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Toward a better understanding of climate and human impacts on late Holocene fire regimes in the Pacific Northwest, USA

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Abstract

In order to fully appreciate the role that fire, both natural and anthropogenic, had in shaping pre-Euro-American settlement landscapes in the Pacific Northwest (PNW), it is necessary to develop a more robust method of evaluating paleofire reconstructions. Here we demonstrate an approach that includes the identification of charcoal morphotypes (i.e. visually distinct charcoal particles), and incorporates both paleoecological and archaeological data sets, to more specifically determine both the nature of past fire regimes (i.e. fuel type and fire severity) and the likely ignition source of those fires. We demonstrate the usefulness of this approach by reconstructing the late Holocene fire and vegetation histories of Lake Oswego (Clackamas County), Oregon, and Fish Lake (Okanogan County), Washington, using macroscopic charcoal and pollen analysis of sediment cores. The histories were compared with climatic records from the PNW as well as archaeological, ethnographic, and historical records from the Lower Columbia River Valley and Southern Columbia Plateau cultural regions. Our results indicate that while centennial-to-millennial-scale climate change had limited influence on the fire regimes at the study sites during the past $\sim$3800 years, the use of fire by Native Americans for a variety of reasons, particularly after ca. 1200 calendar years before present (AD 750), had a far greater impact. Charcoal morphotype ratios also indicate that fires in the two watersheds were fundamentally different in their severity and impact, and led to major shifts in the forests and woodlands surrounding Lake Oswego, but helped maintain the ponderosa pine-dominated forest at Fish Lake. The elimination of fire from the two study sites during the past 100–300 years is likely the combined result of Euro-American contact and the arrival of disease in the PNW, as well as 20th-century fire suppression and grazing effects on fuel continuity, which has implications for future forest management and restoration efforts in the PNW.

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Macroscopic charcoal analysis, charcoal morphotypes, pollen, archaeology, climate, anthropogenic burning

I Introduction

Understanding the role fire played in creating and maintaining ecosystems prior to Euro-American settlement is key to restoring landscape resiliency and viability in the Pacific Northwest (PNW) (Arno and Allison-Bunnell, 2002; Keeley et al., 2009; Ryan et al., 2013). In order to do this, site-specific fire histories that document how fire activity varied on centennial- to millennial-length timescales are needed (Bowman, 2007; Gavin et al., 2007; Whitlock et al., 2010). One way to do this is through the use of macroscopic charcoal analysis of lake and wetland sediments, which can be used to reconstruct high-resolution, long-term, continuous, watershed-scale fire histories (Conedera et al., 2009; Long et al., 1998; Whitlock and Larsen, 2001). In the PNW this method has mostly been used to study higher-elevation sites in the Cascade and Coast ranges of Oregon, Washington, and British Columbia (Canada) (Gavin et al., 2006, 2013; Hallett et al., 2003; Long et al., 1998, 2011; Prichard et al., 2009; Sugimura et al., 2008; Walsh et al., 2017) where mid- to high-severity burns typically occur every 100–400 years during periods of extended drought (Gavin et al., 2007). Fewer studies have looked at past fire regimes in lower-elevation forests and grasslands in the PNW (Brown and Hebda, 2002a, 2002b; Long et al., 2007; Scharf, 2010; Walsh et al., 2008, 2010a, 2010b) where pre-settlement fires are thought to have been frequent ground-clearing events of low- to mid-severity (Agee, 1998; Everett et al., 2000). However, it is these areas that are at greatest risk from increasing wildfire activity and also pose the greatest risk, due at least in part to greater human-caused ignitions (Bartlein et al., 2008) and rapid housing development in the wildland–urban interface (Gude et al., 2008; Radeloff et al., 2005).

In order to successfully restore landscape resiliency and viability, it is necessary to understand the past relationships between fire activity and the factors that influenced its occurrence, frequency, and severity (Bowman et al., 2009). This is especially true if sedimentary-based charcoal records are to be used to project how fire activity might change in light of future climate change (Brücher et al., 2014). While fairly straightforward methods exist to assess fire-history reconstructions within the context of past climatic variability (Daniau et al., 2012; Marlon et al., 2009, 2012; Power et al., 2008), it is less clear how to evaluate these within the context of past human activity (Abrams and Seischab, 1997; Bowman et al., 2011; Mayle and Iriarte, 2012; Walsh et al., 2015). This process is most certainly complicated by the nature of the different types of data; archaeological, ethnographic, and historical data vary considerably in their spatial and temporal resolution from paleoecological data, which typically exist in the form of sedimentary histories (Kirch, 2005; Munoz et al., 2014). However, given the long human history in the PNW (Aikens et al., 2011; Ames, 2003; Waters and Stafford, 2007), serious consideration must be given to the likelihood that human use of fire influenced past fire regimes, and, therefore, paleoecological records must be evaluated within the context of what is known about human history and land-use activities (Scharf, 2009; Walsh et al., 2010b).

Additionally, we argue that a better understanding of past fire regimes comes through the identification of charcoal morphotypes (i.e. charcoal that can be visually identified as having been produced by different fuel sources), which can help qualify past fire regimes. Only a handful of charcoal studies worldwide have differentiated charcoal morphotypes (Enache and Cumming, 2006, 2007, 2008), and a few more have attempted to link those types with their respective fuel sources (Jensen et al., 2007; Kennett et al., 2010; Mustaphi and Pisaric, 2014, 2017; Orvis et al., 2005; Scott et al., 2000; Umbanhowar and McGrath, 1998; Walsh et al., 2008, 2010a, 2010b, 2014). The limited use of this technique may be in part due to the lack of distinct charcoal types encountered during analysis, or by limited awareness of their value for interpreting past fire regimes. However, by better understanding not only when fires burned, but also what type of fuel burned during those episodes (which gives an indication of fire severity and magnitude), a more complete understanding of past fire–climate–human relationships can be obtained.

Here we present case studies from two lower-elevation study sites in the PNW, one from the west side of the Cascades, and one from the east (Figure 1), with the goal of using an interdisciplinary approach to interpreting charcoal-based fire history records. A new record from Fish Lake, Washington, and an extension of a previously published record from Lake Oswego, Oregon (Walsh et al., 2010b), are used to address three specific objectives: 1) to use macroscopic charcoal and pollen analysis of lake sediment cores to reconstruct the late Holocene fire and vegetation histories at two study sites with rich archaeological records; 2) to evaluate the fire histories within the context of known climatic and human influences, both prior to and following Euro-American settlement, using published paleoclimatic and archaeological, ethnographic, and historic records; and 3) to use the identification of charcoal morphotypes to better interpret the charcoal-based fire history reconstructions. Our hope is that this information will provide insights into the coupled socioecological systems influenced by fire for millennia in the PNW, and that this information can improve our ability to manage and model landscape change in the future.

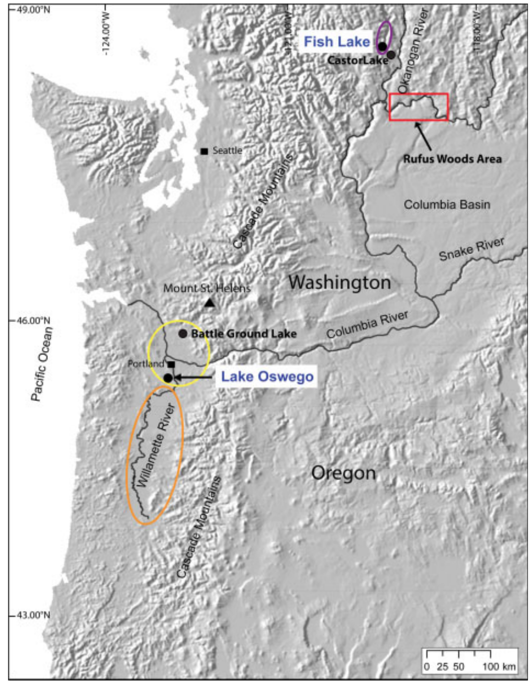

Figure 1. Map of the Pacific Northwest showing the location of the study sites, as well as other localities mentioned in the text. The colored ovals represent the general locations of the Willamette Valley (orange), Lower Columbia River Valley (yellow), and the Sinlahekin Valley (purple). The red box indicates the Rufus Woods study area (Campbell, 1989; Scharf, 2009) (all the figures in color are available online).

II Study sites

1 Case study: Lake Oswego, Oregon

Lake Oswego sits near the northern end of the Willamette Valley, approximately 13 km south of Portland, Oregon (Figure 1). Located primarily in Clackamas County, it is partially surrounded by the city of Lake Oswego (population in 2016: ~38,945) (Figure 2). The lake is long (~4 km), narrow (~0.4 km), and deep (Table 1). It exists within a former channel of the Tualatin River in a depression carved by

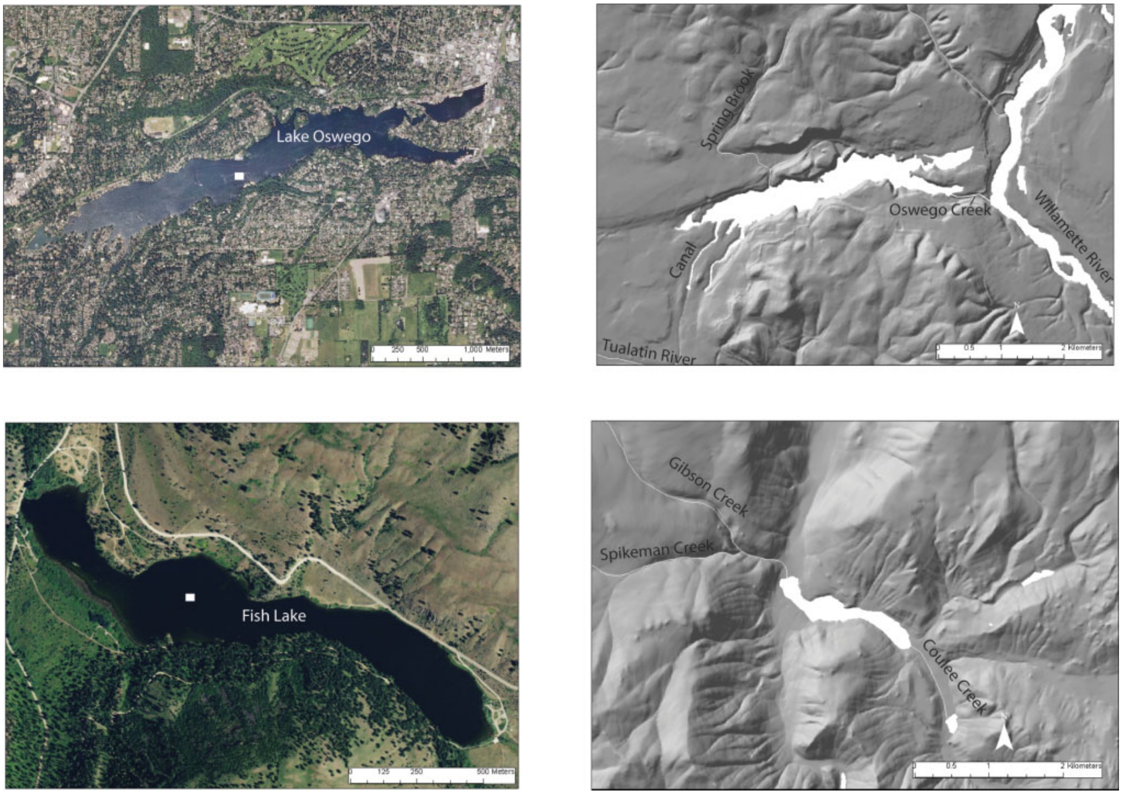

Figure 2. Aerial photos (left) with coring locations indicated by the white box and hillshade maps (right) for Lake Oswego, OR (top), and Fish Lake, WA (bottom) (all the figures in color are available online).
Source: USGS.

Missoula floods when slack water backed up into the Willamette Valley sometime between 12,000 and 18,000 years ago (Johnson et al., 1985; Parsons et al., 1970). The elevation of the lake is 30 m above sea level (asl) and it is surrounded by small hills reaching approximately 120 m asl. Several small creeks feed into the lake, including Spring Brook that flows in from the north, while Oswego Creek connects the east end of the lake to the Willamette River (Figure 2). Originally named Waluga by Native Americans living in the area, the lake was renamed Sucker Lake by Euro-American settlers to the region, and eventually changed to Lake Oswego in AD 1913 (Foster, 2009; Fulton, 2002). The lake was enlarged several times in the late 19th and early 20th centuries by a series of dams that were built across the lake's outlet, as well as the completion of the Tualatin Canal in AD 1873, which temporarily connected the east end of the lake with the Tualatin River (Fulton, 2002). As a result, the lake level was raised by several meters and its length increased by more than a kilometer.

