Research Paper

The Holocene
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Holocene fire history reconstruction of a mid-elevation mixed-conifer forest in the Eastern Cascades, Washington (USA)

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Abstract

Fire histories of mid-elevation mixed-conifer forests are uncommon in the eastern Cascades, limiting our understanding of long-term fire dynamics in these environments. The purpose of this study was to reconstruct the fire and vegetation history for a moist mid-elevation mixed-conifer site, and to determine whether Holocene fire activity in this watershed was intermediate to fire regimes observed at higher and lower elevations in the eastern Cascades. Fire activity and vegetation change was reconstructed using macroscopic charcoal and pollen analysis of sediment core from Long Lake. This site is located ~45 km west of Yakima, WA, and exists in a grand fir-dominated, mixed-conifer forest. Results show low fire activity from ca. 9870 to 6000 cal yr BP, after which time fire increased and remained frequent until ca. 500 cal yr BP. A woodland environment existed at the site in the early Holocene, with the modern coniferous forest establishing ca. 6000–5500 cal yr BP. A mixed-severity fire regime has existed at the site for the past ~6000 years, with both higher- and lower-severity fire episodes occurring on average every ~80–100 years. However, only one fire episode occurred in the Long Lake watershed during the past 500 years, and none within the past ~150 years. Based on a comparison with other eastern Cascade sites, Holocene fire regimes at Long Lake, particularly during the late Holocene, appear to be intermediate between those observed at higher- and lower elevation sites, both in terms of fire severity and frequency.

Keywords

charcoal morphotypes, climate variability, eastern Cascades, fire suppression, Holocene, macroscopic charcoal, Pacific Northwest, pollen

Received 19 September 2019; revised manuscript accepted 3 December 2020

Introduction

Understanding trends in long-term fire activity in multiple forest environments is important for supporting current and future wildfire management strategies such as thinning and prescribed burning (Carcaillet et al., 2010; Westerling and Swetnam, 2003). This is particularly true in the dry forests of the eastern Cascades of Oregon and Washington, which have seen a dramatic rise in recent fire activity (Agee and Lolley, 2006; Arno, 2000; Wimberly and Liu, 2014). Historic fire regimes of low-elevation ponderosa pine (*Pinus ponderosa*)-dominated forests in the eastern Cascades have been extensively studied (Agee, 2003; Camp, 1999; Everett et al., 2000, 2008; Hagmann et al., 2013; Walsh et al., 2018; Wright and Agee, 2004). Fires in these forests were historically of low severity and high frequency (Everett et al., 2000; Swetnam and Dieterich, 1985) with mean fire return intervals (MFRIs) ranging from 3 to 38 years (Agee, 1994, 2003). Past trends in fire activity in high-elevation forests in the Cascades dominated by fir and other subalpine species are also fairly well understood (Agee, 1994; Little et al., 1994; Hemstrom and Franklin, 1982; Walsh et al., 2015, 2017). Fires here tend to be stand-replacing and much less frequent with MFRIs of 300–500 years (Hemstrom and Franklin, 1982; Walsh et al., 2017). However, less research has focused on the long-term role of fire in mid-elevation mixed-conifer (MEMC) forests in the eastern Cascades (Long et al., 2011; Hagmann et al., 2014; Odion et al., 2014).

The assumption that eastern Cascade mid-elevation forests have intermediate or "mixed" fire regimes both in terms of severity and frequency is understandable, but not necessarily correct (Agee, 1994). Mixed-conifer forest fire regimes can vary depending on moisture levels, topography, and site aspect (Agee, 1993; Stine et al., 2014). At present, dry mixed-conifer forests typically experience more frequent low-severity fires, primarily due to less fuel, while moist mixed-conifer forests may see more variability in fire severity and frequency, as well as stand structure and age (Hessburg et al., 2007). Some research has been conducted regarding the long-term role of fire in dry MEMC forests in the eastern Cascades (Bork 1984; Everett et al., 2000; Johnston et al., 2017; Marouka, 1994; Wright and Agee, 2004); however, little has been done in moist MEMC forests (but see Long et al., 2011). Dendrochronology and fire scars are most commonly used to reconstruct fire history, but such studies provide relatively short records of only a few hundred years. Additionally, large, stand-replacing fires are not recorded, but are known to occur in these forests (Agee, 1993; Arno, 1980; Everett et al., 2000; Johnston et al., 2017; Touchan et al., 1996; Wright and Agee, 2004).

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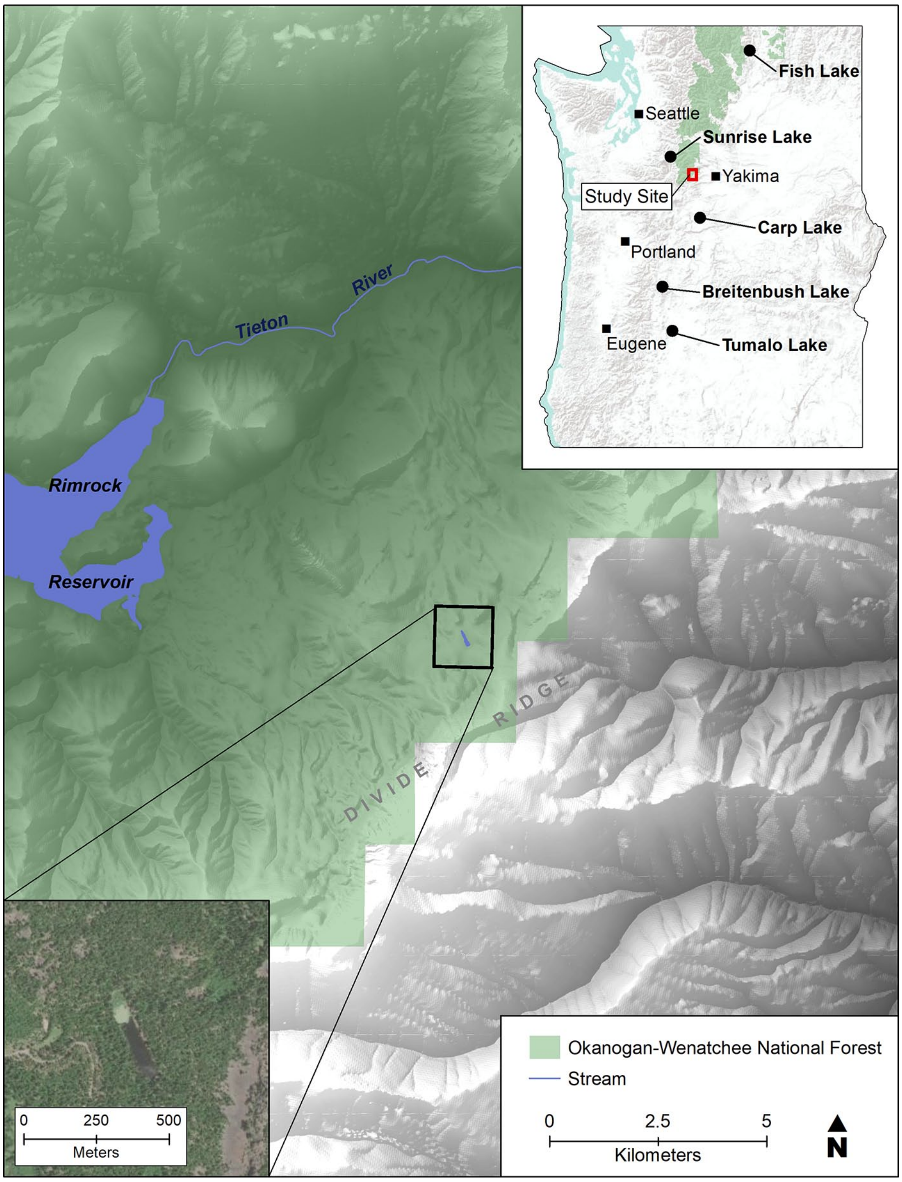

Figure 1. Map of the Long Lake study area. Inset map (upper right) shows the locations of other study sites mentioned in the text. Inset map (lower left) is an aerial photo of Long Lake (source: USGS, 2016).

The purpose of this research was to develop a long-term record of fire activity for one study site in a moist MEMC forest in the eastern Cascades of Washington. We reconstructed the fire and vegetation history of the Long Lake watershed for the past ~9900 years using macroscopic charcoal and pollen analysis of a lake sediment core. We then assessed the record within the context of known climatic variations during the Holocene, and compared the fire and vegetation history reconstructions to sites at both higher and lower elevation to determine if the Holocene fire regimes observed at Long Lake were indeed intermediate in terms of fire severity and frequency. The Long Lake fire history reconstruction was also evaluated within the context of the Pacific Northwest (PNW) regional Holocene biomass burning reconstruction, which includes primarily sites west of the crest of the Cascades (Walsh et al., 2015), as well as additional sites from the eastern Cascades of Washington and Oregon not included in that analysis. Given the large spatial extent of MEMC forests in the eastern Cascades, and in light of current and future climate change, a thorough understanding of the regional fire regime as evidenced at this site and others like it will provide valuable information about wildfire disturbance dynamics. These efforts can contribute to developing better policy aimed at managing the long-term resiliency of these forests (Buechling and Baker, 2004; Everett et al., 1999; Hagmann et al., 2014, Haugo et al., 2010; Stine et al., 2014).

Setting

Study area

Long Lake (46°37.336′N, 121°03.872′W, 1321 m a.s.l.) is located in the southern portion of the Okanogan-Wenatchee National Forest in the eastern Cascades of Washington State, approximately 5 km southeast of Rimrock Reservoir and 45 km west of the city of Yakima (Figure 1). The surface area of Long Lake is approximately 2 ha (275 m north-south by 75 m east-west) with a depth of approximately 1.5 m. Long Lake is in the Middle Tieton River subwatershed, which is within the Yakima River Basin. It has no outlets, and seeps at the south end of the lake are the primary water source along with snow melt. The topography near the site is mountainous with Long Lake occupying a hummocky area formed from mass wasting below Divide Ridge. The surface geology is debris flow and landslide material (Uebelacker, 1980; USFS, 1996) adjacent to Pliocene-Pleistocene age Grande Ronde basalt to the south and east (WSDNR, 1987). There are glacial till

Table 1. Depth of radiocarbon dates and calibrated ages for the Long Lake core (LOL14C).

