Quaternary Science Reviews 177 (2017) 246–264

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Fire-climate-human interactions during the postglacial period at Sunrise Ridge, Mount Rainier National Park, Washington (USA)

Megan K. Walsh [a, *], Michael L. Lukens [b, 1], Patrick T. McCutcheon [c], Greg C. Burtchard [d]

[a] *Department of Geography and Cultural and Environmental Resource Management Program, Central Washington University, 400 E. University Way, Ellensburg, WA, 98926, USA*

[b] *Cultural and Environmental Resource Management Program, Central Washington University, 400 E. University Way, Ellensburg, WA, 98926, USA*

[c] *Department of Anthropology and Cultural and Environmental Resource Management Program, Central Washington University, 400 E. University Way, Ellensburg, WA, 98926, USA*

[d] *Mount Rainier National Park, 55210 238th Avenue East, Ashford, WA, 98304, USA*

ARTICLE INFO

Article history:
Received 4 January 2016
Received in revised form
20 October 2017
Accepted 21 October 2017
Available online 5 November 2017

Keywords:
Charcoal
Pollen
Fire history
Pacific Northwest archaeology
Long-term climate variability
Anthropogenic use of fire

ABSTRACT

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 seek to better manage current fire activity; however, this requires an improved understanding of past fire activity on the mountain. In this study high-resolution macroscopic charcoal analysis and pollen analysis of lake sediment records was used to reconstruct the postglacial fire and vegetation history for the Sunrise Ridge area of MORA. Fire activity was lowest during the Late Glacial when vegetation was sparse and climate was cool and dry. Fire activity increased during the early Holocene as the regional climate warmed and dried, and burnable biomass became more abundant. Fire activity continued to increase into the middle Holocene (until ca. 6600 cal yr BP) even as the regional climate became wetter and eventually cooler; the modern-day mesic forest and subalpine meadow landscapes of the park established at this time. Fire activity was generally highest and mean fire return intervals were lowest on Sunrise Ridge during the late Holocene, and are consistent with tree-ring based estimates of fire frequency. The similarity between the Sunrise Ridge and other paleofire records in the Pacific Northwest suggests that broad-scale climatic shifts, such as the retreat of the Cordilleran ice sheet and changes in annual insolation, as well as increased interannual climate variability (i.e., drought) particularly in the middle to late Holocene, were responsible for changes in fire activity during the postglacial period. However, abundant and increasing archaeological evidence from Sunrise Ridge during the middle to late Holocene suggests that humans may have also influenced the landscape at this time. It is likely that fires will continue to increase at MORA as drought becomes a more frequent occurrence in the Pacific Northwest.

1. Introduction

Mount Rainier National Park (MORA) was created by the United States 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 (MORA, 2003). With the creation of the park, however, came the active management of its landscapes and a heavy emphasis on fire suppression (Dombeck et al., 2004). Until 1988, park staff actively sought to extinguish all forest fires within the boundaries of MORA with the aim of protecting park structures and facilities (MORA, 1988). Recently, park managers concluded that these activities have led to a loss of biodiversity and vigor in vegetation and wildlife. To combat this loss, managers have made returning fire to the park's landscapes a high priority (MORA, 2003). However, in order to effectively achieve this goal, and to make more informed decisions regarding future fires in the park, land managers at MORA need a better understanding of the long-term fire history of the mountain (Hemstrom and Franklin, 1982).

Little is known about the fire history of MORA prior to the 20th century, as only a handful of fire-history reconstructions exist. Using

---

* Corresponding author.

E-mail addresses: megan.walsh@cwu.edu (M.K. Walsh), mike_lukens@nps.gov (M.L. Lukens), patrick.mccutcheon@cwu.edu (P.T. McCutcheon), burtchard@outlook.com (G.C. Burtchard).

[1] Permanent address: Rocky Mountain National Park, 1000 Highway 36, Estes Park, CO 80517-8397.

https://doi.org/10.1016/j.quascirev.2017.10.032

stand-age determinations, Hemstrom and Franklin (1982) determined dates of recent fires within the park; the oldest fire episode occurred in 1230 CE. Using charcoal contained in alpine bog sediments, Sugita (1990) reconstructed fire histories for several sites in the northwest portion of the park, but these records only span the past ~800 years. Also using lake sediments, Dunwiddie (1986) reconstructed fire history in the Paradise area; however, these records only extend as far back as ~6000 years ago and are of too low resolution to calculate fire return intervals. Using macroscopic charcoal analysis, Tweiten (2007) reconstructed the fire history of the Buck Creek watershed located in the northeastern corner of the park; this record provides an important point of comparison with the records developed in this study. Unfortunately, this record ends just before the deposition of the Mazama-O tephra layer (ca. 7627 calendar years before present [cal yr BP]; Zdanowicz et al., 1999). Prior to the research reported in this study, no fire history records from the park extended into the early Holocene or Late Glacial, which has until now, made it difficult to assess fire's role in the long-term development of the park's landscapes.

The primary goal of this research was to illustrate how fire activity has varied in the Sunrise Ridge area of MORA during the postglacial period (the past ~14,500 years). This area was chosen because of its proximity to the park's subalpine meadows, as well as several well-studied archaeological sites. Given the unique depositional context of MORA (i.e., the presence of numerous well-dated and easily recognizable tephra [ash] layers; Mullineaux, 1974; Sisson and Vallance, 2009), it was possible to compare the paleoenvironmental reconstructions developed in this study with others completed in the park and the surrounding region. Also, because some tephra layers were common to both the sediment cores and nearby archaeological sites, we were able to easily compare our paleoenvironmental reconstructions with the existing archaeological record for the Sunrise Ridge area of MORA.

The specific objectives of this research were: 1) to reconstruct the fire history of Sunrise Ridge using high-resolution macroscopic charcoal analysis of lake sediment records from Shadow, Sunrise, and Little Sunrise (informal name) lakes, 2) to reconstruct the related vegetation history of Sunrise Ridge using pollen analysis of the Sunrise Lake record, and 3) to evaluate the paleoenvironmental history of Sunrise Ridge within the context of local to regional climatic variability, and evidence for human land-use activities, during the postglacial period. This research is significant in that it provides the longest and most detailed paleoenvironmental records from the park to date. Our records not only make it possible to evaluate current wildfire activity and associated land-cover shifts within the context of long-term fire activity in the park, but they also contribute to an ongoing assessment of regional fire activity in the PNW during the postglacial period (Walsh et al., 2008, 2015; Marlon et al., 2009).

2. Study area

2.1. Background

Mount Rainier National Park is located in the southern Cascades region of Washington State, just west of the crest of the mountains, and encompasses more than 96,000 ha of diverse mountain environments ranging in elevation from approximately 530 to 4400 m above sea level (a.s.l.) (Franklin et al., 1988; Biek, 2000). The study area is in the northeast quadrant of MORA along Sunrise Ridge, a distinct glacially carved feature that extends 10–12 km in a northeast direction from the mountain (Fig. 1). It 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. Sunrise Ridge became ice free sometime prior to ca. 14,000 cal yr BP with the retreat of glaciers after the last glacial maximum (Crandell and Miller, 1974; Heine, 1998; Hekkers, 2010).

The climate of MORA is typical of a high-elevation environment in the PNW, and the park generally experiences a temperate, maritime climate regime. Winters are cold and wet with considerable snow accumulation between the months of November and April; summers are typically warm and dry with little precipitation falling during the months of July and August (Franklin et al., 1988). Because of its height and breadth, Mount Rainier creates its own rain shadow to the east of the mountain, and as a result, the Sunrise Ridge area of the park experiences relatively dry winter conditions as compared to the west side of the park. Biek (2000) indicates that winter snowfall accumulations can be as little as half at Sunrise as compared with Paradise, which on average can be > 15 m.

According to Franklin and Dyrness (1988), the Sunrise Ridge study area sits near the upper limit of the Mountain Hemlock (*Tsuga mertensiana*) Vegetation Zone (all plant nomenclature is based on USDA, NRCS, (2017)). This zone is characterized by rugged mountainous terrain above 1250 m and is defined at the upper limits by treeline and at the lower limit by closed-canopy forests. Subalpine meadows are perhaps the most striking feature of this zone. The two dominant tree species within this zone are mountain hemlock, more common in cold/moist locations, and subalpine fir (*Abies lasiocarpa*), more common in cold/dry locations. Commonly associated shrub species within this zone include thinleaf huckleberry (*Vaccinium membranaceum*), roughfruit berry (*Rubus lasiococcus*), rusty menziesia (*Menziesia ferruginea*), and Cascade azalea (*Rhododendron albiflorum*). The 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).

At the time of Euro-American settlement in the PNW (ca. 1800 CE), Mount Rainier (or *Takhoma*, perhaps the most common of several names by which it was traditionally known; Smith, 2006) was situated between the ancestral homelands of coastal (Salishan-speaking) tribes to the west of the crest of the Cascades and Plateau (Shahaptan-speaking) tribes to the east (Ruby and Brown, 1988). The park was likely utilized by members of the Puyallup, Nisqually, Mical, Taidnapam, Muckleshoot, and Yakama Nation tribes, all of whom claim some area within the park's current boundaries as part of their ancestral homelands (Smith, 2006). Although notable differences existed in subsistence patterns, tribes of both the Northwest Coast and Plateau cultures moved seasonally to procure resources (Prentiss and Kuijt, 2004; Ames, 2005a). Common to all groups were summer excursions to subalpine environments, such as the ones found at MORA, where both food (e.g., berries, game) and material resources were abundant (Burtchard, 2007).

Oral histories and historic records are fairly straightforward in terms of the use of fire by Native peoples in the PNW prior to Euro-American contact. In the subalpine and upper-elevation forest zones of the Cascades, fire was used to enhance the growth of *Vaccinium* species (i.e., huckleberry, blueberry) and beargrass (*Xerophyllum tenax*), and aid in the drying of berries (Allen, 1916; Mack and McClure, 2003; Lepofsky et al., 2005; Shebitz et al., 2009). Fire was also used to prevent the invasion of shrubs and trees into meadows and camp sites (Johnson and Gottesfeld, 1994). These practices continued into the early 20th century, well within the living memory of tribal elders (French, 1999; Nickels, 2002). Fire reports from Mount Rainier Forest Reserve from 1904 and 1905 recorded that 16 of 32 fires were caused by native peoples (Allen, 1904, 1905). All of these fires were in the southeastern portion of the reserve, an area known for huckleberry gathering (Allen, 1905).

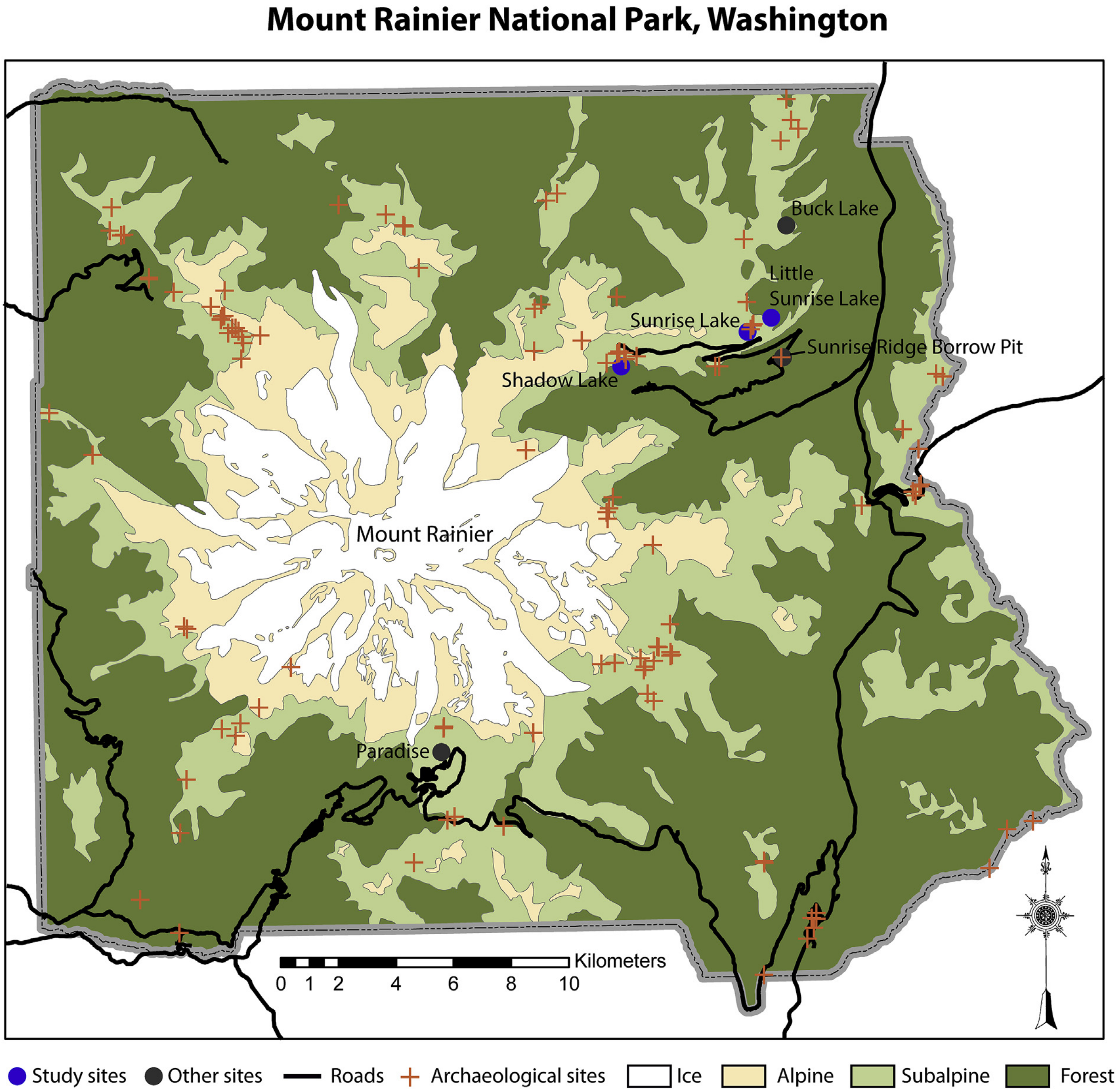

Fig. 1. Map showing Mount Rainier National Park and the location of the study sites (blue circles). Also shown are the location of documented precontact archaeological sites as of 2015 (orange plus signs) and other locations mentioned in the text (gray circles). Gray line indicates the park boundary. The colored shading indicates the park's environmental zones.

Additionally, according to Norton et al. (1999) many areas in the Southern Cascades along the Klickitat trade network were regularly burned to maintain clearings and trail networks essential to trade and travel.

