1200 years of fire and vegetation history in the Willamette Valley, Oregon and Washington, reconstructed using high-resolution macroscopic charcoal and pollen analysis

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Abstract

High-resolution macroscopic charcoal and pollen analyses were used to reconstruct the fire and vegetation history of the Willamette Valley for the last 1200 years. Presented in this paper are three new paleoecological reconstructions from Lake Oswego, Porter Lake, and Warner Lake, Oregon, and portions of previous reconstructions from Battle Ground Lake, Washington, and Beaver Lake, Oregon. The reconstructions show that prior to Euro-American settlement vegetation and fire regimes were influenced by a combination of natural and anthropogenic factors. Battle Ground Lake shows a stronger influence from climate, while Lake Oswego, Beaver Lake, Porter Lake, and Warner Lake were more controlled by human activity. However, human-set fires were also modulated by regional climate variability during the Medieval Climate Anomaly and the Little Ice Age. Fire reconstructions from Battle Ground Lake, Lake Oswego, Beaver Lake, and Porter Lake imply that fires were infrequent in the Willamette Valley 200–300 years prior to Euro-American settlement. The decline of Native American populations due to introduced disease may have led to this reduction in fire activity. The prehistoric record from Warner Lake, however, indicates that fires in the foothills of the Cascade Range were more frequent than on the valley floor, at least until ca. AD 1800. The historic portions of the reconstructions indicate that Euro-American land clearance for agriculture and logging produced the most dramatic shifts in vegetation and fire regimes. All five records indicate that few fires in the Willamette Valley have occurred since ca. AD 1930, and fires today are predominantly grass fires.

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1. Introduction

The current vegetation of the Willamette Valley is vastly different from that seen by 19th-century Euro-American explorers and settlers. Survey notes from the General Land Office (GLO) indicate that pre-settlement vegetation (ca. AD 1850) was a complex mosaic of Quercus (oak) savanna and woodland, grasslands ('prairie' ranging from moist to dry), coniferous upland forest, and extensive riparian forests (Habeck, 1961; Towle, 1982; Christy et al., 1997). Today, only small remnants of these ecosystems remain, precariously perched between rapidly expanding urban and agricultural areas (Hulse et al., 2002). Numerous studies have shown that over the past ca. 150 years, shrubs and trees have established in former wet and upland prairie, and conifers have come to dominate former oak savanna and woodland (Thilenius, 1968; Cole, 1977; Frenkel and Heinitz, 1987; Hibbs et al., 2002). The removal of fire, both naturally- and human-ignited, from these ecosystems is partially, if not entirely, responsible for the magnitude of change seen (Habeck, 1961; Johannessen et al., 1971; Towle, 1982), but the question remains as to how much of the prehistoric fire regime was the result of human modification of the landscape.

Few records of any kind are available to detail the fire history of the Willamette Valley prior to Euro-American settlement. Limited historical records, mainly journal entries by early explorers (ca. AD 1800), make reference to areas of scorched vegetation and attribute these fires to Native Americans (e.g., Wilkes, 1845; Douglas, 1959). Ethnographic studies document the use of fire by the native inhabitants as a means of encouraging the growth of food plants, hunting and warfare tactics, as well as other uses (Boyd, 1999), but the spatial and temporal details of the burning remains unknown (Whitlock and Knox, 2002). Dendrochronological studies that provide a record of past fires on the valley floor are sparse due to the lack of long-lived trees. In a synthesis of ten tree-ring-based fire-history studies from western Washington and Oregon, including studies in valley foothill forests (Impara, 1997; Weisberg, 1997), Weisberg and Swanson (2003) identified four general periods of fire activity: ca. AD 1400s to 1650, widespread burning; ca. AD 1650 to 1800, reduced...
burning; ca. AD 1800 to 1925, increased fire activity; and ca. AD 1925 to present, limited burning. A recent study specifically targeting low-elevation Willamette Valley fringe forests, however, suggests that pre- to postsettlement burning patterns were more spatially variable than Weisberg and Swanson (2003) propose (J. Kertis, personal communication).

In this paper, we use high-resolution macroscopic charcoal and pollen analyses to reconstruct the fire and vegetation history of the Willamette Valley for the last 1200 years. Presented in this paper are three new paleoecological reconstructions from Lake Oswego, Porter Lake, and Warner Lake, Oregon, and portions of reconstructions from Battle Ground Lake, Washington (Walsh et al., 2008), and Beaver Lake, Oregon (Walsh et al., 2010). The purpose of this study was to better understand the fire and vegetation history of the Willamette Valley during the late Holocene with consideration of the roles of climate variability and anthropogenic activities on those histories. This was done by evaluating our reconstructions within the framework of known regional climate shifts and human activity over the last 1200 years. Additional consideration was given to the interplay between climatic variability, human-induced landscape change, and resource (i.e., food) availability.

2. Study area

2.1. Background

The Willamette Valley is a broad structural depression that lies between the Coast and Cascade ranges of northwestern Oregon and southwestern Washington (Fig. 1) (Orr and Orr, 1999). Bounded by the Lewis River to the north, it stretches ~210 km south to Cottage Grove, Oregon, and is typically 40 to 65 km wide with an average elevation of ~90 m above sea level (a.s.l.). The Willamette Valley gently slopes to the north and is drained by the Willamette River, which flows into the Columbia River at Portland. Small hills mark the landscape, which otherwise consists of broad alluvial surfaces (Balster and Parsons, 1968).

Fig. 1. (A) Map of the Pacific Northwest showing the location of the study area (gray box) and the study sites (black dots), and (B) map of the Willamette Valley showing the location of the five study sites.
The climate of the Willamette Valley, as well as the rest of the Pacific Northwest, is characterized by cool wet winters and warm dry summers. Annual precipitation is influenced by the position of the polar jet stream and the contraction and expansion of the northeastern Pacific subtropical high pressure system (Mitchell, 1976; Mock, 1996). In winter, the Pacific subtropical high contracts and the polar jet stream shifts southward to the latitude of the Pacific Northwest, enhancing precipitation in the region. In summer, the jet stream shifts northward as the subtropical high expands (due to increasing seasonal insolation) and suppresses precipitation. The Willamette Valley sits in the rain shadow of the Coast Range and receives an average of 110 cm of precipitation annually, approximately 89% of that between the months of October and May (Western Regional Climate Center, 2009). Precipitation between June and September is infrequent, and a mild summer drought is typical. Temperatures are fairly mild in the Willamette Valley, with an average July temperature of ~19 °C and an average January temperature of ~4.5 °C (Western Regional Climate Center, 2009), although averages vary slightly from north to south. Although somewhat rare, lightning-ignited fires typically occur in the Pacific Northwest during late summer and early fall when effective moisture is lowest and ground heating, which leads to convectional thunderstorms and lightning, is greatest (Bartlein et al., 2008) (see Section 5.1 for further discussion).

The climate of the Pacific Northwest has varied considerably during the last 1200 years, although the exact cause of these variations is not clear. Two relatively well-documented, centennial-scale climate change events are the Medieval Climate Anomaly (ca. 1100–700 cal yr BP [ca. AD 850–1250]; Mann, 2002) and the Little Ice Age (ca. 500–100 cal yr BP [ca. AD 1450–1850]; Grove, 2001). Evidence of the Medieval Climate Anomaly in the western United States comes from tree-ring records (Graumlich, 1993; Stine, 1994; Cook et al., 2004), lake-sediment records (Mohr et al., 2000; Brunelle and Whitlock, 2003), and changes in treeline (Leavitt, 1994). Cook et al. (2004), using annually-resolved tree ring records to extend the Palmer Drought Severity Index to ca. 1200 years ago, calculated the annual percent of the western United States affected by drought from AD 800 to the present. In doing so they provide evidence of substantial periods of elevated aridity in the western United States during the Medieval Climate Anomaly; the four driest periods were centered on AD 936, 1034, 1150, and 1253.

