2.5 fire episodes/1,000 yr at present. Average fire frequency for the late Holocene was 2.8 fire episodes/1,000 yr with a mean fire-return interval of 357 years. Eleven significant fire episodes occurred during the late Holocene ca. 3,350, 3,160, 3,010, 2,530, 2,760, 2,440, 2,050, 1,810, 1,520, 1,190, 520, and 230 cal yr BP. The two largest peaks occurred ca. 2,050 and ca. 1,810 cal yr BP with fire-episode magnitudes of 49.4 and 54.5 particles/cm^3, respectively. Eleven of the thirty significant fire peaks for the entire record for Sunrise Lake occurred during the late Holocene.

In the UL11D core, one significant fire peak (ca. 7,570 cal yr BP) occurred shortly after the deposition of the Mazama-O tephra layer. This fire episode had a peak magnitude of 22 particles/cm^3 and according to the age model occurred approximately 60 years after the deposition of the Mazama-O tephra (Figure 23). The Mazama-O tephra was substantial and spanned 20 cm of the 276 cm core. Charcoal concentration increased significantly to 42 particles/cm^3, 2 cm after the Mazama-O tephra deposit.

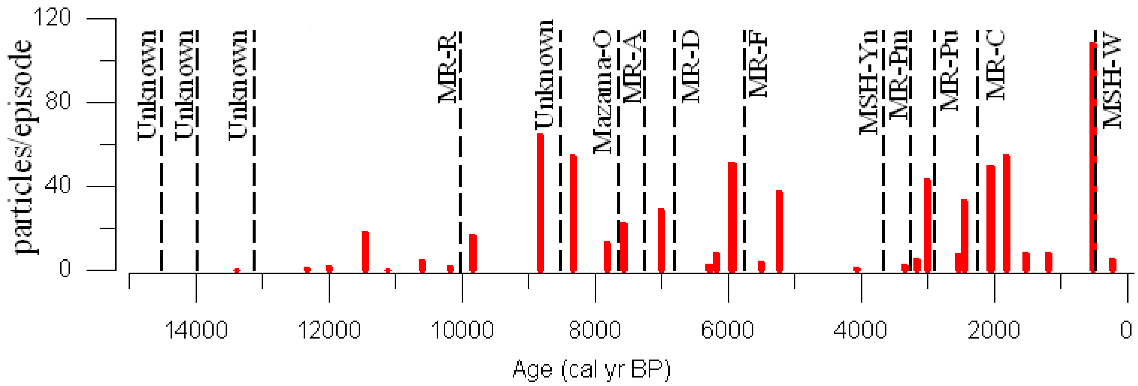

Figure 23. Sunrise Lake fire episodes and peak magnitudes plotted with identified tephra layers against age (cal yr BP). The ca. 3010 cal yr BP fire event occurred 239 years after the deposition of the MR-Pm tephra. The MSH-W tephra deposit occurred after the ca.1810 cal yr BP fire event.

Little Sunrise Lake

Chronology

Twentyfour cm of the short core (LSL11A) from Little Sunrise Lake were combined with the long core (LSL11C) to form a combined core (referred to hereafter as LSL11D). The combined core had a total depth of 173 cm. Once tephra layers were removed, the total adjusted depth for the combined core was 136 cm. The age model for the LSL11D core was developed using three AMS-^{14}C age determinations and the identification of four dated tephra layers (Figure 24 and Table 4). The long core contained five tephra of known age, but only four had reliable enough dates to include in the age model. The resulting age model for the LSL11D core suggests a basal date of 7,627 cal yr BP with a median resolution of 42 years per cm.

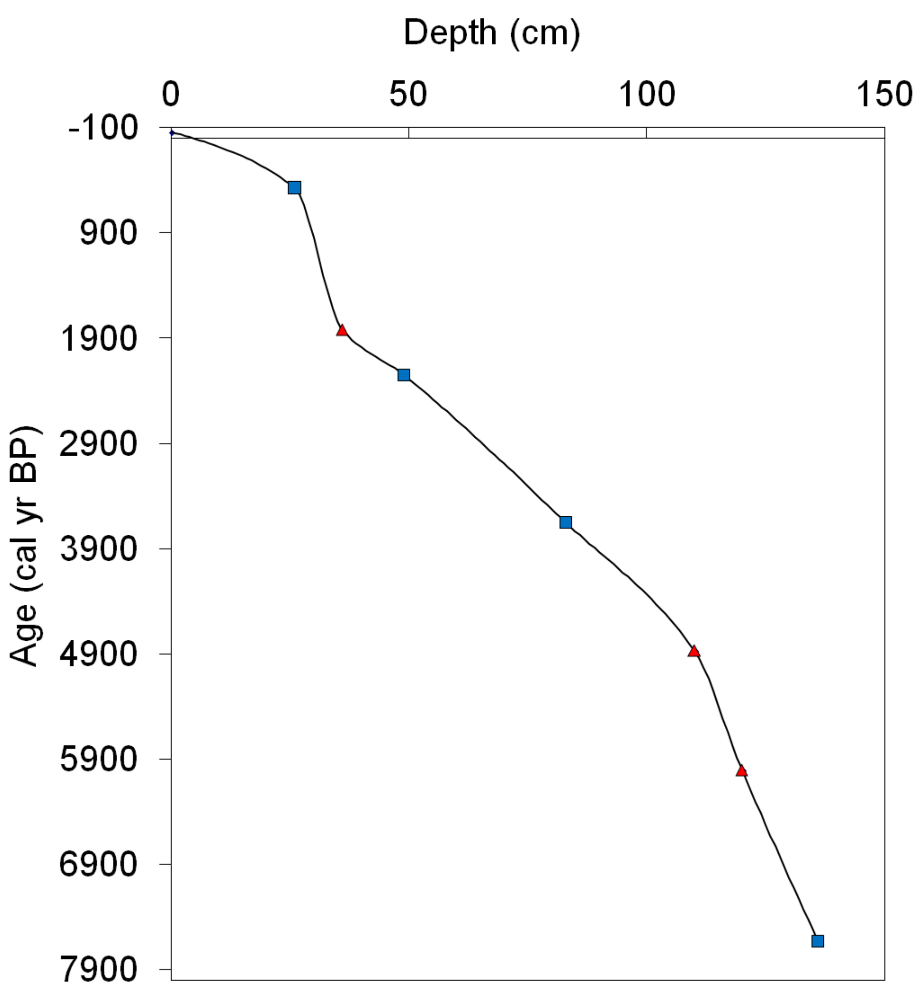

Figure 24. Little Sunrise Lake age model. Red triangles are dates obtained from AMS-^{14}C age determinations. Blue squares are dates from known tephra layers.

Table 4

Age–Depth Relations for Little Sunrise Lake Core

Depth(cm)	Lab Code	Source Material	Age (Cal yr BP)
26		MSH-W	470 [a]
36	LSL11C407	Twig	1820 [c]
49		MR-C	2250 [a]
83		MSH-Yn	3650 [a]
110	LSL11C513	Twig	4868 [b]
120	LSL11C523	Stick	6000 [c]
136		Mazama-O	7627 [d]

[a] Ages as reported in Mullineaux (1974, 1996), Clynne et al. (2004), Donogue et al. (2007) and Sisson and Vallence (2009).
[b] ^{14}C age determinations completed at Beta Analytics AMS Facility (Miami).
[c] ^{14}C age determination completed at DirectAMS Facility (Seattle).
[d] Age as reported in Zdanowicz et al. (1999).

The sedimentation rate for the LSL11D core remained relatively constant from the base of the core through ca. 4,870 cal yr BP (0.009 cm/yr). From ca. 4,870 to 1,820 cal yr BP the sedimentation rate increased to 0.024 cm/yr. From ca. 1,820 to 470 cal yr BP the sedimentation rate slowed to 0.007 cm/yr, but then from ca. 470 cal yr BP until present the sedimentation rate increased substantially to 0.048 cm/yr.

Lithology

The LSL11D core ended at the Mazama-O tephra layer, which made up the bottom 3 cm of the core (Figure 25). It is likely that the lake is older than this, but limited equipment was available to extract the remainder of the core. From 170-167 cm, the core consisted of brown gyjtta. At a depth of 166-165 cm was the MR-A tephra layer. Between 165-162 cm, the core consisted brown gyttja. An unknown tephra layer occurred at a depth of 161-159 cm. Between 159-114 cm, the core changed from light brown to brown to dark brown gyttja. Starting at 114 cm, the MSH-Yn tephra layer spanned 7 cm of the core. From 107-76 cm, the core consisted of brown to dark brown gyjtta. At a depth of 75-48 cm was the MR-C tephra layer. Between 47-27 cm, the core was composed of light brown to brown gyjtta. The MSH-W tephra layer occurred at a depth of 26-24 cm. From 24 cm until the top, the core consisted of dark brown gyjtta.