Depth (cm below surface)	Lab number	Source material	^{14}C date (yr BP)[a]	Age (cal yr BP)[b,c]	2σ Age range (cal yr BP)
251	D-AMS 012601	Needle	1200 ± 30	1120*	1013–1019, 1056–1182, 1212–1225
436	D-AMS 012602	Ponderosa pine needle	2780 ± 30	2870*	2793–2955
553	D-AMS 010180	Twig	3440 ± 30	3690*	3612–3734, 3741–3778, 3787–3827
715	D-AMS 012603	Stick	4630 ± 30	5410*	5300–5332, 5373–5461
892	D-AMS 012604	Twig	8400 ± 40	9460**	9305–9363, 9371–9502

[a]^{14}C age determinations from DirectAMS dating facility, Bothell, WA. Dates rounded to the nearest decade.
[b]Calendar ages determined using Calib 7.1 html (Stuiver et al., 2019). Ages rounded to the nearest decade.
[c]*Denotes median ages used and **denotes age is from the nearest adjacent peak on the probability distribution function.

deposits adjacent to the eastern extent of Rimrock Reservoir, indicating the area around Long Lake may have been glaciated during the Pleistocene (USFS, 1996).

As this area is in the rainshadow of the Cascades, it experiences a continental climate with marine influences; most precipitation occurs in winter (WRCC, 2019).The mean January minimum temperature for the area is −5°C and the mean maximum July temperature is 22°C (PRISM, 2019). The site receives a mean of 888 mm of precipitation annually, with over half falling as snow December-January (PRISM, 2019; WRCC, 2019). The vegetation of the eastern Cascades is characterized by several different mixed-conifer forests (Franklin and Dyrness, 1988). Long Lake exists in the mid-elevation grand fir (*Abies grandis*) transition zone between high-elevation subalpine fir (*Abies lasiocarpa*) and lower elevation ponderosa pine forests. The grand fir series makes up more than one-third of the forest plant series types in this watershed (USFS, 1996). At higher elevations, subalpine fir, Pacific silver fir (*Abies amabilis*), and mountain hemlock (*Tsuga mertensiana*) occur. At lower elevations, dominant tree species include ponderosa pine, Oregon white oak (*Quercus garryana*), Douglas-fir (*Pseudotsuga menziesii*), and grand fir. Grand fir is the dominant tree species within the Long Lake watershed, with ponderosa pine, Douglas-fir, and western white pine (*Pinus monticola*) making up a smaller portion of the forest overstory. The understory is comprised of Sitka alder (*Alnus viridis*), willow (*Salix* spp.), elderberry (*Sambucus* spp.), snowbrush (*Ceanothus* spp.), snowberry (*Symphoricarpos albus*), Cascade grape (*Mahonia aquifolium*), kinnikinnick (*Arctostaphylos uva-ursi*), mint (*Menthe* spp.), wild strawberry (*Fragaria virginiana*), grasses, sedges, and other herbaceous plants commonly found in the eastern Cascades of Washington.

Methods

In summer 2014 a sediment core was taken at a water depth of 1.5 m from the center of Long Lake using a modified Livingston piston corer lowered from a floating anchored platform (Wright et al., 1984). Each drive of the long core (LOL14B) was packaged in plastic wrap and aluminum foil and placed in a pre-cut PVC tube for transport to the Paleoecology Lab at Central Washington University. The sediment-water interface and most recent sediments were recovered using a Bolivia coring device and subsampled in the field at 1-cm intervals (LOL14A). Both cores were kept under refrigeration at 2°C.

In the lab, core LOL14B was split longitudinally and half of the core was sampled for charcoal, loss-on-ignition (LOI), and pollen analysis. Several macrofossils found in core LOL14B were removed and cleaned, five of which were sent to DirectAMS in Bothell, WA, for radiocarbon dating. The calibrated ages of the dates (Table 1) along with the accepted age of the Mazama-O tephra (Egan et al., 2015; Zdanowicz et al., 1999) were used to create an age-depth model for the core, which was developed using a constrained cubic smoothing spline in Excel (Telford et al., 2004). Radiocarbon ages were converted to calibrated years before present (present = AD 1950; cal yr BP) using CALIB version 7.1 (Stuiver et al., 2019). Median ages were chosen if they did not fall in a trough on the probability distribution function. If they did, the age of the highest adjacent peak was used (rounded to the nearest decade). Tephra, likely from the Mount St. Helens-W eruption (MSH-W; 470 cal yr BP; Mullineaux, 1986), was omitted from the age model because it was not identified by microprobe analysis, but was instead used to verify the accuracy of the top portion of the age model. One cubic centimeter samples were taken every 5 cm for LOI analysis and followed the protocol outlined in Heiri et al. (2001). Additionally, a Sapphire Instruments 5-cm magnetic susceptibility (MS) ring sensor was used to determine the ferromagnetic properties of the intact half of core LOL14B at 1-cm intervals in order to identify tephra and erosional deposits.

Macroscopic charcoal analysis techniques followed Whitlock and Larsen (2001) as modified by Walsh et al. (2008). Samples of 2 cm^3 were taken at contiguous 1-cm intervals from cores LOL14A and LOL14B. Charcoal morphotypes were separated visually following descriptions in Walsh et al. (2008, 2010, 2018) in order to infer fuel type and fire severity. Charcoal that was flat with visible stomatal openings was tallied as herbaceous while all remaining charcoal was considered as coming from a woody fuel source. Charcoal concentrations (particles/cm^3) and influx (particles/cm^2/year) were calculated for total charcoal and herbaceous charcoal counts separately. CharAnalysis was used to analyze the charcoal data and reconstruct fire history (Higuera et al., 2010). The data were interpolated to a constant time step based on the median sample resolution of 13 years. The non log-transformed charcoal influx data were smoothed using a Lowess function robust to outliers, and peaks were identified using charcoal residuals with a locally defined threshold. Background smoothing windows widths were tested between 200 and 1000 years. A background window of 600 years was eventually selected for the final analysis because it produced a global signal-to-noise index of 5.5, which is well above the cutoff value of 3 (Kelly et al., 2011), and because it maximized the fire signal. Charcoal peaks with $<5\%$ chance of coming from the same Poisson distribution within 75 years were eliminated from the analysis. CharAnalysis results were summarized using time periods designated in Walsh et al. (2017) for ease of comparison.

Pollen samples were taken at 20-cm intervals, with additional samples taken 2 cm above and below the Mazama tephra layer for a total of 40 pollen samples. Samples were processed using standard techniques outlined in Faegri et al. (1989). At least 300 pollen grains were counted per sample to determine the percent abundance of each taxa, and pollen grains were identified to the lowest taxonomic level possible using published atlases and the Central Washington University pollen reference collection. Pollen percentages for most taxa were calculated using the total terrestrial pollen sum. *Pinus* pollen not identified as either yellow pine (subgenus *Pinus*) or white pine (subgenus *Strobus*) was

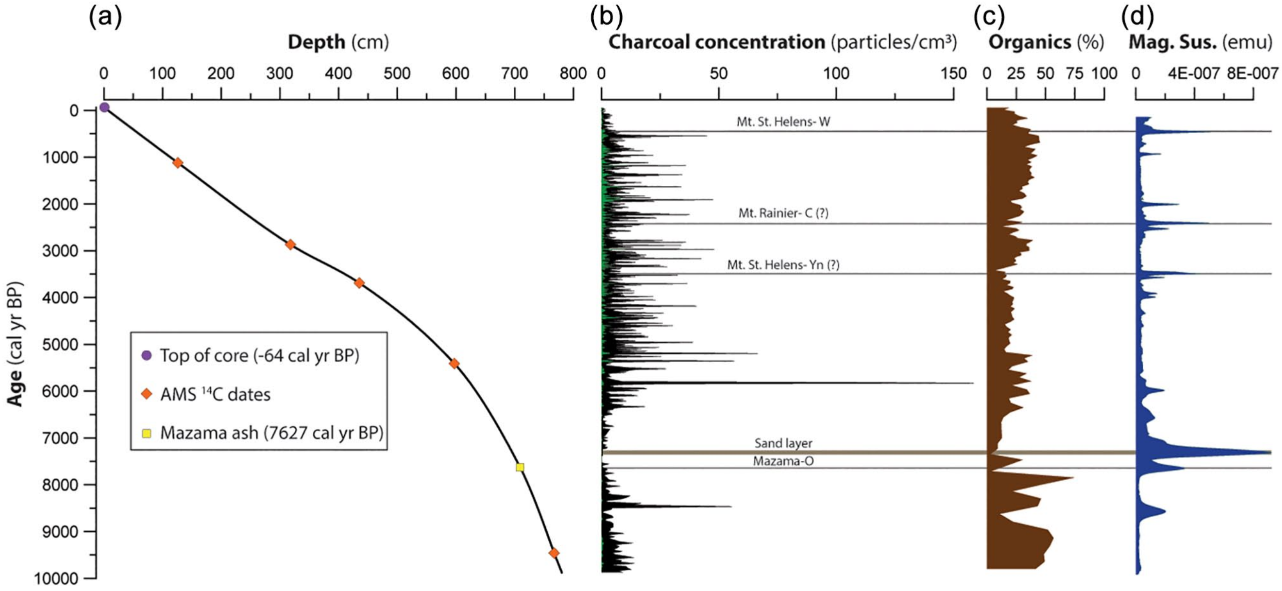

Figure 2. (a) Age-depth model, (b) charcoal concentration (particles/cm^3, total concentration = black curve, herbaceous concentration = green curve), (c) loss-on-ignition (% organics), and (d) magnetic susceptibility (electromagnetic units) plotted against age (cal yr BP) for the LOL14C record.

counted as *Pinus* undifferentiated (undiff.). Pollen identified as *Spirea, Holodiscus*, and Rosaceae were grouped together as Rosaceae undiff. Pollen identified as *Senecio*-type, *Helianthus*-type, and *Agoseris*-type were grouped together as Asteraceae. Pollen identified as *Lysichiton americanus* was not included in the total terrestrial pollen sum because of its high abundance in multiple levels. Percentages of *Lysichiton*, aquatic, and semi-aquatic taxa were calculated using the total pollen sum. Pollen zone boundaries were determined using a constrained cluster analysis (Grimm, 1987).