The climate of Lake Oswego is typical of the PNW west of the Cascades with warm, dry summers and cool, wet winters (Table 1). Average annual precipitation ($\sim$1170 mm), however, is lower than more coastal locations due to its existence in the rain shadow of the Oregon Coast Range (WRCC, 2017). General Land Office maps indicate that the pre-settlement

Table 1. Physical and climatic data for Lake Oswego and Fish Lake.

	Lake Oswego, OR	Fish Lake, WA
Latitude	45°24'40" N	48°36'50" N
Longitude	122°39'58" W	119°42'2" W
Elevation (m)	30	548
Area (ha)	160	41.3
Drainage basin area (ha)	1600	Unknown
Maximum water depth (m)	17	18
Climate station[a]	Oregon City	Conconully
Location relative to site	9 km SE	7 km SW
Period of meteorological record	1971–2000	1971–2000
Mean min. Jan. temp (°C)	2.1	–9.7
Mean max July temp (°C)	28.1	27.1
Mean annual precipitation (mm)	1170	375
% Precipitation November–April	74	55

[a] Climate data retrieved from the Western Regional Climate Center (https://wrcc.dri.edu/Climsum.html).

vegetation at the site was a mix of Oregon white oak (*Quercus garryana*) woodland and conifer-dominated upland forest, including Douglas-fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*) (Christy and Alverson, 2011). Other common species historically found near the site include grand fir (*Abies grandis*), big leaf maple (*Acer macrophyllum*), Pacific dogwood (*Cornus nuttallii*), Oregon ash (*Fraxinus latifolia*), and red alder (*Alnus rubra*). Today, remnants of these vegetation types are mixed with private houses and urban areas that surround the lake (Figure 2).

Archaeological evidence suggests that Native Americans inhabited the Northwest Coast of the PNW by as early as ca. 13,500 calendar years before present (cal yr BP) (Sobel et al., 2013; Waters et al., 2011) and the Lake Oswego area by ca. 8000–6000 cal yr BP (Burnett, 1991; Hamilton and Roulette, 2005). Prior to Euro-American exploration (ca. AD 1811; Walker and Sprague, 1998) and initial settlement in the Willamette Valley (ca. AD 1830–50s; Bowen, 1978), the Lake Oswego area fell between the traditional homelands of the Clackamas and the Clowewalla peoples, who were part of the Lower Columbia River Chinook cultural area (Chinookan language group), and the Tualatin peoples from the Willamette valley (Kalapuyan language group) (Fulton, 2002; Jacobs, 1945; Ruby et al., 2010). These tribes lived in fairly permanent winter dwellings and migrated during the remainder of the year to areas in which salmon, root crops, berries, and other resources were collected (Boyd and Hajda, 1987; Ellis, 2013; Silverstein, 1990). As with most others in the PNW, tribes in the lower Columbia River and Willamette Valleys were decimated by European disease (e.g. small pox, malaria) by as early as AD 1781, causing a precipitous drop in populations by as much as 80–90% by the mid-19th century (Boyd, 1999; Boyd, 2013). The remaining Clackamas were largely relocated to the Grande Ronde Reservation after the signing of a treaty in AD 1855 (Beckham, 1990), and in AD 1871 numbered only 55 (Ruby et al., 2010).

2 Case study: Fish Lake, Washington

Fish Lake is located in Okanogan County, Washington, at the southern edge of the Sinlahekin Valley (Figure 1). It exists primarily within the boundaries of the Sinlahekin Wildlife Area (SWA), just east of the Okanogan-Wenatchee National Forest, which encompasses more than 1.6 million hectares along the eastern flank of the Cascades Range in Washington. The lake itself is relatively long ($\sim$2 km), narrow ($\sim$0.4 km), and deep (Figure 2; Table 1). It was presumably created by the retreat of the Okanogan lobe of the Cordilleran ice sheet, sometime around 12,000–14,000 years ago (Lesemann and Brennand, 2009).

Surrounded by hills approximately 1000–1500 m in height, Fish Lake sits at an elevation of 548 m asl. Two small creeks, Spikeman and Gibson, flow from the hills west of the lake into its northwest end, while Coulee Creek drains water from its southeast side (Figure 2). Several campsites ring the perimeter of the lake and private residences exist within approximately 2 km.

The climate at Fish Lake is typical of the inland PNW, with hot summers and cold winters (Table 1). Average annual precipitation total is low ($\sim$375 mm), with precipitation spread relatively evenly throughout the year (WRCC, 2017). Fish Lake sits along the ecotone between sagebrush steppe and dry forest. The vegetation near the lake is dominated by ponderosa pine (*Pinus ponderosa*) forest, although this is predominantly found along the south shoreline. Other common trees and shrubs include Douglas-fir, Rocky Mountain maple (*Acer glabrum*), willow (*Salix* spp.), red osier dogwood (*Cornus sericea*), chokecherry (*Prunus virginiana*), serviceberry (*Amelanchier anifolia*), wild rose (*Rosa* spp.), and wax currant (*Ribes cereum*). On the north shore with a southern exposure the vegetation is more sparse, and along with ponderosa pine is dominated by sagebrush (*Artemisia* spp.), antelope bitterbrush (*Purshia tridentata*), smooth sumac (*Rhus glabra*), and herbs including yarrow (*Achillea milefolium*), lupine (*Lupinus*), night-flowering catchfly (*Silene noctiflora*), and grasses (Poaceae family). Many invasive species also exist near the lake, including mullein (*Verbascum sinuatum*), reed canarygrass (*Phalaris arundinacea*), and Loesel's tumble mustard (*Sisymbrium altissimum*).

Native Americas are thought to have inhabited the Okanogan region of the southern Columbia Plateau for the past $\sim$11,000–12,000 years (Baker, 1990; Harder et al., 2009; Prentiss and Kuijt, 2004a), although archaeological evidence is sparse before ca. 6500–7000 cal yr BP (Ames et al., 1998). The Sinlahekin band of the Sinkaietk (or Southern Okanogan; Interior Salish language group (Okanagan); Miller, 1998) lived in and around the valley at the time of contact, subsisting primarily on non-anadromous aquatic resources (e.g. sucker fish, freshwater mussel), game (e.g. deer, elk, bear, bighorn sheep), and plant resources (e.g. wild onions, camas, black tree lichen, berries) (Bouchard and Kennedy, 1984; Cline et al., 1938; Hudson, 1990; Mierendorf, 1981; Turner, 1999). While archaeological evidence from the Sinlahekin Valley is limited, several undated pre-contact sites exist, including circular depressions indicative of pit houses and culturally modified trees (Oliver, 2014; Volkenand et al., 2009). As with the tribes of the Northwest Coast, Plateau populations decreased drastically prior to and following Euro-American contact in the region (ca. AD 1811; Miller, 1998) as the result of disease, with only $\sim$350 Southern Okanogans documented in AD 1853 (Brown, 1968).

Euro-American settlement in the Sinlahekin Valley began in the mid-19th century (ca. AD 1850s) as cattlemen, miners, and homesteaders recognized the value of the area's resources (Anglin, 1995; Gubser, 1905; Waring, 1936; Wilson, 1990). In AD 1883, with the creation of the Colville Reservation, Chief Sarsarpkin, the recognized leader of the remaining Sinkaietk, was encouraged to relinquish his tribal lands in the valley and move to the Colville Reservation (Miller, 1998). He and his family members did not, however, and instead were given allotments in the valley (Beckham, 1998). Following Chief Sarsarpkin's death in AD 1886 the family allotments were eventually traded or sold to settlers, the last of which was relinquished in AD 1909 (Briley, 2014). Homesteading and farming continued in the valley until ca. AD 1940, by which time most agricultural land and irrigation schemes had been abandoned (Boyd, 2010). In AD 1939 the Washington State Game Department made the first purchases of lands in the valley that became the SWA, the oldest in the state of Washington (Washington Department of Fish and Wildlife (WDFW), 2017). Currently, the SWA comprises nearly 6000 hectares owned jointly by the WDFW and the Bureau of Land Management, as well as land leased from the Washington Department of Natural Resources (WDFW, 2017). Today, the SWA is used primarily for hunting and other recreational activities, although grazing and farming occur in limited areas.

III Methods

1 Fieldwork

Sediment cores were recovered from Lake Oswego and Fish Lake in summers 2005 and 2011, respectively, using a modified Livingstone piston corer (Wright et al., 1984) lowered from an anchored floating platform. A 2.77-m-long core (LO05B) was retrieved from Lake Oswego (LO05C) (water depth = 13.4 m) and a 2.80-m-long core (FL11A) from Fish Lake (water depth = 11.1 m). All drive lengths were extruded in the field, described, wrapped in plastic wrap and aluminum foil, encased in split polyvinyl chloride (PVC) lengths, and transported to the lab where they were kept under refrigeration. Additionally, short cores that preserved the sediment–water interface were taken from Lake Oswego (90 cm; LO05C) and Fish Lake (69 cm; FL11D) using a Klein piston corer and a Bolivia corer, respectively. These cores were sub-sampled into sample bags at 1-cm intervals, transported to the lab, and refrigerated.

2 Laboratory techniques and data analysis

In the lab, magnetic readings were taken on the intact long cores at 1-cm intervals using a Sapphire Instruments magnetic coil. This determines the extent to which the material within the core is magnetic, indicating the presence of allochthonous input into the lakes from events such as landslides and volcanic ashfall (Gedye et al., 2000; Thompson and Oldfield, 1986). The cores were then split longitudinally and described based on color and lithology, especially noting the presence of tephra (i.e. volcanic ash) and shells. Macrofossils such as needles and twigs were pulled for radiocarbon dating. Radiocarbon ages were converted to cal yr BP (present = AD 1950) using the Calib 7.1 program (Stuiver et al., 2018). The median age (i.e. the 50th percentile of the probability distribution function (PDF) curve) was chosen as the calibrated (calendar) age if it did not fall in a trough on the PDF curve. If it did, then the value of the nearest, largest peak was chosen. ^{210}Pb ages were determined for the Lake Oswego core using the constant rate of supply model adjusted for the ^{137}Cs peak. Age–depth models for the cores were created using a constrained cubic smoothing spline (except where noted).

Samples of 1 cc were taken every 5 cm for loss-on-ignition to determine the organic and carbonate content of the cores (Dean, 1974). Samples were dried overnight, weighed, and combusted at 550°C and 900°C for two hours in a muffle furnace, respectively. The weight loss after the first burning was used to determine the organic matter content, and the weight loss after the second burning was used to determine the carbonate content. To calculate the percent carbonate matter, the weight lost after the second burning was divided by the dry weight, multiplied by 1.36, and then multiplied by 100 (Heiri et al., 2001).

Pollen analysis followed standard techniques (Faegri et al., 1989). Samples of 1 cc were taken every 5–10 cm and *Lycopodium* was added to each sample as an exotic tracer; 300–500 terrestrial pollen grains and spores were counted per sample. Pollen was identified and tallied at magnifications of 400 and 1000$\times$ and pollen types were assigned based on modern phytogeography and comparison to a 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. Percent tree and shrub cover was calculated by dividing the arboreal pollen sum by the total arboreal plus non-arboreal pollen sum. The arboreal pollen sum included all trees and shrubs, while the non-arboreal pollen sum consisted of all herbaceous plants, including grasses, sedges, and ferns. Aquatics were not used in the ratio. Total pollen accumulation rates were also calculated.