Evidence of cooler temperatures and greater precipitation in the region associated with the Little Ice Age comes from multi-proxy temperature reconstructions (Jones et al., 2001), tree-ring dated glacial advances (Luckman, 1995; Wiles et al., 1999) and tree-ring records (Graumlich and Brubaker, 1986; Graumlich, 1987). Cross-dated subfossil wood from glacial forefields and times of moraine stabilization show several “Little Ice Age” glacial advances in western Prince William Sound, Alaska, during the last 1000 years (Wiles et al., 1999); the first ca. AD 1200–1300, the second ca. AD 1600–1700, and the third AD 1874–1895. Tree-ring data from Graumlich and Brubaker (1986) in Longmire, Washington (46°47'N, 121°44'W, 842 m a.s.l.) show that cool episodes occurred between AD 1600–1650, 1700–1760, and 1860–1900, and that the mean reconstructed temperature (AD 1590–1913) was almost 1 °C lower than the mean temperature of the observed record (AD 1914–1979). Their record shows a distinct rise in temperatures (ca. AD 1840) and a decrease in snow accumulation (ca. AD 1900), marking the end of the Little Ice Age in the Pacific Northwest.

GLO land survey records divide the presettlement vegetation of the Willamette Valley into five general types: riparian forest, prairie, oak savanna, oak woodland, and upland (coniferous) closed forest (Habec, 1961; Johannessen et al., 1971). Kilometer-wide riparian forests once covered the active floodplains of the Willamette River and its tributaries (Towel, 1982; Sedell and Foggatt, 1984). The most common trees were Populus trichocarpa (black cottonwood), Fraxinus latifolia (Oregon ash), Salix spp. (willow), Alnus rubra (red alder), Pseudotsuga menziesii (Douglas-fir), and Acer macrophyllum (big-leaf maple), with an understory of shrubs, including Spiraeea douglasii (hardhack), Berberis aquifolium (Oregon grape) and Sambucus glauca (elderberry) (Franklin and Dyrness, 1988; Frenkel and Heinitz, 1987). Seasonally wet and upland prairie were also widespread on the valley floor and were dominated by Deschampsia cespitosa (tufted hairgrass), but also supported numerous other herbaceous plants (Habec, 1961; Streetfield and Frenkel, 1997). Oak savanna, dominated by Quercus garyryana (Oregon white oak) with the occasional Quercus kelloggii (California black oak) and Pseudotsuga menziesii (Douglas-fir), covered the rolling hills of the valley and lower Coast and Cascade Range foothills (Franklin and Dyrness, 1988). Oak woodland was also found in the valley and was more densely populated with Quercus trees than savanna (Habec, 1961). Closed upland forests dominated at higher elevations along the eastern and western slopes of the valley, with Pseudotsuga menziesii as the dominant species, and Acer macrophyllum, Tsuga heterophylla (western hemlock), Thuja plicata (western red cedar), Quercus garyryana, and Cornus nuttallii (dogwood) also present (Habec, 1961). Additionally, Pinus ponderosa (ponderosa pine) grew on a range of sites from flooded valley bottoms to oak savanna and woodland, and in the lower foothills of the Coast and Cascade ranges (Johannessen et al., 1971; Hibbs et al., 2002). Botanical nomenclature follows Hitchcock and Cronquist (1973).

Archaeological evidence from the Willamette Valley and the lower Columbia River Valley (the portion of the valley immediately to the south and north of the Columbia River) suggests that human populations grew larger and more sedentary during the late Holocene (ca. 3000 cal yr BP — Euro-American contact) (Beckham et al., 1981; Pettigrew, 1990; Ames, 1994; Connolly, 2009). Many settlement sites in the Willamette Valley appear to have been continuously occupied for the last 2000–3000 years, with activities focused on the seasonal processing of vegetable foods (O’Neill et al., 2004). In the early 19th century, Kalapuyan-speaking tribes inhabited most of the Willamette Valley in elongated territories extending from the Willamette River to the Coast or Cascade Range and incorporated river channel, floodplain, and mountains (Zenk, 1990). These groups subsisted by fishing, hunting, and gathering the natural resources found in the valleys and surrounding montane areas, such as the bulb of Camassia spp. (camos lily) and other root crops, nuts, and berries (Zenk, 1990). Native inhabitants followed the seasonal availability of different food sources and used fire as a means of encouraging the growth of many plants (Boyd, 1999; Leopold and Boyd, 1999). In contrast to the Kalapuyans, Chinookan-speaking tribes were gathered in large numbers along both sides of the lower Columbia River and its tributaries at the time of Euro-American contact (Aikens, 1993). Fish was a main staple and settlements were more permanent (Boyd and Hajda, 1984; Pettigrew, 1990).

European contact led to a rapid decline in native populations caused by the outbreak of several epidemics beginning as early as AD 1770 (Boyd, 1985, 1990). Down from a pre-contact population estimate of 16,000, Kalapuyans numbered only 600 in AD 1841 (Wilkes 1926; Boyd, 1990). By AD 1830–1841 the tribal population of the Willamette Valley and lower Columbia River Valley had declined by ~92% (Boyd, 1990). In the 1850s and 1860s, the remaining small populations were moved to reservations in Oregon and Washington, and land in the Willamette Valley was converted to agricultural and homesteads (Beckham, 1990; Marino, 1990). Fires continued to occur as a result of Euro-American land-use activities including land clearance, but by AD 1933, fire suppression efforts had become very successful (Morris, 1934). Today, most fires occur as a result of accidental human ignition or field burning, but lightning-started fires are important in the upland areas surrounding the valley floor (Hardy et al., 2001; Bartlein et al., 2008).
2.2. Study sites

The five study sites examined lie along a north-south transect through the valley (Fig. 1). Battle Ground Lake, Washington (45°48′17″N, 122°29′38″W, 154 m a.s.l.), located approximately 30 km north of the city of Portland sits in a remnant volcanic crater of late Pleistocene age (See Table 1 for site information, Fig. 2A) (Wood and Kienle, 1990). This closed-basin lake is surrounded by a second-growth forest of Pseudotsuga menziesii and Thuja plicata, with scattered Tsuga heterophylla, Abies grandis, Picea sitchensis, Alnus rubra, Acer macrophyllum, Fraxinus latifolia, Salix spp., Corylus cornuta, Cornus nuttallii, Spirea douglasii, and Polystichum (sword fern) (see Barnosky, 1985 and Walsh et al., 2008 for further detail). The site has been a popular recreation destination since the early 20th century and is now part of the Washington State park system (Allworth, 1976).

Lake Oswego, Oregon (45°24′40″N, 122°39′58″W, 30 m a.s.l.), is located approximately 13 km south of the city of Portland and sits in a depression created by the Missoula Floods (presumably the lake formed sometime after the cessation of the flooding) (Johnson et al., 1985) (Table 1, Fig. 2 B). Originally named Sucker Lake, it was surrounded by prairie and oak savanna at the time of settlement. The dam raised the water level by several meters and increased its length from approximately 4.4 to 5.6 km (City of Lake Oswego, 2007). The dam raised the water level by several meters and increased its length from approximately 4.4 to 5.6 km (City of Lake Oswego, 2007). GLO maps indicate that Sucker Lake was surrounded by upland forest at the time of Euro-American settlement and is now part of the Washington State park system (Allworth, 1976).

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Beaver Lake, Oregon (44°33′01″N, 123°10′40″W, 69 m a.s.l.), is a small oxbow lake located in the central Willamette Valley between the Willamette and Calapooya rivers, approximately 7 km ESE of the city of Corvallis (Table 1, Fig. 2 C). It occupies an abandoned meander bend perched above the active floodplain; there are no inflowing or outflowing streams. Water level varies seasonally with precipitation and temperature. Beaver Lake is surrounded by a mixture of second- and third-growth forest, with some recent clear cuts. Major forest components include Pseudotsuga menziesii, Pinus ponderosa, Thuja plicata, Tsuga heterophylla, Alnus rubra, and Fraxinus latifolia, as well as numerous introduced and ornamental species. Today, a mixture of forest and development (including private homes and the town of Lake Oswego) surrounds the site.

Porter Lake, Oregon (44°26′52″N, 123°13′44″W, 73 m a.s.l.), is a small oxbow lake located to the west of the Willamette River, approximately 14 km SSW of the city of Corvallis (Table 1, Fig. 2 D). Similar to Beaver Lake, the lake sits above the active floodplain and is infrequently flooded by the Willamette River. There are no inflowing or outflowing streams. GLO maps indicate that oak savanna surrounded a small riparian shrubland at the time of settlement, with prairie and larger tracts of riparian forest nearby. The current vegetation is a narrow riparian forest similar in composition to that of Beaver Lake. Agricultural fields, predominantly grass seed farms, currently surround Porter Lake.

