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An 11 000-year-long record of fire and vegetation history at Beaver Lake, Oregon, central Willamette Valley

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A R T I C L E I N F O

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A B S T R A C T

High-resolution macroscopic charcoal and pollen analysis were used to reconstruct an 11 000-year-long record of fire and vegetation history from Beaver Lake, Oregon, the first complete Holocene paleoecological record from the floor of the Willamette Valley. In the early Holocene (ca 11 000–7500 calendar years before present [cal yr BP]), warmer, drier summers than at present led to the establishment of xeric woodland of *Quercus*, *Corylus*, and *Pseudotsuga* near the site. Disturbances (i.e., floods, fires) were common at this time and as a result *Alnus rubra* grew nearby. High fire frequency occurred in the early Holocene from ca 11 200–9300 cal yr BP. Riparian forest and wet prairie developed in the middle Holocene (ca 7500 cal yr BP), likely the result of a decrease in the frequency of flooding and a shift to effectively cooler, wetter conditions than before. The vegetation at Beaver Lake remained generally unchanged into the late Holocene (from 4000 cal yr BP to present), with the exception of land clearance associated with Euro-American settlement of the valley (ca 160 cal yr BP). Middle-to-late Holocene increases in fire frequency, coupled with abrupt shifts in fire-episode magnitude and charcoal composition, likely indicate the influence anthropogenic burning near the site. The paleoecological record from Beaver Lake, and in particular the general increase in fire frequency over the last 8500 years, differs significantly from other low-elevation sites in the Pacific Northwest, which suggests that local controls (e.g., shifts in vegetation structure, intensification of human land-use), rather than regional climatic controls, more strongly influenced its environmental history.

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1. Introduction

Paleoecological records from across the Pacific Northwest have increased our understanding of vegetation and climate history since the last glaciation (Hansen, 1947; Hibbert, 1979; Leopold et al., 1982; Heusser, 1983; Whitlock, 1992; Hebda, 1995; Sea and Whitlock, 1995; Worona and Whitlock, 1995; Pellatt and Mathewes, 1997; Grigg and Whitlock, 1998; Pellatt et al., 1998, 2001; Lacourse, 2005). In addition, some studies have also considered the prehistoric role of fire in such areas as southern British Columbia (including Vancouver Island) (Brown and Hebda, 2002a,b, 2003; Gavin et al., 2003; Hallett et al., 2003; Lepofsky et al., 2005), northwestern Washington (Tsukada et al., 1981; Cwynar, 1987; McLachlan and Brubaker, 1995; Gavin et al., 2001; Greenwald and Brubaker, 2001; Higuera et al., 2005; Sugimura et al., 2008), southwestern Washington (Walsh et al., 2008), and western Oregon (Long et al., 1998, 2007; Long and Whitlock, 2002). Conspicuously missing from this network of paleofire and vegetation reconstructions are sites from the Willamette Valley of Oregon, south of the Columbia River, even though this was historically an area of widespread prairie and oak savanna, purportedly maintained by anthropogenic burning (Habeck, 1961; Johannessen et al., 1971). Unfortunately, most natural wetlands in the Willamette Valley lie in floodplain settings, and are typically young or have been disturbed by land-use activities. Hansen (1947) described two valley-floor Holocene pollen records from sites that no longer exist, but these reconstructions lacked radiometric dating, which limits their interpretability.

In this paper, we describe the paleoecological history of Beaver Lake, OR, based on high-resolution macroscopic charcoal, pollen, and sedimentological data. Our objective was to assess the relative influence of natural (i.e., geomorphic development, hydrologic shifts, and millennial- and centennial-scale climate variability) and anthropogenic activities (i.e., Native American burning and

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Euro-American settlement) on the vegetation and fire history of the site over the past 11 000 years. The Beaver Lake reconstruction is also placed within the framework of the Holocene paleoecological history of the Pacific Northwest.

2. Study area

The Willamette Valley forms the southern portion of a structural depression between the Coast and Cascade ranges that stretches from southern British Columbia to central western Oregon (Fig. 1) (Gannett and Caldwell, 1998). Beaver Lake (44°55.03′N, 123°17.78′W, 69 m a.s.l.) is an oxbow lake located in the central Willamette Valley, ~7 km east of Corvallis, OR (16 km east of the Coast Range and 35 km west of the Cascade Range foothills). It occupies an abandoned meander bend that is ~1 km in length and has an average width of 50 m. The site experiences warm dry summers and cool wet winters typical of the Willamette Valley, as a result of the seasonal shift in the position of the polar jet stream and the northeastern Pacific subtropical high-pressure system (Mitchell, 1976; Mock, 1996). The climate of the site is known from the city of Corvallis weather station located ~7.5 km WNW of the site, which for the period of 1971–2000 recorded an average July temperature of 19.2 °C, an average January temperature of 4.6 °C, and an average annual total precipitation of 1109 mm (~78% of it between November and April) (Western Regional Climate Center, 2007). Water depth in Beaver Lake varies seasonally and is typically less than 1.5 m by late summer.

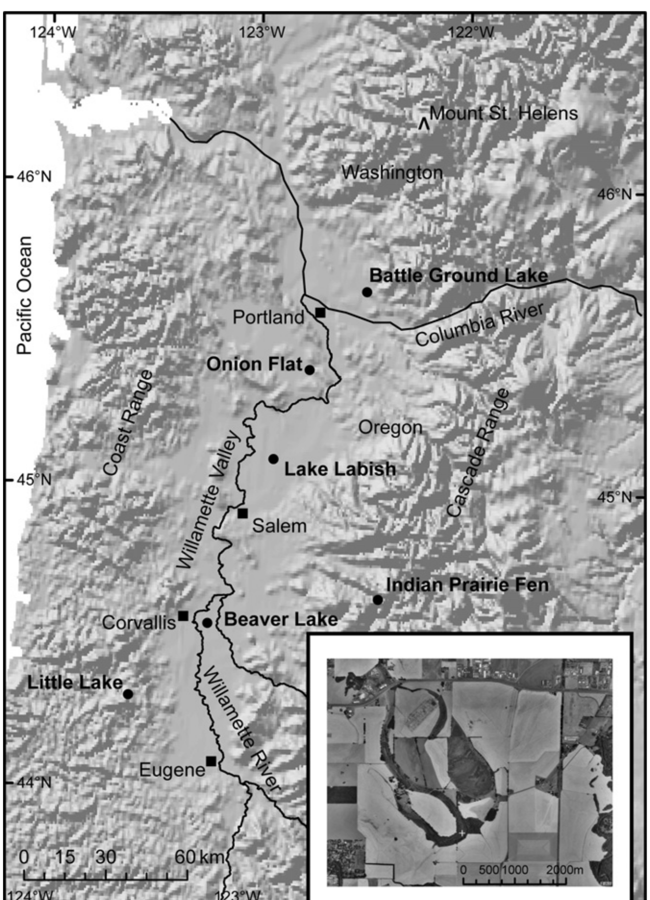

Fig. 1. Map of the Willamette Valley and location of the study site Beaver Lake and other sites mentioned in the text. Inset shows an aerial photograph of the site taken in 2000 with the approximate coring location (white cross) (photo: USGS).

General Land Office (GLO) survey notes from AD 1853 indicate that the study area supported a large *Salix* (willow)-dominated riparian forest, surrounded by prairie on the upland surface east of the lake and to a lesser extent *Quercus garryana* (Oregon white oak) savanna at the time of settlement (Christy et al., 1997). The presettlement *Salix* forest was significantly reduced following Euro-American settlement and had been converted to intensive agriculture by the time of the first aerial photograph in AD 1935. Agricultural production of mostly ryegrass (*Lolium* spp.) and wheat (*Triticum* spp.) continues near the site today (Fig. 1, inset). The current vegetation surrounding Beaver Lake consists of a narrow riparian forest composed of *Salix* spp., *Populus trichocarpa* (black cottonwood), *Fraxinus latifolia* (Oregon ash), and *Q. garryana*, with an understory of *Spiraea douglasii* (hardhack), *Oemleria cerasiformis* (Indian plum), *Rhus diversiloba* (poison oak), and *Symphoricarpos albus* (snowberry). Beaver Lake is presently a shallow eutrophic system, with the littoral zone dominated by wetland vegetation, including *Phalaris arundinacea* (reed canarygrass), *Ludwigia palustris* (water purslane), *Nuphar polysepalum* (yellow pond-lily), and *Lemna* sp. (duckweed). Larger strips of riparian hardwood forest of *Acer macrophyllum* (bigleaf maple) and *P. trichocarpa* grow along the Willamette River (ca 5 km to the west) and the Calapooya River (ca 2 km to the east). Botanical nomenclature follows Hitchcock and Cronquist (1973).

3. Methods

Two sediment cores were recovered from near the center of Beaver Lake using a 5-cm diameter modified Livingstone piston corer (Wright et al., 1983): a 7.87 m-long sediment core (BL93A) in 1993, and an 8.07 m-long sediment core (BL05B) in 2005, which recovered the sediment/water interface. Core segments were extruded on site, wrapped in plastic wrap and foil, transported to the University of Oregon and refrigerated.