For macroscopic charcoal analysis, samples of 1 cc (Lake Oswego) and 2 cc (Fish Lake) were taken at contiguous 1-cm intervals and processed following techniques described in Whitlock and Larsen (2001) and modified by Walsh et al. (2008). Sediment was packed gently but tightly into a modified syringe and washed into a plastic vial with approximately 10 mL of 5% sodium hexametaphosphate. The vial was then capped and gently shaken to loosen the sediment. The samples were left to soak for at least 24 hours. Prior to sieving, ~5 mL of commercial bleach was added to the vial for 1–6 hours, or until the samples disaggregated. The samples were then washed through nested sedimentological screens of 250 and 125 µm. The residual material left in the screens was transferred into scored, labeled petri dishes for counting. The two size classes were counted, and the counts were combined for analysis. Charcoal was divided into two different categories (i.e. woody and herbaceous) based on appearance and comparison to burned reference material (Walsh et al., 2008, 2010a, 2014). Woody particles were identified as consistently black, shiny particles that were three-dimensional in nature (Figure 3(a)). Herbaceous particles, which derive from the photosynthetic parts of grasses, sedges, and other forbs, were identified by their two-dimensional structure (i.e. flat) and by the presence of stomatal openings (Figure 3(b)). Any particles that were clearly charcoal, but were not identified as herbaceous, were categorized as woody. Charcoal concentration (particles/cm^3) was calculated by dividing the total number of charcoal particles in each sample by the volume of the sample (not shown). Charcoal influx (particles/cm^2/yr) was calculated by dividing charcoal concentration by the deposition time (yr/cm) of the samples.

The charcoal records were analyzed statistically using CharAnalysis (Higuera et al., 2009), which decomposes charcoal records into a peak (Cpeak) and background (Cbackground) component in order to determine individual fire episodes. To create the charcoal accumulation rate (CHAR) time series, the program interpolated concentration values to 6- and 10-year time steps for the Lake Oswego and Fish Lake records, respectively, which represents the median temporal resolution of each. The non-log-transformed CHAR time series were then fitted with a locally weighted scatterplot smoothing (LOWESS) function to smooth the series and to model Cbackground. The Cpeak component is the residual after Cbackground is subtracted from the CHAR time series. A locally determined threshold value used to separate fire related (i.e. signal) from non-fire-related variability (i.e. noise) in the Cpeak component was set at the 95th percentile of a Gaussian distribution model of the noise in the Cpeak time series. A variety of window widths (i.e. 200–1000 years) were tested for charcoal peak identification on the records. However, none of the window widths returned a signal-to-noise index greater than 3.0 for either record, which indicates that they are not suitable for peak detection (Kelly et al., 2011); therefore, the analysis was discontinued and fire trends are instead described based on charcoal influx values.

IV Results

1 Case study: Lake Oswego, OR

1.1 Chronology and lithology. Using stratigraphic markers present in both Lake Oswego cores, the

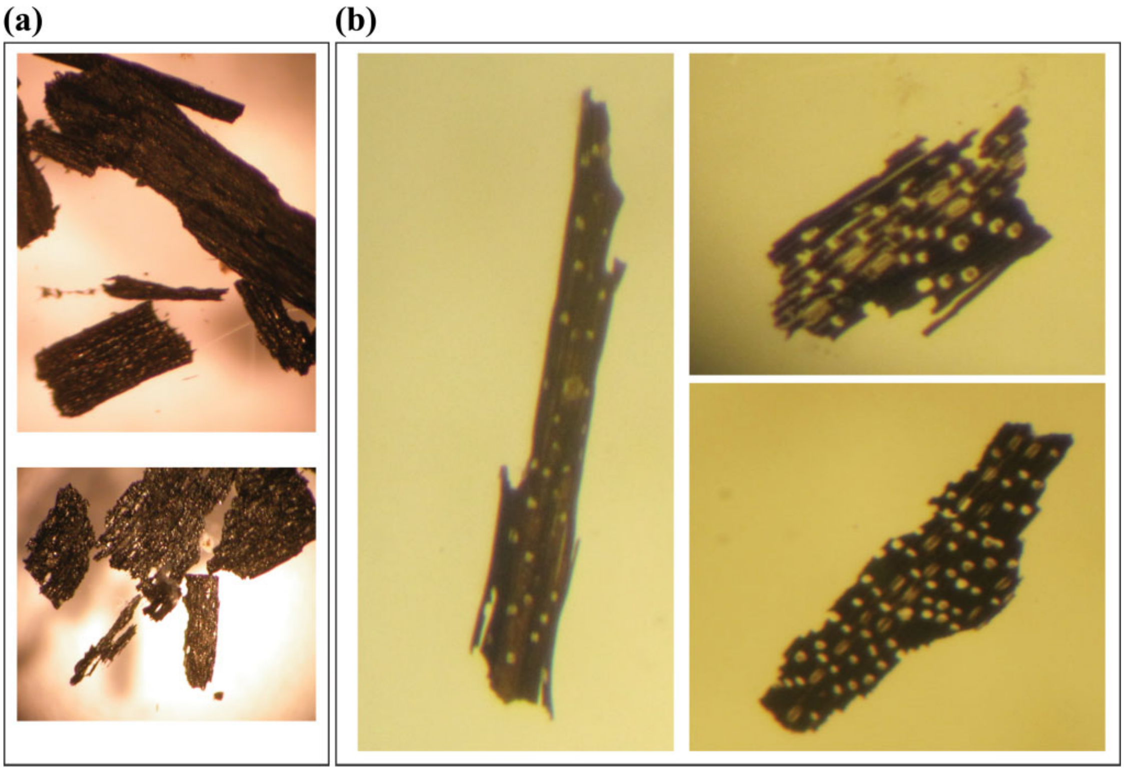

Figure 3. Photos of (a) woody charcoal from the Fish Lake (FL11A) core and (b) herbaceous charcoal. Note the presence of stomatal openings in the herbaceous charcoal. Scales vary, but all charcoal pieces are larger than >125 μm (all the figures in color are available online).

top 11 cm of the LO05C short core were combined with the 2.65 m LO05B long core to create a continuous record from the site (hereafter referred to as core LO05A). Three ^{14}C AMS dates and 10 ^{210}Pb dates were used to develop the age–depth model for the LO05A core (Table 2; Figure 4), which determined a basal age of 3340 cal yr BP. The average sample resolution for the LO05A core is 11.2 yr/cm. The sedimentation rate of the Lake Oswego (LO05A) core is relatively low from the base of the record to a depth of $\sim$170 cm (ca. 3340–1200 cal yr BP) (Figure 4). After that, it first increases and then decreases between the depths of $\sim$170 and 70 cm (ca. 1200–500 cal yr BP). Sedimentation rate remains generally unchanged from $\sim$70 to 25 cm (ca. 500–0 cal yr BP), but increases sharply, and it remains highest above that depth (0 to –55 cal yr BP).

The Lake Oswego core consists almost entirely of brownish/gray clayey gyttja. Relatively higher organic content values occur from the start of the record to ca. 800 cal yr BP (average = 20%), and lower values occur after that (average = 12%). Organic values peak between ca. 950 and 800 cal yr BP and after ca. –50 cal yr BP. The carbonate content of the core is low throughout the entire record, but values are generally highest after ca. 800 cal yr BP. Magnetic susceptibility values are extremely low near the base of the core and show little variation prior to ca. 1200 cal yr BP. After that, the values are higher overall, with the highest values occurring between ca. 800 and 200 cal yr BP.

Table 2. Age–depth relations for the Lake Oswego (LO05A) and Fish Lake (FL11E) cores.

Depth (cm below surface)	Lab number	Source material	Age (^{210}PB, ^{14}C yr BP)[a]	Calibrated age (cal yr BP)
Lake Oswego, OR; core LO05A				
0.0–3.0	–	Lake sediment	2.3[a]	–53.2
3.5–5.5	–	Lake sediment	7.0[a]	–48.5
6.5–8.5	–	Lake sediment	11.4[a]	–44.2
9.0–10.5	–	Lake sediment	14.3[a]	–41.3
11.5–12.5	–	Lake sediment	16.3[a]	–39.2
14.0–15.0	–	Lake sediment	19.6[a]	–35.9
16.5–17.5	–	Lake sediment	27.3[a]	–28.2
19.0–20.0	–	Lake sediment	37.0[a]	–18.5
21.5–22.5	–	Lake sediment	43.2[a]	–12.3
24.0–25.0	–	Lake sediment	55.9[a]	0.4
26.5–27.5		Lake sediment	90.3[a,b]	34.8
29.0–30.0		Lake sediment	155.8[a,b]	100.3
89.0	AA72363	Lake sediment	693 +/–55[c]	670 (552–612, 619–709, 713–726)[e]
169.0	AA72362	Lake sediment	1243 +–/56[c]	1180 (1013–1019, 1056–1288)[e]
273.0	AA69497	Lake sediment	3042 +/–32[c]	3240 (3165–3351)[e]
Fish Lake, WA; core FL11E				
66.0	D-AMS 1217-106	Wood	401 +/–30[d]	500 (326–360, 365–375, 429–514)[e]
123.0	D-AMS 002103	Terrestrial seed	1059 +/–26[d]	970 (928–1002; 1028–1050)[e]
198.0	D-AMS 1217-107	Wood	2216 +/–31[d]	2240 (2150–2323)[e]

[a] ^{210}PB age determination completed by J. Budahn at the USGS Denver Federal Center, Colorado.
[b] Denotes samples not used in the age–depth model.
[c] ^{14}C age determinations from University of Arizona AMS dating facility.
[d] ^{14}C age determinations from DirectAMS dating facility, Seattle, WA.
[e] Calendar ages determined using Calib 7.1 html (Stuiver et al., 2018). Ages rounded to the nearest decade with 2σ ranges reported.

1.2 Pollen and charcoal. Prior to ca. 1200 cal yr BP, the Lake Oswego (LO05A) record is dominated by relatively high but alternating percentages of *Pseudotsuga menziesii*-type and *Thuja plicata*-type pollen, varying between ~10% and 35% (Figure 5). Also found in generally high percentages are *Alnus rubra*-type (~15%), *Fraxinus latifolia*-type (~10%), *Pteridium aquilinum*-type (~8%), and *Polystichum*-type (~7%), with lesser amounts of *Tsuga heterophylla* (~4%), *Pinus* (~3%), *Abies* (~3%), *Corylus* (~4%), *Salix* (~3%), *Quercus garryana*-type (~4%), Poaceae (~5%), and Cyperaceae (~3%). The percent of trees and shrubs remains generally unchanged during this interval at an average of 80% (Figure 6). After ca. 1200 cal yr BP, several taxa increase in abundance, most notably *Alnus rubra*-type and *Pteridium aquilinum*-type. This is accompanied by a decline in the percent of trees and shrubs to ~65% by ca. 1050 cal yr BP. This increase is short-lived, however, and by ca. 950 cal yr BP the percent of trees and shrubs reaches its highest point of the record (~86%), excluding the two most recent decades. By ca. 850 cal yr BP, *Alnus rubra*-type and *Pteridium aquilinum*-type percentages decline and *Pseudotsuga menziesii*-type increases to its highest level the record (~37%).