Warner Lake, Oregon (44°14′46″N, 122°57′27″W, 590 m a.s.l.), is a landslide-dammed lake located in the Coburg foothills of the Cascade Range, approximately 25 km NNW of the city of Eugene (Table 1, Fig. 2 E). GLO maps indicate the site was entirely surrounded by closed upland forest at the time of settlement, but oak woodland, oak savanna, and prairie existed nearby. Today the landscape is a mixture of second- and third-growth forest, with some recent clear cuts. Major forest components include Pseudotsuga menziesii, Pinus ponderosa, Thuja plicata, Tsuga heterophylla, Alnus rubra, Acer macrophyllum, Calocedrus decurrens (incense-cedar), and Arbutus menziesii (Pacific madrone), with an understory of Sambucus racemosa (elderberry), Berberis aquifolium, Polystichum spp., and Equisetum spp. (horsetail).

3. Methods

Field and laboratory methods are described here for the Lake Oswego, Porter Lake, and Warner Lake cores. Methods for Battle Ground Lake and Beaver Lake can be found in Walsh et al. (2008, 2010), respectively, except where noted. In 2004 and 2005, sediment cores were collected from the deepest part of each lake. Long cores were recovered from Lake Oswego (LO05B) and Warner Lake (WL04A) using a 5-cm diameter modified Livingstone piston corer (Wright et al., 1983). Short cores were collected from Lake Oswego (LO05C) and Porter Lake (PL05C) using a Klein piston corer that recovered the sediment-water interface. In the laboratory, long core segments were split longitudinally and photographed, and the lithologic characteristics were described. Terrestrial plant macrofossils (e.g., wood, twigs) were identified and used for 14C-AMS dating whenever possible (otherwise bulk sediment was used). Age-depth models were developed based on 210Pb and AMS 14C age determinations (see Table 2 for Lake Oswego, Porter Lake, and Warner Lake ages). All 14C age dates were converted to calendar years before present (cal yr BP; present = 1950 AD) using Calib 5.0.2 html (Stuiver and Reimer, 2005). 210Pb ages were determined using the constant rate of supply model adjusted for the 137Cs peak.

Magnetic susceptibility, which determines the allochthonous inorganic content of the core (Thompson and Oldfield, 1986; Gedy

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<th>Table 1</th>
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<tr>
<td>Physical and climatic data for the study sites.</td>
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<tr>
<td><strong>Battle Ground Lake</strong></td>
</tr>
<tr>
<td><strong>Latitude</strong></td>
</tr>
<tr>
<td><strong>Longitude</strong></td>
</tr>
<tr>
<td><strong>Elevation (m)</strong></td>
</tr>
<tr>
<td><strong>Area (ha)</strong></td>
</tr>
<tr>
<td><strong>Drainage basin area (ha)</strong></td>
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<tr>
<td><strong>Maximum water depth (m)</strong></td>
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<tr>
<td><strong>Climate Station</strong></td>
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<tr>
<td><strong>Location relative to site</strong></td>
</tr>
<tr>
<td><strong>Ave Jan temp (°C)</strong></td>
</tr>
<tr>
<td><strong>Ave July temp (°C)</strong></td>
</tr>
<tr>
<td><strong>% precip Nov–April</strong></td>
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* Elevationally adjusted interpolations based on CRU CI 2.0 (New et al., 2002).
et al., 2000), was measured on the long cores at contiguous 1-cm intervals using a Sapphire Instruments magnetic coil. Loss-on-ignition analysis, which determines the bulk density, organic, and carbonate content of the sediment (Dean, 1974), was completed at 5-cm intervals on all cores. Samples of 1-cm³ volume were dried at 80 °C for 24 h, weighed, and combusted at 550 °C for 1 h and 900 °C for 2 h. Weight measurements after each combustion determined the percent organic and carbonate content of each sample.

Contiguous 1-cm³ samples were taken for charcoal analysis at 1-cm intervals from the Lake Oswego long core (LO05B) and the Porter Lake short core (PL05C), and at 0.5-cm intervals from the Lake Oswego short core (LO05C) and the Warner Lake long core (WL04A). Charcoal samples were soaked in a 5% solution of sodium hexametaphosphate for 24 h and a weak bleach solution for one hour to disaggregate the sediment. Samples were washed through nested sieves of 250 and 125 μm mesh size, and the residue was transferred into gridded petri dishes and counted (the two size class counts were combined for all analyses). Charcoal particles were identified and tallied as either woody, herbaceous, or lattice type, based on their appearance and comparison to reference material (see Walsh et al., 2010 for photos). Herbaceous charcoal, which comes from grasses or other monocots, was flat and contained stomata within the epidermal walls (Jensen et al., 2007; Walsh et al., 2008). Lattice charcoal, which likely comes from leaves and non-woody material, was only present in the Beaver Lake core. Previous studies indicate that large particles are not transported more than a few kilometers from a fire and thus are an indicator of local activity (Whitlock and Millspaugh, 1996; Whitlock and Larsen, 2001); therefore only charcoal particles >125 μm in minimum diameter were considered. Charcoal counts were divided by the volume of the sample to calculate charcoal concentration (particles/cm³). Charcoal influx (particles/cm²/yr) was determined by dividing charcoal concentration by the deposition time (yr/cm) of the samples.

The charcoal records (except for Porter Lake) were analyzed statistically using the program CharAnalysis (Higuera et al., 2008; http://charanalysis.googlepages.com/), which decomposed the records into a peak (Cpeak) and background (Cbackground) component in order to determine individual fire episodes (Higuera et al., 2008). Concentration values were interpolated to constant time steps, which represented the median temporal resolution of each record, to obtain the charcoal accumulation rate (CHAR) time series. The median temporal resolution for Battle Ground Lake was 6 years, Lake Oswego and Beaver Lake was 5 years, and Warner Lake was 2 years. The non-log-transformed CHAR time series were fitted with a Lowess function to smooth the series and so model Cbackground. The Cpeak component was the residuals after Cbackground was 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. Sensitivity analysis of window widths between 100 to 1000 years showed that the signal-to-noise ratio was maximized at a window width of 500 years for Battle Ground Lake and Lake Oswego, 400 years for Beaver Lake, and 300 years for Warner Lake. Cpeak was screened and peaks were eliminated if the maximum charcoal count from a peak had a >5% chance of coming from the same Poisson-distributed population as the minimum count within the preceding 75 years (Gavin et al., 2006; Higuera et al., 2008).

Pollen samples of 1-cm³ were taken at 5–10-cm intervals and analysis followed standard techniques (Faegri et al., 1989). Lycopodium was added to each sample as an exotic tracer and 300–500 terrestrial pollen grains and spores were counted per sample. Pollen was identified and tallied at magnifications of 400 and 1000×.

Fig. 2. AD 2000 USGS aerial photos of (A) Battle Ground Lake, (B) Lake Oswego, (C) Beaver Lake, (D) Porter Lake, and (E) Warner Lake.
and pollen types were assigned based on modern phytogeography. Pollen counts for terrestrial taxa were converted to percentages using different sums in order to visually maximize changes of less abundant taxa. The terrestrial sum for Lake Oswego excluded Alnus rubra-type, Pteridium, and Poaceae when percentages were calculated for the remaining terrestrial taxa. The terrestrial sum for Porter Lake excluded Salix, Freaxinum latifolia, and Poaceae. The terrestrial sum for Warner Lake excluded Alnus rubra-type and Cupressaceae. The terrestrial sum for Battle Ground Lake excluded Pseudotsuga-type and Thuja-type. Aquatic taxa percentages were calculated using different sums in order to visually maximize changes of less abundant taxa. Aquatic taxa percentages were calculated using different sums in order to visually maximize changes of less abundant taxa. The terrestrial sum for Lake Oswego excluded Alnus rubra-type, Pteridium, and Poaceae when percentages were calculated for the remaining terrestrial taxa. The terrestrial sum for Porter Lake excluded Salix, Freaxinum latifolia, and Poaceae. The terrestrial sum for Warner Lake excluded Alnus rubra-type and Cupressaceae. The terrestrial sum for Battle Ground Lake excluded Pseudotsuga-type and Thuja-type. Aquatic taxa percentages were calculated using different sums in order to visually maximize changes of less abundant taxa. Aquatic taxa percentages were calculated using different sums in order to visually maximize changes of less abundant taxa.