Results

LOL14C chronology, charcoal, and lithology

About 84 cm of sediment was recovered in LOL14A and 775 cm in LOL14B. Based on the presence of the MSH-W tephra in both cores, 12 cm from the top of LOL14A was added to LOL14B to create one continuous record, hereafter referred to as LOL14C. Core LOL14C was 780 cm with the Mazama tephra removed. The age-depth model determined a basal date of 9870 cal yr BP with a median resolution of 12.9 years per sample. Sedimentation rate was slowest from ca. 9870 to 7600 cal yr BP (Figure 2a), but increased from ca. 7600 to 3000 cal yr BP and then remained generally steady to the top of the record.

Total charcoal concentration values were generally low in the early part of the LOL14C record (ca. 9870–6500 cal yr BP), particularly in the ~500 years following the deposition of the Mazama tephra (Figure 2b). Total charcoal concentration values were higher after ca. 6500 cal yr BP with considerably more variability in the record at that time. Total charcoal concentration values were again low by ca. 500 cal yr BP, particularly after ca. 200 cal yr BP. Herbaceous charcoal concentration values were generally low throughout the entire record, but in particular, prior to ca. 5500 cal yr BP. Herbaceous charcoal concentration values were highest between ca. 4000 and 500 cal yr BP.

The lithology of LOL14C was primarily black to very dark brown fine gyttja. Below the Mazama tephra, found at a depth of 710 cm, the sediment was peaty gyttja with fine rootlets. Above the Mazama tephra, the sediment alternated between gyttja, clayey gyttja, and peaty gyttja until 550 cm (ca. 4800 cal yr BP). The remainder of the record was fine dark brown gyttja with some thin laminations. Organic content was less than 50% for most of the record, but values were generally higher prior to the deposition of the Mazama tephra (Figure 2c). MS values were generally low, but included a number of higher values that coincided temporally with both identified and unknown tephra layers (Figure 2d). The higher MS values at ca. 470 cal yr BP almost certainly originate from the deposition of the MSH-W tephra, which was found at similar depths in multiple other cores from the eastern Cascades (Nelson et al. 2011; Walsh et al., 2018). For more lithological results see Rushton (2019).

CharAnalysis

Early Holocene (ca. 9870–8000 cal yr BP): Fire activity was low in the early Holocene as compared to later in the record (Figure 3). Charcoal influx (CHAR), fire frequency, number of fire episodes, and peak magnitude (which is an indication of fire size and/or severity, Higuera et al., 2007), were all lower in this period than in any other (Table 2). CHAR values varied only slightly in the early Holocene, but were highest at ca. 8400 cal yr BP. Mean fire frequency was at or below four fire episodes/1000 years during the early Holocene and varied little (Figure 3c and d). Only six episodes were identified by CharAnalysis, indicating a MFRI of 300 years. Herbaceous CHAR values were lowest in this period (Table 2 and Figure 3e).

Middle Holocene (ca. 8000–4000 cal yr BP): Fire activity changed little from the end of the early Holocene to the beginning of the middle Holocene. CHAR values decreased initially between ca. 8000 and 6800 cal yr BP to near zero, but then increased dramatically in the next thousand years. Fire episodes remained infrequent in the watershed until after ca. 6000 cal yr BP, when they became much more common and of greater peak magnitude. Mean CHAR values more than doubled after this time compared to the early Holocene and first half of the middle Holocene. The largest peak magnitude of the record occurred at ca. 5800 cal yr BP (Figure 3b), beginning several millennia of fire episodes with much higher CHAR values than previously observed in the record. Only seven of the 27 identified fire episodes during the middle Holocene occurred before ca. 6000 cal yr BP. After that time, fire episodes occurred on average every ~100 years as compared to every ~285 years during the previous two millennia. Herbaceous CHAR values were extremely low during the early middle Holocene, but increased considerably during the late middle Holocene (ca. 6000–4000 cal yr BP).

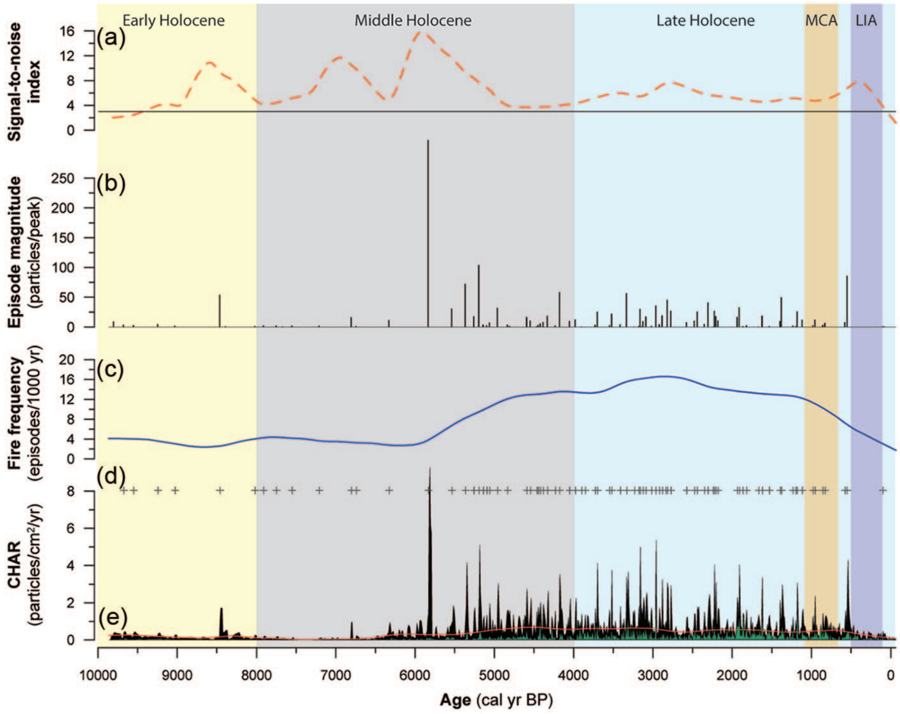

Figure 3. CharAnalysis results showing: (a) signal-to-noise index (SNI), (b) peak episode magnitude (particles/peak), (c) fire frequency (fire episodes/1000 years), (d) fire episodes (plus symbols), and (e) total charcoal influx (CHAR, particles/cm^2/year; black curve), herbaceous charcoal influx (CHAR, particles/cm^2/year; green curve) and background charcoal (red line) plotted against age (cal yr BP) for the LOL14C record. The time periods associated with the Medieval Climate Anomaly (MCA; 1100–700 cal yr BP) and Little Ice Age (LIA; 500–100 cal yr BP) are shown by the vertical orange and purple bars, respectively.

Table 2. Charcoal statistics for the Long Lake (LOL14C) record.

	Mean total charcoal influx	Mean herbaceous charcoal influx	Fire episodes	Mean fire frequency	Mean peak magnitude
	(particles/cm^2/year)	(particles/cm^2/year)	(#)	(episodes/1000 years)	(particles/peak)
Early Holocene (9840–8000 cal yr BP)	0.21	0.004	6	3.33	11.58
Middle Holocene (8000–4000 cal yr BP)	0.54	0.038	27	6.70	28.17
Early Middle Holocene (8000–6000 cal yr BP)	0.12	0.002	7	3.53	5.42
Late Middle Holocene (6000–4000 cal yr BP)	0.95	0.057	20	9.92	36.13
Late Holocene (4000 to −64 cal yr BP)	0.79	0.131	50	12.25	15.24

Late Holocene (ca. 4000 to −64 cal yr BP): As seen in the latter half of the middle Holocene, frequent fire episodes continued to occur throughout the late Holocene. Herbaceous CHAR values were highest during this period. Fire frequency, which began increasing after ca. 6000 cal yr BP, continued to increase to over 16 episodes/1000 years at ca. 2800 cal yr BP. It then decreased throughout the remainder of the late Holocene to near zero at present. CharAnalysis identified 50 fire episodes during this period, with a fire episode occurring on average every ~80 years. However, mean peak magnitude decreased to nearly half of what it was during the second half of the middle Holocene. Fire episodes remained frequent during the years associated with the Medieval Climate Anomaly (MCA; 1100–700 cal yr BP; Mann et al., 2009) with four fire episodes occurring. No fire episodes occurred during the Little Ice Age (LIA; ca. 500–100 cal yr BP; Grove, 2001). Only one fire episode occurred in the last 500 years in the Long Lake watershed, shortly after the end of the LIA (ca. 100 cal yr BP), and recorded a very low peak magnitude.

Pollen

Zone LOL_1 (ca. 9870–5170 cal yr BP): Together trees and shrubs made up a mean of 75% of the total terrestrial pollen in this zone, with shrubs comprising only 2.6% of the total terrestrial sum (Figures 4 and 5c). *Pinus* undiff. was at its lowest level at the start of the record (~8%), but increased until soon after the deposition of the Mazama tephra (~45%), and then decreased towards the end of the zone (~21%). *Abies* percentages were low at the start of the zone (~1%), but also increased after the Mazama eruption (~17%) and remained generally high at the end of the zone (~8%). *Alnus* was a dominant taxa in this zone (~28% mean), but percentages varied widely (~13%–51%). Shrubs like *Artemisia*, Rosaceae undiff., and *Ceanothus* were higher at the beginning of the zone (~2%, 1%, and 2%, respectively) but their percentages decreased toward the end of the zone. Herb pollen percentages averaged ~25% of the total terrestrial sum in this zone, but were generally higher toward the start of the zone (~33%) and lower toward the end (~16%)

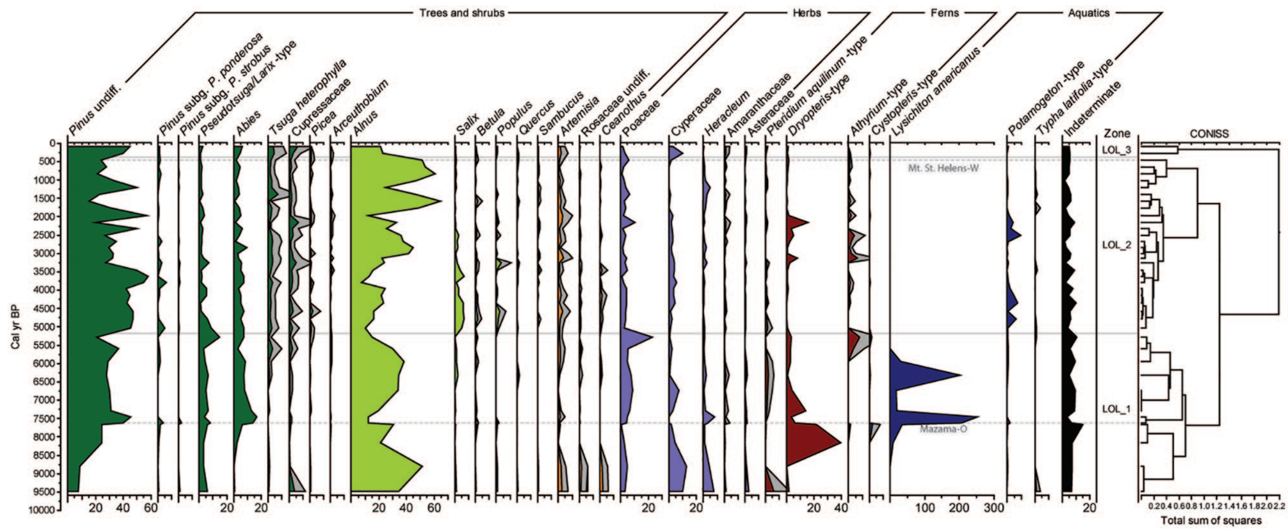

Figure 4. Pollen percentage diagram of select taxa for the LOL14C record. The grey curve is a 3× exaggeration to aid with visualization. Curves are colored by group; coniferous trees are represented in dark green, deciduous trees are in light green, shrubs are in peach, herbs are in light purple, ferns are in maroon, and aquatics and semi-aquatics are in dark blue.