BL93A and BL05B core segments were split longitudinally and photographed, and the lithologic characteristics were described. Magnetic susceptibility was measured in electromagnetic units (emu) to determine the inorganic content of core BL05B (Thompson and Oldfield, 1986). Measurements were taken at contiguous 1-cm intervals using a Sapphire Instruments magnetic coil. Loss-on-ignition analysis on core BL05B was undertaken to determine the bulk density and organic and carbonate content of the sediment (Dean, 1974). Samples of 1-cm^3 volume were taken at 5-cm intervals, dried at 80 °C for 24 h and combusted at 550 °C for 1 h to determine the percent organic content and at 900 °C for 2 h to determine the percent carbonate content.

Pollen samples of 1-cm^3 were taken at 4-cm intervals from the top of core BL93A to a depth of 4.82 m, and at 8–30-cm intervals below that. Pollen samples of 1-cm^3 were also taken at 5-cm intervals (ca 20–80 year intervals) from the top 65 cm of core BL05B. Pollen analysis followed standard techniques (Faegri et al., 1989). *Lycopodium* was added to each sample as an exotic tracer to calculate pollen concentration and 300–500 terrestrial pollen grains and spores were counted per sample. Pollen was tallied at magnifications of 400 and 1000× and identified based on comparison with reference slides and modern phytogeography. *Pinus monticola*-type pollen included the haploxylon pines (*P. monticola* [western white pine], *P. lambertiana* [sugar pine], and potentially *P. albicaulis* [whitebark pine]). *Pinus contorta*-type pollen included diploxylon pines (*P. contorta* [lodgepole pine] and *P. ponderosa* [ponderosa pine]). *Pseudotsuga/Larix*-type pollen was considered to be from *Pseudotsuga menziesii* (Douglas-fir), since *Larix* (larch) grows on the east slope of the Cascade Range (Franklin and Dyrness, 1988). Pollen counts were converted to percentages using different sums to visually emphasize ecologically significant variations. The terrestrial sum included all upland forest, oak savanna, and disturbance taxa, and some wet-prairie (i.e., Apiaceae and Liliaceae) taxa, and was used to calculate the percentages of those taxa. The terrestrial sum plus Poaceae and Cyperaceae was used to calculate percentages for the disturbance taxa. The terrestrial sum plus the riparian sum was used to calculate percentages for Poaceae and Cyperaceae. The terrestrial sum plus the aquatic sum was used to calculate percentages for the aquatic taxa. Arboreal/nonarboreal (AP/NAP) pollen ratio was calculated by dividing the arboreal sum by the total arboreal plus nonarboreal sum. Pollen zones were delimited based on constrained cluster analysis of the original pollen data (not shown; see Pearl, 1999).

Contiguous 1-cm^3 samples were taken from core BL05B for charcoal analysis at 0.5-cm intervals between 0.0 and 2.5 m depth and from 4.5 m depth to the bottom of the core. The remainder of the core was sampled at 1-cm intervals. Charcoal samples were soaked in a 5% solution of sodium hexametaphosphate for >24 h and a weak bleach solution for 1 h 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. Previous studies indicate that large particles are not transported far from the source, typically <2 km, and thus are an indicator of local fire activity (Whitlock and Millspaugh, 1996; Whitlock and Larsen, 2001); therefore, only charcoal particles >125 μm in minimum diameter were considered. Charcoal particles were identified and tallied as either woody, herbaceous, or lattice-type based on their appearance and comparison to burned reference material. Woody charcoal comes from trees and shrubs and was identified by its brittleness and charcoal sheen (Fig. 2a). Herbaceous charcoal, which comes from grasses or other monocots, was flat and contained stomata within the epidermal walls (Fig. 2b) (Jensen et al., 2007; Walsh et al., 2008). Lattice charcoal was flat with latticework pattern to it (Fig. 2c). This charcoal type was not similar to any of the burned reference material, and likely comes from leaves and non-woody material. Comparison of the abundance of charcoal from different sources helped characterize fire activity in different sections of the core by providing information on fuel type. Plant macrofossils, mostly wood fragments, provided material for ^{14}C-AMS dating.

Charcoal counts were divided by the volume of the sample to calculate charcoal concentration (particles/cm^3). Analysis of the charcoal data followed methods outlined in Higuera et al. (2008) and used the statistical program CharAnalysis (Higuera et al., 2008; http://charanalysis.googlepages.com/). Concentration values were interpolated to constant 10-yr time steps, which represents the median temporal resolution of the record, to obtain the charcoal accumulation rate (CHAR) time series. The non-log-transformed CHAR time series was decomposed into peak (C_{peak}) and background ($C_{background}$) components in order to determine individual fire episodes. C_{peak} represents the inferred fire episodes (i.e., one or more fires occurring during the duration of a charcoal peak) (Long et al., 1998; Whitlock and Bartlein, 2004) and $C_{background}$, the slowly varying charcoal trend, has been attributed to many factors, including long-term changes in fuel biomass (Marlon et al., 2006) and area burned (Higuera et al., 2007). A robust Lowess smoother with a 400-yr window width was used to describe $C_{background}$, and C_{peak} was the residuals after $C_{background}$ was subtracted from the CHAR time series. A locally determined threshold value that was used to separate fire-related (i.e., signal) from non-fire related variability (i.e., noise) in the C_{peak} component was set at the 95th percentile of a Gaussian distribution model of the noise in the C_{peak} time series. A visual inspection of sensitivity analyses of window widths between 100 and 1000 years revealed that the signal-to-noise ratio was maximized using a window width of 400 years. C_{peak} was screened and peaks were eliminated if the maximum charcoal

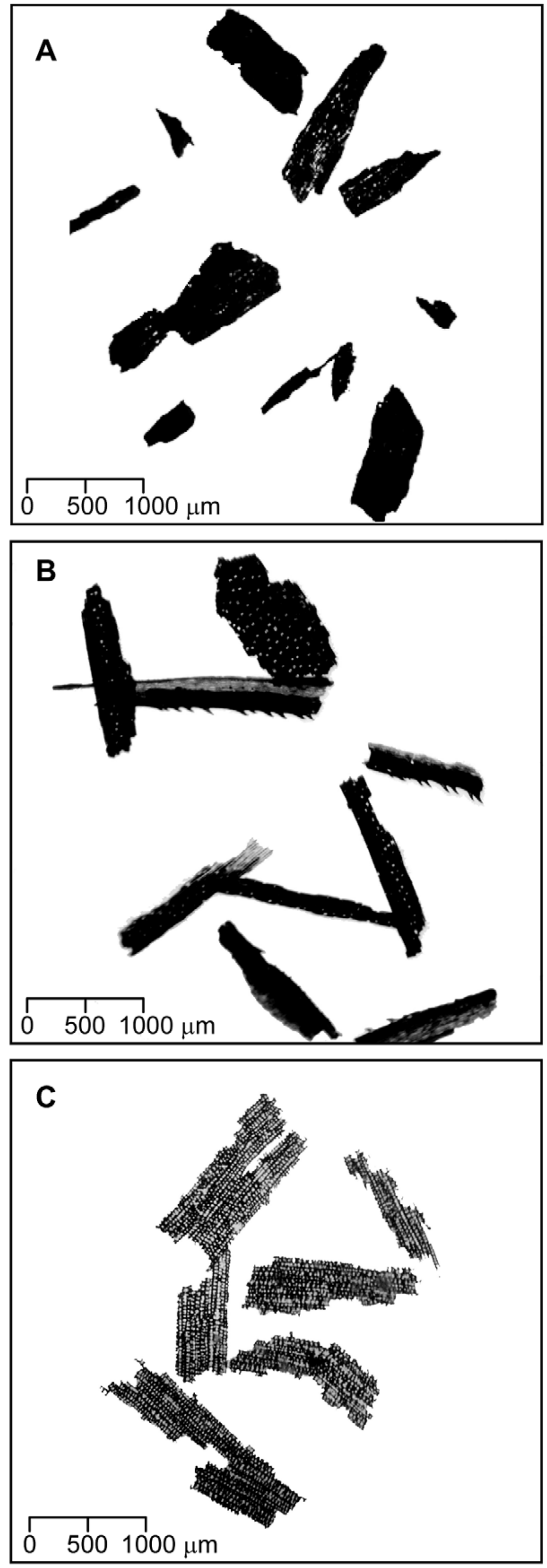

Fig. 2. Photos of A) woody charcoal, B) herbaceous (i.e., grass) charcoal, and C) lattice (source unknown) charcoal particles.

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).