Table 2

<table>
<thead>
<tr>
<th>Depth (cm below mud surface)</th>
<th>Lab number</th>
<th>Source material</th>
<th>Dates (210Pb, 14C yr BP)</th>
<th>Calibrated age (cal yr BP)*</th>
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<td>Lake Oswego, OR: Core LO05C</td>
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<td>Lake sediment</td>
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<td>Lake sediment</td>
<td>155.8±19</td>
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<tr>
<td>89.0</td>
<td>AAA72363</td>
<td>Lake sediment</td>
<td>693±55</td>
<td>670</td>
</tr>
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</table>

| Lake Oswego, OR: Core LO05B |            | Lake sediment  | 1243±5                  | 1180                       |
| 15.70                      | AAA72362   | Lake sediment  | 3042±31                 | 3260                       |
| Porter Lake, OR: Core PLO5C |            | Wood          | 200±25                  | 180                         |

| Warner Lake, OR: Core WLO4A |            | Lake sediment  | 1.7±7                   | -50.3                      |
| 1.0–2.0                     |            | Lake sediment  | 15.8±8                  | -38.2                      |
| 8.0–9.0                     |            | Lake sediment  | 29.8±6                  | -24.2                      |
| 13.0–14.0                   |            | Lake sediment  | 41.3±12                 | -12.4                      |
| 16.0–17.0                   |            | Lake sediment  | 49.7±10                 | -4.3                       |
| 20.0–21.0                   |            | Lake sediment  | 61.1±7                  | 7.1                        |
| 24.0–25.0                   |            | Lake sediment  | 76.0±11                 | 22.6                       |
| 28.0–29.0                   |            | Lake sediment  | 87.6±12                 | 33.6                       |
| 34.0–35.0                   |            | Lake sediment  | 96.6±12                 | 42.6                       |
| 37.0–38.0                   |            | Lake sediment  | 109.6±8                 | 55.6                       |
| 40.0–41.0                   |            | Lake sediment  | 121.7±12                | 67.7                       |
| 43.0–44.0                   |            | Lake sediment  | 147.3±12                | 93.3                       |
| 69.0                        | AAA69046   | Twig          | 277±33                  | 310                        |
| 168.0                       | AAA63176   | Twig          | 813±37                 | 720                        |

* Calibrated ages determined using Calib 5.0.2 html (Stuiver and Reimer, 2005).

** 210Pb age determinations completed by J. Budahn at the USGS Denver Federal Center, Colorado.

*** 14C age determinations completed at the University of Arizona AMS facility.

4.2. Lithology

The lithology, charcoal concentration, organic content, and magnetic susceptibility values for the Lake Oswego (LO05A), Porter Lake (PLO5C), and Warner Lake (WLO4A) vary considerable within and between cores (Fig. 4). Core LO05A consisted almost entirely of brownish/gray inorganic clay sediment (Fig. 4 A). Magnetic susceptibility values were extremely low for the core (~4.5×10^-6 emu) and changed little overall. Organic content was also relatively low (~16%), but rose slightly at the top of the core to ~21%. Black bands occurred in the sediment above 35 cm depth (ca. 120 cal yr BP), presumably the result of pollution, first from iron smelters located on the shores of the lake (ca. AD 1865–1900) and later from recreational motor boat use (ca. AD 1940–present) (City of Lake Oswego, 2007).

The lithology of core PLO5C was inorganic clay sediment from the base of the core to a depth of 29 cm, and fine-detritus gyttja above that (Fig. 4 B). The organic content of the core was almost constant at 12%. A vegetation layer was found at a depth of 83 cm and provided material for a 14C date.

The lithology of WLO4A was inorganic clay sediment from the base of the core to a depth of 80 cm (~22% organics) laminated clay between 80–55 cm depth (~25% organics), fine-detritus gyttja between 55–35 cm depth (~30% organics), unconsolidated medium-detritus gyttja between 35–25 cm depth (~11% organics), and clay above 25 cm depth (~22% organics) (Fig. 4 C). Magnetic susceptibility values remained relatively low throughout most of the core, especially below 55 cm depth. Above 55-cm depth, magnetic susceptibility values were generally higher, indicating greater slopewash of clastic material into the lake. Several magnetic susceptibility peaks correlated well with large charcoal concentration peaks (e.g., 177–167 cm, 124.5 cm, 111.5–107.5 cm, 50.5 cm, and 38.5 cm) suggesting that fires in the watershed triggered allochthonous input into the lake following these events.

4.3. Charcoal and pollen records

4.3.1. Battle Ground Lake, Washington

The Battle Ground Lake charcoal and pollen record was divided into pre- and post-Euro-American settlement zones (Fig. 5). Zone BG05B-1 (ca. AD 1340–1850): high charcoal concentration was recorded at ca. AD 1350 and 1390. Almost no fire activity occurred throughout the rest of zone, indicated by generally low charcoal concentration and low variability in charcoal influx. However, influx variability did increase somewhat between ca. AD 1700–1850. The
Fig. 3. Age-versus-depth relations for (A) Battle Ground Lake (BG05C), (B) Lake Oswego (LO05A), (C) Porter Lake (PL05C), and (D) Warner Lake (WL04A) based on the age model information given in Table 2. The + symbol indicates $^{210}$Pb age determinations and the ♦ symbol indicates AMS $^{14}$C age determinations.

Fig. 4. Lithology, AMS $^{14}$C dates, charcoal concentration (particles/cm$^3$/yr), organic content (%), and magnetic susceptibility (electromagnetic units) for (A) Lake Oswego, (B) Porter Lake, and (C) Warner Lake plotted against sediment depth (cm). Magnetic susceptibility data are not available from Porter Lake.
The Lake Oswego charcoal and pollen record was divided into three zones (Fig. 6). Zone LO05A-1 (ca. AD 800–1200): this zone records a high level of fire activity indicated by high charcoal content and influx. The average herbaceous charcoal content was generally low (7.5%). The pollen record indicates that the local forest was dominated by taxa such as Pseudotsuga, Thuja, Tsuga heterophylla, and some Pinus. Disturbance taxa, including Alnus rubra and Pteridium, were common as well. Other riparian and woodland taxa, such as Fraxinus latifolia, Salix, Populus trichocarpa, Corylus, and Quercus, were present, but relatively low in abundance. The pollen assemblage and the high AP/AP+NAP ratio suggest a closed forest surrounding the site, with some disturbance-related openings and probably a narrow riparian shrubland.

Zone BG05B-2 (ca. AD 1850–2005): this zone shows the impact of Euro-American settlement and land clearance near the site. The charcoal curves recorded the most recent fire within the Battle Ground crater, the Yacolt fire of AD 1902. This fire had a low herbaceous charcoal content (~5%). The subsequent high charcoal values at ca. AD 1930 may be from a re-burn associated with the Yacolt fire (Gray, 1990), although none occurred inside the crater. Charcoal influx remained high through the rest of the zone and charcoal may have come from fires outside the crater or possibly from campfires. The pollen record shows the effects of both logging and fire on the vegetation in the Battle Ground Lake crater over the last 200 years. The drop in Thuja sometime after ca. AD 1800 probably indicates the start of nearby logging associated with the establishment of Fort Vancouver in AD 1825 (Allworth, 1976). The simultaneous drop in Pseudotsuga, Tsuga heterophylla, Pinus, Populus trichocarpa, as well as an additional drop in Thuja, in the late 1800s indicates local logging inside the crater. The forest succession recorded in Zone BG05A-1 occurred again following these events (i.e., an initial rise in Pteridium followed by a subsequent rise in Alnus rubra). Further evidence of Euro-American impact near the site is evident in the rise in Poaceae in the last 50 years, which is the result of grass seed farming in the Willamette Valley and lower Columbia River Valley, and a rise in non-native Rubus in the Pacific Northwest.