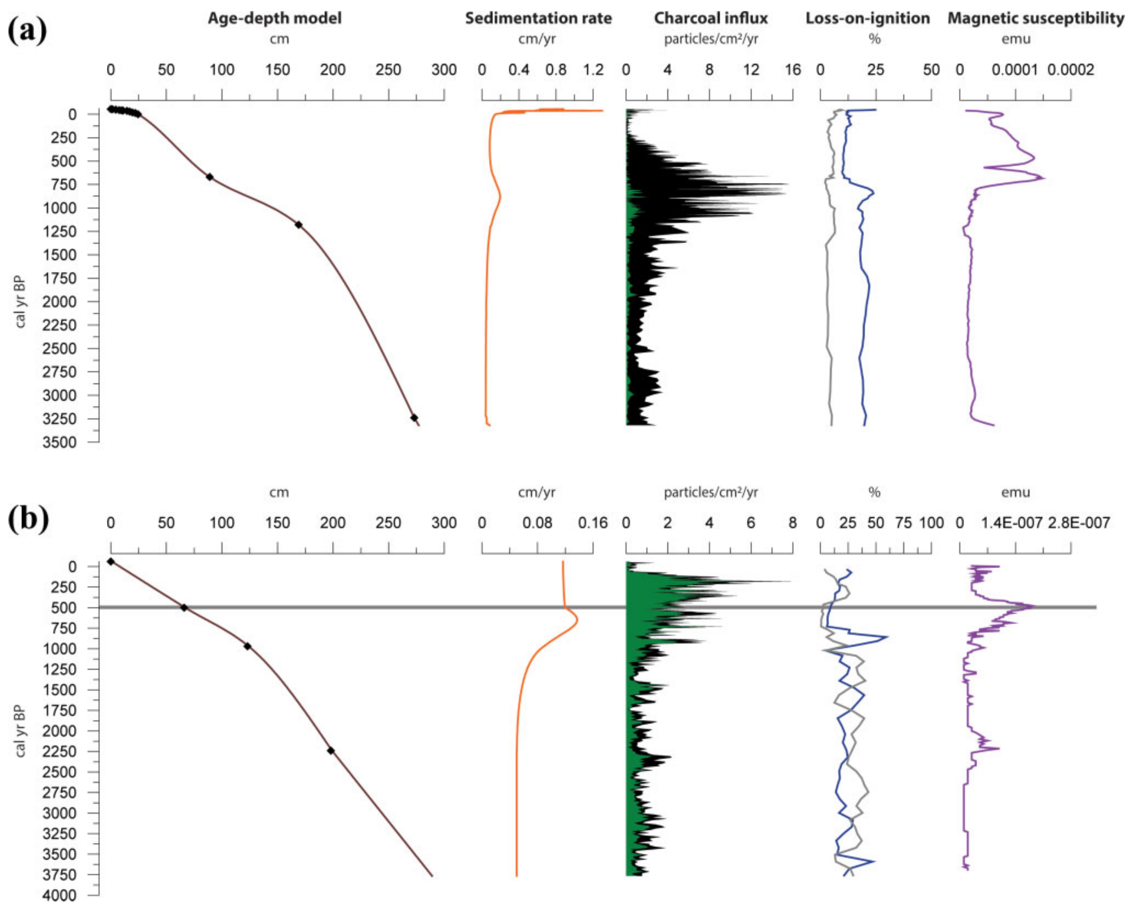

Figure 4. Age–depth model (brown curves; dates provided in Table 2), sedimentation rate (cm/yr; orange curves), total charcoal influx (particles/cm^2/yr; black curves), herbaceous charcoal influx (particles/cm^2/yr; green curves), loss-on-ignition (% organics, blue curves; % carbonates, gray curves), and magnetic susceptibility (electromagnetic units; purple curves) for (a) Lake Oswego (LO05A) and (b) Fish Lake (FL11E) cores (all the figures in color are available online).

However, by ca. 650 cal yr BP, tree and shrub percentages decrease to the lowest level of the record ($\sim$47%). From ca. 850–650 cal yr BP, *Pseudotsuga menziesii*-type decreases dramatically, along with less severe drops in *Thuja plicata*-type, *Tsuga heterophylla*, *Pinus*, and *Abies*. This drop is accompanied first by a rise in *Polystichum*-type, and later, by a rise in *Pteridium aquilinum*-type to its highest level in the record ($\sim$37%) at ca. 700 cal yr BP. After this, *Pteridium aquilinum*-type percentages drop sharply while *Alnus rubra*-type and Poaceae percentages rise sharply at ca. 350 ($\sim$38%) and 200 cal yr BP ($\sim$16%), respectively. Increases in several other herbaceous taxa also occur between 700 and 100 cal yr BP, including *Rumex*, *Plantago*-type, *Agoseris*-type, and *Salsola*-type.

After ca. 100 cal yr BP, the percent of trees and shrub pollen in the Lake Oswego core increases to above $\sim$80%, while percentages of herbaceous taxa generally drop, including Poaceae, *Pteridium aquilinum*-type, *Polystichum*-type, *Rumex*, and *Plantago*-type. Notable increases in *Pseudotsuga menziesii*-type, *Thuja*

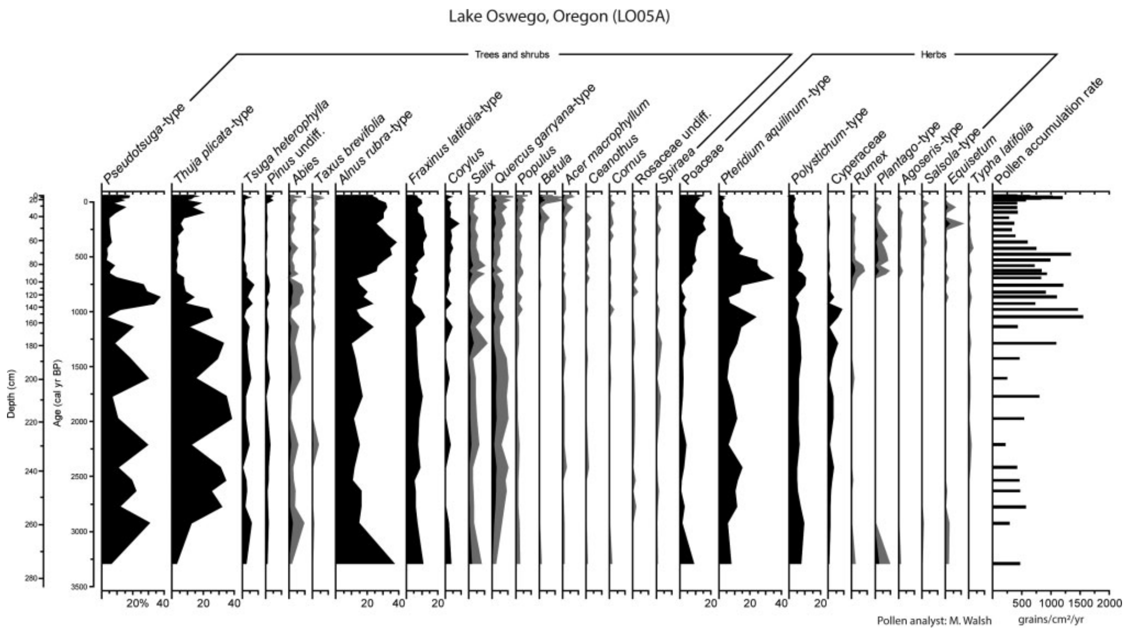

Figure 5. Select pollen taxa and spores (%) and total pollen accumulation rate (grains/cm^2/yr) from the Lake Oswego (LO05A) core plotted against depth (cm) and age (cal yr BP). Gray curves represent a 3× exaggeration of the solid black curve.

plicata-type, *Quercus garryana*-type, *Betula*, and *Acer macrophyllum* all occur after ca. 100 cal yr BP. *Alnus rubra*-type percentages also increase following a brief decline. A drop in *Pseudotsuga menziesii*-type percentages occurs between ca. 50 and 0 cal yr BP, followed by an increase after that time. Increases in most other tree taxa are observed during the last ~50 years of the record, including rises in *Thuja plicata*-type, *Tsuga heterophylla*, *Pinus*, *Abies*, *Taxus brevifolia*, *Salix*, *Quercus garryana*-type, *Populus*, *Betula*, and *Acer macrophyllum*. Slightly higher percentages of Poaceae are also observed during this interval. Notably, the percent of trees and shrub pollen increases to its highest level of ~88% during the most recent two decades of the record.

Charcoal influx values for the Lake Oswego core are generally low from the beginning of the record to ca. 2000 cal yr BP (average = 2.3 particles/cm^2/yr), with even lower values occurring between ca. 2750 and 2550 (average = 1.1 particles/cm^2/yr) (Figures 4 and 6). After ca. 2000 cal yr BP, influx values increase slowly until ca. 1200 cal yr BP (average = 2.9 particles/cm^2/yr), and then more rapidly until ca. 1050 cal yr BP (average = 6.7 particles/cm^2/yr). Following that, influx values decrease somewhat to a low of 3.9 particles/cm^2/yr at ca. 900 cal yr BP, followed by an increase to the highest values of the record between ca. 850 and 750 cal yr BP (average = 11.8 particles/cm^2/yr). Influx values are then variable but decrease from ca. 750 to 500 cal yr BP (average = 7.2 particles/cm^2/yr), and then decrease to almost zero by ca. 200 cal yr BP (average = 2.2 particles/cm^2/yr). Influx values remain low until ca. –10 cal yr BP (average = 0.21 particles/cm^2/yr), after which time they increase slightly toward present (average = 0.91 particles/cm^2/yr).

Overall, the proportion of charcoal identified as herbaceous in the Lake Oswego (LO05A) record is low (average = 8.2%) (Figures 4 and 6). More than one third (136/363) of the samples

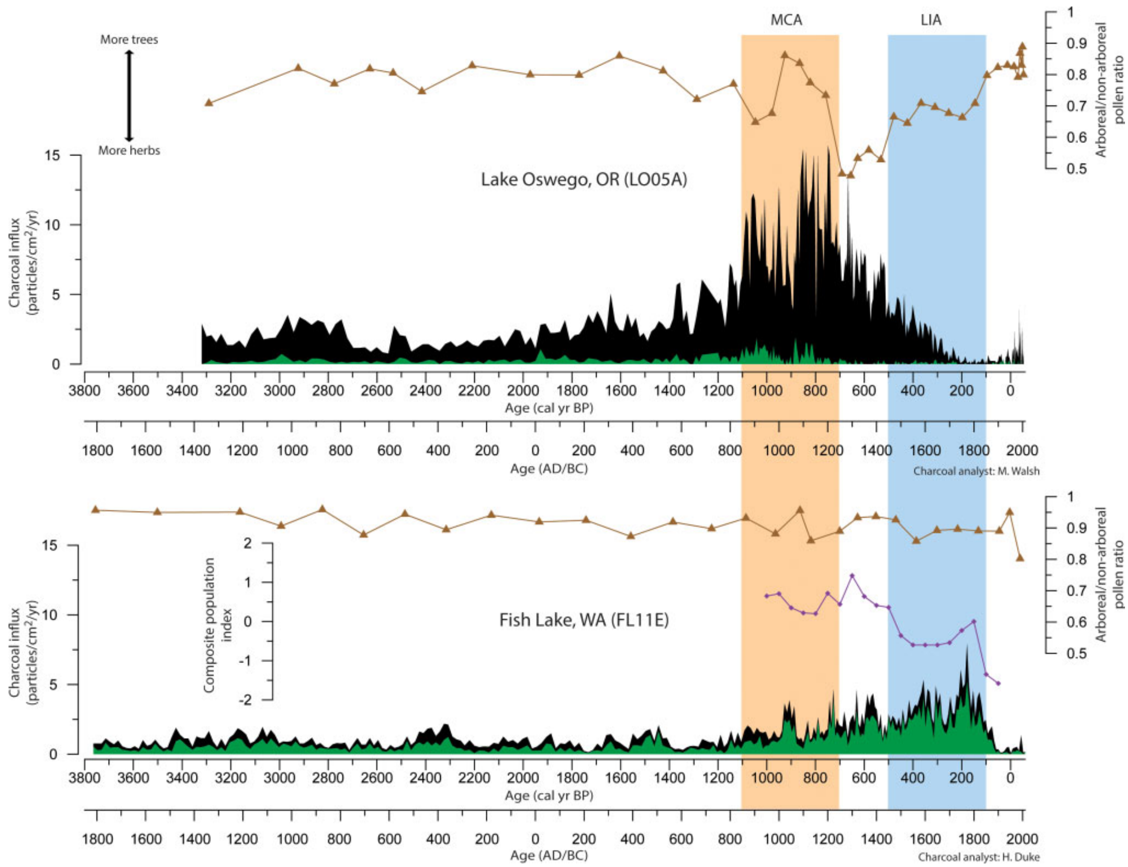

Figure 6. Total charcoal influx (particles/cm^2/yr; black curves), herbaceous charcoal influx (particles/cm^2/yr; green curves), and arboreal/non-arboreal pollen ratios (brown curves) plotted against time (cal yr BP and AD/BC) for the Lake Oswego (LO05A; top) and Fish Lake (FL11E; bottom) cores, and the composite population index for a small portion of the Southern Plateau of Washington (purple curve; Campbell, 1989; Scharf, 2009). Higher arboreal/non-arboreal pollen ratio values indicate more trees and less herbaceous plants (i.e. a more closed landscape) and lower values indicate fewer trees and more herbaceous plants (i.e. a more open landscape). The blue vertical shading indicates the generally cooler conditions of the Little Ice Age (LIA; 500–100 cal yr BP; Grove, 2001), and the orange vertical shading indicates the generally warmer, drier Medieval Climate Anomaly (MCA; 1100–700 cal yr BP; Mann et al., 2009) (all the figures in color are available online).

contain no herbaceous charcoal, while the samples that do have an average of only 13.2%. In general, herbaceous charcoal proportions are higher prior to 800 cal yr BP (average = 9.9%) than after (average = 6.8%), and are highest between ca. 1100 and 950 cal yr BP (average = 10.8%). Herbaceous charcoal content is lowest in the record after ca. 200 cal yr BP, with only 19 of the 94 samples containing any herbaceous charcoal (total = 26 herbaceous/191 total charcoal particles).