The CHAR time series was plotted on a log-transformed scale in order to facilitate comparison among different sections of the core. The charcoal data from core BL05B was described using the pollen zonation of core BL93A. Smoothed fire-episode frequency, mean fire-return interval, and fire-episode magnitude were also calculated and plotted. Fire-episode frequency (episodes/1000 yr) is the sum of the number of fires within a 1000-yr period, smoothed with a Lowess filter. Mean fire-return interval (mFRI) is the average years between fire episodes within a zone. Fire-episode magnitude (particles/cm^2) is the total charcoal influx in a peak and is related to fire size, severity, proximity, and taphonomic processes (Whitlock et al., 2006; Higuera et al., 2007).

4. Results

4.1. Chronology

Eight ^{14}C age determinations on bulk sediment, one AMS ^{14}C age determination, and the accepted age of Mazama ash (Zdanowicz et al., 1999) were used to develop the age–depth model for core BL93A (Table 1, Fig. 3a). Eleven ^{210}Pb age determinations, seven AMS ^{14}C age determinations on wood fragments, one AMS ^{14}C age determination on bulk sediment, and the accepted age of Mazama ash were used to develop the age–depth model for core BL05B (Table 1, Fig. 3b). All ^{14}C age determinations were converted to calendar years before present (cal yr BP; present = 1950 AD) using Calib 5.0.2 html (Stuiver and Reimer, 2005). The probability density function (PDF) curves were plotted (Fig. 3a and b) to show the range of possible calendar ages for each ^{14}C age determination. Calibrated (calendar) ages were selected based on the following criteria: 1) the median age (i.e., the 50th percentile of the PDF) was chosen if it did not fall in a trough on the PDF curve and did not cause a reversal in the core chronology; 2) if the median age fell in a trough on the PDF curve, then the value of the nearest, largest peak was chosen; and 3) if choosing the median age caused a reversal in the core chronology, then the value of the nearest, largest peak that did not lead to a reversal in the core chronology was chosen. All age determinations fell within the 2 σ range of possible ages. The resulting age model for core BL93A was adequately described by a 3rd-order polynomial (age $= -39.03x^3 + 428.13x^2 + 445.13$[depth]), suggesting a basal date of approximately 10 920 cal yr BP (Fig. 3a). A constrained cubic smoothing spline was used to fit the age model of core BL05B, suggesting a basal date of 11 190 cal yr BP (Fig. 3b). Cores BL93A and BL05B were correlated based on the chronology of the two records and the presence of Mazama tephra.

4.2. Lithology

The lithology of cores BL93A and BL05B was nearly identical and only the longer of the two cores (BL05B) is described here (Fig. 4). The base of core BL05B consisted of coarse sand and gravel. Between 8.65 and 7.55 m depth, the sediments were silty gyttja with inorganic silt layers interspersed. Magnetic susceptibility values were highest in this part of the core (~0.0011 emu), and the organic content was lowest (~3%). Between 7.55 and 5.55 m depth, the sediments were clay gyttja (~12.5% organic content) interspersed with inorganic clay, silt, and sand layers. Magnetic susceptibility values dropped to ~0.0003 emu, although peaks in magnetic susceptibility were associated with several silt and clay layers. The sediments from the lower 3 m of the core indicate a period of lacustrine deposition interrupted by periods of flooding, typical of an oxbow lake. Sediments were laminated clay gyttja between 5.55 and 4.85 m depth, and detritus gyttja with some silt and clay between 4.85 and 4.20 m depth. A tephra in the core at 4.00 m depth was assumed to have come from the eruption of Mt. Mazama (Sea and Whitlock, 1995; Walsh et al., 2008). From a depth of 4.20 m to the top of the core, sediments were detritus gyttja containing layers of peat and woody debris. High organic content (~40%) and low magnetic susceptibility indicate a productive lake with little fluvial input. Organic content decreased to ~31.5% in the top 0.25 m of the core, most likely due to erosion following Euro-American removal of the surrounding *Salix*-dominated riparian forest and the conversion of the watershed to agriculture (discussed in Section 4.4).

4.3. Core BL93A pollen record

4.3.1. Zone BL93A-1 (7.78 m–4.57 m; ca 10 920–7250 cal yr BP)

This zone is characterized by relatively high percentages of oak-savanna taxa (i.e., *Pseudotsuga*-type, *Quercus*, *Corylus*, and *A. macrophyllum*) and disturbance taxa, predominantly *Alnus rubra*-type, which dominated through most this zone but declined toward the top (Fig. 5). Percentages of upland-forest taxa were generally low in this zone with the exception of *P. contorta*-type, *Pinus* undifferentiated, *Picea*, *Thuja*-type, and *Polystichum*-type, which were high at the start of the record, and then decreased and remained low until the top of the zone. *Pteridium* was initially high at the start of the record, decreased for most of the zone, and then increased toward the top. Riparian-forest taxa (i.e., *Salix* and *Spiraea*-type) and wet-prairie taxa (i.e., Poaceae [grasses], Cyperaceae, and Apiaceae) were present in very low percentages. The pollen data suggest the presence of xeric woodland near the site, with *A. rubra* and some *Pteridium* in disturbed areas. The high AP/NAP ratio indicates a relatively closed forest canopy.

4.3.2. Zone BL93A-2 (4.57–3.73 m; ca 7250–5600 cal yr BP)

This zone records the largest vegetation shift at Beaver Lake over the last 11 000 years, from a disturbance-prone Alnus/Quercus/Corylus-dominated oak savanna to a Salix-dominated riparian forest. Percentages of many upland-forest taxa (i.e., *Pinus* undifferentiated, Abies, *Thuja*-type, *Tsuga heterophylla*, and *Dryopoteris*-type) increased in this zone. Oak-savanna taxa percentages remained relatively high but were variable. Percentages of *A. rubra*-type decreased greatly from the previous zone, but remained relatively high. *Pteridium* percentages increased from the previous zone and *Equisetum* (horsetail) percentages were highest in this zone. Riparian-forest taxa percentages of *Salix* increased dramatically and *Fraxinus* first appeared and increased in the zone. Wet-prairie taxa percentages (i.e., Poaceae, Cyperaceae, and Apiaceae) increased steadily above BL93A-1 levels, and Liliaceae pollen first appeared in this zone. Several aquatic taxa, including *Brasenia* (water shield), *Typha latifolia* (broadleaf cattail), and *Nuphar*, were also abundant. The pollen percentages in this zone suggest that upland forest increased in abundance, probably on hillsides near the site, although this pollen may also represent changes in forests of the Coast Range. The high percentages of *Fraxinus* and *Salix*, both of which produce pollen that is not widely dispersed (Faegri et al., 1989), imply the development of riparian forest near Beaver Lake. Elevated percentages of Poaceae, Cyperaceae, Apiaceae, and Liliaceae pollen also suggest increased availability of moisture in the immediate area and likely indicate the development of seasonally wet prairie near the site. Prairie expansion, perhaps at the expense of oak savanna, is further supported by a decrease in the AP/NAP ratio, suggesting less forest cover. Lower percentages than the previous zone of some disturbance taxa (i.e., *A. rubra*-type), yet

Table 1
Age–depth relations for Beaver Lake, OR.

Depth (cm below mud surface)	Lab number	Source material	Dates (^{210}Pb, ^{14}C,volcanic tephra)	Calibrated age (cal yr BP)
Core BL93A				
63.0–70.0	Beta-85262	Lake sediment	1370 ± 80[a]	1100(1078–1412)[b]
101.0–111.0	Beta-81660	Lake sediment	1130 ± 60[a]	1220(930–1221)[b]
218.0–228.0	Beta-72836	Lake sediment	2570 ± 60[a]	2520(2369–2787)[b]
239.0–249.0	Beta-109116	Lake sediment	2920 ± 60[a]	2900(2882–3257)[b]
291.0–301.0	Beta-81661	Lake sediment	2940 ± 60[a]	3310(2927–3322)[b]
390.0–400.0	Beta-81662	Lake sediment	5710 ± 90[a]	6420(6306–6715)[b]
420.0–430.0	Beta-109117	Lake sediment	6070 ± 120[a]	6940(6670–7246)[b]
479.0–481.0	–	Mazama tephra	–	7627 ± 150[c]
670.0–680.0	Beta-109118	Lake sediment	9290 ± 50[a]	10440(10285–10647)[b]
709.0–719.0	Beta-72837	Lake sediment	9860 ± 360[a]	10800(10299–12609)[b]
Age–depth model: $y = -39.03x^3 + 428.13x^2 + 445.13x$				
Core BL05B				
1.0–2.0	–	Lake sediment	3.0[d]	−52.0
5.0–6.0	–	Lake sediment	28.6[d]	−26.4
9.0–10.0	–	Lake sediment	36.9[d]	−18.1
13.0–14.0	–	Lake sediment	41.6[d]	−13.4
17.5–18.5	–	Lake sediment	46.4[d]	−8.6
21.0–22.0	–	Lake sediment	54.8[d]	−0.2
25.0–26.0	–	Lake sediment	68.0[d]	13.0
29.0–30.0	–	Lake sediment	79.0[d]	24.0
33.0–34.0	–	Lake sediment	94.3[d]	39.3
37.0–38.0	–	Lake sediment	117.6[d]	62.6
41.0–42.0	–	Lake sediment	148.7[d]	93.7
45.5–46.5	–	Lake sediment	272.6[d,e]	217.6
84.5	AA71936	Twig	1102 ± 35[f]	980(932–1071)[b]
144.0	AA71937	Twig	1842 ± 42[f]	1750(1635–1878)[b]
220.0	AA71938	Wood	3512 ± 44[f]	3780(3645–3900)[b]
316.5	AA71939	Wood	5050 ± 43[f]	5830(5663–5908)[b]
400.0	–	Mazama tephra	…	7627 ± 150[c]
451.0	AA71940	Twig	8413 ± 51[f]	9330(9304–9526)[b]
555.0	AA71941	Twig	8860 ± 53[f]	9920(9740–10174)[b]
642.5	AA72365	Twig	8776 ± 60[f]	10100(9556–10133)[b]
849.0	AA72364	Lake sediment	9623 ± 96[f]	11100(10704–11212)[b]