4.3.2. Lake Oswego, Oregon

The Lake Oswego charcoal and pollen record was divided into three zones (Fig. 6). Zone LO05A-1 (ca. AD 800–1200): this zone records a high level of fire activity indicated by high charcoal concentration and influx. The average herbaceous charcoal content was generally low (11%). The pollen record shows the successional response of the forest taxa to disturbance. Following the high charcoal values at ca. AD 1350 and 1390, Peridium increased, followed by Alnus rubra, which was eventually replaced by Pseudotsuga and Thuja over the next two hundred years. The small decrease in the AP/AP+NAP ratio further suggests a loss of forest cover following these events. Overall, the pollen assemblage in this zone suggests a closed forest with some disturbance-related openings and a small riparian community near the edge of the lake.

Zone LO05A-2 (ca. AD 1200–1700): this zone records major changes in both the fire regime and vegetation. Higher charcoal concentration occurred between ca. AD 1200–1450 and coincided with a major vegetation shift. At this time, many herbaceous taxa including Poaceae, Polystichum, Peridium, and Rumex increased at the expense of the coniferous taxa, especially Pseudotsuga. The large drop in the AP/AP+NAP ratio at ca. AD 1250 points to the loss of canopy cover near the site. After ca. AD 1450, charcoal concentration decreased sharply to almost zero by ca. AD 1700. As the charcoal input into the lake decreased, the abundance of most herbaceous taxa (i.e., Pteridium, Polystichum, Rumex, and Plantago) decreased. Forest slowly returned to the site over this 350-year period, evidenced by the increased AP/AP+NAP ratio, but it was dominated by Alnus rubra and Fraxinus latifolia instead of Pseudotsuga and Thuja as in Zone LO05A-1. Percentages of Alnus rubra-type, Fraxinus latifolia and Poaceae remained high throughout the zone. The average herbaceous charcoal content was low for this zone (3.6%), which implies that mostly woody material was burned.

Zone LO05A-3 (ca. AD 1700–2005): this zone records almost no fire activity near the site. Charcoal concentration remained near zero, and although charcoal influx varied greatly, it was still low. For the first time in the record, charcoal influx values of zero were recorded starting at ca. AD 1740. The average herbaceous charcoal content of the zone was higher than the previous two zones (10.6%), indicating that a greater proportion of herbaceous vegetation was burned. The lack of fire activity near the site after ca. AD 1700 evidently led to a major shift in the vegetation. Coniferous taxa, such as Pseudotsuga and Thuja, increased in abundance again at this time, while herbaceous...
taxa, such as Poaceae, Polystichum, Pteridium, Rumex, and Plantago, all generally decreased from the beginning to the end of the zone. Alnus rubra continued to be a major forest component. Decreased percentages of Pseudotsuga-type and Thuja-type after ca. AD 1840 are the result of logging near the lake. The pollen assemblage at ca. AD 1851 is consistent with the GLO map of this area, which indicates a mixture of closed upland forest and oak woodland.

4.3.3. Beaver Lake, OR

The Beaver Lake charcoal and pollen record was divided into pre- and post-Euro-American settlement zones (Fig. 7). Zone BL05B-1 (ca. AD 1460–1830): this zone records little fire activity near the site. Charcoal concentration and influx remained low in this zone and the vegetation remained relatively constant. Salix, Alnus rubra, and Fraxinus latifolia dominated the local riparian shrubland and Pseudotsuga and Thuja probably grew in nearby upland closed forests, while Corylus, Quercus, Spiraea, Poaceae, Cyperaceae, and Pteridium grew in surrounding savanna and prairie.

Zone BL05B-2 (ca. AD 1830–2005): this zone records the impact of Euro-American settlement and land clearance near the site. Starting as early as ca. AD 1830, the fire regime at Beaver Lake changed. Charcoal influx became much more variable and higher charcoal concentration was recorded. Fire activity at the beginning of this zone was probably the result of local land clearance and produced a high proportion of a different type of charcoal (i.e., lattice charcoal, which was not identified as either woody or herbaceous) than the fire activity of the previous 350 years. The vegetation also changed dramatically near Beaver Lake following settlement. Salix and Cyperaceae increased in
abundance initially at ca. AD 1900, but then sharply decreased over the next 100 years. *Pseudotsuga*, *Thuja*, *Alnus rubra*, *Fraxinus latifolia*, *Quercus*, and *Spiraea* all decreased in abundance after settlement, although some taxa have rebounded in recent years (e.g., *Pseudotsuga*, *Alnus rubra*, and *Fraxinus latifolia*). Higher *Pteridium* percentages after ca. AD 1850 probably indicate a more open landscape near the site, which is further supported by the drop in the AP/AP+NAP ratio. The sharp increase in Poaceae pollen at ca. AD 1930 recorded the conversion of the region to an intensely cultivated grass landscape. Herbaceous charcoal content also increased greatly at this time; from AD 1960–2005, the average was 23%, with some values as high as 58%. Evidently, a large percentage of the charcoal reaching the lake today is from the burning of nearby grass fields. A large peak in Corylus pollen at ca. AD 1950 indicates the intensification of hazelnut farming near the site (O’Connor, 2006). Several other ornamental/cultigen taxa were recorded after ca. AD 1850, including Brassicaceae (mustard family), *Juglans* (walnut), and *Plantago*-type (plantain, probably the non-native *Plantago lanceolata* [English plantain]).

### 4.3.4. Porter Lake, OR

The Porter Lake charcoal and pollen record was divided into pre- and post-Euro-American settlement zones (Fig. 8). Zone PL05C-1 (ca. AD 1730–1830): this zone records little fire activity near the site, indicated by low charcoal concentration. The average herbaceous content of this zone was relatively high (55%), suggesting that mostly herbaceous material was burned. The vegetation remained fairly stable during this zone and validates the ca. 1851 GLO map of the area surrounding Porter Lake, which suggests that riparian shrubland and oak savanna surrounded the site at the time of settlement. Relatively high percentages of *Alnus rubra*-type, *Fraxinus latifolia*, *Salix*, and *Populus trichocarpa*-type indicate that these taxa dominated the local riparian shrubland, as well as the larger tracts of nearby riparian forest. Relatively high percentages of *Quercus* and *Corylus* indicate that extensive oak savanna surrounded the site. Poaceae and *Pteridium* were probably common in the understory of the savanna but may have also come from nearby prairie. *Pseudotsuga*-type, *Thuja*-type, and *Pinus* percentages likely reflect nearby upland closed forest not shown on the GLO map.

Zone PL05C-2 (ca. AD 1830–2005): this zone records the impact of Euro-American land clearance for agriculture near the site. After ca. AD 1830, charcoal concentration and influx values greatly increased in the Porter Lake record. High charcoal concentration between ca. AD 1860–1920 probably indicate several decades of burning related to local land clearance (Morris, 1934). The average herbaceous charcoal content of this period was 18%, suggesting that a greater proportion of woody material burned as compared to Zone PL05C-1. After ca. AD 1920, charcoal concentration and influx values decreased toward present. Today, very little charcoal accumulates in the lake, and a relatively high percentage of it is herbaceous charcoal (average of 39% since AD 1960), most likely from the burning of nearby grass fields. This is consistent with the rise in Poaceae pollen after ca. AD 1915. Also notable is the increase in *Fraxinus latifolia* after ca. AD 1850, as other riparian trees, such as *Salix* and *Populus trichocarpa*, decreased. Decreased percentages of *Quercus* and *Corylus* after ca. AD 1950 indicate the loss of nearby savanna, although *Corylus* has increased in recent decades (again, probably due to hazelnut farming near the site). *Alnus rubra* and *Equisetum* both increased in abundance after ca. AD 1850 and indicate increased disturbance near the site. Other invasive and exotic species found in the record after AD 1850 included *Juglans* and *Rubus*, and increased percentages of non-native *Salvia*-type (Russian thistle).

### 4.3.5. Warner Lake, OR

The Warner Lake charcoal and pollen record was divided into four zones (Fig. 9). Zone WL04A-1 (ca. AD 1075–1350): this zone records relatively little fire activity near the site. Charcoal concentration values and charcoal influx variability were generally low compared to later in the record, but the average herbaceous charcoal content was relatively high (26%). The pollen assemblage of this zone suggests that *Pseudotsuga*, *Cupressaceae*, and *Alnus rubra* were the major components of the local forest, with Poaceae, *Polystichum*, and *Pteridium* dominating the understory. *Tsuga heterophylla*, *Pinus*, and *Acer macrophyllum* were also present in the forest in lower abundance, and *Fraxinus latifolia* and *Salix* grew near the edge of the lake. *Corylus* and *Quercus* likely grew in nearby oak woodland and savanna. *Alnus rubra* and herbs such as Poaceae, *Polystichum*, and *Pteridium* were probably common in the fire-created openings in the forest.