2.2. Study sites

Shadow Lake is the highest of the three lakes (1890 m a.s.l.) and exists within close proximity to the Sunrise Visitor Center (<1 km) (Fig. 1; Table 1). The forest surrounding the lake is composed of predominately subalpine fir, with lesser amounts of whitebark pine (*Pinus albicaulis*), Alaska cedar (*Callitropsis nootkatensis*), and mountain hemlock. Shrubs surrounding the lake include pink mountainheath (*Phyllodoce empetriformis*), western moss heather (*Cassiope mertensiana*), and patches of dwarf blueberry (*Vaccinium caespitosum*). A variety of perennial grasses, sedges, and subalpine wildflowers such as subalpine lupine (*Lupinus latifolius* var. *subalpinus*), broadleaf arnica (*Arnica latifolia*), subalpine fleabane (*Erigeron peregrinus*), Cascade aster (*Eucephalus ledophyllus*) and white pasqueflower *(Pulsatilla occidentalis)* are present in the open meadow around the lake.

Sunrise Lake, which sits at an elevation of 1768 m a.s.l., is located 5.25 km to the northeast of Shadow Lake on the north side of the ridge proper (Fig. 1, Table 1). The lake itself sits in a basin surrounded on two sides by steep rock and scree fields. The forest surrounding Sunrise Lake consists predominantly of subalpine and noble fir (*Abies procera*), with lesser numbers of mountain hemlock, Pacific silver fir (*Abies amabilis*), whitebark pine, Alaska cedar, and Engelmann spruce (*Picea engelmannii*). The understory comprises mostly white rhododendron (*Rhododendron albiflorum*), thinleaf huckleberry, dwarf blueberry, and pink mountainheath. Forbs in the immediate area include subalpine lupine, littleflower penstemon (*Penstemon procerus*), yellow avalanche-lily (*Erythronium grandiflorum*), and white pasqueflower.

Table 1
Physical and climatic data for Sunrise Ridge study sites.

	Shadow Lake	Sunrise Lake	Little Sunrise Lake
Latitude (°)	46.9114	46.9198	46.9231
Longitude (°)	−121.6571	−121.5886	−121.5836
Elevation (m)	1890	1768	1707
Surface area (ha)[a]	0.48	1.6	0.4
Max. water depth (cm)[a]	493	635	326
Ave. annual temp (°C)[b]	1.7	2.8	2.8
Ave. max summer temp (°C)[b]	18.6	17.2	17.2
Ave. min winter temp (°C)[b]	−8.3	−7.2	−7.2
Ave. annual precip (mm)[b]	1960	1900	1900

[a] Lakes of Washington, Water Supply Bulletin (2012).
[b] Natural Resources Conservation Service (2012).

Little Sunrise Lake is the lowest in elevation of the three lakes (1707 m a.s.l.) and is located approximately 440 m NNE of Sunrise Lake, but exists in a separate sub-basin (Fig. 1, Table 1). The forest surrounding the lake is predominantly subalpine fir and noble fir, with some whitebark pine and Engelmann spruce. Shrubs surrounding the lake include thinleaf huckleberry and pink mountain heather. Forbs in close vicinity to the lake include yellow avalanche-lily, creeping spearwort (*Ranunculus flammula*), green false hellebore (*Veratrum viride*), white marsh marigold (*Caltha leptosepala*), and subalpine lupine.

3. Methods

3.1. Fieldwork

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). 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 plastic wrap 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, including the sediment-water interface. The short cores were subsampled in the field at 0.5-cm intervals and placed in Whirl-pak bags.

3.2. Lab analysis

The chronology of the sediment cores was determined using AMS radiocarbon dating and the identification of dated tephra layers. Plant macrofossils such as wood fragments and twigs provided material for AMS dating (Table 2). ^{14}C dates were converted to calendar years before present (cal yr BP; present = 1950 AD) using Calib 6.0 html (Reimer et al., 2009). Median ages rounded to the nearest decade were used when appropriate. If the median age did not fall within the highest peak on the probability distribution function, the immediate highest value adjacent to the median age was selected and rounded to the nearest decade (see Table 2 for dates and calibrations).

Tephra layers were identified visually by James Vallance at the USGS Cascade Volcano Observatory (Vancouver, WA) and were based on previously published identifications (Mullineaux, 1974, 1996; Clynne et al., 2004; Donoghue et al., 2007; Sisson and Vallance, 2009), as well as their depth in regard to radiocarbon dates in the cores. Only the most easily identifiable tephra layers were included in the age models, and the associated ages based on ^{14}C age determinations were also converted to cal yr BP using Calib 6.0. 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 and combined to create a continuous record for each lake. Specific ages were assigned using a constrained cubic smoothing spline, which provides the most accurate age determination on records with many dates relative to changes in sedimentation rate (Telford et al., 2004).

Magnetic susceptibility was measured at contiguous 1-cm intervals on the intact cores using a Sapphire Instruments magnetic coil in order to help identify tephra layers and to correlate between core segments. Loss-on-ignition was used to determine the organic content of the cores and followed procedures outlined in Dean (1974). Macroscopic charcoal analysis 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 into a plastic vial in a solution of 5% sodium hexametaphosphate for >24 h and a weak bleach solution for 1 h 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; each particle was recorded as either woody or herbaceous charcoal (Jensen et al., 2007; Walsh et al., 2008, 2010a, 2010b). Charcoal counts were converted to charcoal concentrations (particles/cm^3) by dividing by the volume of each sample.

Charcoal data analysis was done using the freely available CharAnalysis program, which identified individual fire episodes within the charcoal record and calculated fire frequency and mean fire-return interval (mFRI) (Higuera et al., 2009). The program output also provided useful indications of fire (peak) magnitude (i.e., 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 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 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 et al., 2006; Higuera et al., 2010). 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 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

Table 2
Age-depth relations for the Sunrise Ridge study sites.

Depth (cm below mud surface)	Lab number	Source material/tephra layer	Measured ^{14}C age and error	Calibrated age (cal yr BP)
Shadow Lake (SL11C)				
14		MSH-W		470[a]
57		MR-C		2250[a]
64	D-AMS 1217-156	twig		2340[b]
81	Beta-340097	twig	2400 ± 30	2460[c]
98		MSH-Yn		3650[a]
118	Beta-340098	twig	5000 ± 30	5740[c]
129		MR-D		6810[a]
137		Mazama-O		7627[d]
Sunrise Lake (UL11D)				
20		MSH-W		470[a]
49	Beta-318018	wood	1790 ± 30	1820[b]
69		MR-C		2250[a]
93	Beta-340101	wood	3060 ± 30	3290[b]
117		MSH-Yn		3650[a]
140		MR-F		5740[a]
145	Beta-318017	plant material	5190 ± 30	5990[b]
159		MR-D		6810[a]
166		Mazama-O		7627[d]
179	Beta-340100	twig	9390 ± 40	10530[b]
Little Sunrise Lake (LSL11D)				
26		MSH-W		470[a]
36	Beta-340095	twig	1850 ± 30	1820[c]
49		MR-C		2250[a]
83		MSH-Yn		3650[a]
110	D-AMS 1217-157	twig		4870[b]
120	Beta-340096	stick	5260 ± 30	6000[c]
136		Mazama-O		7627[d]

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

95th percentile of a Gaussian distribution modeling noise in the CHAR peaks time series. Sensitivity analysis of window widths between 300 and 1000 years showed that the signal-to-noise index (i.e., the measure of the ability of the program to separate between peaks and non-peak values; SNI) was maximized at 1000 years for Shadow Lake, 800 years for Sunrise Lake, and 500 years for Little Sunrise Lake. All CHAR peaks were screened to eliminate those that resulted from statistically insignificant variations in charcoal counts (Gavin et al., 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 and eliminated from the analysis (Higuera et al., 2009).

Pollen analysis followed standard methods outlined in Faegri et al. (1989). Samples of 1 cc were taken every 10 cm and *Lycopodium* was added to each sample as an exotic tracer. Pollen was identified and tallied at magnifications of 400 and 1000x and 300–500 terrestrial pollen grains and spores were counted per sample. Pollen types were assigned based on modern phytogeography and comparison to a CWU reference collection. Pollen counts were converted to percentages of the total terrestrial pollen and spores in each sample. Aquatic taxa percentages were calculated using the terrestrial and aquatic taxa sum. Total pollen accumulation rates (PARs) were also calculated.

4. Results

4.1. Shadow Lake

4.1.1. Chronology and Lithology

After comparing the short core (SL11A) and long core (SL11C) from Shadow Lake, it was determined based on the position of the Mount St. Helens (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 subtracted, the total adjusted length 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 (Fig. 2A, 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 10,180 cal yr BP with a median resolution of 47 years per centimeter.

The SL11C core ended at what is likely the Mount Rainier (MR)-R tephra layer, which made up the bottom 1 cm of the core (Fig. 3). Also found in the SL11C core were the Mazama-O (14 cm), MR-A (1 cm), MR-D (2 cm), MR-F (64 cm), MR-B (1 cm), MSH-Yn (8 cm), MSH-Pm (2 cm), MSH-Pu (2 cm), MR-C (20 cm), and MSH-W (2 cm) tephra layers. The sedimentation rate for SL11C remained relatively constant from ca. 10,180 through 3650 cal yr BP with a rate of 0.009 cm/yr (Fig. 2A). From ca. 3650 to 2340 cal yr BP the sedimentation rate increased substantially to 0.027 cm/yr and then from ca. 2340 cal yr BP until present day the sedimentation rate slowed to 0.025 cm/yr. Organic content was low overall for the core with the highest value being 21% at a depth of 253 cm (Fig. 3; see Lukens, (2013) for further details).

4.1.2. CharAnalysis

Using a background smoothing window width of 1000 years, the global SNI value for core SL11C was maximized at 4.7248. This value indicates that the Shadow Lake record is suitable for peak

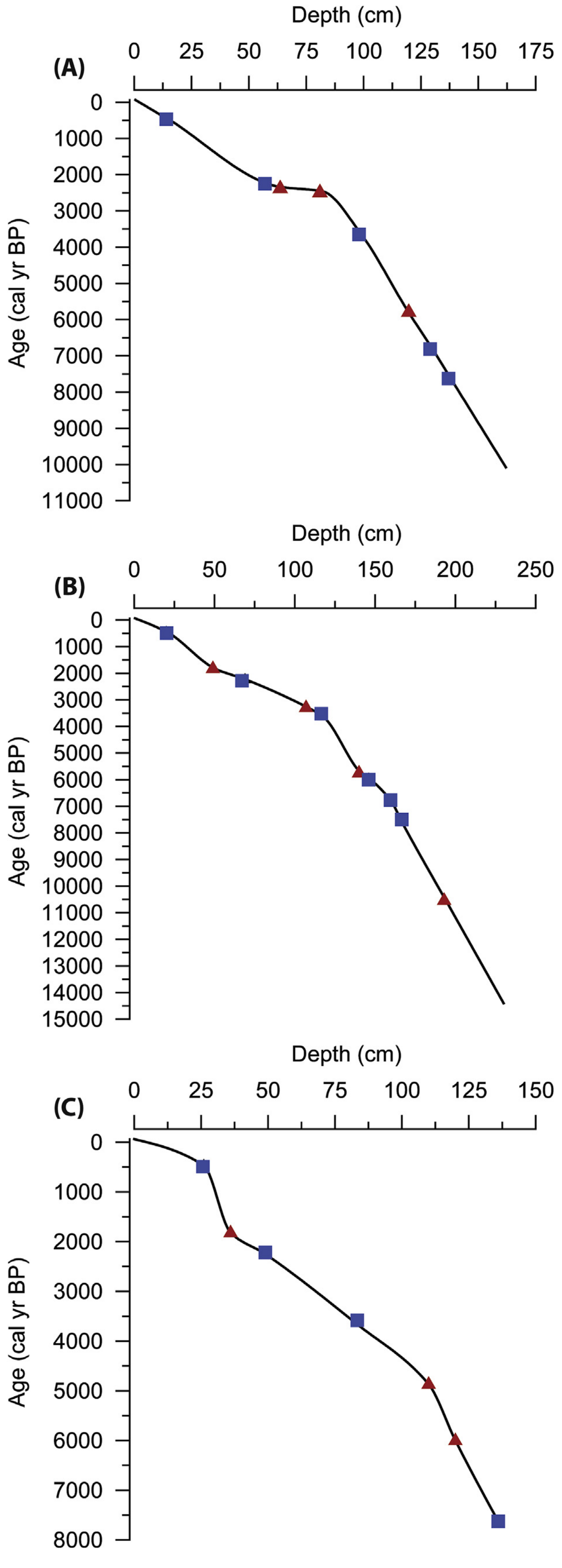

Fig. 2. Age-depth relations for the (A) Shadow Lake, (B) Sunrise Lake, and (C) Little Sunrise Lake cores. Blue squares indicate dates obtained from dated tephra layers and red triangles indicate AMS-^{14}C age determinations (see Table 2 for ages). The slope of the line indicates the sedimentation rate of the core.

detection and that the program was able to identify fire episodes contained within it. A SNI value of 3.0 was determined by Kelly et al. (2011) as the minimum value required to adequately separate charcoal peaks from background charcoal noise. Fig. 4 shows the SNI curve for the SL11C core, which remains above the cut-off threshold of 3.0 for almost the entire record, except for a brief period at the beginning and between ca. 6300–5300 cal yr BP.

4.1.3. Charcoal

Early Holocene (ca. 10,180–8000 cal yr BP; 162-140 cm): Charcoal values during the early Holocene were relatively low and fire episodes occurred infrequently (Figs. 4 and 5, Table 3). Fire frequency increased from no fire episodes at the beginning of the record to 1.4 fire episodes/1000 yr by the end of the period. Two significant fire episodes occurred during this period and peak magnitudes were moderately high. The largest of these peaks occurred at ca. 9220 cal yr BP with a peak magnitude of 39.3 particles/cm^2/peak.

Middle Holocene (8000–4000 cal yr BP; 140-102 cm): Average charcoal concentration and CHAR values during the middle Holocene were generally unchanged from the early Holocene, however, fire episodes occurred more frequently. Fire frequency increased from 1.4 fire episodes/1000 yr at the start of the period, peaked at 2.2 fire episodes/1000 yr at ca. 6400 cal yr BP, decreased to a low of 0.7 fire episodes/1000 yr by ca. 4900 cal yr BP, and increased to 1.8 fire episodes/1000 yr by the end of the period. Nine significant fire episodes occurred during the middle Holocene and peak magnitudes were low. The largest peak occurred at ca. 7790 cal yr BP with a magnitude of 20.4 particles/cm^2/peak.