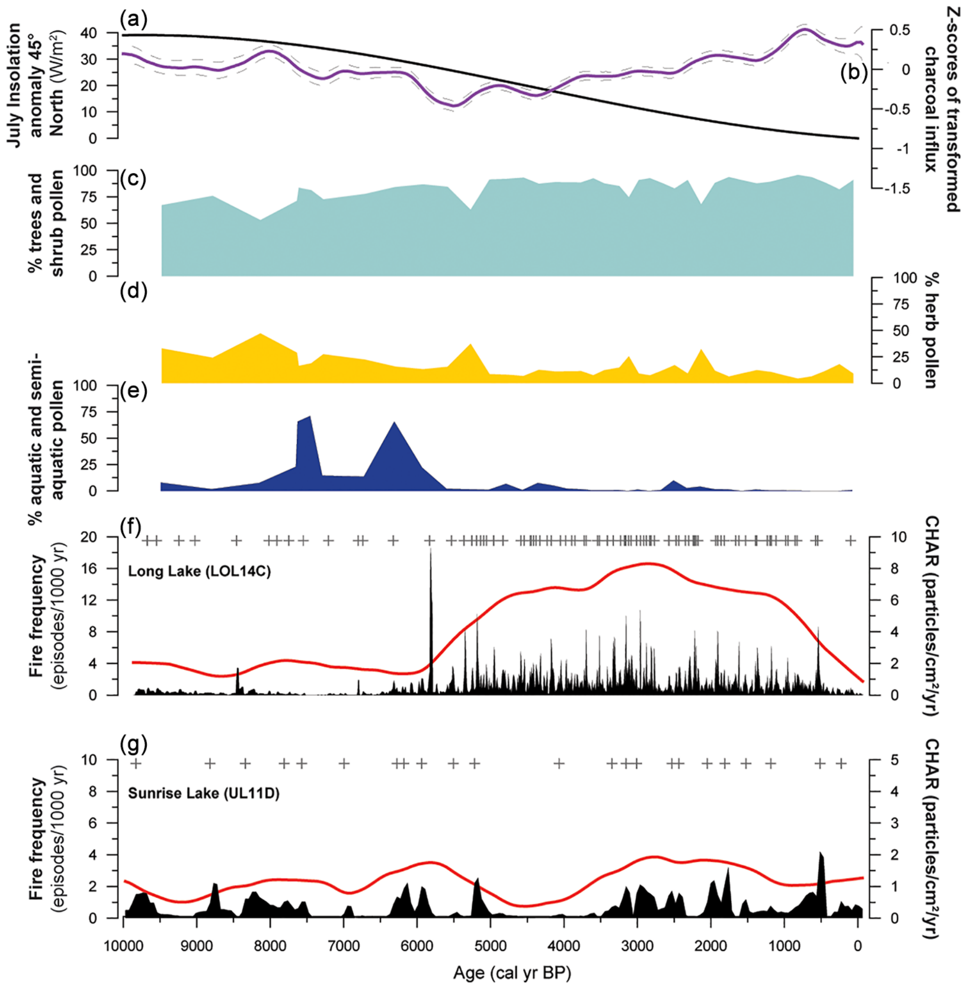

Figure 5. (a) July insolation anomaly curve at 45°N (Berger and Loutre, 1991), (b) PNW regional biomass burning curve with 95% confidence intervals for 34 sites (Walsh et al., 2015), (c) tree and shrub pollen percentage for LOL14C, (d) herbaceous pollen percentage for LOL14C, (e) aquatics and semi-aquatics percentage for LOL14C, (f) fire episodes (plus signs), fire frequency (red line) and CHAR (black curve) for LOL14C, and (g) fire episodes (plus signs), fire frequency (red line) and CHAR (black curve) for Sunrise Lake core UL11D plotted against age (cal yr BP).

(Figure 5d). Ferns were more common in this zone than any other, in particular *Dryopteris*-type (~8.5% mean). *Lysichiton americanus*, a semi-aquatic plant, first appeared at ca. 8150 cal yr BP. Its percentages peaked at ca. 7500 cal yr BP and again at ca. 6300 cal yr BP (1000+ grains were counted in multiple levels), before decreasing sharply and disappearing from the record completely by ca. 5200 cal yr BP. Other aquatic percentages were generally low in this zone (Figure 5e).

Zone LOL_2 (ca. 5170–370 cal yr BP): Tree and shrub pollen percentages were higher in this zone than the previous with a mean of ~94%. Both *Pinus* undiff. and *Alnus* percentages dominated at various times in this zone. *Pinus* undiff. reached its lowest percentages since Zone LOL_1 at ca. 2100 cal yr BP (~19%.), and its highest percentages of the entire record, comprising 50% or more of the terrestrial total several times, at ca. 3800–3600, 2000, and 1200 cal yr BP. Additionally, *Alnus* reached its highest percentage of the record (~64%) at ca. 1600 cal yr BP. *Arceuthobium* (dwarf mistletoe), first appeared in the record at ca. 7650 cal yr BP (~0.2%), but occurred in higher percentages in this zone, seemingly concurrent with a rise in percentages of *Tsuga heterophylla*, Cupressaceae, and *Picea. Salix* percentages were greatest at the start of this zone (~6%), but decreased toward the end. Shrub percentages remained at a fairly stable level during this zone, particularly *Artemisia* (~2% mean); however, Rosaceae undiff. and *Ceanothus* percentages exhibited a slight decrease from the beginning to the end of the zone. Herbaceous taxa percentages, including Poaceae (~4% mean), Cyperaceae (~2% mean), and most other herbs, were lower in this zone as compared to the previous. However, *Dryopteris*-type and *Athyrium*-type both exhibited slightly higher percentages between ca. 3300 and 1500 cal yr BP (~4% and 2% mean, respectively) while *Cystopteris*-type and *Pteridium aquilinum*-type maintained low numbers throughout this zone. Aquatics were generally lower in this zone than the previous (~18% mean), but *Potamogeton*-type and *Typha latifolia*-type percentages were higher in this zone as compared to earlier (~1.7% and 0.2% mean, respectively).

Zone LOL_3 (ca. 370 to −64 cal yr BP): Percentages of tree and shrub pollen were lower in this zone than the previous (~86% mean), with shrubs only comprising ~2% of the total terrestrial sum. Conifer pollen percentages, including *Pinus* undiff., *Abies, Tsuga heterophylla*, Cupressaceae, increased in this zone as percentages of *Alnus* dropped from ~51% to 22% in comparison to the previous zone. Herb pollen percentages initially increased at the start of this zone, but then decreased by the end (from ~18% to 8%).

Discussion

Fire-vegetation-climate interactions

Early Holocene. The early Holocene portion of the Long Lake record is short, with less than 2000 years represented (ca. 9870–8000 cal yr BP). It is possible that the site formed earlier than this, but it seems unlikely given the provenance of the lake, which appears to be the result of mass wasting and not of a glacial origin. Fire episodes, which may include one or more fires that happen close together in time (Long et al., 1998), appear to have been infrequent in the Long Lake watershed during the early Holocene with only six episodes recorded (Table 2 and Figure 5f). This contrasts with the regional fire record for the PNW that indicates high fire activity at numerous sites during this period (Figure 5b; Walsh et al., 2015; Whitlock and Bartlein, 2003). Sunrise Lake (1768 m a.s.l.), which is included in the Walsh et al. (2015) analysis, while not technically in the eastern Cascades (it sits just to the east of the crest of the Cascades), exists at high elevation on the eastern flank of Mount Rainier making it the closest Washington Cascades site (Walsh et al., 2017). This site today is dominated by *Abies lasiocarpa, A. procera* (noble fir), and lesser amounts of *Tsuga mertensiana* and *A. amabilis* (Pacific silver fir). However, in the early Holocene the site was likely a *Pinus*/*Abies*-dominated forest with an *Artemisia*/herbaceous understory. Sunrise Lake experienced only three fire episodes between ca. 10,000 and 8000 cal yr BP (Figure 5g), but episodes were of greater peak magnitude than those observed at Long Lake and contained almost no herbaceous charcoal, indicating fires were larger and/or more severe (see Sunrise Lake fire statistics in Walsh et al., 2017).

Another site, Breitenbush Lake (1681 m a.s.l.) lies in a MEMC forest in the eastern Oregon Cascades and is at present dominated by *A. amabilis, A. procera*, and *T. mertensiana* (Minckley and Long, 2016). Fire episodes were more frequent than at Sunrise Lake during the early Holocene when the forest was *Pinus*/*Abies*/*T. heterophylla*-dominated with an *Alnus, Artemisia*, and Poaceae understory. Six fire episodes were recorded from 10,000 to 8000 cal yr BP (peak episode magnitude was not reported). At nearby Tumalo Lake (1536 m a.s.l.), which is currently dominated by *A. grandis, A. amabilis*, and *Picea engelmannii* (Engelmann spruce), fire episodes were more frequent than at Sunrise, Breitenbush, and Long lakes (~17 occurred in the early Holocene), but were of generally low peak magnitude suggesting smaller or less severe fires than those observed at Sunrise Lake. The warm, dry climatic conditions of the early Holocene led to an open *Pinus* forest with an *Artemisia* understory existing at the site at this time, which was seemingly conducive to frequent fire, but limited fuel availability (Long et al., 2011).