Figure 25. Little Sunrise Lake core drives and lithology. Left, drives 1, 2, and 3. Right, lithology.

The organic content of the core was low near the bottom and increased substantially toward the top, with the overall highest value of 55.8% occurring at a depth of 18 cm (Figure 26). From the start of the core until a depth of 151 cm, the organic content remained low (5-8%). At a depth of 151 cm, the organic content rose to 13.2%. It then decreased and remained low from 146-26 cm (4-7%). Starting at a depth of 23 cm, the organic content increased substantially, peaked (56%) at a depth of 18 cm, sharply decreased to 5.3% at 8 cm, and then increased to 49.6% at 3 cm. In general, the organic content was highest in the top 23 cm of the core (Figure 26).

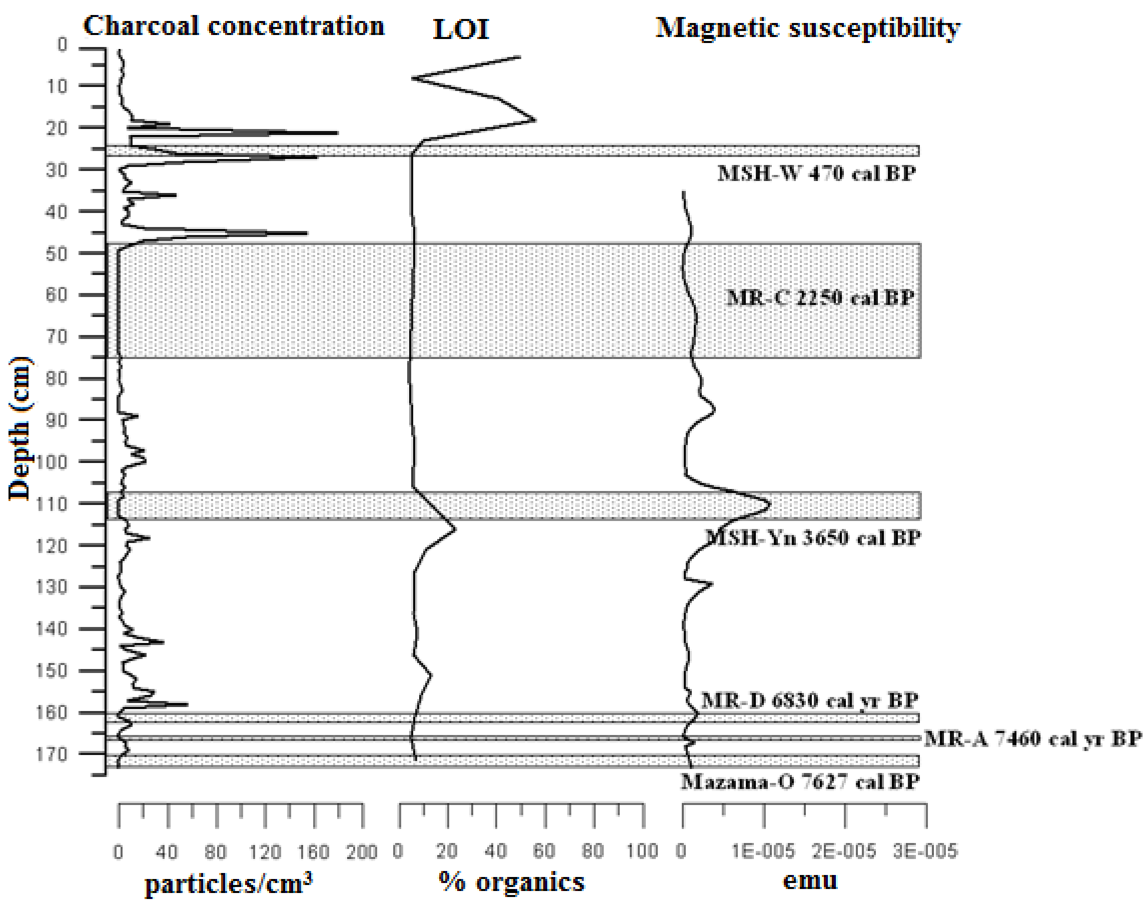

Figure 26. Little Sunrise Lake charcoal concentration, magnetic susceptibility, and organic content plotted against tephra layers by depth.

Magnetic susceptibility readings for the LSL11D core showed higher values for depths associated with tephra layers within the core. Values spiked in association with the Mazama-O, MR-A, and MSH-Yn tephra layers. These spikes in magnetic susceptibility also correlated with a drop in the organic content in the core.

Charcoal Record

Early Holocene (7,627-7,000 cal yr BP, 136-131 cm): Only a short section of the early Holocene was recovered from Little Sunrise Lake. During this 630 year period, charcoal concentrations were low and varied between 0-8.5 particles/cm^2. CHAR values ranged between 0-0.07 particles/cm^2/yr with an average of 0.03 particles/cm^2/yr. Fire frequency increased from 1.7 fire episodes/1,000 yr ca. 7625 cal yr BP to 2.4 fire episodes/1,000 yr at the end of the early Holocene. Average fire frequency for the period was 2.08 fire episodes/1,000 yr with a mean fire-return interval of 480 years. One significant fire episode occurred ca. 7,415 cal yr BP and had a peak magnitude of 0.64 particles/cm^3.

Middle Holocene (7,000-4,000 cal yr BP, 131-92 cm): Charcoal concentrations during the mid-Holocene increased initially ca. 6,650 cal yr BP and then decreased and remained low but variable for the remainder of the period. CHAR values ranged between 0-0.64 particles/cm^2/yr with an average of 0.11 particles/cm^2/yr. Fire frequency decreased from 2.5 fire episodes/1,000 yr at the beginning of the mid-Holocene to 1 fire episodes/1,000 yr ca. 5,820 cal yr BP. Fire frequency then slowly increased to 1.8 fire episodes/1,000 yr by the end of the mid-Holocene. Average fire frequency for the mid-

Holocene was 1.9 fire episodes/1,000 yr with a mean fire-return interval of 526 years. Six significant fire episodes occurred during the mid-Holocene, ca. 6,870, 6,620, 6,320, 5,320, 4,980, and 4,310 cal yr BP. The largest peak occurred ca. 6,620 cal yr BP with a fire-episode magnitude of 24.1 particles/cm^3.

Late Holocene (4,000 cal yr BP - present, 92-0 cm): Charcoal concentrations during the late Holocene remained low and variable from the start of the time period through the deposition of the MR-C tephra deposition. After that, charcoal concentration increased and peaked ca. 2,100 cal yr BP (154.5 particles/cm^2), ca. 530 cal yr BP (163 particles/cm^2) and ca. 320 cal yr BP (179.5 particles/cm^2). Charcoal concentration then decreased substantially until the present. CHAR values ranged between 0-4.4 particles/cm^2/yr with an average of 0.31 particles/cm^2/yr for the period. The highest CHAR value (4.4 particles/cm^2/yr) of the entire record occurred ca. 280 cal yr BP. Fire frequency increased from 1.8 fire episodes/1,000 yr at the beginning of the late Holocene to 2.9 fire episodes/1,000 yr ca. 3000 cal yr BP. It then slowly decreased to 0.4 fire episodes/1,000 yr ca. 1,070 cal yr BP and then increased to 2.8 fire episodes/1,000 yr at present. Average fire frequency for the late Holocene was 1.9 fire episodes/1,000 yr with a mean fire-return interval of 526 years (Figure 27). Eight significant fire episodes occurred during the late Holocene, ca. 3,800, 3,220, 3,090, 2,750, 2,120, 1,790, 490, and 280 cal yr BP. The three largest peaks occurred ca. 2,120 (157.7 particles/cm^3), 490 (135 particles/cm^3), and 280 cal yr BP (particles/cm^3). Eight of the fifteen significant fire episodes for the entire record for Little Sunrise Lake occurred during the late Holocene.