Late Holocene (4000- -61 cal yr BP; 102-0 cm): Average charcoal values increased significantly during the late Holocene and were the highest of the entire record. Herbaceous charcoal concentrations were low overall in the record, but values were highest during this period (0.28 particles/cm^3; Table 3). Average fire frequency was considerably higher in the late Holocene than the previous two periods, although fires still occurred on average only every 378 years. Fire frequency increased from 1.8 fire episodes/1000 yr at the beginning of the period to a high of 3.5 fire episodes/1000 yr by ca. 1960 cal yr BP. It then decreased to 2.7 fire episodes/1000 yr by ca. 1400 cal yr BP, increased again to 3.5 fire episodes/1000 yr by ca. 950 cal yr BP, and decreased to nearly zero at the top of the record. Ten significant fire episodes occurred during the late Holocene, and average peak magnitude was considerably higher than in the previous two periods. The two largest peaks of the entire record occurred at ca. 3430 and ca. 570 cal yr BP with peak magnitudes of 121.7 and 102.4 particles/cm^2/peak, respectively.

4.2. Sunrise Lake

4.2.1. Chronology and Lithology

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 length 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 (Fig. 2B, Table 2). The 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 14,510 cal yr BP with a median resolution of 48 years per centimeter.

Because Sunrise and Shadow lakes sit on different sides of Sunrise Ridge, the tephra layers derived from eruptions of Mt. Rainier contained within each core vary somewhat from one

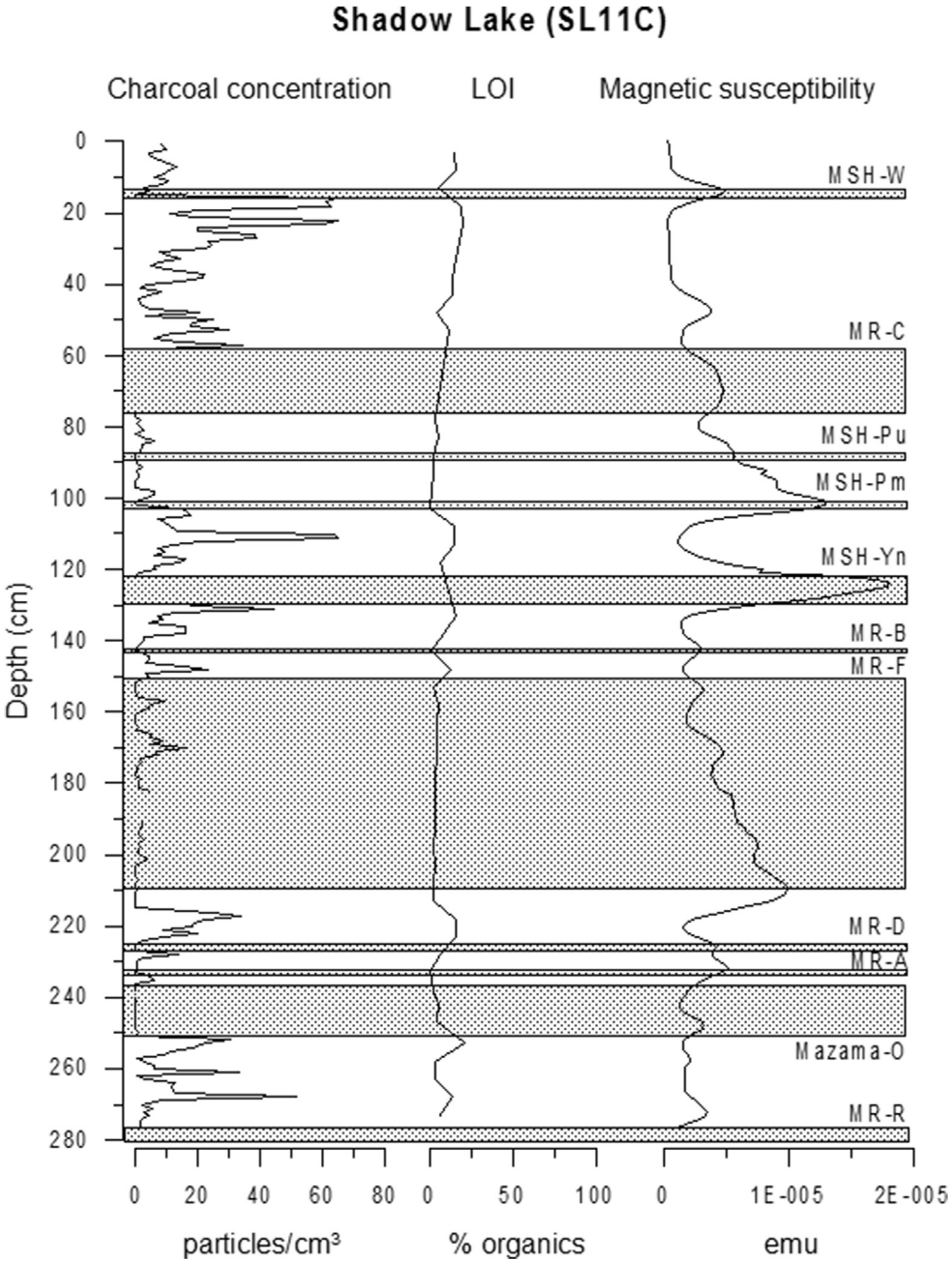

Fig. 3. Shadow Lake (SL11C) charcoal concentration (particles/cm^3), loss-on-ignition (% organic content), and magnetic susceptibility (electromagnetic units; emu) plotted against unadjusted core depth (cm). Tephra layers present in the core are shown in gray.

another (Mullineaux, 1974; Vallance and Scott, 1997; Sisson and Vallance, 2009). The UL11D core ended at an unidentified tephra layer which made up the bottom 4 cm of the core (Fig. 6). Also present in the core were the MR-R (7 cm), Mazama-O (8 cm), MR-D (6 cm), MR-F (1 cm), MSH-Yn (11 cm), MSH-Pm (2 cm), MSH-Pu (1 cm), MR-C (11 cm), and MSH-W (4 cm) tephra, as well as four other unidentified tephra layers. The sedimentation rate for the UL11D core remained relatively constant from the base of the core through ca. 6810 cal yr BP, with an average of 0.005 cm/yr (Fig. 2B). From ca. 6810 to 5740 cal yr BP the sedimentation rate increased to 0.018 cm/yr, but then slowed to 0.016 cm/yr from ca. 5740 to 3650 cal yr BP. From ca. 3650 to 1820 cal yr BP the sedimentation rate increased substantially to 0.037 cm/yr, but then slowed again to 0.026 cm/yr from ca. 1820 cal yr BP until the top of the core. The organic content of the core was low at the bottom and increased substantially toward the top, with the overall highest value of 38% occurring at a depth of 32 cm.

4.2.2. CharAnalysis

Using a background smoothing window width of 800 years, the global SNI value for core UL11D was maximized at 4.6376. This value indicates that the Sunrise Lake record is also suitable for peak detection, although there were a few more periods during which the program struggled to separate signal from background noise as compared to the Sunrise Lake record (Fig. 4). These periods primarily occurred between ca. 13,800–12,200, 10,700–10,400,

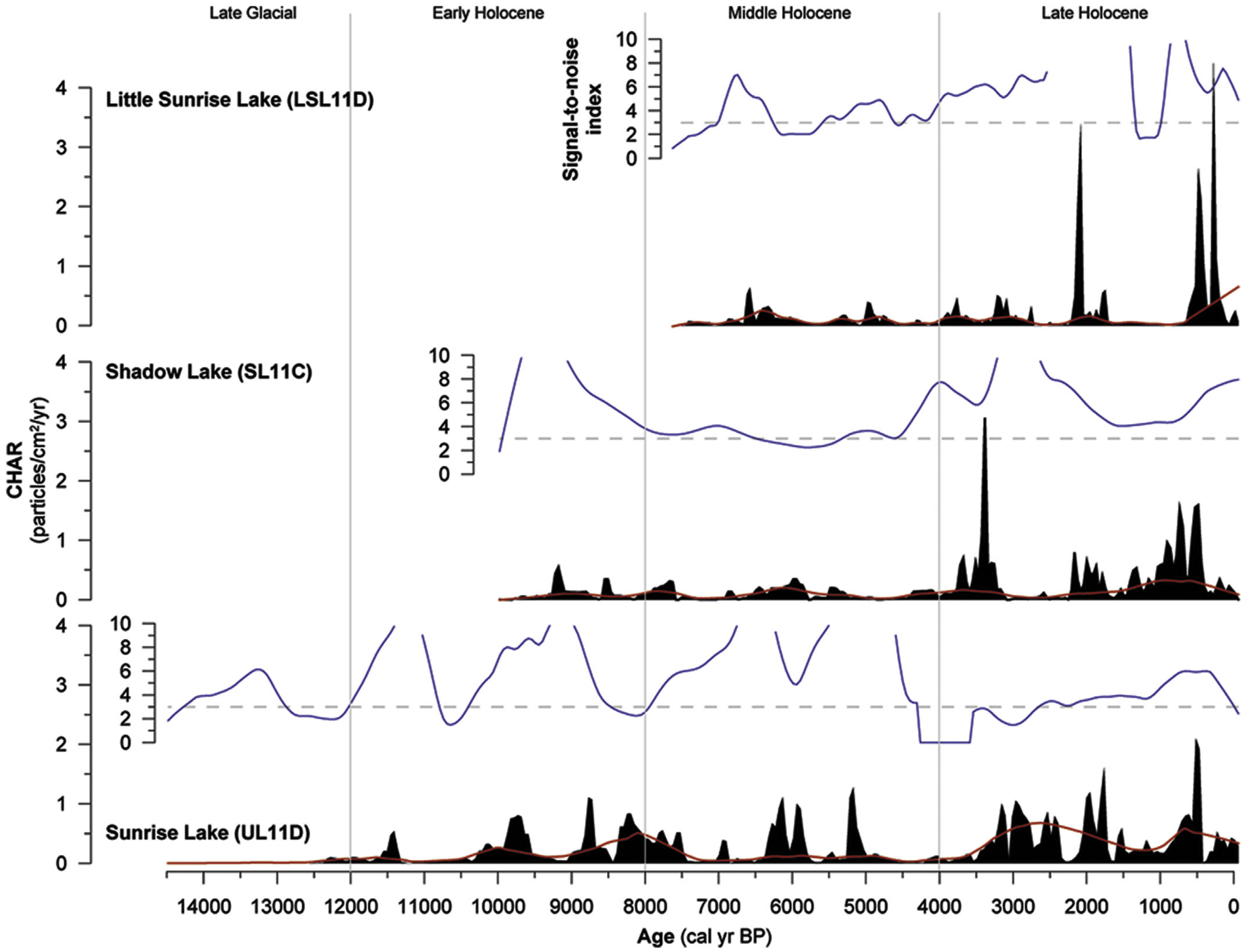

Fig. 4. Charcoal influx (CHAR; particles/cm^2/yr; red line is the background component as determined by CharAnalysis) and signal-to-noise index (SNI; blue line) plotted against age (cal yr BP) for the three paleofire records.

8300–7800, and 4300–2700 cal yr BP.

4.2.3. Charcoal and pollen

Late Glacial (ca. 14,510–12,000 cal yr BP, 230-207 cm): Average charcoal values during the Late Glacial were very low in the Sunrise Lake record (Figs. 4 and 5, Table 3). Fire frequency increased from no fire episodes at the beginning of the record to 1.4 fire episodes/1000 yr by ca. 12,000 cal yr BP. Two significant fire episodes occurred during the Late Glacial, with the largest of these occurring at ca. 13,380 cal yr BP with a peak magnitude of 2.0 particles/cm^2/peak. The Late Glacial portion of the Sunrise Lake pollen record was dominated by high percentages of *Picea*, *Pinus*, *Alnus sinuata*-type (Sitka alder), and *Artemisia* (sagebrush), as well as relatively high percentages of Poaceae (grass family), Cyperaceae (sedge family), *Pteridium aquilinum*-type (bracken fern), *Dryopteris*-type (wood fern), and *Helianthus*-type (sunflower) (Fig. 7). Although *Picea* percentages started high at the beginning of the record, they dropped quickly to zero by ca. 12,000 cal yr BP. At the same time, *Pinus* increased and reached its highest value of the entire record; consistently higher percentages of *Pinus* haploxylon (subg. hap.; white pines) rather than *Pinus*diploxylon (subg. dip.; yellow pines) pollen were observed. Also present in relatively low abundance was *Abies*, *Tsuga mertensiana*, and Cupressaceae (Cypress family, likely *Thuja plicata* [western redcedar] and/or *Callitropsis nootkatensis*).

Early Holocene (12,000–8000 cal yr BP, 207-169 cm): During the early Holocene average charcoal values increased compared to the Late Glacial. Fire frequency primarily increased during the period and reached 2.6 fire episodes/1000 yr by the end of the early Holocene. Six significant fire episodes were registered during this period; the largest of these occurred at ca. 8820 cal yr BP with a peak magnitude of 72.8 particles/cm^2/peak. The early Holocene portion of the pollen record indicates generally higher amounts of *Abies*, *Alnus sinuata*-type, *Tsuga mertensiana*, and Cupressaceae, with decreased abundance of *Pinus*, *Artemisia*, Cyperaceae, *Dryopteris*-type, and *Helianthus*-type. However, *Pinus* values increased again after ca. 10,000 cal yr BP; almost all of the identifiable pollen was from *Pinus* subg. dip. Also present in low numbers were *Picea*, *Tsuga heterophylla*, *Pseudotsuga menziesii*-type (likely Douglas-fir), *Spiraea*, Ericaceae (heath family), *Ceanothus*, Umbelliferae-type (carrot family), and *Eriogonum* (wild buckwheat). Aquatic pollen was generally lower during this period as well.