[a] ^{14}C age determinations were completed at Beta Analytic, Inc.
[b] Calibrated ages determined using Calib 5.0.2 html (Stuiver and Reimer, 2005); 2a range in parentheses.
[c] Age as reported in Zdanowicz et al. (1999).
[d] ^{210}Pb age determinations completed by J. Budahn at the USGS Denver Federal Center, Colorado.
[e] Denotes sample not used in the age–depth model.
[f] ^{14}C age determinations completed at the University of Arizona AMS facility.

higher percentages of others (i.e., *Pteridium* and *Equisetum*) imply that the type of disturbance at the site may have changed, but disturbance in general remained common.

4.3.3. Zone BL93A-3 (3.73–2.32 m; ca 5600–2850 cal yr BP)

This zone is characterized by an increase in *Salix* percentages at the expense of *Fraxinus* and *Spiraea*-type. Percentages of upland-forest taxa and oak-savanna taxa were generally unchanged in this zone compared to the previous zone, although *Thuja*-type pollen reached its highest percentages and *Corylus* percentages gradually decreased. Disturbance-taxa percentages changed little from the previous zone, but with the absence of *Equisetum*, *A. rubra*-type percentages increased slightly from the previous zone and were highly variable. Wet-prairie taxa percentages of Cyperaceae, Apiaceae, and Liliaceae changed little in this zone, while Poaceae percentages generally increased toward the top. High percentages of *Salix* and *Fraxinus* indicate the persistence of riparian forest close to Beaver Lake. Little overall change in oak-savanna taxa and wet-prairie taxa indicate the continued presence of these ecosystems near the site as well. Fairly consistent percentages of *A. rubra*-type and *Pteridium* suggest disturbance (i.e., fire) near the site.

4.3.4. Zone BL93A-4 (2.32–2.00 m; ca 2850–2300 cal yr BP)

This zone is characterized by sharp declines in *Salix*, *Spiraea*-type, Cyperaceae, and Apiaceae percentages. *Brasenia* increased dramatically from the previous zone, along with increased *A. rubra*-type and *Fraxinus*. At the top of the zone, however, the aforementioned taxa had returned to their previous levels. This zone recorded a period of low water or short-term drying at Beaver Lake. Changes in littoral hydrophytes can be considered indicators of water-level variations (Barnosky, 1981; Singer et al., 1996). High percentages of *Brasenia* suggest more littoral zone and decreased water depths in the lake basin. Decreased *Salix* and *Spiraea*-type also suggest drier conditions than before. Increased *A. rubra*-type may indicate greater disturbance at the site or expanded *A. rubra*-dominated riparian forest.

4.3.5. Zone BL93A-5 (2.00–0.18 m; ca 2300–100 cal yr BP)

This zone is generally similar to Zone BL93A-3. Upland-forest taxa percentages changed little in this zone compared to the previous zone. *T. heterophylla* percentages were highest of the record and *Thuja*-type percentages decreased from the bottom to the top of the zone. *T. heterophylla* can be transported relatively long distances on prevailing winds (Minckley and Whitlock, 2000), and is likely a regional signal from the slopes of the Coast and Cascade ranges. Oak-savanna percentages of *Pseudotsuga*-type, *Quercus*, and *A. macrophyllum* remained relatively high, while *Corylus* decreased toward the top of the zone. Percentages of the disturbance taxa *A. rubra*-type decreased in this zone, while *Pteridium* percentages increased to its highest values of the record at the top of the zone. Riparian-forest taxa percentages of *Salix* and *Spiraea*-type increased, while *Fraxinus* decreased. Wet-prairie

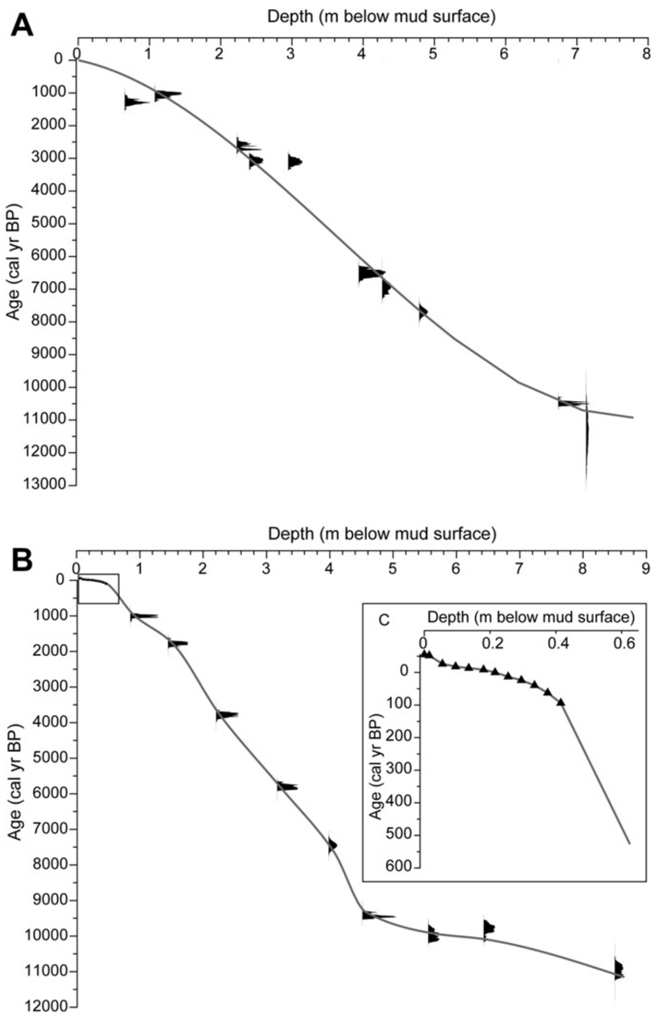

Fig. 3. Depth-versus-age relations for A) core BL93A and B) core BL05B based on the age model information given in Table 1. C) shows the depth-versus-age relations for the top 0.65 m of core BL05B based on ^{210}Pb dating, which is the area indicated by the rectangle on curve B.

percentages of Poaceae increased slightly toward the top of the zone, and Cyperaceae and Apiaceae percentages were higher than the previous zone. Several aquatic taxa were more abundant in this zone, including *Typha* and *Nuphar*. The pollen percentages in this zone suggest a heterogeneous mix of vegetation types around Beaver Lake, similar to the mosaic of *Salix*-dominated riparian forest, prairie, and oak savanna first described by the AD 1853 GLO survey notes.

4.3.6. Zone BL93A-6 (0.18–0.00 m; 100–0 cal yr BP)

The uppermost zone from core BL93A illustrate changes associated with mid-19th century Euro-American settlement and land-use activities and are discussed in further detail in Section 4.4.

4.4. Core BL05B pollen record

The pollen from the top 60 cm of core BL05B illustrate in detail the vegetation change at Beaver Lake over the last ~550 yr (Fig. 6). Little change was observed prior to ca 170 cal yr BP and pollen percentages were generally similar to Zone BL93A-5. Following Euro-American settlement ca AD 1830, *Salix*-dominated riparian forest in the Beaver Lake meander bend, as well as *Quercus*-dominated savanna around the lake, was greatly reduced. *Salix* percentages increased initially following settlement, but then sharply decreased, as did *Spiraea*-type percentages. *Fraxinus* percentages initially decreased but then slightly increased after ca AD 1950. *Quercus* percentages decreased after ca AD 1900 and remained low. *A. rubra*-type declined after ca AD 1775, but became more abundant by ca AD 1950. *Pteridium* abundance increased after ca AD 1850 and has varied since then. The development of intensely cultivated grassland was evidenced by the sharp increase in Poaceae pollen ca AD 1930. Poaceae pollen reached its greatest Holocene abundance ca AD 1960 and remains high today.