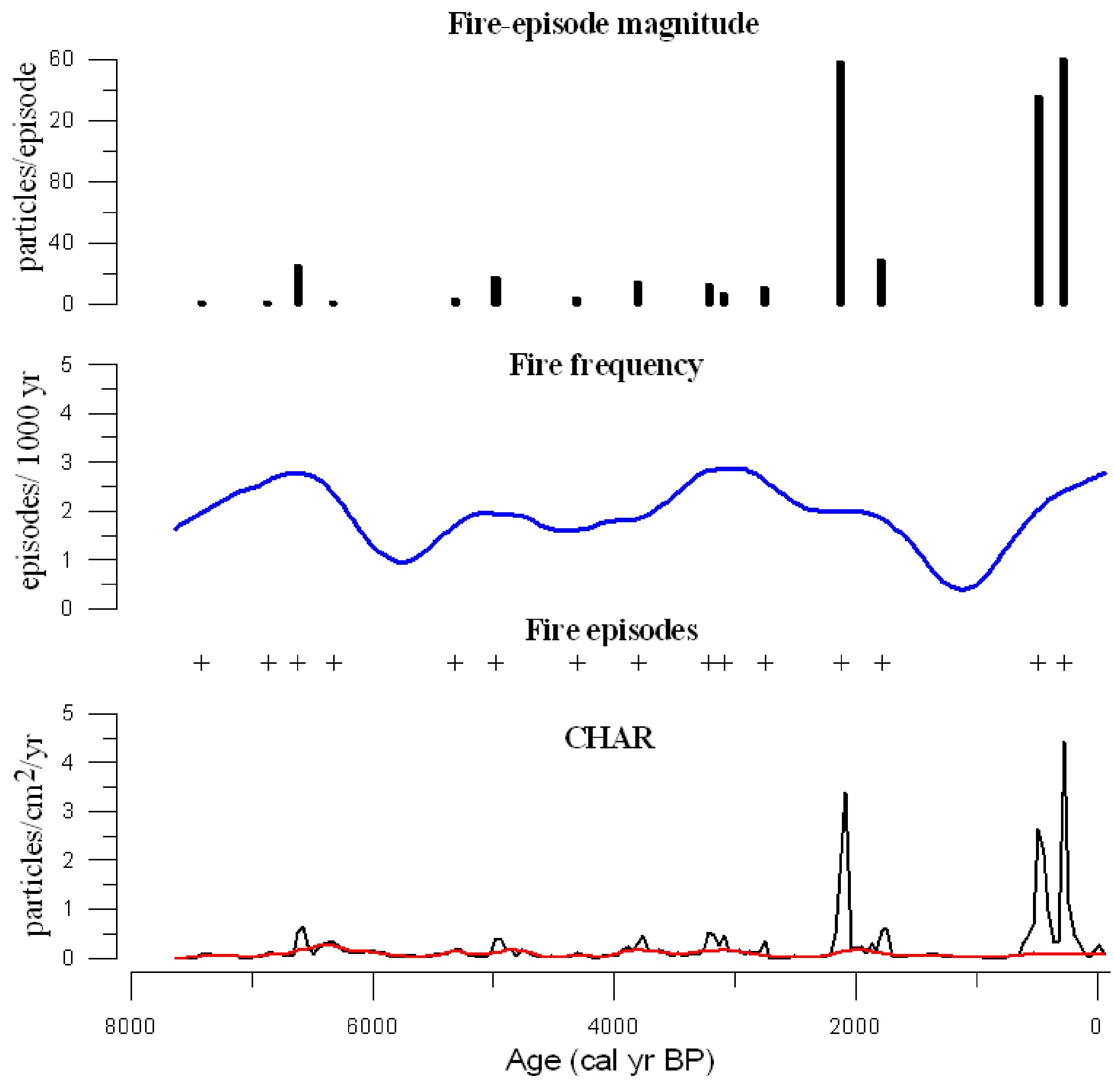

Figure 27. Little Sunrise Lake CHAR, fire episodes, fire frequency, and fire-episode magnitude with tephra layers.

CHAPTER VI

DISCUSSION

Various potential drivers of fire activity through the Holocene have been recognized in previous fire-history studies, including Hallet et al. (2003), Pritchard et al. (2009), and Walsh et al. (2008). However, the relationship between potential drivers and fire activity is still not wholly understood for the PNW, especially in regard to the central Cascades and Mount Rainier. For example, studies from across the Cascades vary on potential causes for increased fire activity during the late Holocene (Hallet et al., 2003; Long et al., 2011; Pritchard et al., 2009; Spooner et al., 2008; Tweiten, 2007). In order to try and address this problem, it is necessary to compare climatic and human land-use records for MORA with the reconstructed fire records for the Sunrise Ridge area. Doing so may make it possible to draw better conclusions regarding possible drivers of fire activity on the Sunrise Ridge during the late Pleistocene and Holocene.

Sunrise Ridge

Late Pleistocene (14000-11,000 cal yr BP)

The Sunrise Lake fire-history reconstruction suggests that fire activity was low in the Sunrise Ridge area during the late Pleistocene. Several fire episodes occurred near the site, but peak magnitudes and CHAR values for these events were low compared to the rest of the record. These results indicate that fires near Sunrise Lake at this time were infrequent and of low-severity/magnitude. With the retreat of the permanent ice on Mount Rainier ca. 14,000 cal yr BP and the likely development of open forest-tundra habitats for a brief period of approximately 500 years, it is likely that this change in vegetation led to the small observed increase in fire activity in the record at this time. Overall, fire activity remained low and variable through the late Pleistocene. During the McNeely I glacial advance (ca. 13,500-12,900 cal yr BP) glaciers on the mountain moved downslope effectively lowering the snowline, which in turn kept fire activity low (1 fire episode occurred during this period). Unlike other mountains in the North Cascades, Mount Rainier has no evidence of a Younger Dryas (ca.12,900-11,600 cal yr BP) glacial advance (Heine, 1998; Hekkers, 2010). During this period, average sea surface temperature and local terrestrial climate proxies indicate cold climatic conditions and drought on the mountain (Hekkers, 2010). Glaciers on Mount Rainier retreated and tree line shifted uphill. Simultaneously, at Sunrise Lake, fire episodes increased in number (3 episodes) and magnitude. This increase was likely due to a rebound of vegetation after the McNeely I glaciers retreated.

In terms of human land use, the presence of Pleistocene megafauna and early fluted points provide some evidence of an early human presence in the vicinity of the Cascades during the period. However, this presence is considered extremely limited and overall human impacts on the landscape minimal due to inhospitable conditions and low numbers of people utilizing the mountain (Burtchard, 2007).

Early Holocene (ca. 11,000-7,000 cal yr BP)

All three reconstructions from the Sunrise Ridge area indicate that fire activity generally increased during the early Holocene (Figure 29). At Shadow Lake from ca. 10,140 cal yr BP (the start of the record) through the end of the early Holocene, fire frequency increased. At Sunrise Lake, fire frequency initially decreased ca. 10,000 to

9,200 cal yr BP and then increased thereafter. At Little Sunrise Lake, fire increased steadily from ca. 7,630 cal yr BP (the start of the record) through the end of the period. Differences between the Shadow and Sunrise Lake reconstructions may be due to the fact that fire frequency is a smoothed output of fire episodes per thousand years from the CharAnalysis program. The first registered fire event in the Shadow Lake record occurred ca. 9,290 cal yr BP and fire events increased in number after that time, creating an increasing fire frequency for the 1,000 yr period. In the Sunrise Lake record, several fire events occurred between ca. 11,000-10,000 cal yr BP, but then the next significant fire event did not occur until ca. 8,820 cal yr BP. This 1,000 year gap in fire caused the fire-return interval to decline at Sunrise Lake during this period. If the Shadow Lake record extended back another thousand years, several fire events might have been recorded, which would have altered the fire frequency output from CharAnalysis to mimic that of Sunrise Lake. It appears from the presence of bedrock at the end of the Shadow Lake core that the lake most likely formed after the retreat of McNeely II glacial ice ca. 10,000 cal yr BP.

After the retreat of the McNeely II glacial ice, increased seasonality due to increasing Northern Hemisphere insolation increased summer temperatures and decreased effective moisture (Thompson et al., 1993). This shift led to warmer summers (i.e., more drought) and colder winters than at present and most likely led to the establishment of more-open, xerophytic vegetation communities on the mountain (Whitlock et al., 2000). Regional records for the PNW show that Holocene warmth began ca. 10,000 cal yr BP and lasted through ca. 7,000 cal yr BP (Pellatt et al., 2008;

Walker and Pellatt, 2008). Climate reconstructions for Mount Rainier based on plant macrofossil and pollen data as well as synchronous North Cascade and Mount Rainier glacial advance-retreat patterns, however, show that maximum Holocene warmth on the mountain lagged behind the rest of the region, starting ca. 8,000 cal yr BP and lasted into the mid-Holocene (ca. 6,000 cal yr BP) (Burtchard, 2003). These findings roughly follow the GISP2 air temperatures as reconstructed by Alley (2000) (figure 28). Increased warmth during the HCO and associated droughts most likely led to a higher occurrence of fire and an overall increase in fire activity on Mount Rainier, as evidenced in the fire record for the Sunrise Ridge.