Middle Holocene (8000–4000 cal yr BP, 169-122 cm): Average charcoal values decreased somewhat during the middle Holocene, however, they were generally similar to the previous period. Fire frequency primarily decreased during the middle Holocene, from 2.4 fire episodes/1000 yr at ca. 8000 cal yr BP to 1.0 fire episodes/

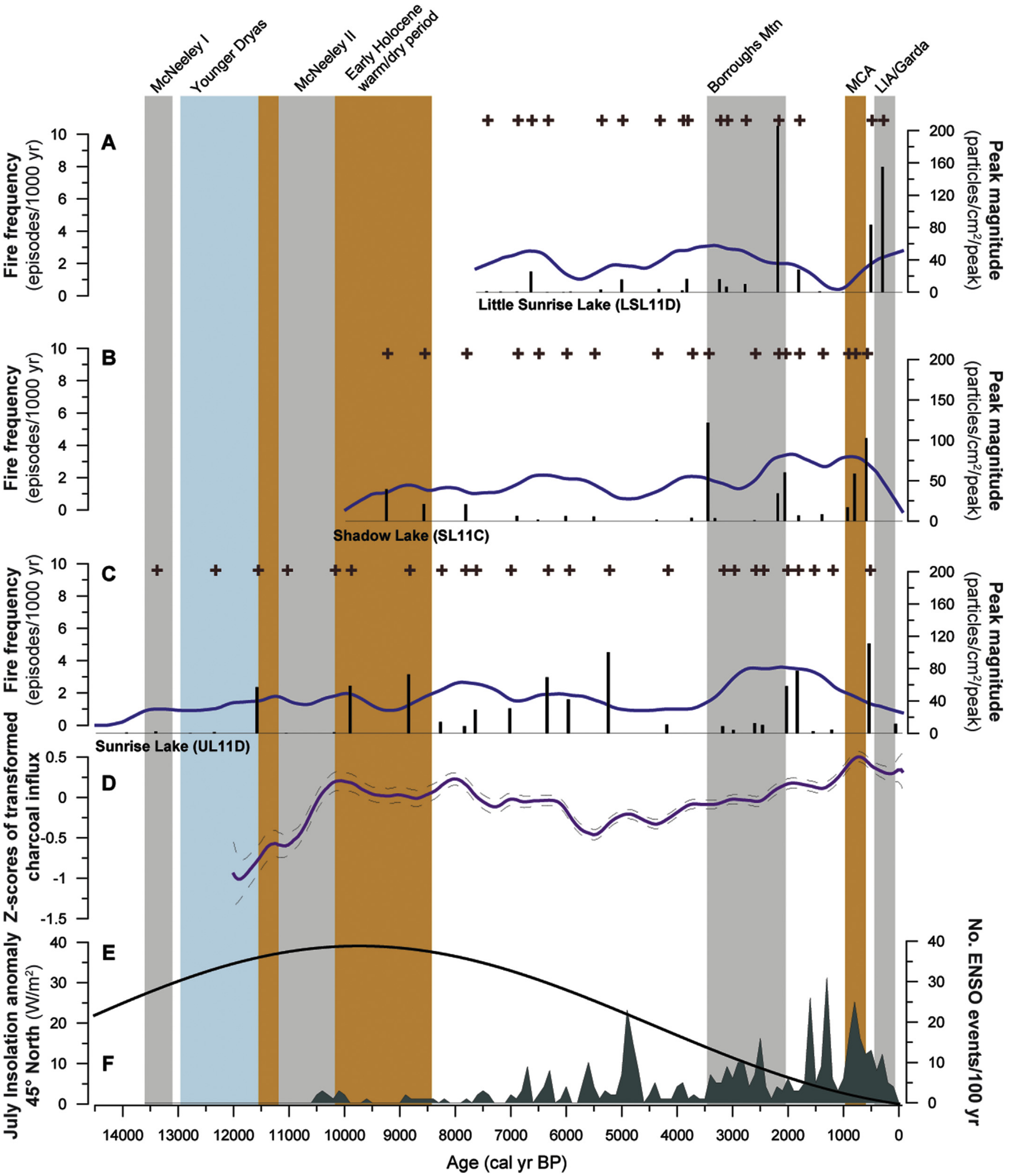

Fig. 5. Fire frequency, fire episodes, and peak magnitudes for (A) Little Sunrise Lake, (B) Shadow Lake, and (C) Sunrise Lake, (D) PNW composite biomass burning curve (n = 34) with 95% confidence intervals (gray dashed lines; Walsh et al., (2015)), (E) July insolation anomaly for 45°N (Berger and Loutre (1991)), and (F) ENSO event frequency (Moy et al., (2002)). Glacial advances documented at MORA are shown with the gray vertical shading. Climate episodes documented in the PNW are shown by the blue and orange vertical shading.

Table 3
Charcoal statistics for the Sunrise Ridge paleofire records.

Study site	Ave. total concentration (particles/cm^3)	Ave. herbaceous concentration (particles/cm^3)	Ave. CHAR (particles/cm^2/yr)	Fire episodes (#)	Ave. fire frequency (episodes/1000 yr)	Mean fire return interval (yrs)	Ave. peak magnitude (particles/cm^2/peak)
Shadow Lake (SL11C)							
Early Holocene (10,180–8000 cal yr BP)	9.1	0.09	0.09	2	1.1	714	30.2
Middle Holocene (8000–4000 cal yr BP)	9.9	0.10	0.09	6	1.4	700	6.9
Late Holocene (4000 to −61 cal yr BP)	12.8	0.28	0.34	10	2.3	378	41.3
Sunrise Lake (UL11D)							
Late Glacial (14,480–12,000 cal yr BP)	1.7	–	0.02	2	0.7	1080	1.6
Early Holocene (12,000–8000 cal yr BP)	26.2	0.03	0.25	6	1.6	680	33.9
Middle Holocene (8000–4000 cal yr BP)	20.0	0.01	0.23	7	1.6	583	41.5
Late Holocene (4000 to −61 cal yr BP)	13.9	0.03	0.43	9	2.3	405	32.0
Little Sunrise Lake (LSL11D)							
Middle Holocene (7627–4000 cal yr BP)	8.1	0.01	0.10	7	2.0	474	7.0
Late Holocene (4000 to −61 cal yr BP)	13.4	0.01	0.31	9	2.0	448	58.0

1000 yr by the end of the period. Average peak magnitude was highest during this period. Seven significant fire episodes occurred during the middle Holocene with the largest of these occurring at ca. 5220 cal yr BP with a magnitude of 100.3 particles/cm^2/peak. Several notable shifts in pollen percentages occurred in the Sunrise Lake record during the middle Holocene. *Pinus* started high at the beginning of the period, but then decreased in abundance after ca. 6300 cal yr BP; greater amounts of *Pinus* subg. hap. and lesser amounts of *Pinus* subg. dip. pollen were recorded. Percentages of *Pseudotsuga menziesii*-type, *Alnus sinuata*-type, and *Pteridium aquilinum*-type also decreased during this period. Conversely, percentages of *Tsuga heterophylla*, *Tsuga mertensiana*, and to some extent Cupressaceae increased during the middle Holocene.

Late Holocene (4000- -61 cal yr BP, 122-0 cm): Average charcoal concentration was lower during the late Holocene than the previous two periods; however, average CHAR was substantially higher. Additionally, average fire frequency was the highest of the entire record, although fire episodes still only occurred on average every 405 years. Fire frequency increased from 1.0 fire episodes/1000 yr at the beginning of the late Holocene, peaked at 3.5 fire episodes/1000 yr between ca. 2800–1700 cal yr BP, and then slowly decreased to 0.78 fire episodes/1000 yr at present. Nine significant fire episodes occurred during the late Holocene with the largest peak of the record occurring at ca. 520 cal yr BP with peak magnitude of 111.1 particles/cm^2/peak. Very little herbaceous charcoal was observed in the Sunrise Lake record, but average concentration was highest during this period and the early Holocene (0.03 particles/cm^3). *Abies* dominated the late Holocene portion of the Sunrise Lake record, along with the highest overall percentages of *Tsuga heterophylla*, *Tsuga mertensiana*, and Cupressaceae. *Picea* generally increased from the beginning to the end of the period, along with an increase in *Pinus* in fairly even amounts of hap. and dip. subgenera. *Pseudotsuga menziesii*-type pollen rebounded slightly during this period, along with higher percentages of Ericaceae, *Helianthus*-type, Umbelliferae-type, and *Eriogonum*. PARs varied widely in this zone. Notably, no pollen was preserved in two samples that followed the deposition of the MSH-Pu and MR-C tephra layers.

4.3. Little Sunrise Lake

4.3.1. Chronology and Lithology

Twenty four cm of the short core (LSL11A) from Little Sunrise Lake were added to the top of the long core (LSL11C) to form a combined core (referred to hereafter as LSL11D). The combined core had a total length of 173 cm. Once the tephra layers were removed, the total adjusted length 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 (Fig. 2C, Table 2). 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 7627 cal yr BP with a median resolution of 42 years per cm.

The LSL11D core ended at the Mazama-O tephra layer, which made up the bottom 3 cm of the core (Fig. 8). It is likely that the lake is older than this, but limited equipment was available to extract the core. Also found in the core were the MR-A (1 cm) and MSH-Yn (7 cm), and MR-C (25 cm) tephra layers, as well as two unidentified tephra layers. The sedimentation rate for the LSL11D core (Fig. 2C) remained relatively constant from the base of the core through ca. 4870 cal yr BP (0.009 cm/yr). From ca. 4870 to 1820 cal yr BP the sedimentation rate increased to 0.024 cm/yr. From ca. 1820 to 470 cal yr BP the sedimentation rate slowed to 0.007 cm/yr, but then increased substantially to 0.048 cm/yr from ca. 470 cal yr BP until present. The organic content of the core was low near the bottom and increased substantially toward the top (Fig. 8). In general, the organic content was highest in the top 23 cm of the core.

4.3.2. CharAnalysis

Using a background smoothing window width of 500 years, the global SNI value for core LSL11D was maximized at 5.1344. This value indicates that even more so than at Shadow and Sunrise lakes, the CharAnalysis program was able to identify fire episodes within the Little Sunrise Lake record (Fig. 4). The only periods where it struggled more so to do this were from ca. 7600–7000,

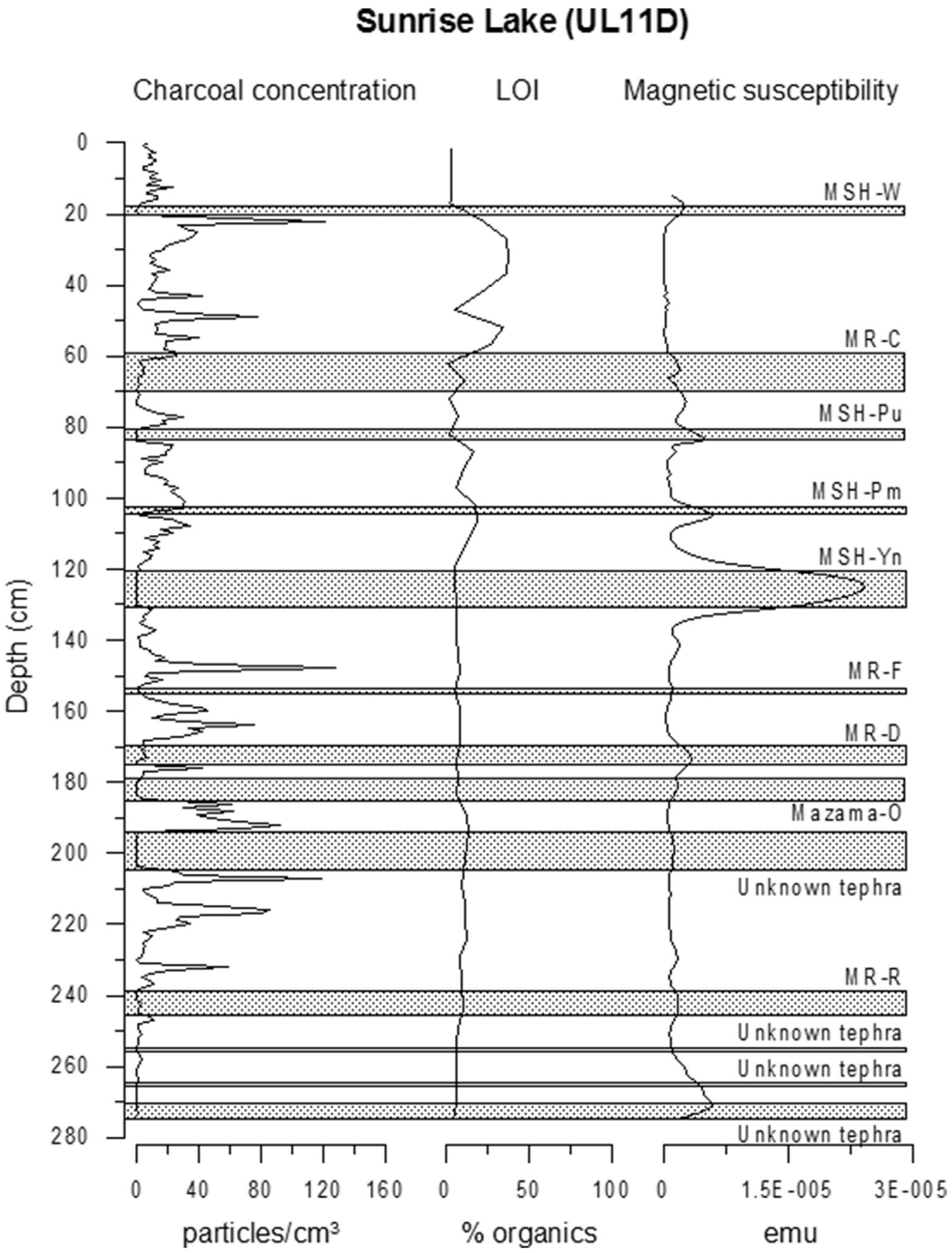

Fig. 6. Sunrise Lake (UL11D) charcoal concentration (particles/cm^3), loss-on-ignition (% organic content), and magnetic susceptibility (electromagnetic units; emu) plotted against unadjusted core depth (cm). Tephra layers present in the core are shown in gray.

6200–5600, and 1500–1100 cal yr BP.

4.3.3. Charcoal

Middle Holocene (7627–4000 cal yr BP, 136-92 cm): Charcoal values at Little Sunrise Lake during the middle Holocene are comparable to those from the same period at Shadow Lake (Figs. 4 and 5, Table 3). Fire frequency increased from 1.7 fire episodes/1000 yr at the beginning of period to 2.8 fire episodes/1000 yr by ca. 6660 cal yr BP. It then decreased to 1.0 fire episode/1000 yr by ca. 5780 cal yr BP. Fire frequency then generally increased to 2.8 fire episodes/1000 yr by the end of the period. Seven significant fire episodes occurred during the middle Holocene. The largest peak occurred at ca. 6620 cal yr BP with a peak magnitude of 25.4 particles/cm^2/peak.

Late Holocene (4000- -61 cal yr BP, 92-0 cm): Average charcoal values increased during the late Holocene at Little Sunrise Lake. Average fire frequency for the late Holocene was the same as the previous period; however, average peak magnitude was an order of magnitude greater. Fire frequency increased from 2.8 fire episodes/1000 yr at the beginning of the late Holocene to 3.1 fire episodes/1000 yr by ca. 3380 cal yr BP. It then slowly decreased to 0.4 fire episodes/1000 yr by ca. 1020 cal yr BP and subsequently increased to 2.8 fire episodes/1000 yr at present. Almost no herbaceous charcoal was observed in the Little Sunrise Lake record.