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*Fig. 8.* Porter Lake (PL05C) charcoal concentration (particles/cm²/yr: black line = total charcoal, gray line = herbaceous charcoal), total charcoal influx (particles/cm²), herbaceous charcoal (%), selected pollen percentages (gray curves represent a 3× exaggeration of solid curve), and AP/AP+NAP ratio plotted against age (AD). The + symbol to the left of the age axis represents the age of the AMS ¹⁴C date.
Zone WL04A-2 (ca. AD 1350–1600): this zone is characterized by greater fire activity than the previous zone. Higher charcoal concentration values were recorded and charcoal influx variability increased. The average herbaceous charcoal content also increased from the previous zone to 29%. Highly variable percentages of *Alnus rubra*-type, generally decreased percentages of *Pseudotsuga*-type, Cupressaceae, and *Tsuga heterophylla*, increased percentages of herbaceous taxa such as Poaceae and *Polystichum*-type, and a generally lower AP/AP+NAP ratio in this zone, suggest a loss of forest cover and a more open environment near the site (i.e., more prairie and oak savanna). Riparian taxa percentages also increased in this zone, including *Salix* and *Populus trichocarpa*-type, as well as *Acer macrophyllum*, *Corylus*, *Quercus*, and *Spiraea*-type.

Zone WL04A-3 (ca. AD 1600–1880): this zone records a large shift in fire activity. Charcoal concentration values generally increased until ca. AD 1800 and charcoal influx variability was even greater than the previous zone. After ca. AD 1800, however, charcoal concentration values dropped to near zero and influx variability increased even further, recording zero values for the first time in the record. The average herbaceous charcoal content for this zone decreased to 24%. The pollen assemblage of this zone is similar to Zone WL04A-1 and suggests that the local forest was dominated by *Pseudotsuga*, Cupressaceae, and *Alnus rubra*, with *Tsuga heterophylla* and *Pinus*. Decreased percentages of *Corylus*, *Quercus*, and other herbs, as well as an increase in the AP/AP+NAP ratio, indicates that oak woodland/savanna and prairie decreased near the site at the beginning of this zone. However, increased *Corylus* percentages after ca. AD 1700 suggest its importance as a member of the local forest understory. The pollen assemblage of this zone is consistent with the ca. AD 1851 GLO map, which indicates that the site was surrounded by an upland closed conifer-dominated forest, but oak woodland/savanna and prairie existed nearby.

Zone WL04A-4 (ca. AD 1880–2004): this zone is characterized by steep declines in percentages of most arboreal taxa, including *Pseudotsuga*-type, Cupressaceae, *Tsuga heterophylla*, *Pinus*, *Alnus rubra*-type, *Fraxinus latifolia*, *Populus trichocarpa*-type, *Acer macrophyllum*, and *Corylus*. Sharp increases first in *Pteridium*, *Polystichum*-type, and other herbs, as well as a drastic drop in the AP/AP+NAP ratio, indicate the loss of forest near the site. The start of this zone coincides with a relatively anomalous period in the core (~40 cm depth) of ‘unconsolidated’ sediment, low organic values, high magnetic susceptibility values, and low charcoal values (Fig. 4 C). This is different from other sections of the core where high magnetic susceptibility values typically correlated well with high charcoal values (i.e., fires triggered hillslope erosion). In this case, all of the evidence points to the start of logging in the watershed (ca. AD 1880) as the trigger for the loss of forest cover, high allochthonous input into the lake, and subsequent rise of non-arboreal taxa in the watershed at this time.

The generally high abundance of *Alnus rubra*, *Polystichum*, and *Equisetum* after ca. AD 1900 suggests that disturbance remained frequent near the site, probably as a result of continued logging in the watershed. High charcoal concentration values occurred at ca. AD 1890 in association with logging and slash pile burning (Agee, 1989). The average herbaceous charcoal content was only 3% between ca. AD 1880–1950, which suggests that mostly woody material was burning. Charcoal concentration and influx remained low between ca. AD 1900–1950, but then increased and remain relatively high at present. This increase was coincident with a rise in herbaceous charcoal (average of 45% after AD 1950) and Poaceae pollen, suggesting grass fires burned in clearings within the watershed or on adjacent valley foothills.

### 4.4. Fire-episode reconstruction

Decomposition of charcoal influx records (CHAR; particles/cm²/yr) from Battle Ground Lake (BG05C), Lake Oswego (LO05A), Beaver Lake (BL05B), and Warner Lake (WL04A) indicate fire-episode occurrence and magnitude over the last 1200 years (Fig. 10). ‘Fire episode’ is used instead of ‘fire’ to describe the statistically significant peaks in the CHAR record because one or more fires could have occurred within the duration of a peak (Long et al., 1998). Years of fire episodes discussed below are the beginning of a charcoal peak in the record. ‘Fire-episode magnitude’ refers to the total charcoal influx in a peak and is hereafter referred to as ‘magnitude’. As suggested by numerous studies, fire-episode ‘magnitude’ may express the actual magnitude (i.e., size/severity) of a fire, but also may be indicative of the proximity of a fire to a site, the taphonomic processes that control charcoal deposition into a site, or some combination of all of these (see Whitlock and Millspaugh, 1996; Clark et al., 1998; Lynch et al., 2004; Higuera et al., 2005; Higuera et al., 2007 for a discussion of this). However, if a fire episode is accompanied by a change in vegetation, and perhaps more so, a change in fuel type (i.e., charcoal type), then it seems more likely that
magnitude is recording fire size and/or severity, not proximity to the site or a change in charcoal taphonomy. We examine these relationships in further detail in Section 5, and while we include descriptions of changes in fire size and severity, these statements should be regarded as speculative.

Analysis of the charcoal record from Battle Ground Lake indicates that 15 fire episodes occurred over the last 1200 years (Fig. 10A). In general, fires were more frequent between ca. AD 800–1200 (10 fire episodes), but were small-to-moderate in magnitude. After that, fires decreased in frequency, but increased in magnitude. Between ca. AD 1300–2005, only five fire episodes occurred, three of which were the largest magnitude fires of the record (ca. AD 1340, 1400, and 1910). No fire episodes occurred between ca. AD 1500–1800.

The charcoal reconstruction from Lake Oswego indicates that 20 fire episodes occurred during the last 1200 years (Fig. 10B). Fires were more frequent before ca. AD 1630, with 17 of the 20 fire episodes of the record occurring during this time. In general, larger-magnitude fire episodes occurred prior to ca. AD 1425 and smaller ones between ca. AD 1425–1630. No fire episodes occurred between ca. AD 1630–1870. Three fire episodes occurred after this time, at ca. AD 1875, 1915, and 1960. The ca. AD 1875 and 1915 fires were small-magnitude events, but the ca. AD 1915 fire episode was relatively large.

The fire-history reconstruction from Beaver Lake indicates that 17 fire episodes occurred over the last 1200 years (Fig. 10C). Eight fires occurred between ca. AD 800–1400 and were relatively moderate in magnitude, with the greatest magnitude fire episodes at ca. AD 1320 and 1390. Six fire episodes occurred between ca. AD 1400–1870 and were small-magnitude events. The largest-magnitude fire episode of the record occurred at ca. AD 1890, followed by two smaller events at ca. AD 1950 and 1960.

The Warner Lake fire-history reconstruction indicates that 34 fires occurred over the last 950 years (Fig. 10D). Eleven fire episodes occurred prior to ca. AD 1400 and were generally small-magnitude. Eighteen fire episodes occurred between ca. AD 1400–1800 and ranged widely from small- to large-magnitude. Two especially large-magnitude fires were recorded at ca. AD 1436 and 1780. Five fire episodes have occurred since ca. AD 1800 and again, vary widely from small- to large-magnitude, with the two largest at ca. AD 1890 and 1960.