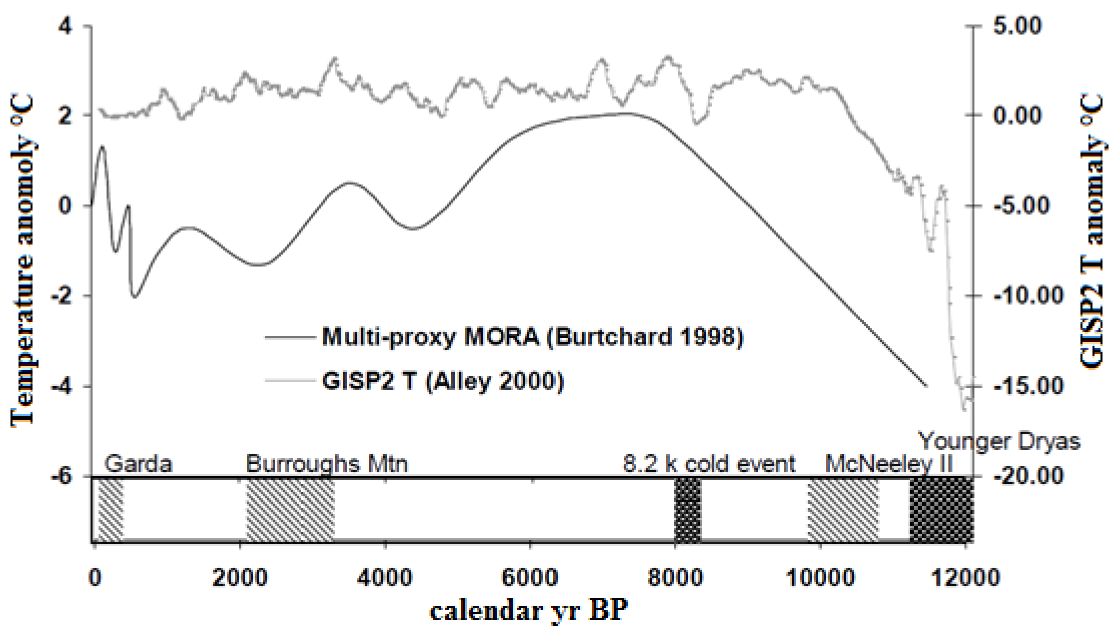

Figure 28. Multi-proxy-based temperature proxy record for Mount Rainier National Park compared to GISP2 air temperatures. Figure from Hekkers (2010).

Volcanic eruptions and the influence of large amounts of tephra on the landscape may have also impacted fire activity on the Sunrise Ridge. Increased fuel as a result of vegetation kill by tephra deposits can lead to high-magnitude fire episodes (McGlone et al., 1981). One significant fire peak (ca. 7,570 cal yr BP) occurred shortly after the deposition of the Mazama-O tephra layer in the Sunrise Lake core, however, the fire was low in magnitude compared to other significant peaks during the time period. Walsh et al. (2008) found a similar fire episode after the Mazama-O deposit at Battle Ground Lake in southwestern Washington, but this event was much larger in magnitude. It does not appear that the fire following the Mazama-O tephra in the Sunrise Lake core greatly influenced the over fire regime for the Sunrise Ridge during the early Holocene.

In terms of human land use at MORA during the early Holocene, forage and ungulate populations that utilized that forage are believed to have been abundant at lower elevations, making it unnecessary to travel to the mountains for subsistence reasons (Burtchard, 2007). In terms of the archaeological record, the earliest number of dated artifacts from the mountain comes from between ca. 10,000 - 7,000 cal yr BP, supporting Burtchard's theory for limited land use during the period. One might speculate that the lack of humans in alpine areas during the early Holocene most likely translates to minimal use of fire on MORA at the time. Burtchard (2007) suggests that the few numbers visiting the mountain most likely utilized lower elevation foothill and valley landforms for seasonal hunting and gathering activities.

Middle Holocene (7,000-4,000 cal yr BP)

During the transition from the early Holocene to the mid-Holocene, fire activity increased at all three sites on the Sunrise Ridge. At Shadow Lake, fire frequency continued to increase through ca. 6,380 cal yr BP. At Sunrise Lake, fire frequency continued to increase through ca. 5,840 cal yr BP. At Little Sunrise Lake, fire frequency continued to increase through ca. 6,580 cal yr BP. Overall; all three lakes had a similar numbers of fire episodes (6-7) that occurred during the mid-Holocene. Sunrise Lake, however, had much higher CHAR values (an average of 0.23 particles/cm^2/yr) compared to Shadow Lake (0.10 particles/cm^2/yr) and Little Sunrise Lake (0.11 particles/cm^2/yr). Shadow and Sunrise Lakes are geographically separated by the Sunrise Ridge and are far enough apart to reasonably have different magnitude fires based upon differences in drainage basin size and vegetation. However, Little Sunrise Lake is located only 440 m to the north- northeast of Sunrise Lake. A plausible explanation for this difference in CHAR values between the two is the fact that Sunrise Lake is much bigger, which translates to the amount of material (including charcoal) that is transported to and entraped in the lake sediments (Marlon et al., 2006).

An increase in fire activity at the start of the mid-Holocene corresponds with the last 1,000 years of the HCO on the mountain. Also of interest, the El Niño–Southern Oscillation (ENSO) variability first became statistically significant ca. 7,000 cal yr BP and coincides with the increase in fire on the Sunrise Ridge at the start of the mid-Holocene (Moy, Seltzer, Rodbell, & Anderson, 2002) (figure 29). Increased available moisture during La Niña years coupled with a higher reoccurrence of drought during El Niño years could have led to a buildup of biomass, a drying of vegetation and a subsequent increase in fire activity. Research by Hessl et al. (2004) and Heyerdahl et al. (2008) on the linkages between drought, fire, and ENSO variability in the PNW over the past several hundred years support a relationship between fire and drought years as recorded in tree-rings which correspond to reconstructed El Niño events.

After ca. 6,380 cal yr BP in the Shadow lake record, ca. 5,840 cal yr BP in the Sunrise Lake record, and ca. 6,580 cal yr BP in the Little Sunrise Lake record, fire frequency decreased (figure 29). The mid-Holocene saw the establishment of oscillating, but generally cooler and moister climatic conditions after the termination of the HCO (Crandell & Miller, 1974). Upper elevation forest cover retreated downslope and alpine tundra and subalpine parklands most likely expanded on the mountain (Burtchard & Swinney 2004). This shift in climate, combined with a decrease in ENSO variability, most likely led to the observed decrease in fire activity in all three records during the middle part of the period. Fire frequency started to increase again ca. 5,500 cal yr BP at Little Sunrise Lake and ca. 4,500 cal yr BP at Shadow and Sunrise Lakes. This increase once again roughly coincides with an increase in ENSO variability (figure 29). At Little Sunrise Lake, two fire events were recorded that were absent in the other two lakes. The two fire events were of low magnitude and had low associated CHAR values, suggesting that these fires were small or in close proximity to the lake (Millspaugh & Whitlock, 1995). However, they did cause the fire frequency for the lake to begin to increase roughly 1,000 years earlier than the other two sites.

During the mid-Holocene, the archeological record for Mount Rainier shows an increase in radiocarbon dates from the Buck Lake site (45PI438) and suggests a heightened use of Mount Rainier's subalpine zone relative to the pre-Mazama component (Burtchard, 2007). According to Burtchard's (2007) model, elevated population density and declining ungulate habitat in the lowlands forced people into the mountains for subsistence purposes. Burtchard suggests that fire-based forest suppression to promote more productive early seral-stage communities in both lowland and upland settings most likely started toward the end of the mid-Holocene (Burtchard, 2007).

Late Holocene (4,000 cal yr BP until present)

From the start of the late Holocene, fire activity continued to increase in all three records. At Shadow Lake, fire frequency increased through ca. 1,960 cal yr BP. At Sunrise Lake, fire frequency increased through ca. 3,000 cal yr BP. At Little Sunrise Lake, fire frequency increased through ca. 2,800 cal yr BP. These increases at all three lakes corresponds with the Burroughs Mountain glacial advance (ca. 3,400-2,200 cal yr BP) and a climate that is thought to have been marked by an increase in precipitation and gradual decline in temperatures as July insolation values dropped toward present day values (Berger, 1991; Pellatt et al. 1998; Thompson et al., 1993). In the Shadow Lake core, a significant fire episode (ca. 2,200 cal yr BP) occurred shortly after the MR-C tephra layer. This fire episode was low in magnitude compared to other significant peaks and does not appear to be the cause for an increase in fire activity during the Burroughs Mountain advance.