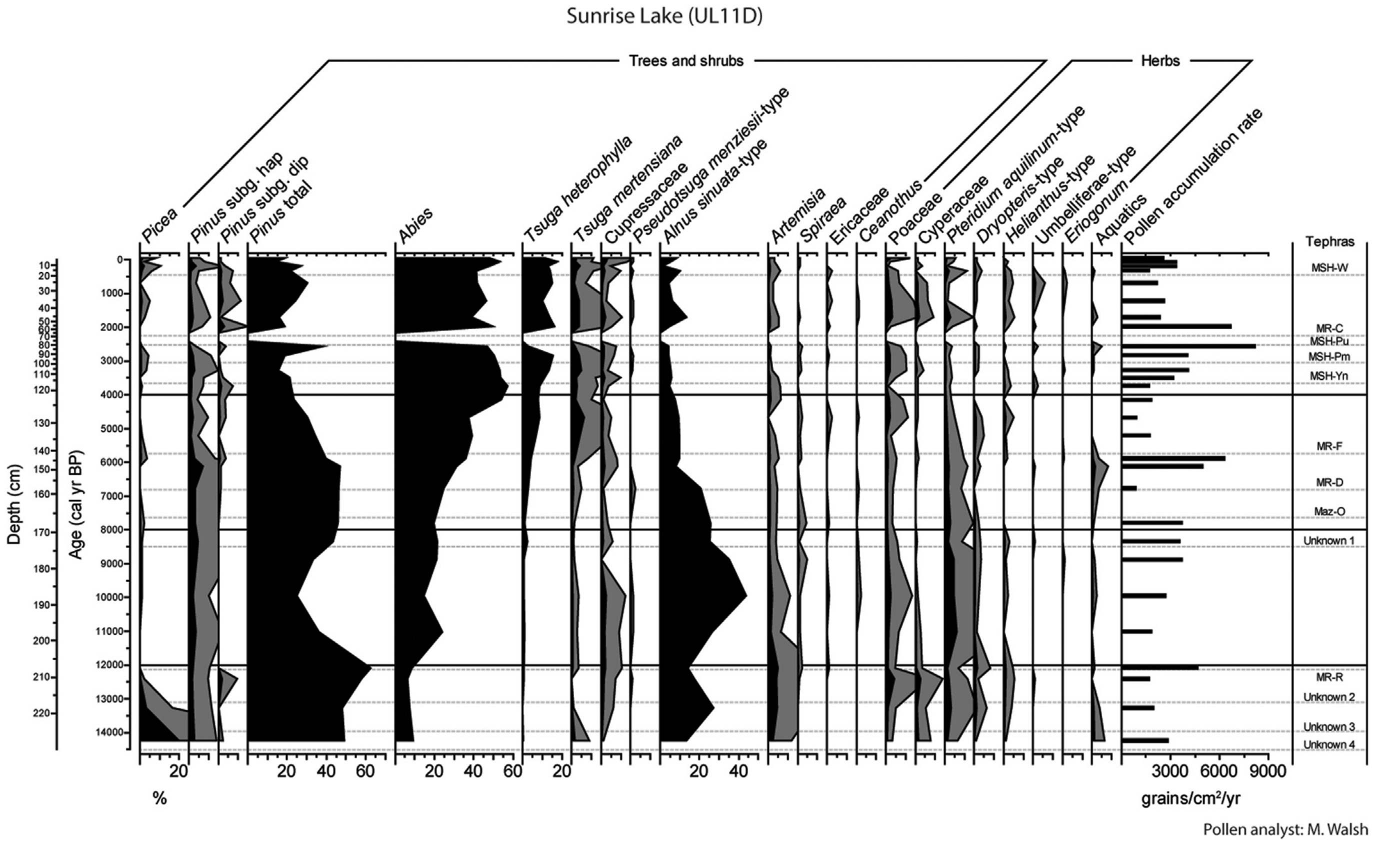

Fig. 7. Select pollen percentages, pollen accumulation rate (PARs), and tephra layers for the Sunrise Lake (UL11D) core plotted against adjusted depth (cm) and age (cal yr BP). Gray shading is a 5x exaggeration of the percentage curves. Note the lack of pollen preserved in the two samples following deposition of the MSH-Pu and MR-C tephra layers.

5. Discussion

5.1. Fire-vegetation-climate interactions on Sunrise Ridge

5.1.1. Late Glacial (ca. 14,510–12,000 cal yr BP)

The Sunrise Lake fire-history reconstruction suggests that following the retreat of the permanent ice on Mount Rainier (ca. 14,000 cal yr BP; Heine, 1998) fire activity on Sunrise Ridge was very low. Two fire episodes occurred in the Sunrise Lake watershed during the portion of the record spanning the Late Glacial, but peak magnitudes and CHAR values were extremely low compared to the rest of the record, indicating these fire episodes were very small in size and/or of low severity (Fig. 5C; Millspaugh and Whitlock, 1995; Higuera et al., 2007). This is similar to several other high-and low-elevation sites in the PNW that show little to no fire activity at this time (Gavin et al., 2001; Brown and Hebda, 2003; Spooner et al., 2007, 2008; Walsh et al., 2008; Gavin et al., 2013). The Sunrise Lake vegetation reconstruction also illustrates that similar to other high-elevation sites in the Cascade and Olympic mountains, the landscape at Sunrise Lake during the Late Glacial was either a parkland or alpine tundra/steppe (Fig. 7; Gavin et al., 2001; Spooner et al., 2008). The presence of high amounts of *Picea* (likely *Picea engelmannii*), *Pinus* subg. hap. (likely *Pinus albicaulis*), *Alnus sinuata*, and *Artemisia* pollen, as well as generally high herbaceous percentages (i.e., Poaceae, Cyperaceae, *Pteridium aquilinum*, *Dryopteris*, *Helianthus*) indicate that cold, dry climatic conditions prevailed at the time (Franklin et al., 1988; Whitlock, 1992), which likely suppressed forest growth and fire activity on Sunrise Ridge. However, because pollen is often transported upslope via wind in alpine environments (Spooner et al., 2007), it is likely that the changes in the Sunrise Lake pollen record represent extralocal changes in vegetation to some extent.

Our interpretation of the Late Glacial climatic conditions at Sunrise Lake is consistent with evidence from oceanic and terrestrial paleoclimatic proxy records as well as paleoclimate model simulations from the PNW (Whitlock, 1992; Thompson et al., 1993; Barron et al., 2003; Liu et al., 2009; Gavin et al., 2013; Bartlein et al., 2014; Gavin and Brubaker, 2015). While warmer than the full glacial, the regional climate during the Late Glacial was still cooler and drier than present. These warmer-than-previous conditions were largely due to the retreat of the Cordilleran ice sheet, increasing atmospheric CO_2 concentrations, and increasing insolation in the PNW (Bartlein et al., 2014), and were the probable cause of the low fire activity at Sunrise Lake between ca. 14,500–12,000 cal yr BP. These factors likely indirectly affected fire activity through forest structure/composition and fuel availability.

The McNeely I glacial advance occurred on Mount Rainier during this period (ca. 13,600–13,200 cal yr BP), at which time glaciers on the mountain moved downslope effectively lowering the snowline (Heine, 1998; Hekkers, 2010). This event may have influenced the fire history of Sunrise Ridge given that only one fire episode was recorded in the Sunrise Lake watershed during this time, and its magnitude is the lowest of the entire record (Fig. 5; 0.05 particles/cm^2/peak). Unlike other mountains in the PNW, Mount Rainier has no evidence of a Younger Dryas glacial advance (ca. 12,900–11,600 cal yr BP; Heine, 1998) and the Sunrise Lake reconstruction supports this by showing no definitive shift in fire activity at that time.

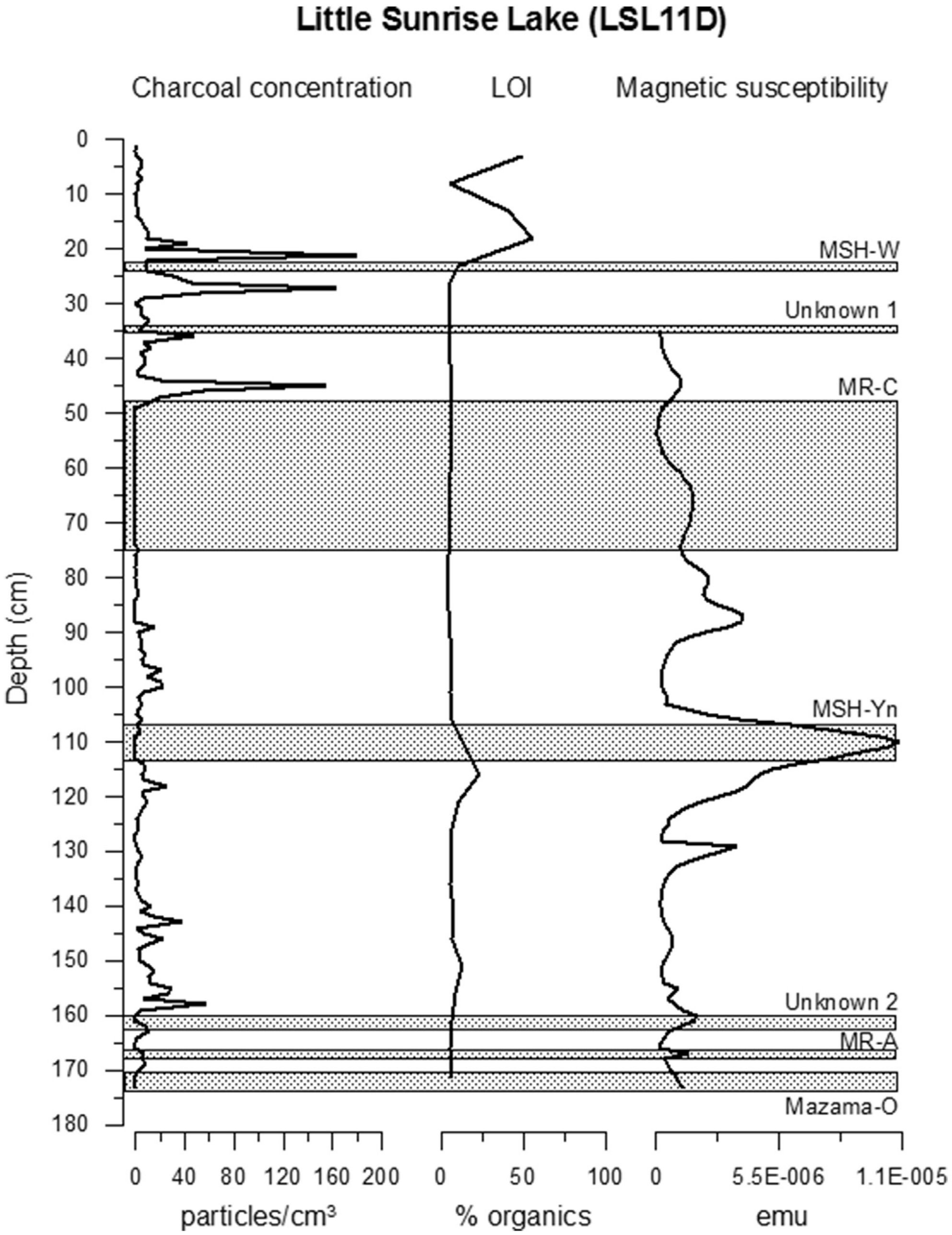

Fig. 8. Little Sunrise Lake (LSL11D) charcoal concentration (particles/cm^3), loss-on-ignition (% organic content), and magnetic susceptibility (electromagnetic units; emu) plotted against unadjusted core depth (cm). Tephra layers present in the core are shown in gray.

5.1.2. *Early Holocene (ca. 12,000–8000 cal yr BP)*

The Sunrise Lake reconstruction indicates that fires became more frequent on Sunrise Ridge during the early Holocene in comparison to the Late Glacial. mFRI decreased from 1080 to 680 years and average peak magnitude increased by more than an order of magnitude, indicating that fires were either larger in size or of higher severity (Table 3). While the Shadow Lake record spans only a portion of the early Holocene, average fire frequency, mFRI, and average peak magnitude were similar to those at Sunrise Lake (Fig. 5B and C). More frequent and larger/more severe fires on Sunrise Ridge during the early Holocene were likely the result of warmer, drier climatic conditions than those experienced during the Late Glacial. Amplified seasonality due to increasing Northern Hemisphere insolation led to higher summer temperatures and decreased effective moisture (Fig. 5E; Berger and Loutre, 1991; Thompson et al., 1993), which in turn created more drought-like conditions during summer and colder, drier winters than before (Bartlein et al., 2014). This is likely why *Abies* (presumably *A. lasiocarpa* and perhaps *A. procera* and *A. amabilis*) increased in abundance at Sunrise Lake during the early Holocene at the expense of *Picea engelmannii* and *Pinus albicaulis*, which require deep snowpacks and cool summer temperatures (Franklin and Dyrness, 1988; Spooner et al., 2008). The vegetation reconstruction indicates the highest percentages of *Alnus sinuata* and *Pteridium aquilinum* during the early Holocene, which indicate shrubby and meadow communities around the site at this time, or in nearby areas, and perhaps a reduction in forest cover (Franklin and Dyrness, 1988).

Regional proxy-based climatic records as well as paleoclimate model simulations show that maximum Holocene warmth (approximately 1–4 °C warmer than present) and minimum precipitation in the PNW occurred between ca. 11,700–9000/8000 cal yr BP (Whitlock, 1992; Pellatt et al., 2000; Barron et al., 2003; Brown et al., 2006; Walker and Pellatt, 2008; Gavin et al., 2013; Gavin and Brubaker, 2015). Several other paleofire reconstructions from the North Cascades show a similar increase in (or relatively high) fire activity during the early Holocene (Hallett et al., 2003; Spooner et al., 2008; Prichard et al., 2009). For the Olympic Mountains, fire activity was more variable between sites, but many saw an increase in either charcoal accumulation rates and/or fire episodes (McLachlan and Brubaker, 1995; Gavin et al., 2001, 2013; Gavin and Brubaker, 2015). Furthermore, most low-elevation sites from Vancouver Island (British Columbia), the Puget Lowland, and the Portland Basin also show increased/high fire activity during the early Holocene (Tsukada et al., 1981; Cwynar, 1987; Brown and Hebda, 2002a, 2002b; Walsh et al., 2008). A composite biomass burning curve for 34 paleofire sites in the PNW (which includes the Sunrise Ridge lake records) indicates that as a whole fire activity increased markedly in the region from ca. 12,000–10,000 cal yr BP and remained high until ca. 8000 cal yr BP (Fig. 5D), likely in response to greater insolation and warm/dry summer conditions (Walsh et al., 2015).

The Sunrise Lake fire-history reconstruction adds to the growing debate concerning the occurrence and impact of the McNeeley II glacial advance on Mount Rainier and the wider region (ca. 10,900–9950 cal yr BP; Heine, 1998). Evidence of this advance and its timing has been disputed given overwhelming evidence of consistently warm, dry climatic conditions in the PNW during the early Holocene (see Thomas et al., 2000; Reasoner et al., 2001; Gavin et al., 2013). In support of this, the fire activity at Sunrise Lake remains generally unchanged from ca. 12,000–10,000 cal yr BP (Fig. 5C). While lacustrine age models are far from perfect (Telford et al., 2004), the Sunrise Lake chronology is anchored by an AMS-^{14}C-dated twig at a depth of 179 cm that returned an age of 10,530 cal yr BP (9390 ± 40 ^{14}C yr BP), placing it squarely within the proposed time of the advance (Heine, 1998). As a result we feel confident in the fire reconstruction of the early Holocene and the fact that fire activity did not decrease significantly during this period. A more pronounced decrease in fire frequency did occur later in the period; however, this took place between ca. 9800–9200 cal yr BP, well after the proposed glacial retreat.