Unfortunately no published records of early Holocene fire activity exist from lower elevation sites in the eastern Cascades, so it is difficult to say whether fire regimes at Long Lake at this time were intermediate in terms of fire severity and frequency to sites at both higher and lower elevations. However, this seems likely given the available data. Fires at even lower elevations than at Long Lake, where vegetation was even more sparse (Whitlock et al., 2000), were likely of lower severity than those at Long Lake, though perhaps more frequent.

Given these trends, fire episodes at Long Lake during the early Holocene were likely more frequent than as indicated by CharAnalysis. This may be the result of the low temporal sampling resolution of the record during this period. Alternatively this could be a result of sediment compaction in this part of the core, or the fact that the site was likely a wetland and not a lake at this point (see discussion below). The sedimentation rate is slowest at this time with a mean of 0.031 cm/year, which may have decreased CharAnalysis' ability to separate charcoal peaks from background charcoal (Higuera et al., 2010). This is supported by the low signal-to-noise index observed from ca. 9870 to 9000 cal yr BP (Figure 3a). The background CHAR indicates that fires were occurring, but the influx peaks (Figure 3e) are less discrete than during the middle and late Holocene. Mean peak magnitude is also lower at this time than in any other period during the record except for the early middle Holocene (Table 2 and Figure 3b). The combined charcoal evidence suggests that fires in the Long Lake watershed during the early Holocene were small or of low severity, but perhaps more frequent than suggested by CharAnalysis. However, the majority of charcoal observed during this period was woody, which indicates that trees, or more likely shrubs, were the fuel source.

In the PNW the early Holocene was warmer and drier than the middle or late Holocene, with decreased water levels recorded in many water bodies (Fulkerson, 2012). This was caused by high summer insolation due to perihelion occurring during the summer in the early Holocene (Figure 5a; Bartlein et al., 1998; Whitlock and Bartlein, 1993). These drier conditions led to more xeric vegetation and open woodlands (Fulkerson, 2012). At Long Lake, *Alnus* (either *A. sinuata* or *A. incana*) and shrubs such as *Artemisia*, Rosaceae, and *Ceanothus* dominated the vegetation assemblage, along with a high abundance of herbaceous plants, such as *Pteridium aquilinum* (bracken fern) and Cyperaceae (likely *Carex geyeri*). Worth noting is that *Alnus* pollen is often over-represented in lake sediment records (Heusser, 1978), so it may have been less abundant at Long Lake than its percentages suggest. Nevertheless, *Alnus, P. aquilinum*, and *C. geyeri* are highly indicative of frequent disturbance and warm summer temperatures (Franklin and Dyrness, 1988; Lillybridge et al., 1995), which supports our interpretation that fires were more frequent than CharAnalysis indicates. The high amount of shrub pollen (e.g., *Alnus, Artemisia*, Rosaceae) in the early Holocene supports the conclusion that this area, like many others in the eastern Cascades and surrounding vicinity, was a woodland environment with frequent disturbance (Mack et al., 1979; Prichard et al., 2009; Walsh et al., 2015). At Carp Lake (714 m a.s.l.) in southcentral Washington, the pollen record indicates that *Pinus* and *Quercus*-dominated forests with substantial amounts of *Alnus* existed at the site due to the warmer and drier conditions than at present (Whitlock et al., 2000). *Alnus* is especially prone to establishing in frequently disturbed areas before other long-lived species become dominant (Parish et al., 1996) and is often a pioneer species after fires (Arno and Allison-Bunnell, 2002; NRCS, 2009). Unfortunately there is no fire reconstruction from Carp Lake, but it seems likely that the site experienced frequent low-severity fires at this time.

Additional lines of evidence suggest that Long Lake experienced considerably warmer and drier conditions during the early Holocene than it does at present. Relatively high amounts of Cupressaceae pollen at Long Lake during the early Holocene are likely attributed to *Juniperus occidentalis* (western juniper), which grows in limited dry habitats near the site today. There is also a high amount of *Artemisia* pollen during this period, possibly indicating the forest-steppe transition zone may have extended to higher elevations than at present (Franklin and Dyrness, 1988). Most notably, the lithology of the LOL14C core during the early Holocene, particularly the presence of some peaty gyttja and high percentage of organics, indicates Long Lake may have been an emergent wetland and not a lake in the early Holocene (Figure 2c). This may have decreased the amount of charcoal that accumulated in the sediment at this time due to greater amounts of shoreline vegetation acting as a filter (Whitlock and Millspaugh, 1996), possibly contributing to the lower than expected fire frequency observed at this time. Closed system water bodies with no substantial inlets or outlets, such as Long Lake, are dependent on climate for maintaining water levels (Steinman et al., 2016), making it all the more likely that the site experienced drying as the result of the prevailing climatic conditions. However, an increase in *Pinus, Abies*, and *Dryopteris* (wood ferns), and *Cystopteris* (fragile ferns) by the end of the early Holocene suggests the landscape was becoming more forested, which is consistent with the timing of these changes at many other sites in the PNW (Walsh et al., 2008, 2015; Whitlock, 1992).

Middle Holocene. Fire activity in the Long Lake watershed was low for the first 2000 years of the middle Holocene before a major increase in CHAR and fire frequency after ca. 6000 cal yr BP (Figures 3 and 5f). This coincides with an increase in biomass burning at many low- to high-elevation sites in the PNW (Figure 5b; Walsh et al., 2015). However at Sunrise Lake (Figure 5g) and Breitenbush Lake, fire frequency remained low with only 3 episodes occurring at each site between ca. 6000 and 4000 cal yr BP (Minckley and Long, 2016; Walsh et al., 2017). In contrast, fires at Tumalo Lake remained fairly frequent, with ~10 episodes occurring during this interval (Long et al., 2011). Number of fire episodes more than quadrupled at Long Lake and fire frequency and mean peak magnitude both more than doubled in the late middle Holocene as compared to the early Holocene, which clearly indicates that more frequent and larger and/or more severe fires burned as compared to earlier in the record (Table 2). However, given the moderate herbaceous CHAR values compared to both earlier and later in the record, and the variability in peak episode magnitude, it would seem that fires occurring during this interval were of both higher and lower severity, burning more woody and herbaceous fuels, respectively.

Given the timing of the increase in fire activity at Long Lake, it seems likely that it was caused by a shift in vegetation at the site and an increase in the amount of burnable biomass. The climate during the middle Holocene was generally cooler and wetter than during the early Holocene, but summers were still drier and winters wetter than at present (Chase et al., 2008; Steinman et al., 2016; Whitlock et al., 2000). The seasonal disparity likely allowed for the accumulation of biomass (fuel) followed by substantial fire activity during the subsequent dry fire season (Prichard et al., 2009; Walsh et al., 2015). Or perhaps, greater interannual climate variability during the middle Holocene, likely through mechanisms proposed in Heyer et al. (2017) and/or Long et al. (2019), increased the likelihood that lightning strikes ignited fuels that were drier due to lower winter snowpacks and increased spring/summer temperatures. Either way, drier than present summers combined with increased biomass abundance during the late middle Holocene supports our interpretation that an increase in fire activity was caused by a combination of climatic factors and fuel availability/condition.

The increase in fire activity at Long Lake during the late middle Holocene may also be due to a rise in anthropogenic use of fire. Throughout the Cascade Range and the PNW fire was used by Native Americans for many reasons such as root crop and berry cultivation, game driving, and trail clearing up until the time of and even following EuroAmerican settlement (Burtchard, 2007; Mack, 2003; Uebelacker, 1980). Archaeological evidence indicates human presence in the Washington Cascades by as early as ca. 9500 cal yr BP (Samuels, 1993; Mack et al., 2010), and more firmly by ca. 8000 cal yr BP (McClure, 1989, 1998). Increasing populations throughout the middle to late Holocene would have raised the likelihood that human ignitions supplemented natural ignitions, even in mountainous regions (Burtchard, 2007; Chatters, 1995). Lightning strikes, which are generally abundant during summer months in the eastern Cascades (Rorig and Ferguson, 1999), were the likely primary ignition source for fires at Long Lake during the middle and late Holocene (Agee, 1994; Bork, 1984; Johnston et al., 2017); however, human-caused fires, both accidental and deliberate, cannot be ruled out (USFS, 1996).

The shift in vegetation at the time of the Mazama eruption, or shortly thereafter (Figure 4) marks the beginning of the establishment of the modern forest, which is generally similar in timing to many other sites in both the eastern Cascades and the PNW (Haydon, 2018; Long et al., 2014; Mack et al., 1976; Walsh et al., 2008, 2015; Whitlock, 1992). It is possible that the deposition of approximately 7 cm of tephra at Long Lake led to these observed changes; however, this seems unlikely given that the vegetation assemblage at several sites located much closer to the eruption were not severely impacted by even thicker tephra deposits (Long et al., 2014). With that said, several taxa display an abrupt change in abundance at this time; *Pinus* (likely *P. monticola*) and *Abies* (likely *A. grandis*) replace *Alnus*, while *Populus, Artemisia*, Poaceae, *Heracleum*, Amaranthaceae, Asteraceae, *Lysichiton americanus*, and *Potamogeton* increased. Increases in *Pinus, Abies*, Poaceae and monolete ferns (*Dryopteris, Athyrium* and *Cystopteris*) at the expense of *Alnus*, shrub pollen and *P. aquilinum* likely indicate forest closure due to generally cooler, moister climatic conditions (Bartlein et al., 1998, 2014; Whitlock, 1992). However, the immediate rise in *L. americanus* following the deposition of the Mazama tephra is notable and could represent greater littoral area at the site during still dry summers, or perhaps indicates a shift in the hydrology of the site as the result of the tephra accumulation on the surrounding landscape. *Pinus* produces large amounts of pollen, exaggerating its presence on the landscape; thus, its high abundance during this period was likely in part the result of both upslope and downslope transport (Hebda and Allen, 1993; Brown et al., 2017). *Abies*, which produces much less pollen (Hebda and Allen, 1993; Mack et al., 1978), was likely the dominant taxa in the forest overstory after this time, as it is at present. The disappearance of *L. americanus* by at ca. 5200 cal yr BP and the increase in *Potamogeton* near the end of the middle Holocene, as well as changes in the core's lithology and a decrease in the percentage of organics, indicate that Long Lake had shifted from a wetland to a lake by this time.