2 Case study: Fish Lake, WA

2.1 Chronology and lithology. Using the Mt. Saint Helens-W (MSH-W) tephra layer present in both Fish Lake cores, the top 10 cm of the FL11D short core were combined with the

2.79 m FL11A long core to create a continuous record from the site (hereafter referred to as core FL11E). Three ^{14}C AMS dates and an age of -61 cal yr BP (present = AD 1950) were used to develop the age–depth model for the FL11E core (Figure 4), which determined a basal age of 3780 cal yr BP. The average sample resolution of the FL11E core is 13.3 yr/cm. The age–depth model for the Fish Lake short core (FL11D) was developed using linear regression based on the accepted age of the MSH-W tephra (470 yr BP, AD 1480; Mullineaux, 1986), which was found at a depth of 60 cm, and the age of –61 cal yr BP (AD 2011) for the top of the core (age model not shown). Although the MSH-W tephra was not identified using microprobe analysis, we feel certain of its provenance given the age of an adjacent radiocarbon date in core FL11A (Table 2) and its similar depth in a nearby lake sediment core (Nelson et al., 2011).

The sedimentation rate of the Fish Lake (FL11E) core increases slowly from the base of the core to a depth of ~125 cm (ca. 3780–1000 cal yr BP), after which time it increases more quickly to a depth of 90 cm (ca. 700 cal yr BP). The sedimentation rate then decreases somewhat to a depth of 66 cm (ca. 500 cal yr BP), and remains constant above that. The Fish Lake core consists primarily of inorganic banded clayey gyttja ranging in color from greenish gray at the bottom of the core, to dark brown near the top. Loss-on-ignition results show that the organic content of the core ranges from a high of 59% to a low of 4%, with an average of 20% for the FL11E core. Organic content is variable from the start of the record to ca. 1050 cal yr BP, peaks at ca. 900 cal yr BP, and then sharply decreases and remains low above that. Carbonate content is variable until ca. 1100 cal yr BP (~12–43%), decreases and remains generally low until ca. 470 cal yr BP, peaks locally at ca. 350 cal yr BP, and then decreases to the top of the core. Several shell layers exist in the core and likely contribute to the variability in the carbonate values.

Magnetic susceptibility values are generally low from the start of the core to ca. 900 cal yr BP, with slightly higher values between ca. 2250 and 2000 cal yr BP. Values increase after 900 cal yr BP to the highest values of the record at 470 cal yr BP. This peak coincides with the presence of the MSH-W tephra layer in the core. Magnetic susceptibility values then decrease sharply and remain generally low until the top of the record, with some variability after ca. 200 cal yr BP.

2.2 Pollen and charcoal. The Fish Lake (FL11E) pollen percentages remain generally consistent throughout the entire record, with the exception of the last ~100 years (Figure 7). *Pinus* pollen dominates the record, making up between ~40% and 65% of the total. Although most of the *Pinus* pollen is undifferentiated, the large majority of that which could be identified as either subgenus *Pinus* or *Strobus* is the former, indicating that it likely came from ponderosa pine, which grows at the site today. In addition, a ponderosa pine needle was found at a depth of 55 cm, confirming its presence prior to Euro-American settlement. Also present in relatively high percentages are *Pseudotsuga/Larix*-type (~7%), *Abies* (~3%), *Juniperus*-type (~3%), *Alnus incana*-type (~6%), *Betula* (~5%), Poaceae (~5%), Cyperaceae (~3%), and *Artemisia* (~2%). Lesser percentages of *Tsuga heterophylla*, *Salix*, *Rhus*, *Sambucus*, *Populus*, *Salsola*-type, *Helianthus*-type, and *Typha latifolia*-type were observed, with even smaller amounts of a few other trees and herbs. The percent of trees and shrubs remains generally unchanged throughout the record (~85–95%) (Figure 6). Notable changes in the percentage of certain taxa prior to ca. 100 cal yr BP include the appearance of *Picea* in the record for the first time at ca. 3200 cal yr BP, a slight increase in *Juniperus*-type after ca. 2500 cal yr BP, a decrease in *Typha latifolia*-type after ca. 1000 cal yr BP, and an increase in *Salix* and *Rhus* after ca. 850 cal yr BP. The

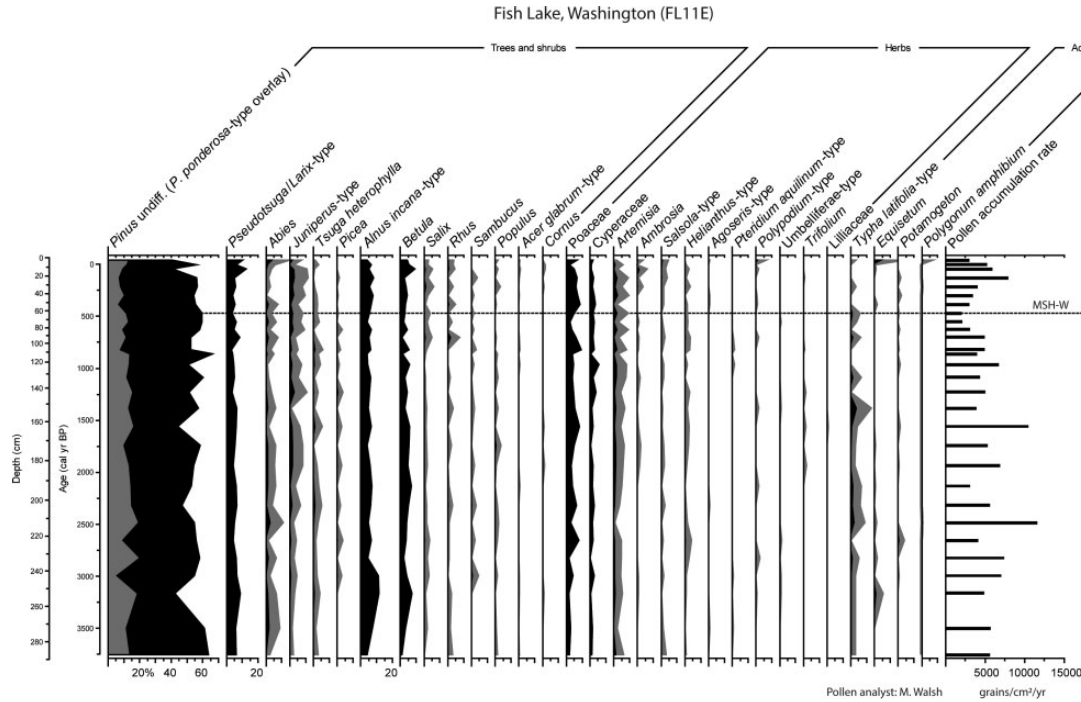

Figure 7. Select pollen taxa and spores (%) and total pollen accumulation rate (grains/cm^2/yr) from the Fish Lake (FL11E) core plotted against depth (cm) and age (cal yr BP). Gray curves represent a 3× exaggeration of the solid black curve. The Mount St. Helens-W tephra is indicated by the dashed horizontal bar.

deposition of the MSH-W tephra is followed by a drop in *Tsuga heterophylla* and *Picea*, as well as an increase in *Alnus incana*-type and Poaceae. These changes may be indicative of the impact that the MSH-W tephra had on the landscape (Zobel and Antos, 1997), with a decrease in the percentage of trees and shrubs immediately following the eruption and generally more open conditions surrounding the site at that time.

Charcoal influx values for the Fish Lake (FL11E) core are generally low but variable from the beginning of the record to ca. 1200 cal yr BP (average = 0.93 particles/cm^2/yr), with even lower values occurring between ca. 3000–2500 (average = 0.76 particles/cm^2/yr), 2250–2100 (average = 0.75 particles/cm^2/yr), and 1400–1300 cal yr BP (average = 0.45 particles/cm^2/yr) (Figures 4 and 6). Influx values then increase from ca. 1200–180 cal yr BP (average = 2.54 particles/cm^2/yr), reaching their highest value of 7.92 particles/cm^2/yr at ca. 180 cal yr BP. Periods of slightly lower influx values occur within this time frame, including between ca. 900–850 (average = 1.54 particles/cm^2/yr) and 550–500 cal yr BP (average = 2.01 particles/cm^2/yr). Influx values decrease sharply after ca. 180 cal yr BP to almost zero by ca. 50 cal yr BP. Influx values are lowest for the last $\sim$110 years of the record with an average of only 0.37 particles/cm^2/yr.

The overall proportion of charcoal identified as herbaceous is generally high throughout the Fish Lake (FL11E) record (average = 59.3%) (Figure 6). The majority of the samples (211/289) have herbaceous charcoal percentages $\geq$50%. Intervals with the lowest proportions of herbaceous charcoal occur between ca.

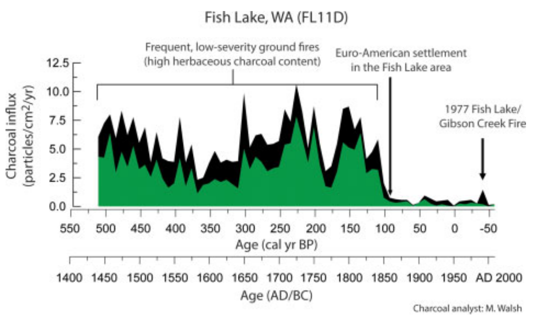

Figure 8. Total charcoal influx (particles/cm^2/yr; black curve) and herbaceous charcoal influx (particles/cm^2/yr; green curve) plotted against time (cal yr BP and AD/BC) for the Fish Lake (FL11D) short core. Note the steep drop in charcoal influx ca. 100 cal yr BP (AD 1850) at the time of Euro-American settlement in the Sinlahekin Valley (all the figures in color are available online).

3450–3300 (average = 49.8%), 2450–2200 (average = 43.9%), 1100–1000 (average = 49.8%), and 100 cal yr BP–present (average = 46.6%), while intervals with the highest herbaceous charcoal content occur between ca. 850–750 (average = 73.8%) and 550–250 cal yr BP (average = 76.4%). Only two samples contain no herbaceous charcoal, and both occur within the last 70 years. Additionally, only two samples contain only herbaceous charcoal, three and four charcoal particles, respectively, and occur within the last 35 years.

The Fish Lake (FL11D) short-core charcoal record is similar to that of the long core (Figure 8). Charcoal influx values are relatively high at the start of the record at ca. 515 cal yr BP (6.50 particles/cm^2/yr), but then generally decrease until ca. 375 cal yr BP (2.22 particles/cm^2/yr). Influx values then increase to their highest level of the record (10.2 particles/cm^2/yr) at ca. 230 cal yr BP, followed by a decline to a local minimum of 2.93 particles/cm^2/yr at ca. 190 cal yr BP. Influx values then increase again to 8.33 particles/cm^2/yr at ca. 160 cal yr BP, before decreasing dramatically by ca. 100 cal yr BP to 0.72 particles/cm^2/yr. Influx values remain extremely low from that time until present (average = 0.49 particles/cm^2/yr) with only one small rise in charcoal influx at –35 cal yr BP (1.38 particles/cm^2/yr). Herbaceous charcoal proportions are generally high for the short-core record, with an average of 60.5% prior to 100 cal yr BP, and an average of 49.1% after that time.

V Discussion

1 Late Holocene fire and vegetation history

Paleoenvironmental reconstructions from the Lake Oswego and Fish Lake study sites indicate that fire was a near-constant presence on the landscape during the late Holocene, at least prior to Euro-American contact and settlement (Figures 6 and 8). While it was not possible to statistically calculate fire frequency for the two records (Kelly et al., 2011), the reconstructions suggest that fires occurred at shorter intervals than the sampling resolution of the cores (i.e. Lake Oswego: average of 11.2 yr/cm; Fish Lake: average of 13.3 yr/cm). For Fish Lake, this estimate is consistent with tree ring studies from the SWA, which indicate mean fire-free intervals of ∼6–9 years during the pre-settlement era (Schellhaas et al., 2009), as well as research conducted elsewhere in the dry forests of the eastern Cascades that calculated mean fire-free intervals of as short as approximately seven years (Everett et al., 2000; Wright and Agee, 2004). Tree-ring-based fire frequency estimates are not available from the Willamette Valley proper; however, one study from the Willamette Valley foothills suggest pre-settlement fire-free intervals of ∼10–50 years (Robbins, 2005). Fire activity, however, did vary considerably within and between the two study sites during the late Holocene, and the likely influences of that variability are discussed below.