5. Discussion

5.1. The Pre-Euro-American Settlement Landscape of the Willamette Valley (ca. AD 800–1830)

The prehistoric reconstructions from the five study sites reveal some similarities in fire activity across the Willamette Valley (Fig. 11). Prior to ca. AD 1450, Battle Ground Lake, Lake Oswego, and Beaver Lake recorded relatively high fire activity. Fire episodes were moderately frequent at all of these sites during this period; however, the effects on the vegetation varied. At Battle Ground Lake, generally low-magnitude (presumably small and/or low-severity) fire episodes prior to ca. AD 1200 seem to have had little impact on the surrounding forest, but two higher-magnitude (presumably larger and/or more-
severe) fire episodes at ca. AD 1340–1400 briefly opened the landscape for the next approximately 100 years (Fig. 10). At Lake Oswego, relatively frequent, moderate-magnitude fire episodes between ca. AD 1100–1400 led to a shift from a relatively closed forest dominated by Pseudotsuga, Thuja, and Alnus rubra to an open landscape dominated by herbaceous taxa, such as Poaceae, Polystichum, and Pteridium. Similarly at Beaver Lake, relatively frequent, low- to moderate-magnitude fire episodes before ca. AD 1400 maintained openness near the site, although the impact was less than at Lake Oswego.

The Battle Ground Lake, Lake Oswego, and Beaver Lake fire histories are also alike in that they record a general drop in fire activity after ca. AD 1450, but again, the effects that this had on the vegetation varied. Few fire episodes occurred at Battle Ground Lake after ca. AD 1450 and the vegetation at the site remained generally unchanged. At Lake Oswego, fire episodes continued to occur until ca. AD 1630, but greatly decreased in magnitude over that time. The vegetation at the site responded to the lower fire activity by steadily increasing forest cover, which implies that fire episodes were smaller and/or lower-severity, or possibly farther away from the site. Lower-magnitude fire episodes than before also continued to occur at Beaver Lake after ca. AD 1450, but the vegetation remained generally unchanged.

The fire activity trends illustrated in the Willamette Valley reconstructions are generally similar to tree-ring-based fire-history
records from the Pacific Northwest. Weisberg and Swanson (2003) suggested that burning was relatively widespread before ca. AD 1650. This is consistent with the records from Battle Ground Lake, Lake Oswego, and Beaver Lake; however, their findings suggested that this period of high fire activity lasted until later than indicated by the Battle Ground record (which lasted until ca. AD 1475), but is consistent with the sharp decline in fire activity at Lake Oswego at ca. AD 1650. The remainder of the prehistoric fire reconstructions from Battle Ground Lake, Lake Oswego, Beaver Lake, and the short prehistoric record from Porter Lake is also consistent with their findings of reduced burning between ca. AD 1650–1800 (Fig. 11).

Centennial-scale climate change may help explain the fire histories of the Willamette Valley. The relatively high fire activity at Battle Ground Lake, Lake Oswego, and Beaver Lake between ca. AD 850–1250 (Fig. 11) may be the result of warmer and drier conditions during the Medieval Climate Anomaly (Cook et al., 2004). Only at the Battle Ground Lake and Lake Oswego was the number of fire episodes during the Medieval Climate Anomaly greater than the number of fire episodes during the Little Ice age, at all three sites, fire-episode magnitude was much higher (Fig. 10). The subsequent reduction in fire activity at Battle Ground Lake, Lake Oswego, and Beaver Lake after ca. AD 1450 could be the result of regionally cooler temperatures and a greater precipitation (Graumlich and Brubaker, 1986; Cook et al., 2004) during the Little Ice Age (AD 1450–1850; Grove, 2001). At all three sites, fire episodes were infrequent and/or low-magnitude during this time. For example, only two fire episodes occurred at Battle Ground Lake during the Little Ice Age and both were extremely low-magnitude. Fire episodes at Lake Oswego greatly decreased in magnitude after ca. AD 1450 and did not occur between ca. AD 1630–1870. Although fires continued to occur at Beaver Lake during the Little Ice Age, they were all low-magnitude events.

Climate change, however, does not explain the record from Warner Lake, which indicates that fire episodes were generally less frequent between ca. AD 1075–1400, but then increased in frequency and magnitude until ca. AD 1800. It is possible that the higher elevation of Warner Lake (590 m a.s.l.) led to more frequent lightning ignitions than on the valley floor. The National Interagency Fire Center suggests that lightning-fire ignition rates for the Willamette National Forest were 43 lightning fires/400,000 ha/yr for the period of 1970–2002, or 0.0001075 lightning fires/ha/yr (reported in Kay, 2007). At Jim’s Creek (~850 m a.s.l.), a 276 ha former oak savanna in the Willamette National Forest, Day (2005) reported seven lightning-fire ignitions since 1970. This suggests that lightning strikes are not uncommon in the lower Cascade foothills. However, if lightning was the primary ignition source for fires at Warner Lake, then fire-episode frequency should have decreased during the Little Ice Age due to increased effective moisture that would have reduced the duration of summer drought and thereby lowered the opportunity for lightning strikes to ignite fires.

Anthropogenic burning may help explain the elevated fire activity at Warner Lake as compared to the other Willamette Valley sites. Cultural records suggest relatively large populations inhabited the valley prior to Euro-American contact and that settlement patterns were heterogeneous and determined by resource availability (Boyd and Hajda, 1984; O’Neill et al., 2004). There is no archaeological evidence from the Warner Lake watershed, but it seems likely that this forest-savanna-prairie ecotone was visited at least seasonally by Native Americans. The elongated territories of the Kalapuyans extended into the Coburg foothills of the Coast Range (Zenk, 1990), and Warner Lake may have offered important summer resources since lakes and perennial streams are somewhat rare in this area. Higher fire frequency between ca. AD 1350–1800 (Fig. 11) may have been an attempts to increase openness near the site since periodic burning would have encouraged the growth of important food resources, including berries (Mack and McClure, 2002), acorns (Devine and Harrington, 2006), and Camassia bulbs (Turner and Kuhnlein, 1983), and would have created more open habitat which was good for hunting deer and other game (Boyd, 1999). The shift in the fire regime at Warner Lake at ca. AD 1800 coincides well with the timing of Native American population decline in the valley suggested by Boyd (1990), and may explain the decrease in fire activity after ca. AD 1790. Additional archaeological and fire-history records from the foothills of the Oregon Coast Range are needed to substantiate this hypothesis.

Native American use of fire may also help explain why fire histories are different between valley-floor sites. At Battle Ground Lake, the Pseudotsuga/Thuja forest of the late Holocene (Walsh et al., 2008) was probably relatively unimportant in terms of resource availability. This may explain why the Chinookan-speaking tribes of the lower Columbia River valley lived in more permanent dwellings along the Columbia River and its tributaries and relied heavily on fish (e.g., salmon) as a diet staple (Boyd and Hajda, 1984). This also likely explains why no archaeological evidence of Native American activity has been found in the Battle Ground Lake crater. Camassia grew at the site in the early Holocene, and in the late Holocene, it probably grew in nearby prairies and oak savannas (Boyd and Hajda, 1984). These surrounding environments may have been burned regularly (Leopold and Boyd, 1999), but such fires were not reflected in the Battle Ground Lake charcoal record. In addition, the lake did not contain fish until it was stocked in ca. AD 1900 (Allworth, 1976). The relative lack of resources at Battle Ground Lake and the fact that the fire-history reconstruction correlates well with known climatic shifts during the last 1200 years suggests little prehistoric human influence at the site.