Pseudotsuga/*Larix*-type, likely *Pseudotsuga menziesii*, abundance increased shortly after the increase in shade-tolerant conifer taxa, indicating co-dominance in the forest with *Abies*. *Arceuthobium* also increased as the Long Lake area became more forested. Though the first appearance of *Arceuthobium* is shortly after *Pinus* becomes the dominant tree taxa, its greatest numbers coincide with high amounts of *T. heterophylla* and Cupressaceae in the late Holocene. Despite the cooler, wetter climate and high amounts of coniferous pollen in the middle Holocene, the continued presence of *Alnus* and *P. aquilinum*, and the high CHAR values throughout the period, indicate frequent disturbance in the area and probably forest openings in which these taxa grew (Franklin and Dyrness, 1988).

Late Holocene. Fire activity at Long Lake remained high throughout most of the late Holocene; however, fire frequency began to decrease after ca. 3000 cal yr BP. The CHAR trend is generally consistent with the PNW biomass burning trend, which continued to increase until ca. 900 cal yr BP (Figure 5b; Walsh et al., 2015). The Long Lake fire frequency trend is somewhat similar to that of Sunrise Lake, which shows a small increase in fire episodes from the middle to late Holocene, before declining after ca. 2000 cal yr BP (Figure 5g; Walsh et al., 2017). However, peak episode magnitude continued to be much higher at Sunrise Lake than at Long Lake, suggesting that fires, although less frequent, were of greater size and/or severity at Sunrise Lake. At Breitenbush Lake, fire frequency also increased during the first part of the late Holocene, but then decreased somewhat after ca. 2500 cal yr BP (Minckley and Long, 2016). The vegetation assemblage changed little at Long Lake (and most other sites in the PNW) during the late Holocene, so fluctuations in fuel availability were likely less important during this period as compared to earlier, which means that something else was influencing fire activity. In general, the climate of the late Holocene in the PNW was even cooler and wetter than earlier due to continued decreases in summer insolation (Figure 5a; Bartlein et al., 1998, 2014; Walker and Pellatt, 2008). Even so, fires continued to burn frequently in the Long Lake watershed, at least until ca. 500 cal yr BP. It is possible that human use of fire supplemented natural ignitions during the late Holocene, but is impossible to know to what extent if any.

A cool neoglacial period started at ca. 4000–3000 cal yr BP and is associated with glacial advances in the region (Coulthard et al., 2013; Menounos et al., 2009; Whitlock et al., 2000). While this period does not appear to have had a major influence on fire activity at Long Lake, it coincides with an increase in effective moisture as illustrated by the rise in *Abies*, Cupressaceae, *T. heterophylla* as well as monolete ferns. The *T. heterophylla* and Cupressaceae (likely *Thuja plicata* and/or *Callitropsis nootkatensis*) pollen observed in the record at this time likely originated from higher elevations, but their increase also signals increased levels of regional precipitation (Gavin et al., 2013). The consistent presence of *Abies* indicates it was a staple of the forest in the Long Lake watershed throughout the late Holocene. The decrease in *Alnus* in the last several centuries supports the observation that fire activity decreased in the Long Lake watershed, particularly after ca. 500 cal yr BP, and coincidentally, shade-tolerant conifer taxa increased at the site.

During the last 4000 years, fire activity at Long Lake clearly exhibited characteristics of both high- and low-elevation fire regimes (Figures 5 and 6). Trends in CHAR were more similar between the MEMC forest at Long Lake and the subalpine forest at Sunrise Lake, particularly during the LIA (Figure 6a and b). The notable decrease in CHAR associated with LIA, which was generally cool and wet (Graumlich and Brubaker, 1986), is especially pronounced in both records and is one of the strongest documented trends in fire activity in the PNW during the post-glacial period (Marlon et al., 2012; Walsh et al., 2015). Similarities also exist between the Long Lake and Tumalo Lake records; CHAR and fire frequency both decrease to near zero at Tumalo Lake

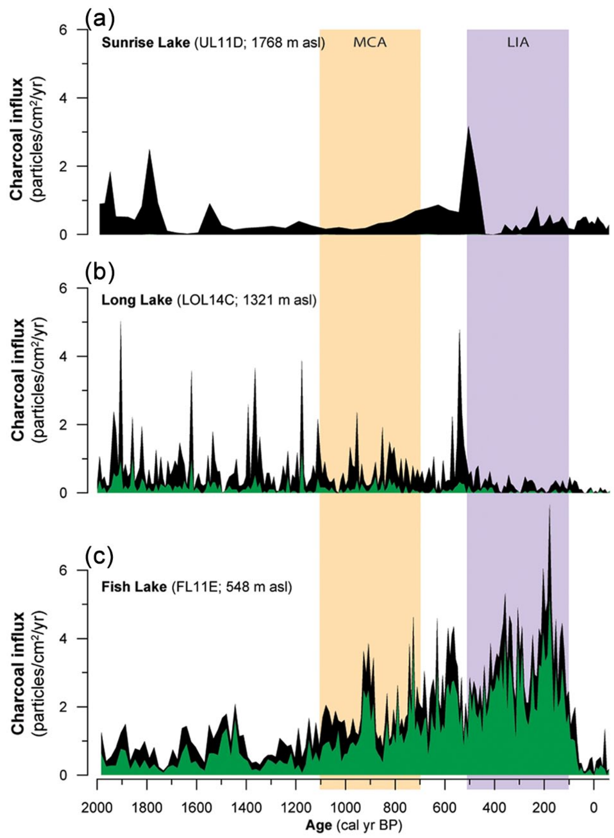

Figure 6. Charcoal influx comparison of fire activity for the last 2000 years at high-, mid-, and low-elevation sites plotted against age (cal yr BP). (a) Sunrise Lake core UL11D (Walsh et al., 2017), (b) Long Lake core LOL14C, and (c) Fish Lake core FL11E (Walsh et al., 2018). Total charcoal concentration is shown by the black curve, herbaceous charcoal concentration is shown by the green curve. The time periods associated with the Medieval Climate Anomaly (MCA; 1100–700 cal yr BP) and Little Ice Age (LIA; 500–100 cal yr BP) are shown by the vertical orange and purple bars, respectively.

during the past ~1400 years (Long et al., 2011). However, fire activity remained generally high at Breitenbush Lake, which experienced little to no decrease in CHAR or fire frequency during the late Holocene (Minckley and Long, 2016).

When considering the frequency of fires (~80 years MFRI) and the "peakiness" of the Long Lake CHAR record during the past 4000 years, these trends are more similar to lower elevation fire regimes than higher (Figure 6b and c). Fish Lake (548 m a.s.l.) sits in the eastern Cascades of north-central Washington, and for at least the past 3800 years has existed near the ecotone between ponderosa pine-dominated forest and sagebrush steppe (Walsh et al., 2018). During the late Holocene, fires likely occurred more frequently at Fish Lake than the sampling resolution of the core (median of ~13 years), which puts Long and Fish lakes much closer together in terms of fire frequency than Sunrise Lake, which had a MFRI of ~400 years during the late Holocene (Walsh et al., 2017). Similarities also exist in the amount of herbaceous charcoal found in the Long and Fish lake records. Herbaceous CHAR was highest at Long Lake during the late Holocene, and at Fish Lake herbaceous charcoal made up nearly 80% of the total charcoal observed during the same period. In contrast, herbaceous charcoal was almost completely absent from the Sunrise Lake record, indicating more similar fuel sources at Fish and Long lakes (Walsh et al., 2008). Given the late Holocene MFRI at Long Lake, and the mixture of fuels burned, fires during this period were likely of mixed-severity, with more frequent lower-severity fires occurring in between less frequent stand-replacing events. This is consistent with findings from several dendrochronological-based studies of historic fire activity in MEMC forests of eastern Washington and Oregon (see Stine et al., 2014 for a review).

Additionally, both the Fish and Long lake records exhibit a fire suppression signal beginning ca. 100 cal yr BP (Figure 6b and c). However, the impact it had on the fire regime at Fish Lake was much more pronounced than at Long Lake. Much of the increase in burning in the Fish Lake watershed during the late Holocene, particularly during the LIA, has been attributed to anthropogenic use of fire, which decreased as native peoples were removed both forcibly and by disease at the start of EuroAmerican settlement (ca. AD 1850; Walsh et al., 2018). The fire suppression signal at Long Lake, while less pronounced (because fire activity was already low due to the climatic conditions of the LIA), is still apparent. The lack of fire in the Long Lake watershed during the last ~150 years is most likely the result of fuel changes accompanying grazing and logging activities in the 19th and 20th centuries (Haugo et al., 2010; Uebelacker, 1980), as well as active fire suppression in the 20th and 21st centuries (Agee, 1993; Stine et al., 2014).

Conclusion

Both the fire activity and vegetation assemblage at Long Lake varied widely during the past ~9900 years, primarily as the result of climatic shifts, and to a lesser extent human land use actions. Fire activity was generally low in the Long Lake watershed in the early Holocene and the first half of the middle Holocene, likely due to a warmer, drier climate than at present and low amounts of burnable biomass. However, fire frequency was likely higher during these periods than was indicated by CharAnalysis as a result of the low temporal resolution in this part of the record. Fire activity became much more common after ca. 6000 cal yr BP, which was coincident with the establishment of the modern forest as the regional climate became cooler and wetter. This increase in fire occurred simultaneous to an increase recorded at numerous sites in the PNW, and is attributed to higher amounts of burnable biomass coupled with greater climatic variability. Fire activity remained high at Long Lake into the late Holocene and only began to decrease after ca. 3000 cal yr BP, but was a consistent presence until ca. 500 cal yr BP. The most recent interval of the Long Lake fire history reconstruction shows a clear departure from the established fire regime during the previous ~5500 years. Fifty fire episodes occurred during the late Holocene, but only a single fire episode was recorded after 500 cal yr BP (at ca. AD 1850). It is understandable that the LIA caused a drop in fire activity at Long Lake, as it did at numerous sites across the PNW. However, fire frequency should have increased again after this period, but it did not. The lack of fire at Long Lake during the past ~150 years, which is likely the result of the combined effects of grazing, logging, and fire suppression, has most certainly contributed to dense stands of shade-tolerant trees observed in the watershed at present.