Further indication of Euro-American impact on the vegetation near Beaver Lake is evident in the initial decrease of *Pseudotsuga*-type pollen percentages after ca AD 1850 as a result of logging, and a slight increase after ca AD 1950 with the elimination of fire and spread of *Pseudotsuga* into oak savanna (Johannessen et al., 1971). A large peak in *Corylus* pollen at ca AD 1950 is attributed to large-scale hazelnut farming near the site, given that Linn County is one of seven counties that account for 97.5% of the commercial hazelnut production in Oregon (O'Connor, 2006). Pollen from additional ornamental/cultigen taxa appeared in the uppermost sediments of the core after ca AD 1950, including Brassicaceae (mustard family) and *Juglans* (walnut) pollen. *Plantago*-type (plantain) pollen also appeared ca AD 1850 and generally increased in abundance toward the top of the record. This is probably the non-native *Plantago lanceolata* (English plantain), commonly found in remnant Pacific Northwest prairies (Dunwiddie et al., 2006).

4.5. Core BL05B charcoal record

4.5.1. Zone BL05B-1 (8.67–3.84 m; 11 190–7250 cal yr BP)

Fire activity was highly variable in this zone (Fig. 7). Charcoal concentration values ranged between 0 and 176 particles/cm^3 and CHAR values ranged between 0 and 43 particles/cm^2/yr (see Table 2 for zone averages). The highest CHAR value of the record occurred ca 10 000 cal yr BP. Fire-episode frequency (hereafter called fire frequency) increased from 8 episodes/1000 yr at the beginning of the record to 9 episodes/1000 yr ca 10 500 cal yr BP, decreased to 4 episodes/1000 yr ca 8800 cal yr BP, and then increased to 6 episodes/1000 yr at the top of the zone. Fire-episode magnitude varied widely from 0.3 to 336 particles/cm^2. The mFRI was highest of the record. Herbaceous charcoal content was also highest in this zone, especially before ca 9500 cal yr BP; lattice charcoal content was lowest.

4.5.2. Zone BL05B-2 (3.84–3.05 m; 7250–5600 cal yr BP)

CHAR was generally low in this zone (0–0.9 particles/cm^2/yr), but charcoal concentration remained relatively high (8–138 particles/cm^3). Fire frequency increased to 8 episodes/1000 yr ca 6300 cal yr BP, and then decreased to 6 episodes/1000 yr at the top of the zone. Fire-episode magnitude was lower than the previous zone and varied between 0.03 and 209 particles/cm^2. Herbaceous charcoal content was lower in this zone than before; lattice charcoal content was higher.

4.5.3. Zone BL05B-3 (3.05–1.86 m; 5600–2850 cal yr BP)

Charcoal concentration and CHAR values remained generally unchanged from the previous zone. Charcoal concentration values ranged between 2 and 170 particles/cm^3 and CHAR values ranged between 0 and 8.3 particles/cm^2/yr. Fire frequency increased to 10 episodes/1000 yr ca 4130 cal yr BP, decreased to 8 episodes/1000 yr ca 3300 cal yr BP, and then increased to 9 episodes/1000 yr at the top of the zone. Fire-episode magnitude was lower and ranged between 0.03 and 102 particles/cm^2. Herbaceous charcoal content decreased slightly in this zone as compared to the previous interval, while lattice charcoal content increased.

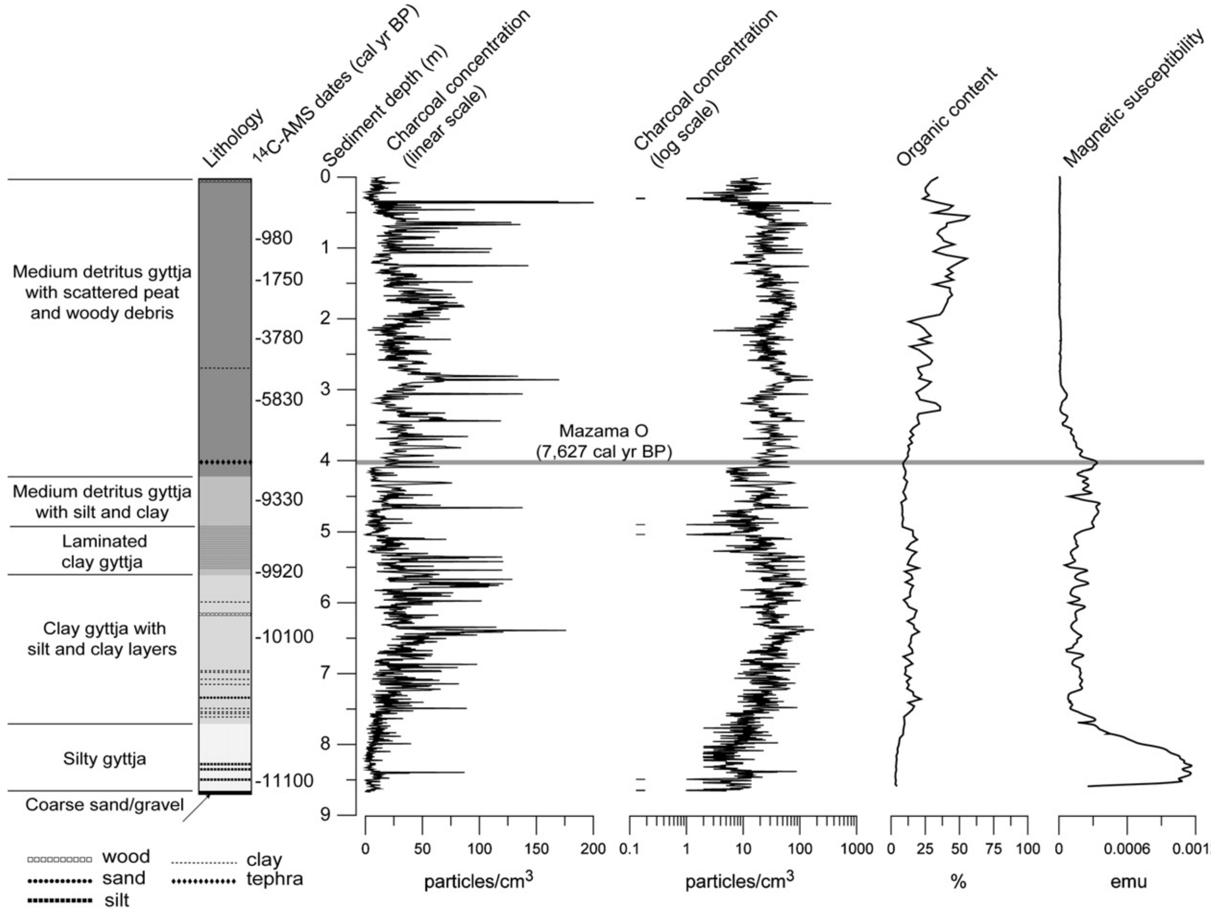

Fig. 4. Lithology, ^{14}C-AMS dates, charcoal concentration (linear scale), charcoal concentration (log scale), organic content, and magnetic susceptibility for core BL05B plotted against depth (*m*). The vertical ticks on the charcoal concentration (log scale) curve represent zero values.

4.5.4. Zone BL05B-4 (1.86–1.68 m; 2850–2300 cal yr BP)

Charcoal concentration and CHAR increased in this zone as compared to the previous interval. Charcoal concentration values ranged between 18 and 87 particles/cm^3 and CHAR values ranged between 0.6 and 2.9 particles/cm^2/yr. Fire frequency remained near 9 episodes/1000 yr in this zone and fire-episode magnitude was low and ranged from 1.2 to 24 particles/cm^2. Grass charcoal content increased from the previous zone and lattice charcoal content dropped sharply.

4.5.5. Zone BL05B-5 (1.68–0.63 m; 2300–100 cal yr BP)

Charcoal concentration and CHAR decreased from the previous zone. Charcoal concentration values ranged between 5 and 143 particles/cm^3 and CHAR values ranged between 0 and 10 particles/cm^2/yr. Fire frequency decreased slightly to 8 episodes/1000 yr ca 2000 cal yr BP, and then increased to 14 episodes/1000 yr at the top of the zone. Fire-episode magnitude increased sharply from the previous two zones and ranged between 1 and 138 particles/cm^2. Herbaceous charcoal content decreased in this zone, while lattice charcoal content increased.

4.5.6. Zone BL05B-6 (0.63–0.0 m; 100 to −55 cal yr BP)

Charcoal concentration dropped in this zone compared to the previous one and was lowest of the record while CHAR increased sharply and was the highest of the record. Charcoal concentration values ranged between 0 and 355 particles/cm^3 and CHAR values ranged between 1 and 20 particles/cm^2/yr. Fire frequency increased slightly from 14 to 15 episodes/1000 yr from the bottom to the top of the zone. The mFRI was the lowest of the record and fire-episode magnitude, which ranged from 10 to 259 particles/cm^2, was the highest. Additionally, herbaceous charcoal content was lowest of the record and lattice charcoal content was highest.