The increase in fire does, however, correspond with an increase in ENSO variability (Moy et al., 2002). The higher number of recorded ENSO events through the late Holocene most likely led to dramatic differences in winter snow pack from one year to the next (Mote et al., 2005). Past ENSO variability most likely impacted the snowpack in the PNW in a similar manner as found by Mote et al. (2005) during the 20th century, with higher spring snowpacks and snow water equivalent (SWE) values associated with La Niña years and low snowpacks, SWE, and drought during El Niño years. Observations of recent El Niño/ La Niña winters in the Cascades and on Mount Rainier suggest that it is possible to have a positive glacial balance during periods with a higher number of ENSO events, as long as the total glacial budget is skewed toward the positive (higher accumulation of snow than loss which translates to increased glacial ice) by heavy winter snowpacks during La Niña years (Burbank, 1982; Riedel & Larrabee, 2012). This observed trend could explain the higher fire frequency during the Burroughs Mountain glacial advance in the Sunrise Ridge reconstructions.

Following that, fire activity decreased at Shadow Lake from ca. 1,960 to 1,300 cal yr BP, from ca. 3,000 to 1,040 cal yr BP at Sunrise Lake, and ca. 2,800 to 1,120 cal yr BP at Little Sunrise Lake. This decrease in fire activity was marked by a decrease in fire frequency and fire-episode magnitude at all three lakes and corresponds with a significant decrease in ENSO variability and reflects the colder, wetter climate of the time (Berger & Loutre, 1991; Pellatt et al., 1998). Fire activity then increased from ca.1,300 to 550 cal yr BP at Shadow Lake, from ca. 1,040 cal yr BP until present at Sunrise, and from ca. 1,120 cal yr BP until present at Little Sunrise. This initial increase in fire activity corresponds with the Medieval Climate Anomaly (ca. 1,100–600 cal yr BP), which was marked by warmer temperatures and drought (Mann, 2003). At Sunrise Lake, the highest magnitude fire episode for the entire record occurred ca. 520 cal yr BP, and at Little Sunrise Lake, the second highest magnitude fire for the entire record occurred ca. 500 cal yr BP. These fires occurred during a period of drought in the western United States (ca. 600-525 cal yr BP) that followed the MCA and preceded the Little Ice Age (LIA). These fires are most likely a result of a drying of vegetation and a higher availability of fuel (Cook et al., 2004).

The LIA became established in the PNW ca. 500 cal yr BP and lasted through ca. 110 cal year BP (Graumlich & Brubaker, 1986; Grove, 2001). Overall, the period was marked by expanded glacial activity and cooler temperatures (1°C colder than the mean for 1914-1979; Graumlich & Brubaker, 1986). However the LIA was not a continuous period of glacial growth or cold temperatures. Instead, the period was marked by swings in precipitation, temperature, and drought (Graumlich& Brubaker, 1986). From ca. 300 to 260 cal yr BP (1650 to 1690 AD), warm summer temperatures and low snow accumulations were recorded in tree-ring records (Graumlich & Brubaker, 1986). From ca. 230 to 220 cal yr BP (1720 to 1730 AD), warm summer temperatures once again set in, leading to a period of moraine stabilization on Mount Rainier, and extreme drought years in the Columbia Basin (Graumlich, 1987;

Graumlich & Brubaker, 1986). Coincidently, both of these periods saw increases in ENSO variability (figure 29).

At Little Sunrise Lake, the largest magnitude fire-event in the record occurred ca. 280 cal yr BP. This fire episode corresponds with the period of higher than average summer temperatures and low snow accumulation noted by decreased growth in tree-rings (Graumlich & Brubaker, 1986). The preceding cool, wet episode from ca. 350 to 300 cal yr BP most likely allowed for the buildup of forest vegetation (Graumlich & Brubaker, 1986) and warm dry conditions from ca. 300 to 260 cal yr BP most likely led to drought and subsequent severe fire. At Shadow Lake, a fire-episode occurred ca. 220 cal yr BP and at Sunrise Lake a fire-episode occurred ca. 230 cal yr BP. Both were of low magnitude and occurred during a brief period of moraine stabilization and higher than average summer temperatures from ca. 260 to 190 cal yr BP (1690-1760 AD) (Graumlich & Brubaker, 1986). These fires were most likely due to higher than average summer temperatures, but were of low magnitude due to the shortage of dry fuels from the short window of warm, drying conditions.

During the late Holocene, the archaeological record at MORA shows a high density and relatively high diversity of artifacts recovered from ca. 3,600 to 2,200 cal yr BP at the Sunrise Ridge Borrow Pit site (45PI408) (McCutcheon, 1999). There is a marked increase in artifact diversity and density immediately atop the MSH-Yn tephra deposits (ca. 3,650 cal yr BP) compared with earlier deposits at the Buck Lake site (45PI438) (Burtchard 1998; Dampf 2002; McCutcheon 1999). Fire frequency

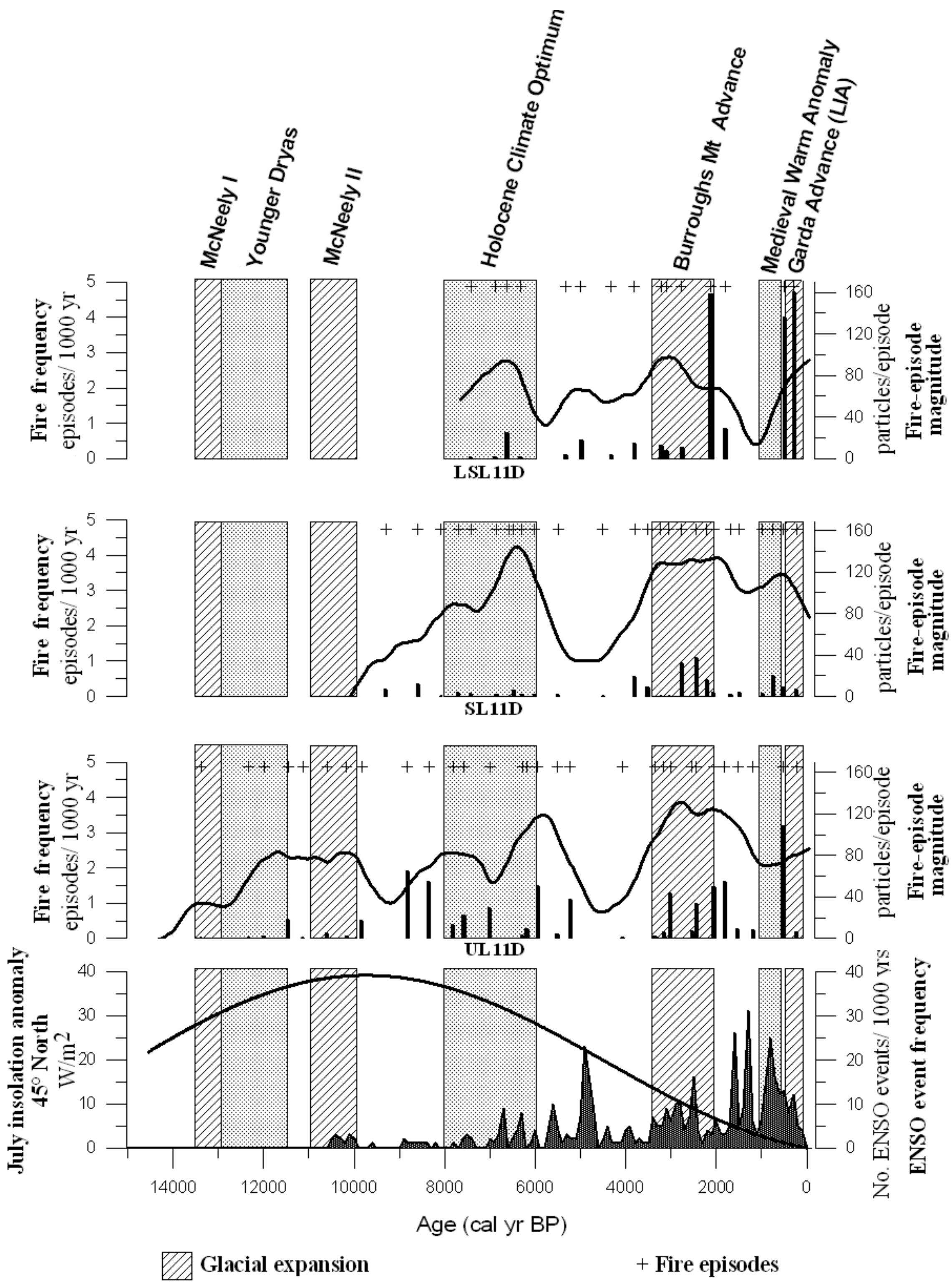

Figure 29. Fire frequency, fire events, and fire-episode magnitudes and climate episodes/ periods of glacial advance, July insolation anomaly, and ENSO events. Data for insolation from Berger & Loutre (1991). Data for ENSO from Moy et al. (2002).

substantially increased in the Sunrise Ridge area between the MSH-Yn and MSH Pu tephras and peaks at all three sites during this period. Fire-event magnitude also increased compared to before the MSH-Yn tephra, but was still much lower than the highest magnitude fire-episodes toward the end of the late Holocene (Figure 29). Burtchard (2007) suggests that cool neoglacial conditions during the late Holocene further increased Native Peoples' dependency on fire to combat forest encroachment, enhance ungulate forage on the mountain, and increase the productivity of culturally significant plant species such as huckleberry and bear grass. It seems plausible that Native People would have utilized fire to higher and higher degrees during the late Holocene in order to maintain and enhance grasslands and meadows and to stop tree encroachment as climate shifted toward colder and wetter conditions on the mountain. More frequent but lower intensity fires, such as those inferred from the Sunrise Ridge fire reconstructions between the MSH-Yn and MSH-Pu tephras, could possibly reflect an anthropogenic influence on the fire regime during the time (Figure 30).