Given the available paleoecological evidence from the eastern Cascades, the MEMC forest at Long Lake seems to have an intermediate fire regime to sites at higher and lower elevations, both in terms of fire frequency and severity. While this conclusion is speculative for the early and middle Holocene (no published charcoal records exist from sites lower in elevation than Long Lake for these periods), this is clearly the case for the late Holocene. It seems likely that early Holocene fires at Long Lake burned more frequently than at higher-elevation sites, but were limited in terms of size and/or severity by fuel availability, similar to what was observed at Tumalo Lake. Given the mixture of fuel sources consumed and the variable peak magnitude, a mixed-severity fire regime undoubtedly established at Long Lake during the second half of the middle Holocene. The fires that occurred during this period were considerably more frequent, but of smaller size and/or lower severity at Long Lake than at higher-elevation sites, in particular Sunrise Lake. The reconstructed trends in fire activity at Long Lake suggest that for as long as a moist MEMC forest has existed at the site (since ca. 6000–5500 cal yr BP), it has been maintained by a mixed-severity fire regime in which fires of both low and high severity burned. For at least the late Holocene, this places it in between high-elevation sites that experienced infrequent, stand-replacing fires (Minckley and Long, 2016; Walsh et al., 2017), and low-elevation sites where frequent, low-severity fires maintained more open forests (Everett et al., 2000; Walsh et al., 2018).

Many forests throughout the PNW have clearly been altered in terms of their fire regimes and forest structure and composition since EuroAmerican settlement, and we are only beginning to fully understand the impact this has on the resiliency of these forests. It is well documented that EuroAmerican fire exclusion affected fire regimes in the lower-elevation forests of the eastern Cascades. It is now clear from our results that the late Holocene fire regime of the Long Lake watershed, and potentially other moist MEMC forests in the eastern Cascades, have also been influenced by both recent climatic shifts as well as post-EuroAmerican settlement land use practices. With a late Holocene MFRI of ~80 years and an absence of fire in the Long Lake watershed for the last ~150 years, time is of the essence for identifying effective fire management strategies and applying them to the landscape. It is important to note that this site has clearly experienced fairly frequent moderate- to high-severity fires during the past ~6000 years. We should therefore expect the incidence of these events to increase in light of continued climatic warming.

Acknowledgements

The authors would like to thank K. Ferrier, D. Pilkington, and S. Adolphson for assistance with fieldwork. We would also like to thank two anonymous reviewers for their helpful comments that greatly improved this manuscript.

Author contributions

ZAR carried out the collection and analysis of the core, including the charcoal and pollen analysis, and co-wrote the manuscript. MKW carried out the collection of the core, assisted with data analysis and interpretation, and co-wrote and edited the manuscript.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Central Washington University College of the Sciences provided funding for this research.

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References

Agee JK (1993) *Fire Ecology of Pacific Northwest Forests*. Washington, DC: Island Press.

Agee JK (1994) *Fire and Weather Disturbances in Terrestrial Ecosystems of the Eastern Cascades*. General Technical Report PNW-GTR-320. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Agee JK (2003) Historical range of variability in eastern Cascades forests, Washington, USA. *Landscape Ecology* 18(8): 725–740.

Agee JK and Lolley MR (2006) Thinning and prescribed fire effects on fuels and potential fire behavior in an eastern Cascades forest, Washington, USA. *Fire Ecology* 2(2): 142–158.

Arno SF (1980) Forest fire history in the northern Rockies. *Journal of Forestry* 78(8): 460–465.

Arno SF (2000) *Fire in Western Forest Ecosystems*. General Technical Report RMRS-GTR-42-vol. 2. Ogden, UT: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Arno S and Allison-Bunnell S (2002) *Flames in our Forest: Disaster or Renewal?* Washington, DC: Island Press.

Bartlein PJ, Anderson KH, Anderson PM et al. (1998) Paleoclimate simulations for North America over the past 21,000 years: Features of the simulated climate and comparisons with paleoenvironmental data. *Quaternary Science Reviews* 17(6–7): 549–585.

Bartlein PJ, Hostetler SW and Alder JR (2014) Paleoclimate. In: Ohring G (ed.), *Climate Change in North America*. New York: Springer, pp.1–52.

Berger A and Loutre MF (1991) Insolation values for the last 10 million years. *Quaternary Science Reviews* 10(4): 297–317.

Bork JL (1984) *Fire history in three vegetation types on the eastern side of the Oregon Cascades*. MS Thesis, Oregon State University, Oregon.

Brown KJ, Hebda NJ, Conder N et al. (2017) Changing climate, vegetation, and fire disturbance in a sub-boreal pine-dominated forest, British Columbia, Canada. *Canadian Journal of Forest Research* 47(5): 615–627.

Buechling A and Baker WL (2004) A fire history from tree rings in a high-elevation forest of Rocky Mountain National Park. *Canadian Journal of Forest Research* 34(6): 1259–1273.

Burtchard GC (2007) Holocene subsistence and settlement patterns: Mount Rainier and the montane Pacific Northwest. *Archaeology in Washington* 13: 3–44.

Camp A (1999) Age structure and species composition changes resulting from altered disturbance regimes on the eastern slopes of the Cascades Range, Washington. *Journal of Sustainable Forestry* 9(3/4): 39–67.

Carcaillet C, Bergeron Y, Ali AA et al. (2010) Holocene fires in eastern Canada: Towards a forest management perspective in light of future global changes. *PAGES News* 18(2): 58–60.

Chase M, Bleskie C, Walker IR et al. (2008) Midge-inferred Holocene summer temperatures in southeastern British Columbia, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 257(1–2): 244–259.

Chatters JC (1995) Population growth, climatic cooling, and the development of collector strategies on the Southern Plateau, Western North America. *Journal of World Prehistory* 9(3): 341–400.

Coulthard B, Smith DJ and Lacourse T (2013) Dendroglaciological investigations of mid-to late-Holocene glacial activity in the Mt. Waddington area, British Columbia Coast Mountains, Canada. *The Holocene* 23(1): 93–103.

Egan J, Staff R and Blackford J (2015) A high-precision age estimate of the Holocene Plinian eruption of Mount Mazama, Oregon, USA. *The Holocene* 25(7): 1054–1067.

Everett R, Lehmkuhl J, Schellhaas R et al. (1999) Snag dynamics in a chronosequence of 26 wildfires on the east slope of the Cascade Range in Washington State, USA. *International Journal of Wildland Fire* 9(4): 223–234.

Everett RL, Schellhaas R, Keenum D et al. (2000) Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. *Forest Ecology and Management* 129(1): 207–225.

Everett R, Baumgartner D, Ohlson P et al. (2008) Structural classes and age structure in 1860 and 1940 reconstructed fir-pine stands of eastern Washington. *North American Naturalist* 68(3): 278–290.

Faegri K, Kaland PE and Krzywinski K (1989) *Textbook of Pollen Analysis*. New York, NY: John Wiley and Sons.

Franklin JF and Dyrness CT (1988) *Natural Vegetation of Oregon and Washington*. Corvallis, OR: Oregon State University.

Fulkerson TJ (2012) *Climate Change at the Pleistocene-Holocene Boundary in the Pacific Northwest: A Comparison of Proxy Datasets and the Archaeological Record*. MA Thesis, Eastern Washington University, Washington State.

Gavin DG, Brubaker LB and Greenwald DN (2013) Postglacial climate and fire-mediated vegetation change on the western Olympic Peninsula, Washington (USA). *Ecological Monographs* 83(4): 471–489.

Graumlich LJ and Brubaker LB (1986) Reconstruction of annual temperature (1590–1979) for Longmire, Washington, derived from tree rings. *Quaternary Research* 25(2): 223–234.

Grimm EC (1987) CONISS: A Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences* 13(1): 13–35.

Grove AT (2001) The "Little Ice Age" and its geomorphological consequences in Mediterranean Europe. *Climatic Change* 48(1): 121–136.

Hagmann RK, Franklin JF and Johnson KN (2013) Historical structure and composition of ponderosa pine and mixed-conifer forests in south-central Oregon. *Forest Ecology and Management* 304: 492–504.

Hagmann RK, Franklin JF and Johnson KN (2014) Historical conditions in mixed-conifer forests on the eastern slopes of the northern Oregon Cascade Range, USA. *Forest Ecology and Management* 330: 158–170.

Haugo RD, Hall SA, Gray EM et al. (2010) Influences of climate, fire, grazing, and logging on woody species composition along an elevation gradient in the eastern Cascades, Washington. *Forest Ecology and Management* 260(12): 2204–2213.

Haydon KC (2018) *Postglacial fire, vegetation, and environmental change in the Sinlahekin Wildlife Area, Okanogan County, Washington (USA)*. MS Thesis, Central Washington University, Washington State.

Hebda RJ and Allen GB (1993) Modern pollen spectra from west central British Columbia. *Canadian Journal of Botany* 71(11): 1486–1495.

Heiri O, Lotter AF and Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology* 25(1): 101–110.

Hemstrom MA and Franklin JF (1982) Fire and other disturbances of the forests in Mount Rainier National Park. *Quaternary Research* 18(1): 32–51.

Hessburg PF, Salter RB and James KM (2007) Re-examining fire severity relations in pre-management era mixed conifer forests: Inferences from landscape patterns of forest structure. *Landscape Ecology* 22(1): 5–24.

Heusser CJ (1978) Modern pollen rain of Washington. *Canadian Journal of Botany* 56(13): 1510–1517.

Heyer JP, Brewer SC and Shinker JJ (2017) Using high-resolution reanalysis data to explore localized western North America hydroclimate relationships with ENSO. *Journal of Climate* 30(14): 5395–5417.

Higuera PE, Gavin DG, Bartlein PJ et al. (2010) Peak detection in sediment–charcoal records: Impacts of alternative data analysis methods on fire-history interpretations. *International Journal of Wildland Fire* 19(8): 996–1014.

Higuera PE, Peters ME, Brubaker LA et al. (2007) Understanding the origin and analysis of sediment-charcoal records with a simulation model. *Quaternary Science Reviews* 26 (13–14): 1790–1809.