1.1 Lake Oswego, OR. The vegetation reconstruction from Lake Oswego suggests that a relatively dry Douglas-fir forest with some oak woodland existed near the site at the start of the record (Figure 5). Such ecosystems were widespread west of the Cascades during the early part of late Holocene, especially at lower elevations (i.e. Vancouver Island (Brown and Hebda, 2002a); Lower Columbia River Valley (Walsh et al., 2008); Willamette Valley (Walsh et al., 2010a); Oregon Coast Range (Worona and Whitlock, 1995). Fire activity remained generally low but consistent in the watershed until ca. 2000 cal yr BP (50 BC) (Figure 6), indicated by the relatively stable percentages of *Pteridium aquilinum* pollen until that time. *P. aquilinum* is a fern that typically grows in disturbed areas and thrives in forest openings created by fire (Franklin and Dyrness, 1988; Tiedemann and Klock, 1976), and in this case indicates that at least portions of the forest/woodland surrounding the site remained open. Given the stable percentages of most taxa and the relatively high arboreal/non-arboreal pollen ratios, it is likely that fires during this period were patchy in nature and had little overall impact on the surrounding forest beyond creating intermittent canopy openings and temporarily clearing the forest understory. However, the low herbaceous charcoal content of this part of the record (average = 11.1%) indicates that these fires were of high enough severity to burn trees and shrubs, and were likely the cause of the observed tradeoffs between *Pseudotsuga menziesii* and *Thuja plicata* as the dominant forest taxa. *P. menziesii* is less tolerant of low-light conditions than *T. plicata* and would have been outcompeted in areas not experiencing recent fire (Franklin and Dyrness, 1988).

After ca. 2000 cal yr BP, fire activity increased at Lake Oswego until ca. 750 cal yr BP (AD 1200); however, the fires were not of large enough size/severity to cause a fundamental change in the vegetation surrounding the site until after ca. 1500 cal yr BP (AD 450). With increasing fire activity after this time, forests near Lake Oswego became more open (as indicated by the drop in the arboreal/non-arboreal pollen ratio), primarily due to a decrease in the abundance of both *P. menziesii* and *T. plicata*. Concurrent increases in the abundance of *Alnus rubra* and *P. aquilinum* also signal greater openness, as both species would have thrived due to less competition for sunlight with the dominant over-story trees (Agee, 1993; Uchytil, 1989). The forest continued to open until ca. 1050 cal yr BP (AD 900), when a brief decline in burning led to a resurgence of *P. menziesii*, as well as smaller increases in *T. heterophylla*, *Pinus*, and *Abies*, as indicated by the higher arboreal/non-arboreal pollen ratios observed until ca. 850 cal yr BP (AD 1075).

Fire activity then intensified again between ca. 850 and 700 cal yr BP (AD 1100–1250) and had an even more profound impact on the local vegetation, causing first a drop in the dominant tree taxa (i.e *P. menziesii*, *T. plicata*, *T. heterophylla*, *Pinus*, *Abies*) and a subsequent increase in *P. aquilinum* and other herbs first, followed by an increase in Poaceae and *A. rubra* slightly later. The even lower herbaceous charcoal content of this part of the record (average = 5.5%) suggests that primarily trees and shrubs burned during this period, leading to the most open forest/woodland conditions found at the site during the past approximately 3300 years. Additional support of this interpretation comes from the higher-than-previous magnetic susceptibility values and lower-than-previous % organic values (Figure 4), and may have caused the increased sedimentation rate at this time. Higher magnetic susceptibility values likely indicate greater slopewash into the lake following more frequent and/or severe fires, which subsequently would have led to lower % organic values as the sediment was composed of a greater proportion of allochthonous (externally-derived) material.

After ca. 700 cal yr BP (AD 1250), the arboreal/non-arboreal pollen ratio increased as fire activity decreased at Lake Oswego (Figure 6). Burning within the watershed was almost nonexistent by ca. 200 cal yr BP (AD 1750), after which time the arboreal/non-arboreal pollen ratios rose dramatically to the highest levels of the record, indicating the final closure of the forests surrounding the site prior to logging and urban/suburban development in the Lake Oswego watershed ca. AD 1840 (see Walsh et al., 2010b for further details). This is illustrated by the increased abundance of *P. menziesii* and *T. plicata* and decreased abundance of Poaceae and *P. aquilinum* at that time.

1.2 Fish Lake, WA. Fire activity at Fish Lake remained generally unchanged from ca. 3800 to 1200 cal yr BP (1850 BC–AD 750; Figures 4 and 6). During this period, frequent, low-severity (or small) fires likely burned in the watershed with little impact on the vegetation, as indicated by the nearly constant and high arboreal/non-arboreal pollen ratios. The high herbaceous charcoal content during this period (average = 53.9%) indicates that fires were likely low-severity ground fires that did little more than keep the understory clear, perpetuating the survival of the *Pinus ponderosa*-dominated forest. The composition of the forest changed very little during this period, indicating that the "modern" forests of this region became established prior to ~3800 cal yr BP; this is documented by several other nearby vegetation reconstructions (Dalan, 1985a, 1985b; Mack et al., 1979; Prichard et al., 2009; Whitlock and Bartlein, 1997).

A general increase in fire activity followed at Fish Lake from ca. 1200 to 180 cal yr BP (AD 750–1770); however, unlike at Lake Oswego, this increase had little impact on the overall structure of the surrounding forest (Figures 6 and 7). During this period the average herbaceous charcoal content was even higher than earlier (65.9%), indicating that the number of fires or perhaps the spatial scope of burning increased, but not the severity of the fires. If fires had increased in severity, we would expect an increased proportion of woody charcoal. It is possible that the higher charcoal influx values observed in the part of the record were the result of greater amounts of charcoal being washed into the lake by increasing amounts of precipitation during the late Holocene, but this is unlikely given that the increase persists through both the Medieval Climate Anomaly (MCA; 1100–700 cal yr BP; AD 850–1250; Mann et al., 2009) and the Little Ice Age (LIA; 500–100 cal yr BP, AD 1450–1850; Grove, 2001) (discussed in detail in the following section). The sedimentation rate of the core does increase modestly after ca. 1200 cal yr BP (Figure 4); however, the major increase in charcoal influx occurs after it again decreases, so it is unlikely that this is the cause.

Fire activity declined sharply in the Fish Lake watershed after ca. 180 cal yr BP (AD 1770) and was almost entirely absent from the landscape by ca. 100 cal yr BP (AD 1850; Figures 6 and 8). As a result of this almost complete cessation of burning in the past 160 years, the forest around the site closed, which is illustrated by the rise in the abundance of *Pseudotsuga/Larix* and *Abies* pollen beginning ca. 50 cal yr BP (AD 1900) (Figure 7) and the initial increase in the arboreal/non-arboreal pollen ratio at ca. 20 cal yr BP (AD 1930) (Figure 6). The impacts of this are still visible at the site today (Figure 9), particularly along the north-facing side of the lake where formerly wide-spaced *P. ponderosa* trees have been slowly encroached upon by more shade-tolerant *P. menziesii* and *Abies grandis* (grand fir) trees (Franklin and Dyrness, 1988; Haeuser, 2014). The last pollen ratio value of the record is somewhat counterintuitive to this as it is the lowest of the record (implying that the forest was most open at that time), but it likely reflects 20th-century logging elsewhere within the Fish Lake watershed or nearby areas of the Okanogan National Forest.

2 Fire–climate–human interactions

2.1 Lake Oswego, OR. Late Holocene climate variability in the PNW likely influenced the fire

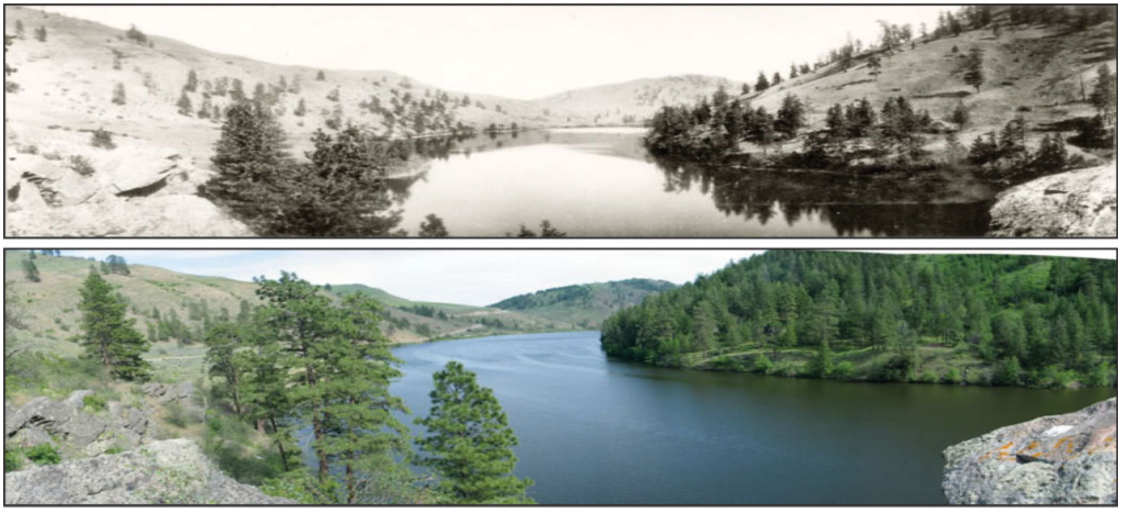

Figure 9. Photographs of Fish Lake taken in ca. 1906 (top; F. Matsura) and 2006 (bottom; D. Swedberg) looking east. Note the open landscape on the south shore of the lake in the earlier photograph and the dramatic increase in tree cover that has occurred by the time the later photograph was taken. Additional images available at: http://wdfw.wa.gov/lands/wildlife_areas/sinlahekin/gallery/sinlahekin_historical.php (all the figures in color are available online).

history of the two study sites through its effects on temperatures (and, thus, fire season length), drought, winds, and lightning. At Lake Oswego, fire activity was low during the early part of the late Holocene, ca. 3340–2000 cal yr BP (1390–50 BC), which was likely a response to the generally cool/wet regional conditions that prevailed as compared to earlier (Bartlein et al., 1998, 2014). Most vegetation reconstructions show that the modern forests of the PNW became established sometime between ca. 5000 and 3000 years ago, and are evidence of the cooling and moistening conditions at this time (Walsh et al., 2008, 2015; Whitlock, 1992). Cool conditions, however, never seem to completely exclude fire from the site during this period, which is also true at many other sites in the PNW (Hallett et al., 2003; Long et al., 1998; Prichard et al., 2009). Fire activity increased slowly during the next several hundred years and then sharply during the MCA. Subsequently, fire activity at the site dramatically decreased during the LIA (Figure 6). This trend is common in the PNW as numerous charcoal-based fire history reconstructions from a variety of environmental settings show both their highest and lowest levels of burning during the MCA and the LIA, respectively (Marlon et al., 2009; Walsh et al., 2015). For example, at Battle Ground Lake, located approximately 45 km NNE of Lake Oswego, the generally warm/dry conditions of the MCA (Cook et al., 2004; Mann et al., 2009) appear to have facilitated numerous fires, while the generally cool conditions of the LIA (Graumlich and Brubaker, 1986; Mann et al., 2009) led to an almost complete absence in burning (Walsh et al., 2008, 2010b). However, the climatic variability during neither the MCA nor the LIA were of sufficient length or intensity to cause a change in forest structure or composition at Battle Ground Lake. This is in direct contrast to the vegetation changes that occurred at Lake Oswego during these same climatic periods, which were the most dramatic of the $\sim$3340 year-long record.