In general, during the late Holocene fire frequency for the three sites increased from roughly a low of 2 fires per thousand years (500 year return fire interval) at the start of the period to a high of 4 fires per thousand years (250 year return fire interval) ca. 3,000 cal yr BP. This change is considered a significant increase for subalpine forests (MORA FMP, 2005). Based on the reconstructed fire-episode magnitudes, fires presumably became more severe during the late part of the Holocene (ca. 2,000 cal yr BP to present) as compared to the start of late Holocene This interpretation is supported by the fact that the most severe fire episodes in the Sunrise Ridge records occurred during periods thought to have been marked by warm temperatures and drought (Cook et al., 2004; Graumlich, 1987; Graumlich & Brubaker, 1986).

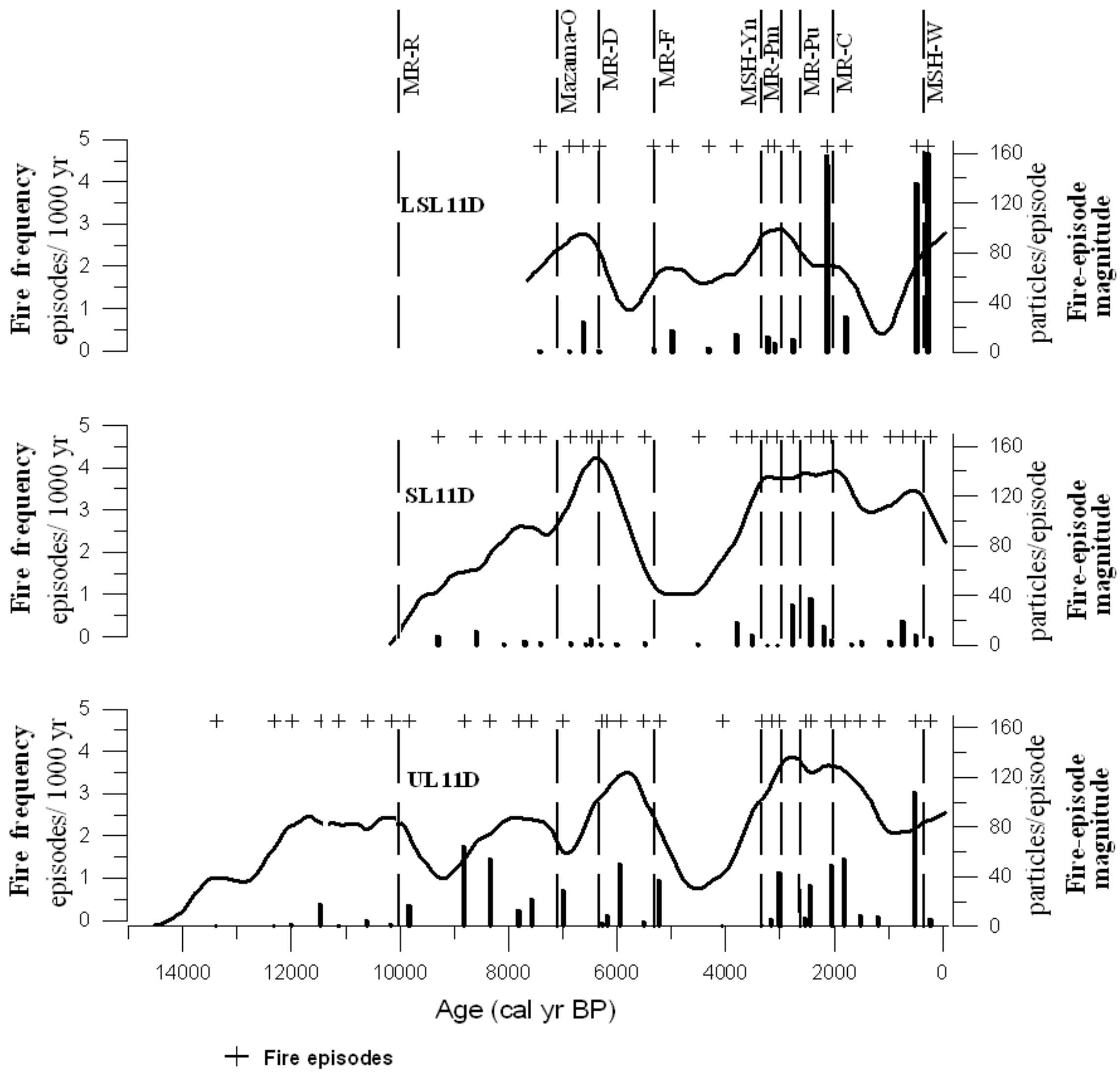

Figure 30. Fire frequency, fire events, and fire-episode magnitudes plotted against tephra layers.

Because macroscopic charcoal analysis was used to reconstruct fire history, presumably, the individual fire reconstructions from the three sites in the Sunrise Ridge area only registered fires episodes that occurred within each respective watershed

(Clark et al., 1998; Gardner & Whitlock, 2001; Long et al., 1998; Millspaugh & Whitlock, 1995). However, fire activity, including the ages of significant fire events and fire-episode magnitude, was remarkably similar for all three sites, especially during the late Holocene. This similarity would suggest that fire activity across the entire Sunrise Ridge area likely exhibited similar trends as the three lakes in this study during the late Pleistocene and Holocene. In light of these findings, the results of this thesis can therefore be considered as a fire record for the Sunrise Ridge as a whole.

Regional Fire History Comparison

Records of fire activity during the late Pleistocene and Holocene from across the Pacific Northwest can be used to place the fire activity for the Sunrise Ridge into context and can also be used to evaluate the potential drivers of that fire activity. If regional climate is the primary driver behind fire activity in the PNW, sites across the region, especially those with similar geographic locations and forest types as those for the Sunrise Ridge should display similar trends in fire activity. If regional climate is not the primary driver or if other influences have had a major impact on fire activity (such as anthropogenic use of fire) the reconstructions should presumably vary from site to site and reflect more local impacts.

Late Pleistocene (14,000-11,000 cal yr BP)

High elevation sites across the Cascades show both similarities and differences in fire activity during the late Pleistocene as compared to the Sunrise Ridge. During the late Pleistocene, fire activity the on Sunrise Ridge was low overall but did increase slightly through the period. At Ridley Lake, in North Cascades National Park, fire activity also remained low through the period (Spooner et al., 2008). Cold, dry climatic conditions are thought to have suppressed forest growth and fire activity in the Cascades at the time (Spooner et al., 2008). Tumalo Lake (in the southern Cascades) unlike the Sunrise Ridge and Ridley Lake, had the highest fire activity of the record starting ca. 12,000 cal yr BP until the end of the period, but these fires did not produce abundant charcoal and were of low magnitude (Long et al., 2011). According to the authors, the low abundance of charcoal but high fire frequency during the late Pleistocene is due to the presence of grasslands and dry-adapted vegetation.

For the Olympic Mountains (Martins and Moose lakes), an isolated mountain chain on the Olympic Peninsula of Washington, fire activity, similar to the Sunrise Ridge, remained low to non-existent through the late Pleistocene (Gavin, McLachlan, Brubaker, & Young , 2001). The presence of cold-adapted species in the pollen record for Martins and Moose lakes indicate that prior to ca 11,000 cal yr BP, the climate was cold and dry (Gavin et al. 2001).