Johnston JD, Bailey JD, Dunn CJ et al. (2017) Historical fire–climate relationships in contrasting interior Pacific Northwest forest types. *Fire Ecology* 13(2): 18–36.

Kelly RF, Higuera PE, Barrett CM et al. (2011) Short paper: A signal-to-noise index to quantify the potential for peak detection in sediment–charcoal records. *Quaternary Research* 75(1): 11–17.

Lillybridge TR, Kovalchik BL, Williams CK et al. (1995) *Field Guide for the Forested Plant Associations of the Wenatchee National Forest*. General Technical Report, PNW-GTR-359. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Little RL, Peterson DL and Conquest LL (1994) Regeneration of subalpine fir (*Abies lasiocarpa*) following fire: Effects of climate and other factors. *Canadian Journal of Forest Research* 24(5): 934–944.

Long CJ, Power MJ and Bartlein PJ (2011) The effects of fire and tephra deposition on forest vegetation in the Central Cascades, Oregon. *Quaternary Research* 75(1): 151–158.

Long CJ, Power MJ, Minckley TA et al. (2014) The impact of Mt Mazama tephra deposition on forest vegetation in the Central Cascades, Oregon, USA. *The Holocene* 24(4): 503–511.

Long CJ, Shinker JJ, Minkley TA et al. (2019) A 7600 yr vegetation and fire history from Anthony Lake, northeastern Oregon, USA, with linkages to modern synoptic climate patterns. *Quaternary Research* 91(2): 705–713.

Long CJ, Whitlock C, Bartlein PJ et al. (1998) A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Canadian Journal of Forest Research* 28(5): 774–787.

Mack CA (2003) A burning issue: American Indian fire use on the Mt. Rainier Forest Reserve. *Fire Management Today* 63(2): 20–24.

Mack CA, Chatters JC and Prentiss AM (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 RN, Bryant VM Jr and Fryxell R (1976) Pollen sequence from the Columbia Basin, Washington: Reappraisal of postglacial vegetation. *The American Midland Naturalist* 95(2): 390–397.

Mack RN, Bryant VM Jr and Pell W (1978) Modern forest pollen spectra from eastern Washington and northern Idaho. *Botanical Gazette* 139(2): 249–255.

Mack RN, Rutter NW and Valastro S (1979) Holocene vegetation history of the Okanogan Valley, Washington. *Quaternary Research* 12(2): 212–225.

Mann ME, Zhang A, Rutherford S et al. (2009) Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326(5957): 1256–1260.

Marlon JR, Bartlein PJ, Gavin DG et al. (2012) Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences* 109(9): E535–E543.

Marouka KR (1994) *Fire history of pseudotsuga menziesii and abies grandis stands in the blue mountains of Oregon and Washington*. MS Thesis, University of Washington, Seattle, Washington.

McClure RH (1989) Alpine obsidian procurement in the southern Washington Cascades: Preliminary research. *Archaeology in Washington* 1: 59–69.

McClure RH (1998) Prehistoric archaeology in the southern Washington Cascades. In: Burtchard GC (ed.) *Environment Prehistory and Archaeology of Mount Rainier National Park, Washington*. International Archaeological Research Institute, Inc. Submitted to Mount Rainier National Park, Ashford, Washington, pp.59–75.

Menounos B, Osborn G, Clague JJ et al. (2009) Latest Pleistocene and Holocene glacier fluctuations in western Canada. *Quaternary Science Reviews* 28(21–22): 2049–2074.

Minckley TA and Long CJ (2016) Paleofire severity and vegetation change in the Cascade Range, Oregon, USA. *Quaternary Research* 85(2): 211–217.

Mullineaux DR (1986) Summary of pre-1980 tephra-fall deposits erupted from Mount St. Helens, Washington State, USA. *Bulletin of Volcanology* 48(1): 17–26.

Natural Resources Conservation Service [NRCS] (2009) Sitka Alder Plant Fact Sheet. Available at www./plants.usda.gov/factsheet/pdf/fs_alvis.pdf (accessed 27 April 2019).

Nelson DB, Abbott MB, Steinman B et al. (2011) Drought variability in the Pacific Northwest from a 6,000-yr lake sediment record. *Proceedings of the National Academy of Sciences* 108(10): 3870–3875.

Odion DC, Hanson CT, Arsenault A et al. (2014) Examining historical and current mixed-severity fire regimes in ponderosa pine and mixed-conifer forests of western North America. *PLoS One* 9(2): e87852.

Parish R, Coupe R, Lloyd D et al. (1996) *Plants of Southern Interior British Columbia and the Inland Northwest*. Vancouver, BC: Lone Pine.

Prichard SJ, Gedalof ZE, Oswald WW et al. (2009) Holocene fire and vegetation dynamics in a montane forest, North Cascade Range, Washington, USA. *Quaternary Research* 72(1): 57–67.

PRISM Climate Group (2018) PRISM Climate Data. Oregon State University. Available at www.prism.oregonstate.edu (accessed 26 April 2019).

Rorig ML and Ferguson SA (1999) Characteristics of lightning and wildfire ignition in the Pacific Northwest. *Journal of Applied Meteorology* 38(11): 1565–1575.

Rushton ZA (2019) *Holocene fire history reconstruction of a mid-elevation mixed conifer forest in the Eastern Cascades, Washington*. MS Thesis, Central Washington University, Ellensburg, Washington.

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

Steinman BA, Pompeani DP, Abbott MB et al. (2016) Oxygen isotope records of Holocene climate variability in the Pacific Northwest. *Quaternary Science Reviews* 142: 40–60.

Stine P, Hessburg PF, Spies TA et al. (2014) *Ecology and Management of Moist Mixed-conifer Forests in Eastern Oregon and Washington: A Synthesis of the Relevant Biophysical Science and Implications for Future Land Management*. US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Stuiver M, Reimer PJ and Reimer RW (2019) CALIB 7.1. Available at: http://calib.org (accessed 4 May 2019).

Swetnam TW and Dieterich JH (1985) Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. In: *Proceedings—symposium and workshop on wilderness fire*. Gen. Tech. Rep. INT-GTR-182, Ogden, UT: US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Telford RJ, Heegaard E and Birks HJB (2004) All age-depth models are wrong: But how badly? *Quaternary Science Reviews* 23(1–2): 1–5.

Touchan R, Allen CD and Swetnam TW (1996) *Fire history and climatic patterns in ponderosa pine and mixed-conifer forests of the Jemez Mountains, northern New Mexico*. United States Department of Agriculture, Forest Service General Technical Report Rocky Mountain, pp.33–46.

Uebelacker ML (1980) *Land and life in the Naches river basin: A cultural resource overview*. Report, US Forest Service, Region 6, Wenatchee National Forest.

United States Forest Service [USFS] (1996) *Tieton Watershed Analysis*. Naches Ranger District, WA.

Walker IR and Pellatt MG (2008) Climate change and ecosystem response in the northern Columbia River basin—A paleoenvironmental perspective. *Environmental Reviews* 16: 113–140.

Walsh MK, Duke HJ and Haydon KC (2018) Toward a better understanding of climate and human impacts on late-Holocene fire regimes in the Pacific Northwest, USA. *Progress in Physical Geography: Earth and Environment* 42(4): 478–512.

Walsh MK, Lukens ML, McCutcheon PT et al. (2017) Fire–climate–human interactions during the postglacial period at Sunrise Ridge, Mount Rainier National Park, Washington (USA). *Quaternary Science Reviews* 177: 246–264.

Walsh MK, Marlon JR, Goring SJ et al. (2015) A regional perspective on Holocene fire–climate–human interactions in the Pacific Northwest of North America. *Annals of the Association of American Geographers* 105(6): 1135–1157.

Walsh MK, Whitlock C and Bartlein PJ (2008) A 14,300-year-long record of fire–vegetation–climate linkages at Battle Ground Lake, southwestern Washington. *Quaternary Research* 70(2): 251–264.

Walsh MK, Whitlock C and Bartlein PJ (2010) 1200 Years of fire and vegetation history in the Willamette Valley, Oregon and Washington, reconstructed using high-resolution macroscopic charcoal and pollen analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 297(2): 273–289.

Washington State Department of Natural Resources [WSDNR] (1987) Geologic Map of the Mount Rainier Quadrangle. Compiled by Schasse HW. *WA Division of Geology and Earth Resources Open File Report* 87-16.

Westerling AL and Swetnam TW (2003) Interannual to decadal drought and wildfire in the western United States. *EOS Transactions* 84(49): 545–560.

Western Regional Climate Center (2019) Western U.S. Climate Historical Summaries. Available at www.wrcc.dri.edu/Climsum.html (accessed 26 April 2019).

Whitlock C (1992) Vegetational and climatic history of the Pacific Northwest during the last 20,000years: Implications for understanding present-day biodiversity. *Northwest Environmental Journal* 8: 5–28.

Whitlock C and Bartlein PJ (1993) Spatial variations of Holocene climatic change in the Yellowstone region. *Quaternary Research* 39(2): 231–238.

Whitlock C and Bartlein PJ (2003) Holocene fire activity as a record of past environmental change. *Developments in Quaternary Sciences* 1: 479–490.

Whitlock C and Larsen C (2001) Charcoal as a fire proxy. In: Smol JP, Birks HJ and Last WM (eds.) *Tracking environmental change using lake sediments: Terrestrial, Algal and Siliceous Indicators*. Dordrecht: Springer, pp.75–97.

Whitlock C and Millspaugh SH (1996) Testing the assumptions of fire-history studies: An examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6(1): 7–15.

Whitlock C, Sarna-Wojcicki AM, Bartlein PJ et al. (2000) Environmental history and tephrostratigraphy at Carp Lake, southwestern Columbia basin, Washington, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology* 155(1–2): 7–29.

Wimberly MC and Liu Z (2014) Interactions of climate, fire, and management in future forests of the Pacific Northwest. *Forest Ecology and Management* 327: 270–279.

Wright CS and Agee JK (2004) Fire and vegetation history in the eastern Cascade Mountains, Washington. *Ecological Applications* 14(2): 443–459.

Wright HE, Mann DH and Glaser PH (1984) Piston corers for peat and lake sediments. *Ecology* 65(2): 657–659.

Zdanowicz CM, Zielinski GA and Germani MS (1999) Mount Mazama eruption: Calendrical age verified and atmospheric impact assessed. *Geology* 27(7): 621–624.