In contrast, sites farther south in the Willamette Valley may have experienced a greater human influence. Archaeological evidence from Lake Oswego suggests human occupation at the site between ca. 6000–300 years ago (Burnett, 1995), and historical records indicate that the Clackamas (considered to be part of the Chinookan tribal group) probably lived in fairly permanent dwellings near the site prior to Euro-American settlement (Ruby and Brown, 1992; Pettigrew, 1990). Kalapuyan tribes also may have seasonally migrated to the lake to take advantage of the abundance of root crops, fish, and waterfowl (Kohnen, 2008). Frequent anthropogenic burning enabled by the warmer and drier climate of the Medieval Climate Anomaly likely explains the high fire activity at Lake Oswego before ca. AD 1450, although it is possible that more frequent lightning striking, the result of greater ground heating and convection during the Medieval Climate Anomaly, were the ignition source for these fires. However, given that this fire-regime shift forced what seems to be an advantageous change in the vegetation (at least in terms of resource availability) that is not observed in any of the other pollen records, and the fact that fire episodes continued near Lake Oswego into the Little Ice Age when cooler and wetter conditions than today should have suppressed naturally-ignited fires, supports the hypothesis that these were human-set fires. The drop in charcoal influx starting at ca. AD 1450 and the lack of fire episodes between ca. AD 1630–1870 may indicate human abandonment of the Lake Oswego area due to drastic declines in Native American populations associated with Euro-American contact (Boyd, 1990), but it could also be the result of the climatic conditions of the Little Ice Age. However, given the fact that fire activity had all but ceased by ca. AD 1700, which is the same time that humans are suspected to have abandoned the area (Burnett, 1995), a human-related explanation seems more likely. Either way, the fire history from Lake Oswego indicates that the upland closed forest and oak woodland that surrounded the site at the time of Euro-American settlement had not burned in more than 200 years.

O’Neill et al. (2004) suggested that seasonally inundated, fluvial areas (i.e., river and stream edges and floodplains) were the focus of land and resource use in the central and lower Willamette Valley due to the abundance of Camassia and other wetland staples and the relative ease of harvesting these plants from the soft soil as compared to more dense upland soils. Bowden (1995) argued that the late-Holocene inhabitants of the lower Willamette Valley relied heavily on
the harvesting of *Cannassia* as a food source, and its distribution and abundance determined the location of settlements and duration of occupation throughout the year. Relatively abundant archaeological evidence (i.e., mounds containing artifact assemblages and human burial remains; see Bowden, 1995) near Beaver Lake suggests hunting and gathering activities took place near the site. Because fire was used for such activities (Boyd, 1999), human-set fires are likely part of the charcoal record. Increased fire activity at Beaver Lake throughout the middle and late Holocene until ca. AD 1450 (Walsh et al., 2010) indicates that this area may have been intensely used as a resource base for several thousand years. The reduction in fire activity after ca. AD 1450 may have been caused by cooler conditions associated with the Little Ice Age; however, it could also be the result of human abandonment of the area.

5.2. The Post-Euro-American settlement landscape of the Willamette Valley (ca. AD 1830–present)

Fire and vegetation reconstructions from the five study sites reveal the nature and magnitude of landscape change experienced in the Willamette Valley since Euro-American settlement. Battle Ground and Warner lakes recorded concurrent logging and burning activities in the local watersheds (ca. AD 1890–1910), which were expressed by the large drops in AP/AP+NAP ratios. Beaver and Porter lakes also recorded major post-Euro-American settlement fire episodes (ca. AD 1880–1890) as a result of burning associated with land clearance for agriculture. The anomalous increase in AP/AP+NAP ratios at Porter Lake at ca. AD 1900 probably reflects a reduction in the extent of prairie, as this land was most highly prized for settlement and agriculture (Bowen, 1978). The fire records from Battle Ground, Beaver, Porter, and Warner lakes are somewhat consistent with the findings of Weisberg and Swanson (2003) (who identified a second period of widespread fire from ca. AD 1800–1925), but indicate that fires associated with Euro–American settlement were greatest at the turn of the 20th century.

The exception to this trend is Lake Oswego, where only a small Euro–American settlement signal was recorded. The persistently high AP/AP+NAP ratios, which unlike the Battle Ground Lake, Beaver Lake, and Warner Lake records, do not show the effects of logging in the watershed and are probably a result of the diversion of the Tualatin River into the lake (AD 1863). This would have greatly increased the source area from which pollen was accumulating and may have masked the local vegetation signal. The fire-history reconstruction does, however, record a small-magnitude fire episode at ca. AD 1875, which likely came from burning associated with an iron blast furnace that operated with limited success near the lake between ca. AD 1865–1884 and was powered by charcoal produced from local timber (Minor and Kuo, 2008).

Few fires occurred in the Willamette Valley after ca. AD 1930, indicating the effectiveness of fire suppression efforts (Morris, 1934). Two fire episodes that occurred at Beaver Lake and three at Warner Lake after ca. AD 1950 were probably small or low-severity grass fires, given the high proportion of herbaceous charcoal. One fire episode also occurred at Lake Oswego and although it did not have a high proportion of grass charcoal, the timing (ca. AD 1960) suggests that it was related to land clearance activities.

6. Conclusions

Through an examination of high-resolution charcoal and pollen records from the five study sites and their comparison to independent records of regional climate variability and human activity, we believe the reconstructions clearly show that prior to Euro-American settlement fire and vegetation regimes of the Willamette Valley were influenced by a combination of natural and anthropogenic factors. Fire activity at some sites appears to have been controlled almost exclusively by climate, whereas at others, human activity was the key controlling factor. Resource availability, which probably to a great extent determined human habitation patterns in the valley, likely explains why some sites were maintained by Native American fires and others were not. For example, Battle Ground Lake near the northern end of the valley had few important resources and remained forested up to Euro-American time. This, along with evidence that changes in the charcoal record corresponded well with known climatic shifts, suggests that human ignitions contributed little if at all to the pre-Euro-American settlement fire regime. On the other hand, the location of Beaver Lake in a seasonally inundated area of the valley that provided abundant resources was more likely to have been subjected to anthropogenic fires. Human-set fires near Lake Oswego also seem to be the best explanation for the observed changes in the fire and vegetation history. However, the incidence of both natural- and human-started fires was likely modulated by regional climate variations during the Medieval Climate Anomaly and the Little Ice Age. This is consistent with the observation that lightning-ignited and human-ignited fires co-vary with one another in the region; both are more frequent than normal during drier-than-average fire seasons, and less frequent than normal during wetter-than-average fire seasons (Bartlein et al., 2008).

Much paleoecological work has been done in an effort to link prehistoric human use of fire to vegetation patterns (see Delcourt and Delcourt, 1997; Foster et al., 2002; McGlone et al., 2005; McDadi and Hedba, 2008; McWethy et al., 2009). To a lesser extent, studies have focused on the relationship between climate change and human use of fire (Haberle, 2005; Black and Mooney, 2006). We acknowledge that the exact interplay between climate, fire, and vegetation in the Willamette Valley remains unclear. Difficulty separating natural and anthropogenic influences on fire regimes is complicated by the obscurity of the temporal and spatial scales of climate variability and human land-use practices (Haberle and David, 2004). Additional charcoal studies from the Willamette Valley would allow for a more critical assessment of past fire regimes and help determine whether they were more so controlled by regional climate change or human land-use practices. We hypothesize that if the former is true then sites might show a similar pattern to that of Battle Ground Lake. However, if the latter is true then fire histories might show a wide range of site-to-site variability.

All four valley-floor fire reconstructions, including the short prehistoric record from Porter Lake, imply that fire episodes in Willamette Valley, whether the result of climate or human activities, were low-magnitude and infrequent in the 200–300 years prior to Euro-American settlement. The prehistoric record from Warner Lake, however, indicates that fire episodes in the foothills of the Cascade Range were much higher magnitude and more frequent than on the valley floor, at least until ca. AD 1800. This may be the result of more frequent lightning strike ignitions, or from anthropogenic burning near the site and its subsequent cessation as a result of Native American population decline resulting from introduced disease (Boyd, 1990). Additional study sites from ecologically similar areas in the Cascade foothills would illustrate whether the high fire activity at Warner Lake was a local phenomenon (making it more likely that the fire regime was human-controlled), or whether this activity was typical of similar areas in the valley (making it more likely that the fire regime was climatically-controlled).

Finally, the historic portions of the reconstructions indicate that humans predominately influenced fire regimes in the Willamette Valley since Euro-American settlement. High-magnitude fire episodes associated with land clearance activities were relatively synchronous between the study sites (ca. AD 1880–1910), with the exception of Lake Oswego. In addition, the most dramatic shifts in vegetation at most sites during the last 1200 years occurred in association with Euro-American land clearance for agriculture and logging. Few fires have occurred in the Willamette Valley since ca. AD 1930 and today are predominantly grass
fires. This information should be helpful because it provides an historical context for evaluating recent shifts in plant communities in the Willamette Valley as a result of Euro-American settlement, and provides critical baseline information needed to aid management and restoration decisions.

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