5. Discussion

5.1. Beaver Lake fire and vegetation history

Regional climate variability and local geomorphic/hydrologic development in the Willamette Valley have influenced Beaver Lake and its fire and vegetation history over the last ca 11 000 years. Between ca 15 000 and 12 800 cal yr BP, as many as 40 outburst floods from glacial Lake Missoula flowed down the Columbia River (Waitt, 1985; Allen et al., 1986), inundated the Willamette Valley and deposited an enormous amount of sediment across the valley floor (Allison, 1978). This basin fill has been eroded and redeposited throughout the late Pleistocene and Holocene by the Willamette River and its tributaries (Gannett and Caldwell, 1998). The formation of the Beaver Lake meander bend occurred soon after the cessation of these floods, evidenced by the age of the lowest sediments and the lake's position on the Winkle geomorphic unit, the oldest erosional/alluvial terrace associated with the present drainage system (Balster and Parsons, 1968). The location of Beaver Lake and the lithology of the core indicate that the site has been subject to flooding, but the continuity and character of the sediments (e.g., the presence of laminations and absence of any obvious

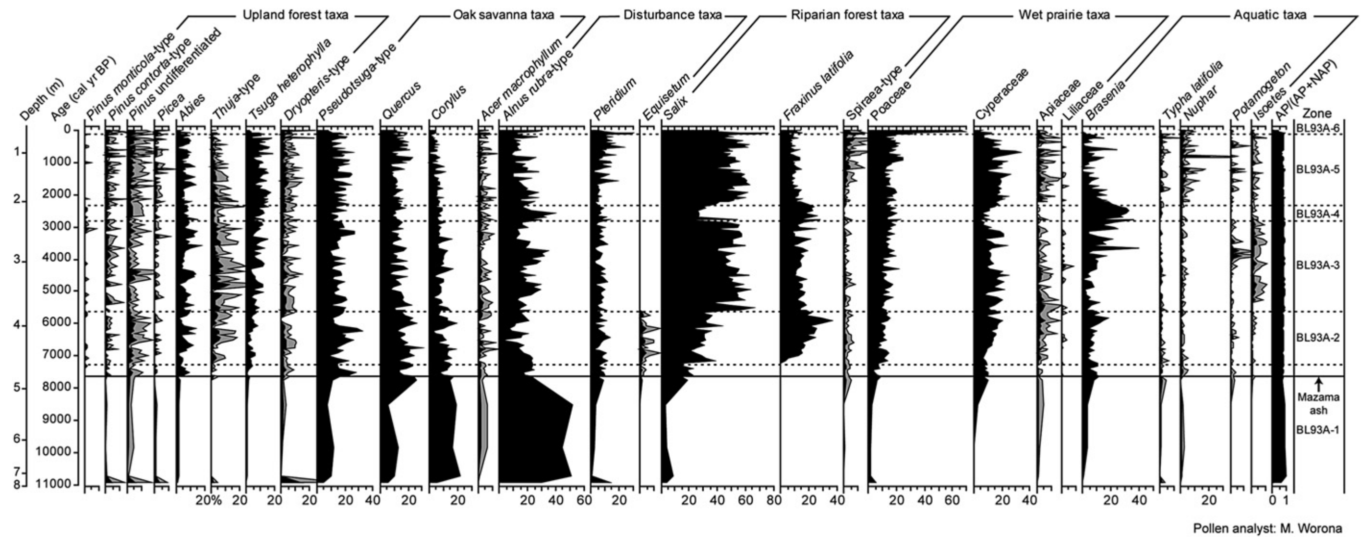

Fig. 5. Percentages of selected pollen taxa and spores, and AP/NAP ratio from core BL93A plotted against age (cal yr BP). Gray curves represent a 3X exaggeration of solid black curve. Dashed lines indicate zone boundaries.

hiatus in the age–depth plot) suggests that flooding did not substantially erode or modify the sediment record.

Although the Beaver Lake record does not technically extend into the late-glacial period, the earliest pollen samples from zone BL93A-1 seem to have captured the end of the *P. contorta* (lodgepole pine)-dominated landscape described by Hansen (1947). Similar *Pinus*-dominated landscapes existed further north in the lower Columbia River Valley and the Puget Trough (Whitlock, 1992). The long-term climate history of the Pacific Northwest changed gradually during the Holocene as the Earth's orbital parameters changed (i.e., timing of perihelion, tilt of the Earth's axis) (Fig. 8) (Berger and Loutre, 1991; Kutzbach et al., 1993). Paleoclimatic model simulations show that during the early Holocene (ca 11 000–7500 cal yr BP) when summer insolation was amplified and effective moisture was reduced, the Pacific Northwest experienced warmer summers and drier conditions than present (Thompson et al., 1993; Bartlein et al., 1998). Xerophytic (drought-tolerant) taxa, including *Quercus* and *Pseudotsuga* (Minore, 1979), and disturbance-tolerant taxa, such as *Corylus*, *A. rubra*, *Quercus*, and *Pseudotsuga* (Agee, 1993), were more abundant near Beaver Lake in the early Holocene.

Studies from additional sites in the Willamette Valley and other areas of the Pacific Northwest reveal early-Holocene trends similar to those observed at Beaver Lake. At Lake Labish and Onion Flat, *Quercus* expansion occurred prior to the deposition of Mazama ash (ca 7627 cal yr BP; Zdanowicz et al., 1999) (Hansen, 1947). An expansion of *Quercus*, *A. rubra*, and *Pteridium* was also noted at Little Lake in the central Oregon Coast Range in the early Holocene (Worona and Whitlock, 1995), at a time when fire frequency was also high (Long et al., 1998) (Fig. 8). *Quercus* and *Corylus* pollen maxima were recorded at Indian Prairie Fen in the central Cascade Range in the early to middle Holocene (ca 10 000–7000 cal yr BP),

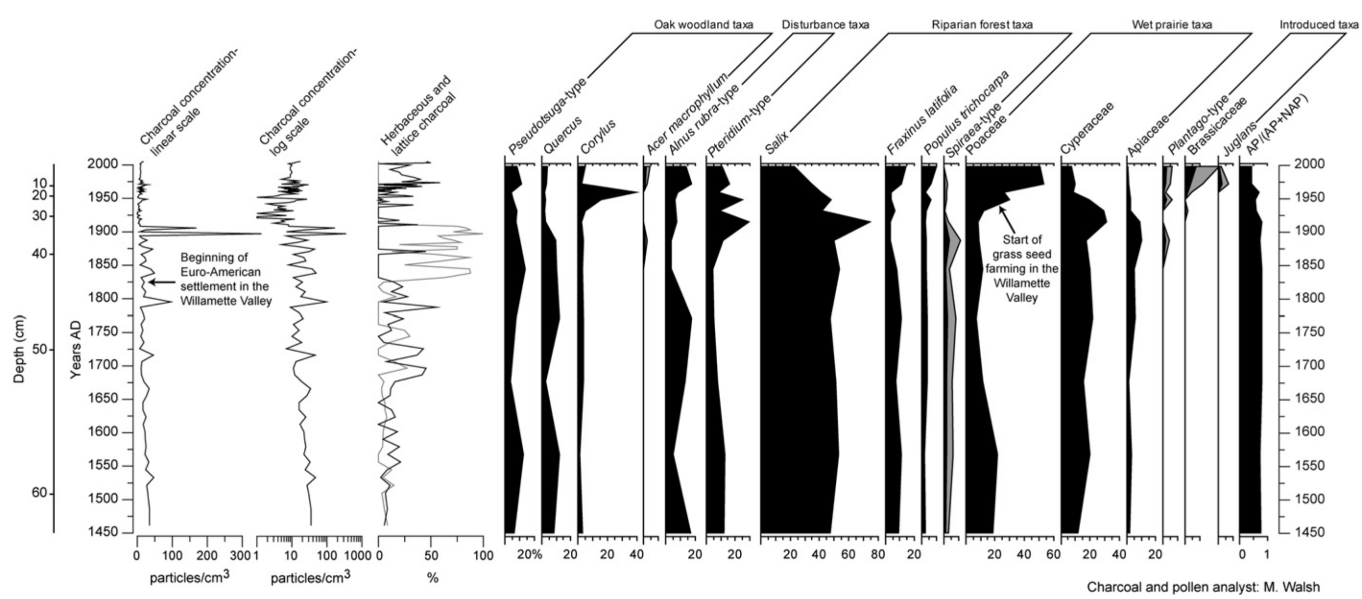

Fig. 6. Charcoal concentration (linear scale), charcoal concentration (log scale), herbaceous (black line) and lattice (gray line) charcoal, selected pollen taxa percentages, and AP/NAP ratio from the top 65 cm of core BL05B plotted against depth (cm) and age (yr AD). Gray curves represent a 3X; exaggeration of solid black curves.