5.1.3. *Middle Holocene (8000–4000 cal yr BP)*

All three sites on Sunrise Ridge recorded a similar number of fire episodes during the middle Holocene, but there was substantial variability in CHAR values, mFRIs, and peak magnitudes between the sites (Fig. 5A–C, Table 3). Fires were most frequent at Little Sunrise Lake and least frequent at Shadow Lake, however CharAnalysis struggled during this period to identify charcoal peaks in the Shadow Lake record (Fig. 4), so the number of fire episodes determined is likely lower than the actual number of fires that occurred in the watershed. Importantly, average peak magnitudes at Little Sunrise and Shadow lakes during the middle Holocene were almost identical, and were low, indicating that fires were either small and/or of low severity. Average peak magnitudes at Sunrise Lake, however, were the highest of the entire record and were much larger than those observed at the other two sites, suggesting much bigger and/or more severe fires occurred. These differences are likely explained by differences in drainage basin size and dominant vegetation at each site (Millspaugh and Whitlock, 1995; Marlon et al., 2006; Higuera et al., 2007); Sunrise Lake has the largest and most heavily forested watershed. While fire frequency was on average higher on Sunrise Ridge during the middle Holocene as compared to earlier, at least at Shadow and Sunrise lakes, all three sites show a decrease in fire frequency starting near the middle of the period. This decrease in fire activity after ca. 6600 cal yr BP (earlier at Sunrise Lake) is generally consistent with the trend in the composite biomass burning curve for the PNW during the middle Holocene (Fig. 5D; Walsh et al., 2015).

Paleoclimate proxy records and model simulations indicate a transition to cooler, wetter conditions in the PNW during the middle Holocene (Bartlein et al., 1998; Walker and Pellatt, 2003; Liu et al., 2009; Gavin et al., 2013). As Northern Hemisphere insolation decreased and atmospheric circulation began to resemble that of present-day (i.e., the polar jet stream became focused on the PNW instead of a split flow around the Laurentide ice sheet), regional climates first became wetter and then eventually cooler (Kutzbach et al., 1993; Bartlein et al., 2014). This increase in effective moisture is reflected in the increasing abundance of mesic taxa from sites across the PNW during the middle Holocene (Cwynar, 1987; Whitlock, 1992; Worona and Whitlock, 1995; Gavin et al., 2001; Brown and Hebda, 2002a, 2003; Spooner et al., 2007, 2008; Walsh et al., 2008; Prichard et al., 2009; Gavin et al., 2013; Gavin and Brubaker, 2015), including sites within MORA (Dunwiddie, 1986; Tweiten, 2007). At Sunrise Lake, *Abies*, *Tsuga heterophylla* (likely blown upslope from lower elevations), and *Tsuga mertensiana* increased between ca. 7000–6000 cal yr BP as *Pinus*, *Alnus sinuata*, and *Pteridium aquilinum* decreased (Fig. 7). Almost all sites in the PNW show a shift in vegetation beginning during the middle Holocene toward forests that essentially resemble modern-day forests, with few compositional changes after that time (Whitlock, 1992; Walsh et al., 2008; Gavin and Brubaker, 2015).

With the establishment of these more mesic forests as the result of cooler and wetter regional climatic conditions, fire activity decreased at many sites in the region during this period (Long et al., 1998; Gavin et al., 2001; Brown and Hebda, 2002a; Hallett et al., 2003). One explanation for the overall initial increase in fire activity on Sunrise Ridge at the beginning of the middle Holocene, followed by a later decrease, is that the regional climate was still transitional at this point. It is possible that with winters becoming wetter the vegetation at the sites began shifting toward their present-day state, but summers remained sufficiently dry to support fires. If this was the case, this transitional period did not last long given that fire frequency decreased on Sunrise Ridge after ca. 6600 cal yr BP, which is consistent with the progressively cooler, wetter conditions in the PNW toward the end of the middle Holocene (Gavin and Brubaker, 2015). This trend is also consistent with the composite PNW biomass burning curve (Walsh et al., 2015) as well as paleofire reconstructions from sites in the North Cascades (Spooner et al., 2007, 2008).

5.1.4. *Late Holocene (4000 cal yr BP until present)*

Although regional paleoclimate proxy records and model simulations indicate that the late Holocene was the coolest and wettest interval in the PNW during the past ~12,000 years (Walker and Pellatt, 2003; Bartlein et al., 2014; Gavin and Brubaker, 2015), fire activity was on average higher on Sunrise Ridge during the past 4000 years than during any other period in the record. The vegetation reconstruction from Sunrise Lake supports this interpretation of cool, wet conditions on the mountain during this period (i.e., the highest percentages of *Abies*, *Tsuga heterophylla*, and *Tsuga mertensiana* were observed during the late Holocene). However, the fire reconstructions show that all three sites experienced the greatest number of fire episodes and shortest mFRIs at this time (Fig. 5A–C; Table 3). Notably, our late Holocene mFRI estimates of 378, 405, and 448 years are similar to Hemstrom and Franklin's (1982) calculation of a pre-European settlement natural fire rotation of 465 years for the entire park. Also notable is that both

Shadow and Sunrise lakes experienced their largest increase in fire frequency in the late Holocene during the time period that corresponds with the Burroughs Mountain glacial advance (ca. 3400–2200 cal yr BP), which is thought to have been a period of increased precipitation and cooler temperatures (Crandell and Miller, 1974; Hekkers, 2010). However, most of the episodes that occurred during this period were of low peak magnitude, indicating that the advance may have acted to decrease fire size and/or severity.

One possible explanation for the overall higher fire activity on Sunrise Ridge during the late Holocene is the influence of El Niño–Southern Oscillation (ENSO) on PNW interannual climate variability (Moy et al., 2002). While the connection between present-day ENSO events (i.e., El Niño and La Niña phases) and fire activity in the PNW in not entirely clear (see Walsh et al., 2015 for a discussion), research shows that winter/spring snowpack is less and regional temperatures are warmer during El Niño (warm) phases, with the reverse true during La Niña (cool) phases (Clark et al., 2001; Mote et al., 2003). The likely impact this has on fire activity in the PNW is a warmer, drier, and longer summer fire season with more widespread fire during El Niño events (Hessl et al., 2004; Heyerdahl et al., 2008). According to Moy et al. (2002), ENSO events first became statistically significant after ca. 7000 cal yr BP, but increases in ENSO event frequency particularly after ca. 3500 cal yr BP would have increased summer drought and caused more frequent fire weather during El Niño phases, leading to an increase in fire activity on Sunrise Ridge even while the overall regional climate was cool and wet (Fig. 5F). Our hypothesis is consistent with findings from Hemstrom and Franklin (1982) who showed that most major fire episodes at MORA during the past ~800 years occurred during years of pronounced drought.

Higher fire activity during the Medieval Climate Anomaly (MCA; ca. 1100–700 cal yr BP; Mann et al., 2009), which was marked by warmer temperatures and periods of extended drought in the PNW (Cook et al., 2004, 2014), is common across many paleofire sites in the PNW (Marlon et al., 2012). The MCA is the period of highest biomass burning for the PNW composite curve (Fig. 5D; Walsh et al., 2015) and it is also the period of highest ENSO variability in the past 1000 years (Fig. 5F; Moy et al., 2002). Interestingly though, fire episodes only occurred at one site on Sunrise Ridge (Shadow Lake) during the MCA, potentially indicating that there was little climatic change at MORA during this period. Conversely, the Little Ice Age (LIA; ca. 500-100 cal yr BP; Grove, 2001), which was marked by expanded glacial activity on Mount Rainier (Garda advance; ca. 500-90 cal yr BP), cooler temperatures, and lowered snowlines (Crandell and Miller, 1974; Hekkers, 2010), appears to have only caused a decrease in fire activity at Shadow and Sunrise lakes. Little Sunrise Lake actually experienced increased fire frequency during the LIA and one of its largest peak magnitude episodes. However, the LIA was not a continuous period of glacial growth or cold temperatures, but instead was marked by swings in precipitation, temperature, and discrete episodes of moraine building (Burbank, 1982; Graumlich and Brubaker, 1986), and likely explains how at least one severe and/or large fire occurred at Little Sunrise Lake during the LIA.

A number of paleofire reconstructions from across the PNW show increased fire activity during the late Holocene, although the exact timing varies between sites and regions (McLachlan and Brubaker, 1995; Long et al., 1998; Gavin et al., 2001, 2006; Brown and Hebda, 2002a, 2002b, 2003; Hallett et al., 2003; Long et al., 2007; Spooner et al., 2008; Prichard et al., 2009; Walsh et al., 2010a, 2010b; Long et al., 2011; Gavin et al., 2013). Additionally, an increase in biomass burning between ca. 5500–900 cal yr BP is the most striking trend in the PNW composite curve (Fig. 5D), and is particularly pronounced at sites from an inland, high-elevation, or forested (both wet and dry) setting (see Walsh et al., 2015). Within MORA, fire activity increased at nearby Buck Lake until ca. 2800 cal yr BP and then decreased following that (Tweiten, 2007). Besides the factors discussed above, several other ecological and climatic hypotheses have been developed to explain the late Holocene increase in fire activity in the PNW, including increased fuel availability, a greater number of lightning strikes, and more frequent or extended periods of summer drought caused by something other than ENSO variability (Hallett et al., 2003; Gavin et al., 2007; Spooner et al., 2008; Prichard et al., 2009; Long et al., 2011; Gavin and Brubaker, 2015; Walsh et al., 2015). However, given the growing number of archaeological sites discovered at MORA (Burtchard, 2003, 2007) and the pervasive and well-documented use of fire by Native American prior to and immediately after Euro-American contact in the PNW (Boyd, 1999; Mack, 2003), it is necessary to consider the possibility that human-set fires contributed not only to the late Holocene fire history of Sunrise Ridge, but also to the entire postglacial fire history of the park.

5.2. *Postglacial human-environment interactions on Sunrise Ridge*

The first colonizing populations in North America likely arrived in the PNW ca. 13,800–12,800 cal yr BP, or earlier, following the movement of Pleistocene megafauna south through an ice-free corridor between the Cordilleran and Laurentide ice sheets (Ames, 2003; Waters and Stafford, 2007; Waters et al., 2011). The presence of Pleistocene megafauna and early fluted points provide some indication of human presence in the vicinity of the Cascades during the Late Glacial period (Hollenbeck and Carter, 1986; Zweifel and Reid, 1991), but there is no direct evidence of humans at MORA at this time (Burtchard, 2003). The Sunrise Lake paleoenvironmental reconstruction indicates that fires were infrequent on Sunrise Ridge during the Late Glacial, likely due to low amounts of burnable biomass as the result of persistently cool, dry regional conditions. Human use of subalpine environments at MORA, much less their impact on the landscape, was likely minimal due to inhospitable and temporally variable climatic conditions (i.e., the McNeeley I glacial advance), the low value of subalpine environments at this time in terms of the resources offered, as well as the abundance of Rancholabrean fauna at lower elevations (Burtchard, 2007). Instead, human resource extraction was likely focused on more productive and easily accessible locations east and west of the Cascades (Waters and Stafford, 2007; Burtchard, 2007).

For the Washington Cascades, the oldest culturally-related radiocarbon age comes from an early Holocene archaeological deposit found near the Cedar River north of MORA and dates to ca. 9500 cal yr BP (Samuels, 1993). An almost identical age was reported by Mierendorf and Foit (2008) from the North Cascades. Comparably early dates have also been reported recently from Buck Lake in MORA (Burtchard, 2007), and south of the mountain at Beech Creek near Packwood, WA (Mack et al., 2010). Human use of the Buck Lake site (45PI438), which is located approximately 7.5 km NNE of Sunrise Lake at 1704 m a.s.l., occurred at ca. 9000 cal yr BP (Fig. 1). 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) (Burtchard, 2007). With the warmer and drier conditions of the early Holocene, faunal ranges probably expanded across more wide-ranging prairies and oak savanna environments found in the Puget Lowland and Willamette Valley (Whitlock, 1992). At higher elevation, the Sunrise Ridge paleoenvironmental reconstruction indicates that cold, sparse late-glacial forests gave way to more productive environments that included some closed forests, but also an increased abundance of shrubby and herbaceous meadow communities. An increase in fire activity as well at this time created more early seral-stage environments that would have been beneficial to both large fauna and humans (Burtchard, 2007). As a result, human use of montane and subalpine environments, like those of MORA, likely increased but remained moderate to low given relatively small human populations and abundant game at low elevations, making travel to and use of subalpine environments a lower priority as compared to later in the Holocene (Burtchard, 2003, 2007).

Radiocarbon-dated cultural deposits are more common from the middle Holocene and firmly establish human presence in the Washington Cascades by 8000 cal yr BP (McClure, 1989, 1998). As the result of cooler, wetter regional climatic conditions, the Sunrise Lake and Buck Lake pollen records show an increase in forest cover but the persistence of a shrub/herbaceous understory after this time (Tweiten, 2007). Loss of forage in the lowlands due to forest encroachment along with increasing regional population density may have contributed to an increase in human use of higher elevations, particularly during the late summer months (Chatters, 1995a, 1998; Burtchard, 2007). This is supported by the MORA archaeological record, which shows an increase in cultural artifacts between ca. 7500 and 6300 cal yr BP (McClure, 1998; Burtchard, 2003). As noted above, the oldest cultural deposit known at MORA is from the Buck Lake site. Throughout its use range, which extends into the late Holocene, the site was most likely used repeatedly as a seasonal base camp from which hunting parties were dispatched, and a location for floral and faunal processing (Burtchard, 2007; Schurke, 2011). This evidence suggests that humans may have contributed to the fire regime at this time, or at least benefitted from abundant early seral-stage environments. This may have been particularly true at Shadow and Little Sunrise lakes where but peak magnitudes were low in comparison to Sunrise Lake (Fig. 5A and B; Table 3). Small/low-severity fires, whether set by humans or not, probably helped maintain huckleberry patches and game forage (Mack, 2003; Smith, 2006)

During the late Holocene pre-contact population density in the PNW reached its peak (Chatters, 1995b; Ames, 2005a) and climatic conditions became the coolest and wettest of those experienced during the Holocene (Bartlein et al., 1998; Gavin and Brubaker, 2015), leading to the establishment of the modern landscapes on Sunrise Ridge. As a result, declining ungulate habitat at lower elevations reached a point at which competition for available resources was likely too great to reliably sustain previous foraging practices (Chatters, 1995b; Ames, 2005b; Burtchard, 2007). Food collection in the uplands would have increased as a greater importance was placed on alternative high-value resources such as mountain goats, mountain beaver, marmots, and huckleberries, which were not available in high abundance in the lowlands (Burtchard, 2007). Along with this shift came a presumed focus on fire-based forest management to combat forest encroachment and promote more productive early seral-stage communities in both lowland and upland settings (Lepofsky et al., 2005; Smith, 2006). While not evidence of anthropogenic burning, the archaeological record from MORA illustrates that Native Peoples continued to exploit subalpine environments such as those found on Sunrise Ridge during much of the late Holocene. The Sunrise Ridge Borrow Pit site (45PI408) shows a high density and relatively high diversity of artifacts recovered from ca. 3600–2200 cal yr BP (Fig. 1; McCutcheon, 1999; Chatters et al., 2017; Parfitt and McCutcheon, 2017), and at Buck Lake artifact diversity and density increased immediately after the MSH-Yn tephra deposit (ca. 3650 cal yr BP) (Tweiten, 2007; Burtchard, 2007, 2009). Fire frequency increased most dramatically at Shadow and Sunrise lakes between the MSH-Yn and MSH-Pu tephras (ca. 3650–2500 cal yr BP), even though regional climatic conditions were becoming less favorable overall for fire. Taken together this evidence suggests heightened use of MORA's subalpine zone and a possible anthropogenic contribution to the fire regimes during the late Holocene.