It is possible that the reverse situation occurred, and that shifts in the Lake Oswego vegetation occurred prior to, and in fact led to, increased fire activity during the MCA and vice versa during the LIA. However, two lines of evidence suggest this is not the case. First, although the resolution of the charcoal and pollen records differ, the increase in fire activity leading up to the MCA occurs prior to the arboreal/non-arboreal pollen ratio reaching a level outside of its range of variability observed during the previous 2000 years (Figure 6). Second, sites in the PNW do not typically show major shifts in either vegetation structure or composition during the MCA or the LIA (Walsh et al., 2010b, 2015). However, at Lake Oswego fire activity varied widely enough during those climatic periods that it caused a fundamental change in the vegetation from a closed forest to a more open woodland or savanna. It seems clear that a fire regime shift was the catalyst necessary to induce this magnitude of a change on the landscape.

If a shift in vegetation did not cause the increase in fire activity at Lake Oswego, then what did? Lightning strikes are generally rare in the Willamette Valley at present (Rorig and Ferguson, 1999), and while the warmer/drier conditions of the MCA (Mann et al., 2009) may have led to increased convection and a greater number of lighting-ignited fires (as is projected under future climatic scenarios; Romps et al., 2014), it seems unlikely that this change alone could account for a more than doubling of fire activity at the site (measured in terms of charcoal influx values). It is perhaps more likely that late Holocene climatic variability mediated anthropogenic land-use activities near Lake Oswego, essentially making it more or less likely that human-ignited fires could burn seasonally dry vegetation (Kay, 2007).

The question, then, is why Native Americans would have purposely burned the forests and woodlands surrounding Lake Oswego. Prehistoric human use of fire is thought to have been widespread in the PNW and done for a variety of purposes (Boyd, 1999; Knox, 2000; Leopold and Boyd, 1999; Lepofsky et al., 2005). At higher elevations, fire was used to encourage berry yields (e.g. *Vaccinium* spp.; French, 1999; Mack and McClure, 2002) and clear trails through mountain passes (Norton et al., 1999), among other reasons. In the lower Columbia River and Willamette Valley regions of the PNW, ethnographic studies document the use of fire by the Chinookan and Kalapuyan people as part of their subsistence strategy (Boyd, 1999; Gahr, 2013). Camas grounds (*Camassia* spp.) were burned over to increase yields during subsequent harvests (Deur and Turner, 2005; Gritzner, 1994; Turner and Kuhnlein, 1983). Oak savanna was kept open through repeated burning that encouraged higher acorn yields (Ames, 2005a; McCarthy, 1993), and prairies were burned to create greater amounts of forage and, in return, higher game populations (Lyman, 2006; Norton, 1979a).

At Lake Oswego, fire was likely used by the Clackamas, Clowewalla, and Tualatin peoples during the late Holocene in order to promote the growth of important food resources and encourage the persistence of ecologically productive ecosystems (i.e. forest/woodland/prairie ecotones). Camas, a root crop that is high in carbohydrate and vegetable proteins, was an important food resource for these groups (Ames, 2005b; Gahr, 2013; Silverstein, 1990). The cooked tuber added sweetness to other foods and provided a balance to diets that were high in animal fats and proteins (Gritzner, 1994). Historically, and in remnant patches today, camas grows in seasonally moist environments along the edges of marshes, lakes, and rivers, as well as in wet meadows in *Pinus ponderosa* forest (Gritzner, 1994; Turner and Kuhnlein, 1983). Although no camas pollen was found in the Lake Oswego record (likely because the plants are insect pollinated and pollen is produced in small amounts), camas historically grew throughout the Willamette Valley and Portland Basin (Gritzner, 1994; Turner and Kuhnlein, 1983), and almost certainly grew near the many ponds and wetlands that existed around Sucker Lake prior to the raising of the lake level during the late 18th and early 19th centuries (Fulton, 2002). Numerous camas gathering grounds are documented to have existed near the site prior to Euro-American contact (see map in Boyd and Hajda, 1987). It is likely that these areas were burned as often as annually in order to keep them clear of trees and shrubs and to add essential nutrients to the soil (Norton, 1979a; Turner and Bell, 1971).

Fires were also likely set at Lake Oswego to encourage the growth of *Pteridium aquilinum*, or bracken fern, which flourishes in early seral stage communities (Franklin and Dyrness, 1988). *Pteridium*, or more specifically the rhizomes of the plant, is recognized in many parts of the world as a valued food source (Hodge, 1973; McGlone et al., 2005; May, 1978; Veitch, 1990) and by many tribes of western Washington (Norton, 1979b). The plant was abundant near Lake Oswego during the late Holocene as evidenced by its high pollen percentages, particularly following the major increase in fire activity that began ca. 1200 cal yr BP (AD 750). Additionally, frequent burning may have also made the forests and woodlands around Lake Oswego easier to navigate, making it possible to reach the shoreline and gather other important wetland resources such as *Sagittaria latifolia* (wapato), which likely grew in and around Sucker Lake and its adjacent ponds and wetlands (Boyd and Hajda, 1987; Silverstein, 1990). More open forests also would have encouraged higher populations of large game (e.g. deer, elk), which were a staple food source of peoples living in the lower Columbia River and Willamette Valley (Gahr, 2013; Nelson, 1974; Pettigrew, 1990; Silverstein, 1990). Lastly, fire may have been used to keep trails clear through the Lake Oswego area, given its strategic topography as a lower elevation cut-through between the Willamette and Tualatin Rivers (Fulton, 2002; Hamilton and Roulette, 2005).

What is known of late Holocene human history from the Northwest Coast and lower Columbia River archaeological record more broadly, and the Lake Oswego record more specifically, lends further support to our interpretation that the charcoal record from the site primarily reflects an anthropogenic land-use signal. Archaeological evidence from the Pacific period (ca. 3750–200 cal yr BP; 1800 BC–AD 1750) implies that the populations of the lower Columbia River, as well as the Northwest Coast as a whole, became more sedentary and focused on wetland and riverine environments during the late Holocene (Ames, 2005a; Campbell and Butler, 2010; Pettigrew, 1981, 1990), perhaps in response to the cooler/wetter climatic conditions at this time (Gavin and Brubaker, 2015; Bartlein et al., 1998). This increase in sedentism was accompanied by a rise in population density and the intensification of food harvesting, production, and storage (Ames, 2005b; Sobel et al., 2013). As a result, it is likely that fire, which was by far the most powerful prehistoric land management tool available (Kimmerer and Lake, 2001; Williams, 2002), would have been used more frequently to increase resource production in order to support this growing population.

While the archaeological record from Lake Oswego is limited, available evidence suggests repeated and perhaps sustained use of the area during the Holocene. Excavations of the Burnett and Pinson sites indicate that humans utilized an area adjacent to the east end of the lake during the early Holocene (ca. 9000/8000–6000 cal yr BP; 7050/6050–4050 BC), likely as a seasonal camp where they maintained hunting equipment, butchered animals and processed hides, and possibly processed plants (Burnett, 1991, 1995; Hamilton and Roulette, 2005). A more recent excavation of a former shoreline of Sucker Lake (now under Lake Oswego), however, suggests that at least some of the area around Lake Oswego was continuously utilized from the early Holocene until the late precontact period, ca. 300 cal yr BP (AD 1650; Punke et al., 2011). Interpretation of the artifacts recovered imply that the site served as a location for the manufacturing and maintenance of specialized tools (e.g. woodworking, butchering, or digging tools), the processing and preparation of food items, and the maintenance of fishing and hunting equipment (Punke et al., 2011). Given that hunting and plant processing activities were both taking place at the site, it is highly likely that human use of fire accompanied these activities.

Perhaps most compelling in terms of understanding human–landscape interactions at Lake Oswego is the timing of the major increase and decrease in fire activity during the late Holocene. The dramatic increase, which occurred between ca. 1200 and 700 cal yr BP (AD 750–1250) does not coincide with any known change in climate, but does coincide with estimates of the largest populations in the PNW prior to Euro-American settlement. Populations are thought to have peaked in the PNW around 950 cal yr BP (AD 1000) and decreased thereafter for unknown reasons (Ames, 2005a; Chatters, 1995). However, other estimates suggest that the peak occurred later, ca. 500 cal yr BP (AD 1450; Klein-Goldewijk et al., 2010). While pre-contact population estimates are uncertain, is it thought that at least 200,000 people inhabited the Northwest Coast (Boyd, 1990), with more than 15,000 Chinooks living along the lower Columbia River (Boyd, 2013). First documented contact between lower Columbia River Chinooks and Europeans occurred in AD 1792, although undocumented contact likely took place in the 17th and early 18th centuries (Brooks, 1876; Erlandson et al., 2001; Lang, 2013).

As elsewhere in the Americas, interaction between these groups triggered an almost immediate and massive population decline due to the effects of introduced disease (primarily smallpox and malaria) (Boyd, 1990). Populations in the lower Columbia River Valley are thought to have declined somewhere between 80% and 90%, with lower Columbia River Chinooks one of the most hard-hit groups (Boyd, 2013). Although it is plausible that population declines reduced fire activity at Lake Oswego, the paleofire evidence does not support this interpretation. By the time of the earliest documented smallpox outbreak, AD 1781 (Boyd, 2013), fire activity at the site was already near zero (Figure 6). The major decline in fire activity at Lake Oswego took place several centuries before this, with the most precipitous drop occurring between 500 and 200 cal yr BP (AD 1450–1750).

It may be that disease arrived in the PNW prior to direct contact between lower Columbia River populations and Europeans and was the cause of the observed drop in fire activity at Lake Oswego. Dobyns (1966) and Campbell (1989) hypothesize that smallpox may have spread north after its initial introduction into Mexico by Cortez in AD 1520 (see discussion in Boyd, 2013). If this is the case, the disease may have reached the PNW and within a matter of decades passed from one group to another along established trade routes, and could at least partially explain the declining fire activity after ca. 400 cal yr BP (AD 1550). Another explanation may be that a change in lifeways of the inhabitants of the PNW, more specifically their subsistence patterns, occurred as a result of European contact with the New World. It is well documented that European goods made their way to the PNW prior to contact with whites in the late 18th century (Erlandson et al., 2001; Lang, 2013; Sobel et al., 2013). A change in technology and the movement away from a reliance upon plant resources may also be reflected in the Lake Oswego fire reconstruction, instead of a decline in regional populations. However, without further excavation of the archaeological record from this site and others in the region, these hypotheses remain untested. What is clear is that after Euro-American contact and settlement of the Lake Oswego area, little to no fire activity occurred, at least not on the scale of the burning that took place prior to ca. 200 cal yr BP (AD 1750).

2.2 Fish lake, OR. Given the lack of variability in the Fish Lake pollen record during the late Holocene (prior to Euro-American settlement), it is difficult to discern any past vegetation–climate relationships at the site (Figures 4 and 6). It is clear, however, that the cooler conditions that began in the region ca. 5000–4000 cal yr BP (Chatters, 1998; Walker and Pellatt, 2008) led to the establishment of the modern vegetation at the site prior to the start of the record (Figure 7). Very few compositional changes occurred after that time, and none that can be specifically tied to known climatic shifts. In addition, little can be said about the influence of climate variability on the Fish Lake fire history prior to ca. 1200 cal yr BP (AD 750), except perhaps that fire activity was relatively low and stable during that time, which fits well with what is known about climate (Walker and Pellatt, 2008). There is evidence of a few "neoglacial" cooling events from the region, primarily marked by glacial advances in the Canadian Cordillera (Osborn, 1986; Ryder, 1987), but none of these are clearly reflected in the paleoenvironmental reconstruction from Fish Lake.

More notable are the changes that occurred at Fish Lake after ca. 1200 cal yr BP, but once again these are difficult to resolve with what is currently known about past climatic shifts in the region. In particular, fire activity increased at Fish Lake during the MCA; however, as with the Lake Oswego fire reconstruction, this increase is part of a larger trend that began several hundred years prior to the MCA and continued long after. In fact, fire activity continued to increase at Fish Lake to its highest levels well into the LIA (ca. 180 cal yr BP; AD 1770). If, indeed, climatic conditions in the interior PNW were cooler and wetter during the LIA as studies suggest (Luckman, 1986, 2000), then something other than climate variability is needed to explain this increase in fire activity. Admittedly, the climate during the LIA likely varied significantly enough that it was possible for fires to still ignite and burn during warmer, drier years, even if it was a period of overall cooler, wetter conditions (Walker and Pellatt, 2008). However, some research from the Columbia Plateau suggests a more local response to climatic changes associated with the MCA and the LIA (Chatters, 1998). An oxygen isotope-based record from the Rufus Woods Lake area indicates that precipitation increased during the MCA and subsequently decreased during the LIA (Scharf, 2010). If, indeed, effective moisture was lower on the Plateau than other areas of the PNW during the LIA, then this may help explain the rise in fire activity at Fish Lake at that time, although ignitions would have been less likely to start fires given the cooler temperatures.