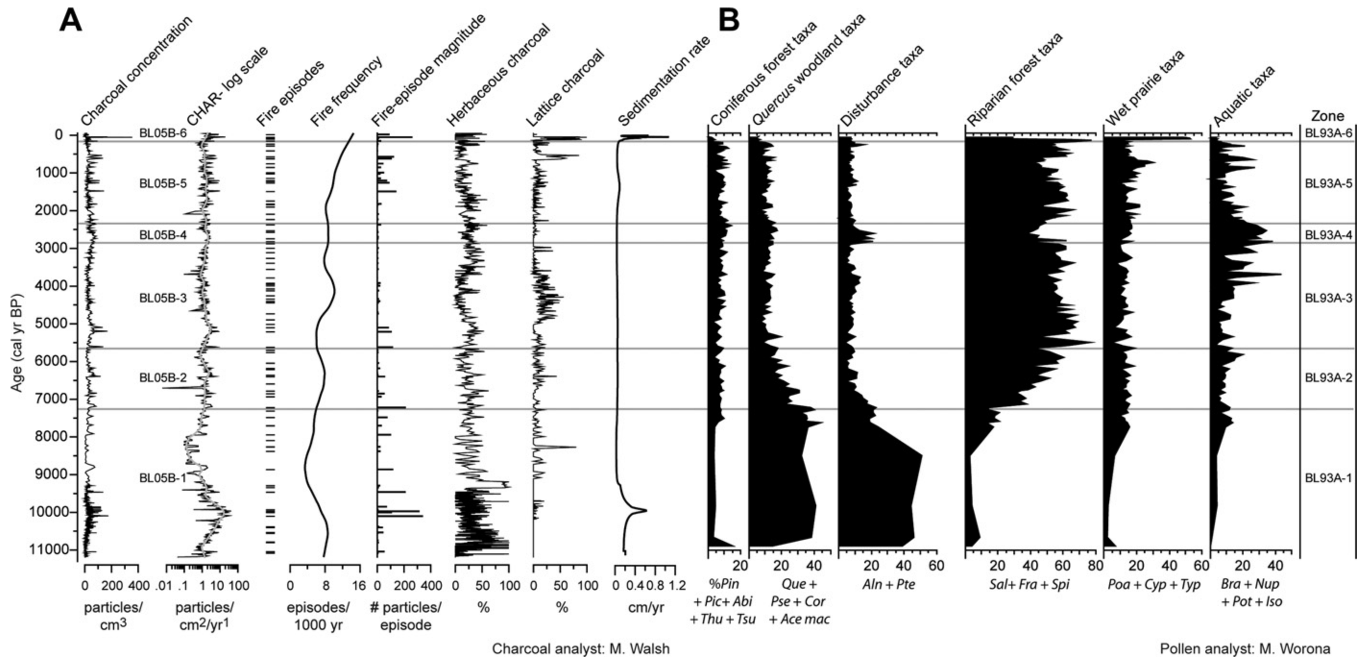

Fig. 7. A) Core BL05B charcoal concentration, charcoal accumulation rate (log scale), fire episodes, fire frequency, fire magnitude, herbaceous charcoal, lattice charcoal, and sedimentation rate plotted against age (cal yr BP). B) Core BL93A selected summed pollen percentages plotted against age (cal yr BP). Pollen abbreviations are as follows: Pic = *Picea*, Abi = *Abies*, Thu = *Thuja plicata*, Tsu = *Tsuga heterophylla*, Que = *Quercus*, Pse = *Pseudotsuga menziesii*, Cor = *Corylus*, Ace mac = *Acer macrophyllum*, Aln = *Alnus rubra*, Pte = *Pteridium*, Sal = *Salix*, Fra = *Fraxinus latifolia*, Spi = *Spiraea*, Poa = Poaceae, Cyp = Cyperaceae, Typ = *Typha latifolia*, Bra = *Brasenia*, Nup = *Nuphar*, Pot = *Potamogeton*, Iso-*Isoetes*.

when these taxa apparently extended their elevational range to as much as 500 m above the Willamette Valley floor (Sea and Whitlock, 1995). *Quercus* and herb-dominated savanna also extended north to Battle Ground Lake in the lower Columbia River Valley (Whitlock, 1992), and prairies in the central Puget Trough expanded as well (Hibbert, 1979). The fire history from Battle Ground Lake indicates relatively frequent, low- to moderate-severity fires burning mostly herbaceous material helped maintain the open landscape (Fig. 8) (Walsh et al., 2008). The early-Holocene savanna at Battle Ground Lake featured less *Corylus* and more Poaceae and other herbs (Barnosky, 1985) than at Beaver Lake, suggesting a more open landscape in the lower Columbia River Valley as compared to the central Willamette Valley.

Fire frequency was relatively high at Beaver Lake before 9500 cal yr BP with a large proportion of herbaceous charcoal recorded, suggesting frequent grass fires. However, several large-magnitude fire episodes recorded ca 10 000 cal yr BP were dominated by woody charcoal, likely indicating local forest fires. Although it is possible that floods transported charcoal during this period, the lack of a correspondence between inorganic (i.e., sand, silt, clay) layers and charcoal peaks suggests the fires were local. Frequent lightning ignitions, the result of generally warm and dry conditions in the early Holocene and increased convection due to stronger radiational heating at the surface (Bartlein et al., 1998), likely caused the high fire activity. Additionally, the presence of quickly-regenerating herbaceous vegetation (e.g., *Pteridium*, Poaceae) could have contributed to the ability of the landscape to burn frequently. This is supported by the high proportion of herbaceous charcoal in the record during this period (~30%). Fire activity decreased after 9500 cal yr BP at Beaver Lake, although a drop in sedimentation rate in the core at this time may over-emphasize the decline (Fig. 7). Less frequent silt and clay layers after ca 9000 cal yr BP also suggest reduced flooding and greater hydrologic isolation of the oxbow lake. The drop in *A. rubra* pollen after ca 9000 cal yr BP is consistent with decreased flooding and fires at this time. After this, *Quercus* increased to its highest level, suggesting that it may have colonized the former fluvially-disturbed habitats previously dominated by *A. rubra*.

Cooler and effectively wetter conditions than before, the result of decreasing summer insolation (Bartlein et al., 1998), and changes in the Willamette River system in the middle Holocene (ca 7500–4000 cal yr BP) (Parsons et al., 1970) likely led to the

Table 2
Average charcoal concentration values, CHAR values, fire frequency, fire-episode magnitude, mean fire-return interval, herbaceous charcoal, and lattice charcoal for Beaver Lake core BL05B.

Zone: age (cal yr BP)	Charcoal concentration (particles/cm^3)	CHAR (particles/cm^2/yr)	Fire frequency (episodes/1000 yr)	Fire-episode magnitude (particles/cm^2)	Mean fire-return interval (yr)	Herbaceous charcoal (%)	Lattice charcoal (%)
BL05B-6: 100–55	16.4	4.4	14	119	55	12	13
BL05B-5: 2300–100	30.1	1.8	10	34	126	18	8
BL05B-4: 2850–2300	55.0	1.9	9	8	116	27	2
BL05B-3: 5600–2850	35.4	1.6	8	14	157	21	12
BL05B-2: 7250–5600	35.2	1.6	7	39	155	23	6
BL05B-1: 11 190–7250	25.3	3.0	6	65	223	29	0.6