6. Conclusions

The charcoal and pollen records presented here illustrate that fire activity varied continuously in the Sunrise Ridge area of MORA during the postglacial period, and are generally consistent with many other paleoenvironmental reconstructions from the PNW. While overall fires were infrequent at MORA during the postglacial period, variability in peak frequency and magnitude indicate that fire activity primarily responded to major climatic shifts and increased variability, as well as climate-induced changes in vegetation. Fire activity was low during the Late Glacial when cold, dry conditions and relatively sparse vegetation suppressed fire episodes. Low fire frequencies and peak magnitudes during this period indicate that few fires burned, and those that did were likely of small size and/or low severity. Because of the harsh environmental conditions and the presumed difficulty of traveling to and existing in subalpine environments at this time, as well as the lack of any dated cultural sites, human use of and impact on the environments of Sunrise Ridge during the Late Glacial was likely negligible.

During the early Holocene as the regional climate of the PNW became warm and dry, subalpine parkland or tundra/steppe habitat present on Sunrise Ridge during the Late Glacial gave way to a mixture of *Pinus*/*Abies*-dominated forests, as well as expanded shrub and herbaceous meadow communities. As a result, fire activity increased on Sunrise Ridge, presumably as fuel became more abundant and fires burned larger areas and/or were of greater severity. Human presence likely increased in the Washington Cascades and perhaps at MORA during the early Holocene, and anthropogenic fires may have contributed to the Sunrise Ridge fire regimes. While the number of dated cultural deposits has recently increased, their relatively low count makes it difficult to fully assess human-environment interactions during this interval. However, we assume that the human impact on subalpine environmental processes was relatively low at this time.

During the middle Holocene (ca. 7000–6000 cal yr BP), modern Sunrise Ridge landscapes established in response to cooler, wetter conditions than before. This is indicated by an increased abundance of *Abies*, *Tsuga heterophylla*, *Tsuga mertensiana*, and Cupressaceae. Although regional climate was less conducive to fire activity during this interval than earlier, fires were generally more frequent on Sunrise Ridge during the early part of the middle Holocene (until ca. 6600 cal yr BP) as compared to later. It is likely that a transitional climate (i.e., increasingly wet conditions with persistently dry summers) led to this observed increase in fire activity. However, the number and type of dated cultural sites also increased at MORA during this interval, which may indicate greater human use of and impact on the landscapes of Sunrise Ridge.

At the end of the middle Holocene and the beginning of the late Holocene (ca. 4500–2000 cal yr BP) fire activity increased on Sunrise Ridge as regional climatic conditions became cooler and wetter, albeit the timing and magnitude varied between the three study sites. While seemingly contradictory to climatic trends, this increase is generally consistent with a region-wide assessment of fire activity in the PNW that shows a steady increase in fire activity after ca. 5500 cal yr BP. Increasing climatic variability (i.e., drought) due to an increase in ENSO variability after ca. 7000 cal yr BP during the late Holocene is one explanation for the observed increase; however, it is also probable that human-set fires on the mountain increased at this time as a means of combating forest encroachment in resource-rich, early seral-stage environments. No matter the source, based on this evidence it seems likely that fire activity will increase in the Sunrise Ridge area of MORA in the future, particularly if drought becomes a more frequent occurrence.

Acknowledgements

The authors would like to thank the many field and lab volunteers who helped make this research possible. Funding was provided by a National Park Service George M. Wright Climate Change Fellowship (Lukens) and Central Washington University start-up funds and a CWU College of the Science Faculty Summer Grant (Walsh).

References

Allen, G.F., 1904. Report of Fires in the Mount Rainier Forest Reserve. Record Group 95, Box 7. Unpublished report on file. National Archives and Records Administration, Washington, DC.

Allen, G.F., 1905. Report of Fires in the Mount Rainier Forest Reserve. Record Group 95, Box 7. Unpublished report on file. National Archives and Records Administration, Washington, DC.

Allen, G.F., 1916. Forests of Mount Rainier National Park. US Department of the Interior, Office of the Secretary, Washington D.C.

Ames, K.M., 2003. The Northwest Coast. Evol. Anthropol. 12, 19–33.

Ames, K.M., 2005a. Political and historical ecologies. In: Biolsi, T. (Ed.), A Companion to the Anthropology of American Indians. Blackwell Publishing, Oxford, pp. 7–23.

Ames, K.M., 2005b. Intensification of food production on the Northwest Coast and elsewhere. In: Duer, D., Turner, N. (Eds.), Keeping it Living: Traditions of Plant Use and Cultivation on the Northwest Coast of North America. University of Washington Press, Seattle, pp. 64–94.

Barron, J.A., Heusser, L., Herbert, T., Lyle, M., 2003. High-resolution climatic evolution of coastal northern California during the past 16,000 years. Paleoceanography 18, 1020. https://doi.org/10.1029/2002PA000768.

Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb III, T., Whitlock, C., 1998. Paleoclimatic simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quat. Sci. Rev. 17, 549–585.

Bartlein, P.J., Hostetler, S.W., Alder, J.R., 2014. Paleoclimate. In: Ohring, G. (Ed.), Climate Change in North America. Springer, New York, pp. 1–52.

Berger, A., Loutre, M.F., 1991. Insolation values for the last 10 million years. Quat. Sci. Rev. 10, 297–317.

Biek, D., 2000. Flora of Mount Rainier National Park. Oregon State University Press, Corvallis.

Boyd, R.T., 1999. Indians, Fire, and the Land in the Pacific Northwest. Oregon State University Press, Corvallis.

Brown, K.J., Hebda, R.J., 2002a. Ancient fires on southern Vancouver Island, British Columbia, Canada: a change in causal mechanisms at about 2000 ybp. Environ. Archaeol. 7, 1–12.

Brown, K.J., Hebda, R.J., 2002b. Origin, development, and dynamics of coastal temperate conifer rainforests of southern Vancouver Island, Canada. Can. J. For. Res. 32, 353–372.

Brown, K.J., Hebda, R.J., 2003. Coastal rainforest connections disclosed through a late quaternary vegetation, climate, and fire history investigation from the Mountain Hemlock Zone on southern Vancouver Island, British Columbia, Canada. Rev. Palaeobot. Palynology 123, 247–269.

Brown, K.J., Fitton, R.J., Choups, G., Allen, G.B., Wahl, K.A., Hebda, R.J., 2006. Holocene precipitation in the coastal temperate rainforest complex of southern British Columbia, Canada. Quat. Sci. Rev. 25, 2762–2779.

Burbank, D.W., 1982. Correlations of climate, mass balances, and glacial fluctuations at Mount Rainer, Washington, USA, since 1850. Arct. Alp. Res. 14, 137–148.

Burtchard, G.C., 2003. Environment, Prehistory and Archaeology of Mount Rainier National Park, Washington. International Archaeological Research Institute, Inc. Submitted to Mount Rainier National Park, Ashford, Washington.

Burtchard, G.C., 2007. Holocene subsistence and settlement patterns: Mount Rainier and the montane Pacific Northwest. Archaeol. Wash. 13, 3–44.

Burtchard, G.C., 2009. Buck Lake Archaeological and Paleoenvironmental Project. Mount Rainier National Park. Archaeological Reconnaissance Report 2009-41. Submitted to Mount Rainier National Park, Ashford, Washington.

Chatters, J.C., 1995a. Resource intensification and demography on the Columbia Plateau of western North America. In: Paper Presented at the 60th Meeting of the Society for American Archaeology, Minneapolis.

Chatters, J.C., 1995b. Population growth, climatic cooling, and the development of collector strategies on the southern Plateau, Western North America. J. World Prehistory 9, 341–400.

Chatters, J.C., 1998. Environment. In: Walker Jr., D.E. (Ed.), Handbook of North American Indians, Vol. 12: Plateau. Smithsonian Institution Press, Washington DC, pp. 29–48.

Chatters, J.C., Brown, J.W., Hackenberger, S., Mccutcheon, P., Adler, J., 2017. Calcined bone as a reliable medium for radiocarbon dating: a test using paired North American samples. Am. Antiq. 82 (3), 593–608.

Clark, M.P., Serreze, M.C., McCabe, G.J., 2001. The historical effect of El Niño and La Niña events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River basins. Water Resour. Res. 37, 741–757.

Clynne, M.A., Champion, D.E., Wolfe, E.W., Gardner, C.A., Pallister, J.S., 2004. Stratigraphy and paleomagnetism of the Pine Creek and Castle Creek eruptive episodes, Mount St. Helens, Washington. In: EOS Transactions, American Geophysical Union 85(47). Fall Meeting Supplement, Abstract V43E-1453.

Cook, B.I., Smerdon, J.E., Seager, R., Cook, E.D., 2014. Pan-continental droughts in North America over the last millennium. J. Clim. 27, 383–397. https://doi.org/10.1175/JCLI-D-13-00100.1.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004. Long-term aridity changes in the Western United States. Science 306, 1015–1018.

Crandell, D.R., Miller, R.D., 1974. Quaternary Stratigraphy and Extent of Glaciation in the Mount Rainier Region, Washington. United States Government Printing Office, Washington, D.C, 59.

Cwynar, L.C., 1987. Fire and the forest history of the North Cascade range. Ecology 68, 791–802.

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J. Sediment. Petrology 44, 242–248.

Dombeck, M.P., Williams, E.J., Wood, A.C., 2004. Wildfire policy and public lands: integrating scientific understanding with social concerns across landscapes. Conserv. Biol. 18, 883–889.

Donoghue, S.L., Vallance, J., Smith, I.E.M., Stewart, R.B., 2007. Using geochemistry as a tool for correlating proximal andesitic tephras: case studies from Mt Rainier (USA) and Mt Ruapehu (New Zealand. J. Quat. Sci. 22, 395–410.

Dunwiddie, P.W., 1986. A 6000-year record of forest history on Mount Rainier, Washington. Ecology 67, 58–68.

Faegri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis. John Wiley and Sons, New York.

Franklin, J.F., Dyrness, C.T., 1988. Natural Vegetation of Oregon and Washington. Oregon State University Press, Corvallis.

Franklin, J.F., Moir, W.H., Hemstrom, M.A., Greene, S.E., Smith, B.G., 1988. The Forest Communities of Mount Rainier National Park. Scientific Monograph Series No. 19. US Department of the Interior, National Park Service, Washington, D.C.

French, D., 1999. Aboriginal control of huckleberry yield in the Northwest. In: Boyd, R. (Ed.), Indians, Fire, and the Land in the Pacific Northwest. Oregon State University Press, Corvallis, pp. 31–35.

Gavin, D.G., Brubaker, L.B., 2015. Ecological Studies. Late Pleistocene and Holocene Environmental Change on the Olympic Peninsula, Washington, vol. 222. Springer, New York.

Gavin, D.G., Brubaker, L.B., Greenwald, D.N., 2013. Postglacial climate and fire-mediated vegetation change on the western Olympic Peninsula, Washington (USA). Ecol. Monogr. 83, 471–489.

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

Gavin, D.G., Hu, F.S., Lertzman, K., Corbett, P., 2006. Weak climatic control of stand-scale fire history during the late Holocene. Ecology 87, 1722–1732.

Gavin, D.G., McLachlan, J.S., Brubaker, L.B., Young, K.A., 2001. Postglacial history of subalpine forests, Olympic Peninsula, Washington, USA. Holocene 11, 177–188.

Graumlich, L.J., Brubaker, L.B., 1986. Reconstruction of annual temperature (1590-1979) for Longmire, Washington, derived from tree rings. Quat. Res. 25, 223–234.

Grove, A.T., 2001. The "little ice age" and its geomorphological consequences in Mediterranean Europe. Clim. Change 48, 121–136.

Hallett, D.J., Lepofsky, D.S., Mathewes, R.W., Lertzman, K.P., 2003. 11,000 years of fire history and climate in the mountain hemlock rain forests of southwestern British Columbia based on sedimentary charcoal. Can. J. For. Res. 33, 292–312.

Heine, J.T., 1998. Extent, timing, and climatic implications of glacier advances Mount Rainier, Washington, USA, at the Pleistocene/Holocene transition. Quat. Sci. Rev. 17, 1139–1148.

Hekkers, M.L., 2010. Climatic and Spatial Variations of Mount Rainier's Glaciers for the Last 12,000 Years. Unpublished M.S. Thesis. Portland State University, Portland, Oregon.

Hemstrom, M.A., Franklin, J.F., 1982. Fire and other disturbances of the forests in Mount Rainier National Park. Quat. Res. 18, 32–51.

Hessl, A.E., Don, M., Schellhaas, R., 2004. Drought and Pacific decadal oscillation linked to fire occurrence in the inland Pacific Northwest. Ecol. Appl. 14, 425–442.

Heyerdahl, E.K., McKenzie, D., Daniels, L.D., Hessl, A.E., Littell, J.S., Mantua, N.J., 2008. Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900). Int. J. Wildland Fire 17, 40–49.

Higuera, P.E., Peters, M.E., Brubaker, L.A., Gavin, D.G., 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quat. Sci. Rev. 26, 1790–1809.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Brown, T.A., Kennedy, A.T., Hu, F.S., 2008. Frequent fires in ancient shrub tundra: implications of paleorecords for arctic environmental change. PLoS One 3, e0001744.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S., Brown, A., 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. Ecol. Monogr. 79, 201–219.

Higuera, P., Gavin, D., Bartlein, P., Hallett, D., 2010. Peak detection in sediment-charcoal records: impacts of alternative data analysis methods on fire-history interpretations. Int. J. Wildland Fire 19, 996–1014.

Hollenbeck, J.L., Carter, S., 1986. A Prehistoric and Ethnographic Overview of the Wenatchee National Forest. Wenatchee National Forest, Wenatchee, Washington.