During the late Pleistocene, similar to the fire-history reconstruction for the Sunrise Ridge, low-elevation sites across the PNW show little to no fire activity. These sites range from forest on Vancouver Island to the Oregon coast (Brown & Hebda, 2002; Cwynar, 1987; Tsukada, Sugita, & Hibbert, 1981; Walsh et al., 2008). For example, at Battle Ground Lake, a low elevation forested site in the lower Columbia River Valley, fire frequency remained low from ca. 14,300-13,100 cal yr BP (Walsh et al., 2008). After that, fire activity increased with more frequent fire episodes that burned mostly woody vegetation. According to the authors, at the start of the late Pleistocene regional climate was still likely cold and dry, and vegetation was sparse, which in turn supported little fire activity. As conditions warmed in the transition from the late-glacial to the early Holocene, a more closed forest developed and fire episodes increased in frequency and size or severity, likely due to increased fuel biomass (Walsh et al., 2008). This increase during the transition from the late-glacial to the early Holocene is also recorded in the Sunrise Ridge records.

Early Holocene (11,000-7,000 cal yr BP)

During the early Holocene, fire activity generally increased on the Sunrise Ridge from the start of the period through ca. 8,000 cal yr BP, followed by a small decrease in fire activity through ca. 7,000 cal yr BP. In general, records from the North Cascades (Frozen Lake, Mount Barr Cirque Lake, Ridley Lake, and Panther Pot Holes) show a similar increase in fire frequency at the start of the early Holocene through ca. 8,500 cal yr BP and a decrease in activity afterwards (Hallet et al., 2003; Pritchard et al., 2009; Spooner et al., 2008). Generally warmer, drier climatic conditions are thought to have prevailed at this time in the North Cascades, which led to the increase in fire activity at the start of the period (Hallet et al., 2003; Pritchard et al., 2009; Spooner et al., 2008). In the Southern Cascades, fire-episode frequency at Tumalo Lake declined after ca. 9,200 cal yr BP and remained low through the early Holocene (Long et al., 2011). According to the authors, an increase in fir (*Abies*) and a decrease in sagebrush (*Artemisia*) in the Tumalo Lake watershed, along with a decline in fire-episode frequency suggests that more mesic environmental conditions prevailed during early Holocene as compared to the late Pleistocene (Long et al., 2011). Unlike the records for the Sunrise Ridge and the

North Cascades, fire frequency decreased during the early Holocene at Tumalo Lake, suggesting that local climate in the southern Cascades was wetter than found in the North Cascades at the time.

For the Olympic Mountains, fire activity was quite different between the Martins and Moose lake records during the early Holocene. Fire activity remained low in the Martins Lake record; however, at Moose Lake high charcoal concentrations suggest that fires were more common than at any other time in the sediment record (Gavin et al., 2001). Martins Lake probably remained above tree-line during this period, while a dramatic increase in vegetation cover was noted in the Moose Lake watershed. According to the authors, the forest expansion at Moose Lake was probably a response to a warmer and drier regional climate.

Similar to fire activity on Sunrise Ridge, fire frequency increased at the start of the early Holocene in low elevation forests and then decreased through the end of the period (Brown & Hebda, 2002; Cwynar, 1987;Tsukada, Sugita, & Hibbert, 1981; Walsh et al., 2008). For example, at both Battle Ground Lake and Little Lake (located in a coastal forest in Oregon), frequent fire episodes of low-to-moderate severity occurred. At Battle Ground an increase in herbaceous (i.e., grass) charcoal content was noted (Walsh et al., 2008). At Little Lake, the fire interval for the period averaged 110 ± 20 years (Long et al., 1998). An increase in fire frequency at both lakes was most likely a result of warmer, drier climatic conditions during the period and greater summer drought (Long et al., 1998; Walsh et al., 2008).

Middle Holocene (7,000-4,000 cal yr BP)

During the mid-Holocene, fire activity increased substantially on the Sunrise Ridge from ca. 7,000 through 6,000 cal yr BP and then decreased through the end of the period. At Buck Lake, fire frequency also increased significantly from the start of the record (ca. 7,000 cal yr BP) through ca. 6,500 cal yr BP and like the Sunrise Ridge, decreased through the end of the mid-Holocene (Tweiten, 2007). However, this increase in fire activity at Buck Lake and the Sunrise Ridge is not reflected at other sites in the Cascades. In the North Cascades, fire activity on the whole remained low throughout the middle Holocene (Hallet et al., 2003; Pritchard et al., 2009; Spooner et al., 2008). In the southern Cascades, fire frequency continued to decline (Long et al., 2011). Specifically at Tumalo Lake, fire frequency declined to between 4 and 6 fire episodes per 1,000 years as compared to the early Holocene (Long et al., 2011). In general, cooler and moister climatic conditions established in the PNW at the time. However, on Mount Rainier, the HCO is thought to have persisted through ca. 6,000 cal yr BP, which could account for its seemingly anomalously high fire frequency.

Similar to records for other lakes in the North Cascades, but unlike the Sunrise Ridge, fire activity remained low throughout the mid-Holocene in the Olympic Mountains (Gavin et al., 2002). Pollen assemblages from the study sites indicate that forests began to resemble modern high-elevation forests during this period (Gavin et al., 2002). The establishment of these more modern forests suggests that cooler and moister climatic conditions began to prevail during the period, thereby reducing fire frequency (Gavin et al., 2002).

Fire frequency in low elevation forests, unlike the Sunrise Ridge, generally decreased throughout the mid-Holocene (Brown & Hebda, 2002; Cwynar, 1987; Tsukada, Sugita, & Hibbert, 1981; Walsh et al., 2008). At Battle Ground Lake, a sharp decrease in fire frequency occurred from ca. 6,700 to 5,400 cal yr BP (Walsh et al., 2008). Fire frequency then increased through ca. 4,600 cal yr BP, followed by a general decrease through the end of the period. At Little Lake and Taylor Lake, both located in coastal forests in Oregon, fire activity decreased through the mid-Holocene (Long et al., 1998; Long & Whitlock, 2002). At Little Lake, the mean fire interval lengthened to 160 ± 20 years (Long et al., 1998). For Battle Ground Lake, the authors explain that the establishment of the modern forest and increased fuel loads likely led to the brief rise in fire activity. Modern forest assemblages supported less frequent but mostly large or high-severity fire episodes between ca. 5,400 and 4,600 cal yr BP. The climate was transitional at this point, with winters becoming wetter, but with summers still sufficiently dry to support fires. The subsequent decrease in fire-episode frequency at the end of the period is consistent with cooler, wetter conditions in conjunction with the onset of cool humid conditions (Walsh et al., 2008). At Little Lake and Taylor Lake fire frequency decreased for similar reasons (Long et al., 1998; Long & Whitlock, 2002).

Late Holocene (4,000 cal yr BP until present)

On the Sunrise Ridge, fire frequency increased from the start of the late Holocene through ca. 2,500-2,000 cal yr BP, decreased through ca. 1,000 cal yr BP and then increased through end of the period. At Buck Lake, fire activity much like on the Sunrise Ridge, increased through ca. 2,800 cal yr BP and then decreased after that, with three fire episodes occurring in the last 1,000 years of the record (Tweiten, 2007). Other high-elevation sites across the Cascades also show a similar trend in fire activity during the late Holocene to that of the Sunrise Ridge and Buck Lake. Fire activity increased during the late Holocene at all of the sites, but the timing of this increase varied. Frozen Lake and Mount Barr Cirque Lake in the North Cascades of British Columbia and Tumalo Lake in the Southern Cascades of Oregon show the biggest differences in timing as compared to the Sunrise Ridge (Hallet et al., 2003; Long et al., 2011). Fire frequency at Frozen Lake and Mount Barr Cirque Lake initially decreased between ca. 3,500 to 2,400 cal years BP and then increased between ca. 2,400 and 1,300 cal yr BP (Hallet et al., 2003). The authors suggest that the initial decrease and lag in fire activity was due to Neoglacial advances in the region. At Tumalo Lake, fire frequency increased starting ca. 3,000 cal yr BP and peaked ca. 1,400 cal yr BP, but then declined to present day values (Long et al., 2011). Records from Panther Pot Holes and Ridley Lake show a general increase in fire activity starting at the beginning of the period and are extremely similar to fire activity on the Sunrise Ridge (Pritchard et al., 2009; Spooner et al., 2008). Fire activity at all three of these sites peaked for the late Holocene between ca. 3,000 and 2,000 cal yr BP. After that, the three records show a general decrease in fire until ca. 1,000 cal yr BP. Fire frequency then increased between ca. 1,000 and 500 cal yr BP which coincides with the MCA (Pritchard et al., 2009; Spooner et al., 2008). For the Cascades as a whole, reasons proposed for increase in fire activity during the late Holocene center on increased fuel availability, periods of summer drought, and anthropogenic burning (Hallet et al., 2003; Long et al., 2011; Pritchard et al., 2009; Spooner et al., 2008; Tweiten, 2007).