Another explanation comes from Nelson et al. (2011), who reconstructed a 6000-year-long drought record from nearby Castor Lake, and identified a link between El Niño/Southern Oscillation (ENSO) variability and regional drought events during the late Holocene. As ENSO variability increased during this period (Moy et al., 2002), fires may have burned more frequently and easily due to periodic drought (Nelson et al., 2011; Walsh et al., 2015). Even if this is the case, this does not explain the precipitous drop in fire activity in both fire records from Fish Lake observed after ca. 180 cal yr BP (AD 1770), which coincides with the end of the LIA and a period of relatively high ENSO event frequency and strength in the PNW (Barron and Anderson, 2010; Walker and Pellatt, 2008). In particular, if lightning strikes, which are common at present in the dry eastern Cascades and Okanogan Highland forests and often ignite wildfires (Bartlein et al., 2008; Kay, 2007), were the primary ignition source for fires at Fish Lake during the late Holocene, then there is no reason why fire should have all but ceased ca. 100 cal yr BP (AD 1850). The timing of this drop was ∼60–75 years before organized fire suppression efforts began (Everett et al., 2000; Hessburg et al., 2005).

Equally important as lightning are human ignitions, which occur frequently in the dry forests of the eastern Cascades (Bartlein et al., 2008). Humans have inhabited the Okanogan region of the Southern Plateau for the past ∼11,000–12,000 years (Baker, 1990; Harder et al., 2009; Prentiss and Kuijt, 2004a) and it is likely that changes in the frequency and intensity of past human-ignited fires are reflected in the Fish Lake record. Unfortunately, no dated archaeological evidence exists from the immediate vicinity surrounding Fish Lake. There is some evidence of prehistoric land use in the SWA in the form of circular depressions, indicative of pit houses, and culturally modified trees (Oliver, 2014; Volkenand et al., 2009), and much ethnographic and historic literature on the original inhabitants of the Okanogan region (Baker, 1990; Cline et al., 1938; Hudson, 1990), but little formal archaeological work has been undertaken here. However, it is possible to draw some conclusions about possible human influences on the fire history based on the regional archaeological, ethnographic, and historic literature.

The native peoples who inhabited the Southern Plateau are described as complex hunter-gatherers, meaning, in part, that they were relatively sedentary but moved seasonally to procure resources (Binford, 1980; Prentiss, 2012; Prentiss and Kuijt, 2004b). Archaeologic research shows that permanent winter/early spring villages consisting of subterranean pit houses were located primarily along major waterways, with tribes moving to upland environments during summer and fall (Ames et al., 1998). This pattern appears to have been in place by ca. 5000 yr BP (3050 BC); however, it was only after ca. 3600–3500 yr BP (1650–1550 BC) that the delayed-consumption collector strategy, which involved procuring and storing large amounts of resources (e.g. salmon, roots), was firmly in place on the Southern Plateau (Campbell, 1985; Chatters, 1995; Prentiss, 2012). As in areas of western Oregon, Washington, and British Columbia, camas grew in many parts of the Plateau and Intermontane Northwest and was one of the most highly sought after and frequently traded resources (Gritzner, 1994; Hudson, 1990; Thoms, 1989). Fire was almost certainly used as a management tool to increase the productivity of camas and other important root crops (Lepofsky and Peacock, 2004; Turner, 1999), although there is little mention of its use in existing ethnographic accounts of the Sinkaietk or Southern Okanogan (Cline et al., 1938; Hudson, 1990). However, other accounts indicate the use of fire for such purposes by neighboring tribes like the Colville, Nez Perce, Kalispel, and Coeur d'Alene (Boyd, 1999; Cline et al., 1938, Lahren, 1998; Marshall, 1999; Robbins, 1999), so it is probable that it was used by the inhabitants of the SWA, given that many resources respond well to fire grow there today and presumably did in the past (Visalli, 2003).

It is also likely that fires were ignited by travelers on the Southern Plateau to clear trails that served as corridors connecting areas of settlement with those where seasonal resources were harvested, and along trade routes, which was a major component of Plateau culture (Hayden and Schulting, 1997). Some evidence of prehistoric and historic single-track trails have been found in the SWA (Boyd, 2010; Volkenand et al., 2009), and even today the road through the area is an important low-elevation corridor between the Southern and Northern Plateau. Frequent firing would have made passage through the forest easier, first on foot and then on horseback by the early 18th century (Walker and Sprague, 1998); however, few formal studies on trails exist from the PNW (see Norton et al., 1999 for an example) and none from the Okanogan region. Additionally, fire was in all probability used to increase browse for deer and elk in the SWA, as the grassy understory of the ponderosa pine-dominated forest would have responded well to it, leading to decreased tree density and increased shrub and herb coverage (Hessburg et al., 2005). Hunting of ungulates was an important component of the subsistence strategy on the Plateau (Chatters, 1998) and is reflected in several pictographs from the area (Corner, 1968; Hudson, 1990). Beginning in 1913, much of the Sinlahekin Valley was designated as a mule deer reserve, which attests to the abundance of game in the area, and the SWA remains popular for hunting today (WDFW, 2017).

Late Holocene population estimates are generally more available for the Plateau as compared to the Northwest Coast and may shed light on some of the observed changes in fire activity at Fish Lake. Most archaeological and demographic work indicates that populations were low on the Plateau prior to ca. 5000–4000 yr BP (3050–2050 BC) but increased after that, particularly after ca. 2000 yr BP (50 BC), peaking between ca. 1800 and 800 yr BP (AD 150–1150) (Ames, 2000; Chatters, 1995). This is coincident with the initial increase in fire activity at Fish Lake ca. 1200 cal yr BP (AD 750), and may indicate a greater focus on the plant resources near the site and the use of fire to manage them. Populations are then thought to have decreased during the MCA, as illustrated by the Campbell (1989) population estimate (Figure 6), as well as by Chatters (1995) and Ames (2000). Several studies indicate the abandonment of a large area of the Plateau by ca. 900–700 yr BP (AD 1050–1250), likely a result of the warmer/drier conditions associated with the MCA, which may have reduced the productivity of Pacific fisheries (Chatters, 1995; Prentiss, 2012). Without reliable salmon runs, the harvesting and storage of root crops, berries, and other plant resources, as well as hunting, would have been more heavily relied upon, and the places where those resources grew or where prey browsed may have required more intensive management (Lepofsky and Peacock, 2004). This would explain why fire activity continued to increase at Fish Lake during the MCA, even if populations decreased overall.

The Campbell (1989) estimate shows that populations in the Rufus Woods study area again increased near the end of the MCA (between ca. 800 and 600 cal yr BP (AD 1150–1350)), but then decreased until ca. 450 cal yr BP (AD 1500). This latter drop is not reflected in the Fish Lake fire reconstruction; fire activity instead continued to increase at this time. It could be that changes in fire activity at the site are not representative of population changes, but instead reflect changes in the organization of villages and related subsistence strategies. Notable changes have been documented through much archaeological work in the mid-Fraser River Valley and other parts of the Northern Plateau, showing that larger, aggregated lowland pithouse villages existed and fewer root-roasting facilities in upland areas existed between ca. 1600 and 800 yr BP (AD 350–1150) (Lepofsky and Peacock, 2004), followed by a return to smaller, more dispersed settlements after that time (Kuijt and Prentiss, 2004). These changes were likely linked to climatic shifts and related changes in salmon abundance; however, the fire activity at Fish Lake does not exactly match up with the timing of these observed changes in the archaeological record.

The fire reconstruction from Fish Lake corresponds with what is known about population trends on the Plateau after ca. 500–400 yr BP (AD1450–1550). It seems that at this time populations again increased, perhaps as salmon runs recovered as a result of cooler/wetter conditions associated with the LIA (Chatters, 1995; Kuijt and Prentiss, 2004). Figure 6 shows that populations in the Rufus Woods area stabilized and then increased after ca. 400 cal yr BP (AD 1550) in concert with fire activity at Fish Lake (Campbell, 1989; Scharf, 2002). Although the timing is different than at Lake Oswego, the sharp decline in fire activity observed at Fish

Lake beginning ca. 180 cal yr BP (AD 1770; Figure 8) matches well with Campbell's population estimate and almost certainly indicates the arrival and impact of disease on populations in this part of the Southern Plateau; the first documented smallpox epidemic also occurred in AD 1770s (Boyd, 1998). Some researchers hypothesize that the Rocky Mountains acted as a geographic barrier and delayed the arrival of disease to this region of the PNW; however, once diseases arrived, a rapid decline in populations on the Plateau followed, with most tribes decimated by the mid- to late 19th century (Boyd, 1998). Fire activity at Fish Lake reached near zero by ca. 100 cal yr BP (AD 1850), which marks the final removal of any remaining "Indian" influence from the land, as it coincides with the period of Euro-American settlement in the Sinlahekin Valley, and the creation of the Colville Reservation and development of allotments within the SWA (Beckham, 1998; Gubser, 1905; Miller, 1998; Waring, 1936). Almost no fires have occurred at the site since AD 1850, with the exception of the Fish Lake/Gibson Creek fire which burned in the watershed on July 27, 1977, the result of an escaped campfire. The near-absence of herbaceous charcoal is consistent with the fact that this fire burned at a high severity (Figure 8).

VI Conclusions

While climatic influences are always important for determining factors such as length of the fire season and potential land cover, climate variability during the past $\sim$3800 years seems to have only marginally influenced the fire history of the two study sites. This is most evident at Lake Oswego during the MCA and the LIA when fire activity, respectively, substantially increased and decreased. These climatic periods are known to have caused some of the most widespread and well-documented shifts in fire activity in the PNW (Marlon et al., 2009; Walsh et al., 2015); however, at Fish Lake a very different trend in fire activity occurred. By going one step further and evaluating these records within the context of the known archaeological, ethnographic, and historical history, it becomes clear that humans were likely the primary disturbance agent at both sites during the late Holocene, particularly after ca. 1200 cal yr BP (AD 700). Although it is impossible to determine with absolute certainty that the paleoenvironmental histories from the two study sites were influenced by human actions prior to Euro-American settlement, it seems likely that they were, and for varying reasons. To further test our hypotheses regarding the timing and causes of increases and especially decreases in fire activity, like those witnessed at Lake Oswego and Fish Lake, we urge that future studies make use of a similar interdisciplinary approach to investigate the effects of contact, the spread of disease, and Euro-American settlement in the PNW and other regions of North America. As a result of these kinds of studies, we will be forced to rethink what we know about pre-Euro-American settlement fire regimes, which influences the options considered for landscape restoration and opens the door for greater inclusion of traditional ecological knowledge and wisdom (Bachelet et al., 2011; Turner et al., 2000).

While the frequency of fire at the two sites appears similar, the high proportion of herbaceous charcoal observed in the Fish Lake record indicates the fires that burned its watershed during the late Holocene were different than those at Lake Oswego. High-severity fires in the Lake Oswego watershed burned more trees and shrubs, and caused a fundamental shift in the vegetation at the site from ca. 900–600 cal yr BP (AD 1050–1350). Low-severity fires at Fish Lake seemingly kept the status quo and helped perpetuate the open ponderosa pine-dominated forest observed at the time of settlement. Even when fire activity increased after ca. 1200 cal yr BP (AD 750), the relative proportion of wood to herbaceous charcoal recorded in the Fish Lake reconstruction did not change at this time, so it is likely that fires only became more frequent in the watershed, but did not increase in severity. Only the AD 1977 Fish Lake/Gibson Creek Fire stands out as being different from the previous ~3800 years of fire activity recorded at Fish Lake. We argue that without the identification and quantification of the relative proportion of the different charcoal morphotypes encountered in the record, the differences in fire regimes would not be as distinct, and, perhaps, the likely source of those fires would have remained less clear as well. From our viewpoint, the benefits associated with identifying and quantifying different charcoal morphotypes, at least with respect to separating herbaceous from woody charcoal, far outweigh the costs and effort. We therefore recommend that differentiating between key morphotypes be undertaken in all future charcoal-based fire history studies.

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