Jensen, K., Lynch, E.A., Calcote, R., Hotchkiss, S.C., 2007. Interpretation of charcoal morphotypes in sediments from Ferry Lake, Wisconsin, USA: do different plant fuel sources produce distinctive charcoal morphotypes? Holocene 17, 907–915.

Johnson, L.M., Gottesfeld, J., 1994. Aboriginal burning for vegetation management in northwest British Columbia. Hum. Ecol. 2, 171–187.

Kelly, R.F., Higuera, P.E., Barrett, C.M., Hu, F.S., 2011. A signal-to-noise index to quantify the potential for peak detection in sediment-charcoal records. Quat. Res. 75, 11–17.

Kutzbach, J.E., Guetter, P.J., Behling, P.J., Selin, R., 1993. Simulated climatic changes: results of the COHMAP climate-model experiments. In: Wright Jr., H.E., Kutzbach, J.E., Ruddiman, W.F., Street-Perrott, F.A., Webb III, T., Bartlein, P.J. (Eds.), Global Climates since the Last Glacial Maximum. University of Minnesota Press, Minneapolis, pp. 24–93.

Lepofsky, D., Hallett, D., Lertzman, K., Mathewes, R., McHalsie, A., Washbrook, K., 2005. Documenting precontact plant management on the Northwest Coast: an example of prescribed burning in the Central and Upper Fraser Valley, British Columbia. In: Deur, D.E., Turner, N.J. (Eds.), Keeping it Living: Traditions of Plant Use and Cultivation on the Northwest Coast. University of Washington Press, Seattle, pp. 218–239.

Liu, Z., Otto-Bliesner, B.L., He, F., Brady, E.C., Tomas, R., Clark, P.U., Carlson, A.E., Lynch-Stieglitz, J., Curry, W., Brook, E., Erickson, D., Jacob, R., Kutzbach, J., Cheng, J., 2009. Transient simulation of last deglaciation with a new mechanism for Bølling-Allerød warming. Science 325, 310–314. https://doi.org/10.1126/science.1171041.

Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H., 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Can. J. For. Res. 28, 774–787.

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

Long, C.J., Power, M.J., Bartlein, P.J., 2011. The effects of fire and tephra deposition on forest vegetation in the central Cascades, Oregon. Quat. Res. 75, 151–158.

Lukens, M.L., 2013. The Roles of Humans and Climatic Variability on the Fire History of Subalpine Meadows- Mount Rainier National Park (Washington). Unpublished M.S. Thesis. Central Washington University, Ellensburg, Washington.

Mack, C., 2003. A burning issue: American Indian fire use on the Mt. Rainier Forest Reserve. Fire Manag. Today 63, 20–24.

Mack, C.A., Chatters, J.C., Prentiss, A.M., 2010. Archaeological Data Recovery at the Beech Creek Site (45LE415), Gifford Pinchot National Forest, Washington. Report submitted to Gifford Pinchot National Forest, Trout Lake, Washington.

Mack, C.A., McClure, R.H., 2003. *Vaccinium* processing in the Washington Cascades. J. Ethnobiol. 22, 35–60.

Mann, M.E., Zhang, A., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. Science 326, 1256–1260.

Marlon, J.R., Bartlein, P.J., Walsh, M.K., Harrison, S.P., Brown, K.J., Edwards, M.E., Higuera, P.E., Power, M.J., Anderson, R.S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F.S., Lavoie, M., Long, C., Minckley, T., Richard, P.J.H., Shafer, D.S., Tinner, W., Umbanhowar Jr., C.E., Whitlock, C., 2009. Wildfire responses to abrupt climate change in North America. Proc. Natl. Acad. Sci. 106, 2519–2524.

Marlon, J., Bartlein, P.J., Whitlock, C., 2006. Fire-fuel-climate linkages in the Northwestern USA during the Holocene. Holocene 16, 1059–1071.

Marlon, J.R., Bartlein, P.J., Long, C., Gavin, D., Anderson, R.S., Briles, C.E., Colombaroli, D., Brown, K.J., Hallett, D.J., Power, M.J., Scharf, E., Walsh, M.K., 2012. A long-term perspective on wildfires in the western US. Proc. Natl. Acad. Sci. 109, 3203–3205.

McClure Jr., R.H., 1989. Alpine obsidian procurement in the southern Washington Cascades: preliminary research. Archaeol. Wash. 1, 59–69.

McClure Jr., R.H., 1998. Prehistoric archaeology in the southern Washington Cascades. In: Burtchard, G.C. (Ed.), Environment Prehistory and Archaeology of Mount Rainier National Park, Washington. International Archaeological Research Institute, Inc, pp. 59–75. Submitted to Mount Rainier National Park, Ashford, Washington.

McCutcheon, P.T., 1999. Central Washington University's 1997 Systematic Archeological Survey in Mount Rainier National Park. Central Washington University. Report submitted to Mount Rainier National Park, Ashford, Washington.

McLachlan, J., Brubaker, L.B., 1995. Local and regional vegetation change on the northeastern Olympic Peninsula during the Holocene. Can. J. Bot. 73, 1618–1627. https://doi.org/10.1139/b95-175.

Mierendorf, R.R., Foit, F., 2008. 9,000 Years of Earth, wind, fire and stone at Cascade Pass. In: Paper Presented at the 73rd Annual Meeting of the Society for American Archaeology, Vancouver, British Columbia.

Millspaugh, S.H., Whitlock, C., 1995. A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. Holocene 5, 283–292.

Mount Rainier National Park, 1988. Fire Management Plan. US Department of the Interior, National Park Service. Report on file, Longmire, Washington.

Mount Rainier National Park, 2003. Fire Management Plan. US Department of the Interior, National Park Service. Report on file, Longmire, Washington.

Moy, C.M., Seltzer, G.O., Rodbell, D.T., Anderson, D.M., 2002. Variability of El Niño/southern oscillation activity at millennial timescales during the Holocene epoch. Nature 420, 162–165.

Mote, P.W., Parson, E.A., Hamlet, A.F., Keeton, W.S., Lettenmaier, D., Mantua, N., Miles, E.L., Peterson, D.W., Peterson, D.L., Slaughter, R., Snover, A.K., 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. Clim. Change 61, 45–88.

Mullineaux, D., 1974. Pumice and Other Pyroclastic Deposits in Mount Rainier National Park, Washington. Geological Survey Bulletin 1326. US Department of the Interior, United States Geological Survey, Washington, DC.

Mullineaux, D., 1996. Pre- 1980 Tephra-Fall Deposits Erupted from Mount St. Helens, Washington. U.S. Geological Survey Professional Paper 1563. US Department of the Interior, United States Geological Survey, Washington, DC.

Nickels, A., 2002. History under Fire: Understanding Human Fire Modification of the Landscapes at Mount Rainier National Park. Unpublished M.S. Thesis. Central Washington University, Ellensburg, Washington.

Norton, H.H., Boyd, R., Hunn, E., 1999. The Klikitat trail of south-central Washington: a reconstruction of seasonally used resource sites. In: Boyd, R. (Ed.), Indians, Fire, and the Land in the Pacific Northwest. Oregon State University Press, Corvallis, pp. 65–93.

Parfitt, A.B., McCutcheon, P.T., 2017. Chemical Sourcing of Obsidian Artifacts from the Grissom Site (45-KT-301) to Study Source Variability. J. Northwest Anthropol. 51 (1), 37–72.

Pellatt, M.G., Smith, M.J., Mathews, R.W., Walker, I.R., Palmer, S.L., 2000. Holocene treeline and climate change in the Subalpine Zone near Stoyoma Mountain, Cascade Mountains, southwestern British Columbia, Canada. Arct. Antarct. Alp. Res. 32, 73–83.

Prentiss, W.C., Kuijt, I., 2004. Complex Hunter-Gatherers: Evolution and Organization of Prehistoric Communities on the Plateau of Northwestern North America. The University of Utah Press, Salt Lake City.

Prichard, S.J., Gedalof, Z., Oswald, W.W., Peterson, D.L., 2009. Holocene fire and vegetation dynamics in a montane forest, North Cascade Range, Washington, USA. Quat. Res. 72, 57–67.

Reasoner, M.A., Davis, P.T., Osborn, G., 2001. Evaluation of proposed early-Holocene advances of alpine glaciers in the North Cascade Range, Washington State, USA: constraints provided by palaeoenvironmental reconstructions. Holocene 11, 607–611.

Reimer, P.J., Baillie, M.G.L., Bard, E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51, 1111–1150.

Ruby, R.H., Brown, J.A., 1988. The Indians of the Pacific Northwest. University of Oklahoma Press, Norman.

Samuels, S.R., 1993. The Archaeology of Chester Morse Lake: Long-term Human Utilization of the Foothills in the Washington Cascade Range. Center for Northwest Anthropology Project Report No. 21. Department of Anthropology, Washington State University, Pullman.

Schurke, M.C., 2011. Investigating Technological Organization at the Buck Lake Site (45PI438) in Mount Rainier National Park Using a Lithic Debitage Analysis. Unpublished M.S. Thesis. Portland State University, Portland, Oregon.

Shebitz, D.J., Reichard, S.H., Dunwiddie, P.W., 2009. Ecological and cultural significance of burning beargrass habitat on the Olympic Peninsula, Washington. Ecol. Restor. 27, 306–319.

Sisson, T.W., Vallance, J.W., 2009. Frequent eruptions of Mount Rainier over the last ~2,600 years. Bull. Volcanol. 71, 595–618.

Smith, A.H., 2006. Takhoma: Ethnography of Mount Rainier National Park. Washington State University Press, Pullman.

Spooner, A.M., Brubaker, L.B., Foit Jr., F.F., 2007. Thunder Lake: a Lake Sediment Record of Holocene Vegetation and Climate History in North Cascades National Park Service Complex, Washington. Report submitted to: North Cascades National Park Service Complex, National Park Service, United States Department of the Interior.

Spooner, A.M., Brubaker, L.B., Foit Jr., F.F., 2008. Ridley Lake: a Sediment Record of Holocene Vegetation and Climate History in North Cascades National Park Service Complex, Washington. Report submitted to North Cascades National Park Service Complex, National Park Service, United States Department of the Interior.

Sugita, S., 1990. Palynological Records of Forest Disturbance and Development in the Mountain Meadows Watershed, Mt. Rainier, Washington. Unpublished Ph.D. Dissertation. University of Washington, Seattle, Washington.

Telford, R.J., Heegaard, E., Birks, H.J.B., 2004. All age-depth models are wrong: but how badly? Quat. Sci. Rev. 23, 1–5.

Thomas, P.A., Easterbrook, D.J., Clark, P.U., 2000. Early Holocene glaciation on Mount Baker, Washington state, USA. Quat. Sci. Rev. 19, 1043–1046.

Thompson, R.S., Whitlock, C., Bartlein, P.J., Harrison, S.P., Spaulding, W.G., 1993. Climate changes in the western United States since 18,000 yr BP. In: Wright Jr., H.E., Kutzbach, J.E., Webb III, T., Ruddiman, W.F., Street-Perrott, F.A., Bartlein, P.J. (Eds.), Global Climates since the Last Glacial Maximum. University of Minnesota Press, Minneapolis, pp. 468–513.

Tsukada, M., Sugita, S., Hibbert, D.M., 1981. Paleoecology in the Pacific Northwest I. Late quaternary vegetation and climate. Proceedings- Int. Assoc. Theor. Appl. Limnol. 21, 730–737.

Tweiten, M.A., 2007. The Interaction of Changing Patterns of Land Use, Sub-Alpine Forest Composition and Fire Regime at Buck Lake, Mount Rainier National Park, USA. Report submitted to Mount Rainier National Park, Ashford, Washington.

USDA, NRCS, 2017. The PLANTS Database. National Plant Data Team, Greensboro, NC, USA, 16 October 2017. http://plants.usda.gov.

Vallance, H.W., Scott, K.M., 1997. The Osceola Mudflow from Mount Rainier: sedimentology and hazard implications of a huge clay-rich debris flow. GSA Bull. 109, 143–163.

Walker, I.R., Pellatt, M.G., 2003. Climate change in coastal British Columbia- a paleoenvironmental perspective. Can. Water Resour. J. 28, 531–566.

Walker, I.R., Pellatt, M.G., 2008. Climate change and ecosystem response in the northern Columbia River basin- A paleoenvironmental perspective. Environ. Rev. 16, 113–140.

Walsh, M.K., Whitlock, C., Bartlein, P.J., 2008. A 14,300-year-long record of fire-vegetation-climate linkages at Battle Ground Lake, southwestern Washington. Quat. Res. 70, 251–264.

Walsh, M.K., Pearl, C.A., Whitlock, C., Bartlein, P.J., Worona, M., 2010a. An 11,000-year-long fire and vegetation history from Beaver Lake, central Willamette Valley, Oregon. Quat. Sci. Rev. 29, 1093–1106.

Walsh, M.K., Whitlock, C., Bartlein, P.J., 2010b. 1200 years of fire and vegetation history in the Willamette Valley, Oregon and Washington, reconstructed using high-resolution macroscopic charcoal and pollen analysis. Palaeogeogr. Palaeoclimatol. Palaeoecol. 297, 273–289.

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

Waters, M.R., Stafford Jr., T.W., 2007. Redefining the age of Clovis: implications for the peopling of the Americas. Science 315, 1122–1126.

Waters, M.R., Stafford Jr., T.W., McDonald, G., Gustafson, C., Rasmussen, M., Cappellini, E., Olsen, J.V., Szklarczyk, D., Jensen, L.J., Gilbert, M.T.P., Willerslev, E., 2011. Pre-clovis Mastodon hunting 13,800 Years ago at the Manis site, Washington. Science 334, 351–353.

Whitlock, C., 1992. Vegetational and climatic history of the Pacific Northwest during the last 20,000 years: implications for understanding present-day biodiversity. Northwest Environ. J. 8, 5–28.

Whitlock, C., Bianchi, M.M., Bartlein, P.J., Markgraf, V., Marlon, J., Walsh, M., McCoy, N., 2006. Postglacial vegetation, climate, and fire history along the east side of the Andes (lat 41-42.5°S), Argentina. Quat. Res. 66, 187–201.

Whitlock, C., Larsen, C.P.S., 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments: Biological Techniques and Indicators, vol. 2. Kluwer Academic Publishers, Dordrecht, pp. 75–97.

Worona, M.A., Whitlock, C., 1995. Late quaternary vegetation and climate history near Little Lake, central Coast Range, Oregon. GSA Bull. 107, 867–876.

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

Zdanowicz, C.M., Zielinski, G.A., Germani, M.S., 1999. Mount Mazama eruption: calendrical age verified and atmospheric impact assessed. Geology 27, 621–624.

Zweifel, M.K., Reid, C.S., 1991. Prehistoric use of the central Cascade Mountains of eastern Washington State: an overview of site types and potential resource utilization. Archaeol. Wash. 3, 3–16.