Study sites for the Olympic Mountains, in general, also show an increase in fire activity during the late Holocene. However, the reconstructions for Martins and Moose lakes show substantially different timing for peaks in fire activity (Gavin et al., 2001). At Martins Lake, charcoal concentrations rose through the late Holocene with the highest charcoal concentrations occurring between ca. 3,000 cal yr BP and 1,000 cal yr BP, much like the results for sites in the Cascades and the Sunrise Ridge. For Moose Lake, charcoal concentration remained low and variable except for a spike ca. 3,500 cal yr BP. The authors suggest that the major differences in these records may be due to differences in the local expression of regional climate change and/or differences in soil development and slope stabilization (Gavin et al., 2001).

For low-elevation forests, during the late Holocene, fire frequency varied between sites in the PNW. At Little Lake and Hall Lake, fire frequency continued to decline toward present, which is opposite to the trend in the Sunrise Ridge reconstructions (Long et al., 1998; Tsukada et al., 1981). The authors attribute cool humid conditions and the establishment of mesophytic taxa as the cause for the decrease in fire activity during the time (Long et al., 1998; Tsukada et al., 1981). At Battle Ground Lake, fire episodes were least frequent after ca. 2,500 cal yr BP, with a sharp decrease in fire frequency occurring ca. 1,000 cal yr BP until present (Walsh et al., 2008). At Little Lake, fire episodes in the middle to late Holocene were larger or of higher severity, but less frequent than during the early Holocene (Long et al., 2002). For southern Vancouver Island, East Sooke Fen had higher charcoal influx after ca. 2,000 cal yr BP, Pixie Lake had a higher influx of charcoal until ca. 2,300 cal yr BP and Whyac Lake had a low charcoal influx prior to ca. 2,000 cal yr BP (Brown & Hebda, 2002). The authors suggest the difference in charcoal accumulation between the sites is partially explained by their relative location along a moisture gradient (Brown & Hebda, 2002). The authors attribute the rise in charcoal influx after ca. 2,000 cal yr BP at East Sooke Fen and Whyac Lake to anthropogenic burning.

CHAPTER VII

CONCLUSION

Reconstructions for the three sites along Sunrise Ridge show that fire activity during the late Pleistocene and Holocene was highly variable, but generally consistent across the three study sites. Most notable is the unexpected increase in fire activity during the late Holocene, which occurred as climatic conditions became generally wetter and colder. However, an increase in ENSO variability during the late Holocene and associated drought is most likely the cause for higher fire activity. The results of this thesis are remarkably similar to fire histories from high-elevation sites across the Cascades and the PNW as a whole. These findings suggest that broad-scale climatic conditions, such as changes in insolation and ENSO, were likely the primary driver of fire activity on Mount Rainier. While it is also probable that human-set fires on the mountain increased in the late Holocene as a means of combating vegetation encroachment, it is unclear whether these fires are recorded in the Sunrise Ridge fire-history reconstructions. In terms of the impact of volcanic eruptions on the ecosystems of Mount Rainier, it appears that only two eruptive events and subsequent deposition of tephra led to fire episodes during the last 14,000 years. Both episodes were low in magnitude compared to other significant peaks in the record and do not appear to have greatly altered the area. Future analysis of pollen from the records will help in determining the impacts of these tephras, as well as the impact of individual fire episodes on the surrounding vegetation.

Climate and Future Fire Activity

Based on the results presented here, as well as other fire reconstructions from the PNW, it is reasonably clear that past shifts in climate greatly impacted fire activity in the region. This is important because projected changes in climate are also expected to greatly impact fire activity in the PNW. These changes include increased warmth, shifts in precipitation patterns, and a decrease in snowpack, all by the end of the 21st century. Global climate models (GCMs) for the PNW project increases in annual temperature on average of +1.1°C (2.0°F) by the 2020s, +1.8°C (3.2°F) by the 2040s, and +3.0°C (5.3°F) by the 2080s, compared with the average from 1970 to 1999 (Mote & Salathe, 2010). In all models and scenarios, warming is projected to be largest in summer (Mote & Salathe, 2010). However, slight increases in precipitation are projected in the PNW in all seasons by the 2040s (+4% winter, +5% spring, +3% averaged across all scenarios) except summer (-11% 2040s) (Lutz, Hamlet, & Littell, 2012). By the 2080s, summer precipitation is projected to decrease 14%, with some models projecting reductions of as much as 20–40% (Mote & Salathe, 2010). Projected increases in summer temperature and decreases in summer precipitation will most likely lead to a higher occurrence of drought and subsequent fire.

April 1 snowpack, a key indicator of natural water storage available for the warm season, has declined approximately 25 percent over the past 40 to 70 years throughout the PNW (Karl, 2008). April 1 snowpack is projected to decline as much as 40% in the Cascades by the 2040s (Karl, Melillo, Peterson, & Hassol, 2009). Earlier snowmelt will cause a reduction in the amount of water available to plants during the warm season and will increase the risk of forest fires in the PNW by increasing effective summer moisture deficits (Mearns et al., 2009). Drought stress due to decreased summer moisture and higher temperatures will also increase the frequency and intensity of mountain pine beetle and other insect attacks, further increasing fire risk (Backlund, Janetos, & Schimel, 2009)

In regard to ENSO, it is not yet possible to project whether ENSO variability and strength will increase, decrease, or remain unchanged as a result of increases in atmospheric CO_2 concentrations (Collins et al., 2010; Vecchi et al., 2010; Wittenberg, & Rosati, 2010). However recent satellite observations suggest that the intensity of El Niño events in the central equatorial Pacific has almost doubled in the past three decades, with the strongest warming occurring in 2009-10 (Lee & McPhaden, 2010). Yeh et al. (2009) propose that a more frequent occurrence of El Niño events (an increase as much as five times) under projected global warming scenarios will result from a shoaling (loss of depth or thickness) of the thermocline in the Central Pacific region.

If ENSO activity does increase as projected, coupled with warmer/drier summers and increased drought as projected by GCMs, an increase in fire frequency and severity is almost certain (Karl et al., 2009; Lutz et al., 2012; Mote & Salathe, 2010). Simulations by Rogers et al. (2011), for the PNW, project large increases in area burned (76%–310%) and burn severities (29%–41%) by the end of the twenty-first century. Based upon results from this research, it would appear that fire activity at

MORA will increase substantially if ENSO events (marked by recurrent drought) become more frequent in the future.

Additional Research

It is apparent that further research needs to be conducted in order to reconstruct the fire history for Mount Rainier as a whole. The three lakes studied for this thesis lie along the Sunrise Ridge in the northeast quadrant of MORA and only provide a record of fire activity for that portion of the mountain. As of August 2012, four additional lakes (Reflection Lake, Bench Lake, Tipsoo Pond, and Eunice Lake) have been cored and are in the process of being analyzed in the Paleoecology Lab at Central Washington University.

It is also clear that our current understanding of past climate variability, such as the impacts of ENSO, are lacking. Further research needs to be conducted in order to better understand Holocene climatic changes and how they influenced past fire activity in the PNW. This could possibly be accomplished through the development of additional proxy records, such as tree-ring and sea surface temperature records. In terms of ENSO, a better understanding of the drivers behind the phenomena are needed so that it may be possible to better project ENSO event frequency in the future. If fire activity is truly tied to ENSO, as research suggests, it will then be easier to project future fire activity based upon projections of future ENSO event frequency (Cayan et al., 1999; Hamlet & Lettenmaier, 1999; Heyerdahl et al., 2002, Mote et al., 2005).

Finally, the impact of human use of fire in the Cascades is still not fully understood. Unfortunately, this thesis was unable to pick out a clear human signature or evidence for increases in fire that could clearly be attributed to human-set fires. However, it is not implausible to assume that Native People set fires, even during periods in the reconstructed records when fire activity increased seemingly as a likely result of changes in climate. Oral and written records are clear that indigenous people in the PNW used fire for specific purposes and had a great understanding of the benefits of fire (Allen 1904, 1905; Gottesfeld, 1994; Mack & McClure; 2002; Norton et al., 1999; Plummer, 1900). It may be that some of the fires in the reconstructed record for Sunrise Ridge were set by Native People but are not discernible from other fires in the record. It is also possible that fires set by Native People were of low intensity and therefore did not produce enough charcoal to be registered. Overall, in order to try and better document potential anthropogenic burning, better climate reconstructions need to be developed, additional archaeological sites need to be surveyed, and additional fire histories reconstructed at a finer resolution from lakes surrounding Mount Rainier need to be studied. With additional records it may be possible to distinguish between human-set and naturally-caused fires, especially if some sites show uncharacteristic fire activity as compared to other sites around the mountain.

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