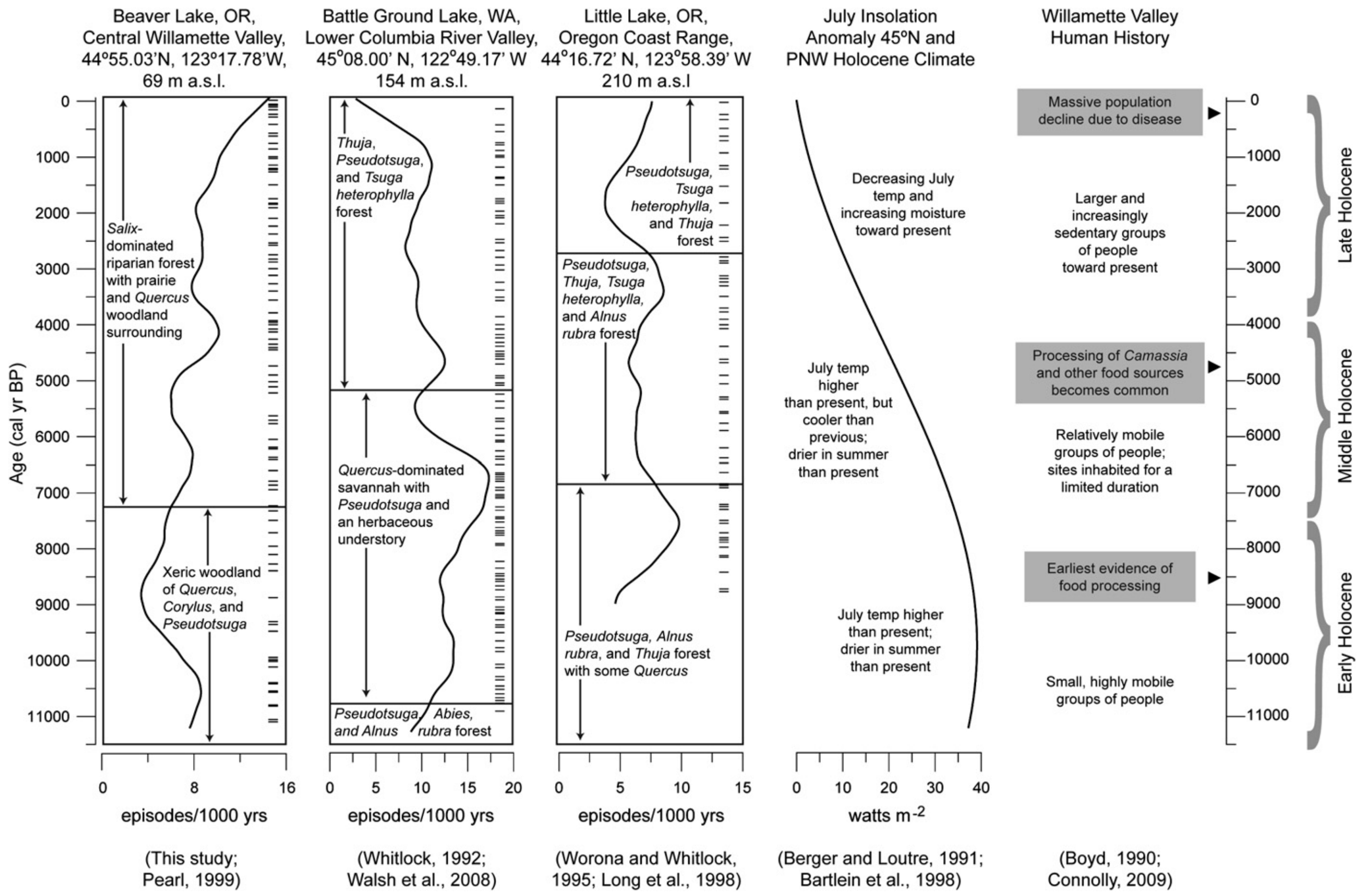

Fig. 8. Reconstructed vegetation, fire frequency, and fire episodes (peaks) plotted against age (cal yr BP) for Pacific Northwest sites. Sites are arranged from low to high elevation (left to right). Also shown are July insolation anomaly for 45°N latitude and Pacific Northwest Holocene climate history; and a generalized human history for the Willamette Valley, Oregon.

establishment of mesophytic and hydrophytic vegetation near Beaver Lake. Increased *Salix* and *Spiraea* ca 7500 cal yr BP and the appearance of *F. latifolia* ca 7250 cal yr BP mark the development of riparian forest at the site. The rise in Poaceae, Cyperaceae, Apiaceae, and Liliaceae ca 7500 cal yr BP is associated with the appearance of wet-prairie habitats. A slight decrease in the AP/NAP ratio, suggests less forest cover than before at the site. Oak savanna, which probably included *Quercus*, *Pseudotsuga*, *Corylus*, and *A. macrophyllum* (Thilenius, 1968), decreased from its early-Holocene maximum, but the pollen data suggest it persisted through the middle and late Holocene (ca 4000 cal yr BP to present), probably on drier hillsides and other upland areas. The lack of silt and clay layers, low magnetic susceptibility values, and increased organic content of the sediment after ca 7500 cal yr BP suggest that the site was infrequently flooded in the middle and late Holocene.

A period of *Equisetum* abundance occurred at Beaver Lake in zone BL93A-2 between ca 7500 and 5600 cal yr BP. *Equisetum* species are proficient colonizers of disturbed areas (Hauke, 1963) including deep tephra deposits (Bilderback and Carlson, 1987) and burned ground (Beasleigh and Yarranton, 1974). The rise in *Equisetum* ca 7600 cal yr BP, which immediately followed the deposition of Mt. Mazama tephra across the valley floor (Hansen, 1947), also occurred during a period of increased fire frequency. The combination of these disturbances likely created a unique environment in which *Equisetum* was allowed to colonize and flourish at the site. The subsequent disappearance of *Equisetum* from the Beaver Lake area at the start of zone BL93A-3 was seemingly the result of increased *Salix* abundance in the riparian forest and fewer fires.

Beyond a short period of inferred low water depth from ca 2850–2300 cal yr BP, during which *Brasenia*, *A. rubra*, and *Fraxinus* expanded at the expense of *Salix* and *Spiraea*, Beaver Lake was relatively uninfluenced by further major hydrologic changes in the middle and late Holocene (Fig. 7).

Pollen records throughout the Pacific Northwest indicate an expansion of mesophytic vegetation in the middle Holocene (Cwynar, 1987; Whitlock, 1992; Worona and Whitlock, 1995; Brown and Hebda, 2002a). At Little Lake, *Thuja* pollen increased at the expense of *Quercus* and *Pseudotsuga* ca 6400 cal yr BP (Worona and Whitlock, 1995). At Indian Prairie Fen, *Abies* expanded at the expense of *Quercus* and *Corylus* ca 7600 cal yr BP (Sea and Whitlock, 1995). *Quercus*-dominated savanna at Battle Ground Lake decreased in the middle Holocene and was replaced by *Pseudotsuga*/*Thuja*-dominated forest ca 5200 cal yr BP (Whitlock, 1992).

Further increases in effective moisture and decreased seasonal differences in insolation in the late Holocene (Bartlein et al., 1998) led to the establishment of modern coniferous forests in the Cascade and Coast ranges. At most sites, this transition is marked by a decline in *Pseudotsuga* and *Alnus* and an expansion of *Tsuga* spp. and *Thuja* (Tsukada et al., 1981; Sea and Whitlock, 1995; Long and Whitlock, 2002; Brown and Hebda, 2003). At Battle Ground Lake, savanna was greatly reduced as indicated by the decrease in *Quercus* and numerous herbaceous taxa (Whitlock, 1992). In contrast, the vegetation record from Beaver Lake showed little change through the middle and late Holocene. The increased presence of conifer pollen likely reflects the expansion of mesophytic forest in the Coast and Cascade ranges and foothill regions of the Willamette Valley (Worona and Whitlock, 1995). *Salix/Fraxinus* riparian forest, herb-dominated wet prairie, and *Quercus*-dominated savanna persist near the site over the last ca 8000 years with little change (Fig. 7).

The Beaver Lake fire-history reconstruction has little similarity with other low-elevation (<500 m a.s.l.) records in the Coast and Cascade ranges, the lower Columbia River Valley, Vancouver Island, or the Puget Lowland. Numerous sites in the Pacific Northwest show that climate-driven vegetation shifts in the middle-to-late Holocene led to decreased fire activity (see Walsh et al., 2008 for a discussion of this). For example, at Battle Ground Lake (Walsh et al., 2008), fire frequency was high ca 6800 cal yr BP when the site was dominated by *Quercus* savanna, but generally decreased toward present as a forest of *Thuja*, *Pseudotsuga*, and *T. heterophylla* became established under cooler and wetter conditions during the late Holocene (Fig. 8). Fire frequency at Little Lake also generally decreased ca 7500 cal yr BP to the present as mesophytic and disturbance (i.e., fire) sensitive taxa expanded near the site (Long et al., 1998) (Fig. 8). In contrast, fire frequency generally increased over the last 9000 years at Beaver Lake (Figs. 7 and 8). The initial increase in fire frequency occurred near the time when the pollen record registered the appearance of wet-prairie taxa near the site at ca 7500, but no subsequent shifts in vegetation composition were recorded that could explain further increases in fire frequency. If fire frequency at Beaver Lake was responding directly to changes in insolation, then one would expect that it would stabilize or even decrease as the regional climate cooled and became wetter toward present, but this did not happen.

Even with this regional shift in climate, summers remained sufficiently warm and dry enough to support fires during the middle-to-late Holocene. At present, lightning-ignited fires occur in the Willamette Valley in late summer when convectional thunderstorms ignite seasonally dried grasses (Bartlein et al., 2008; personal observation). Based on this, several hypotheses could explain the increased fire frequency at Beaver Lake over the last 9000 years; H1) the frequency of summer lightning strikes increased; H2) the frequency of summer lightning strikes remained the same, but the length of summer fire weather (i.e., drought) increased into fall; H3) the frequency of summer lightning strikes remained the same, but changes in vegetation structure allowed for greater ignitions; or H4) human activity increased the number of ignitions. H1) It seems unlikely that fire frequency at Beaver Lake increased because of an increase in summer lightning strike-ignitions during the middle-to-late Holocene. Decreased summer insolation as compared to earlier would have meant less summer ground heating, less convection, and likely fewer lightning strikes (Bartlein et al., 1998). H2) It is possible that a longer fire season led to an increased ignition rate near Beaver Lake during the middle-to-late Holocene, but it is difficult to prove. El Niño Southern Oscillation variability, which typically brings drier conditions to the Pacific Northwest during an El Niño year (Mantua, 2002), is known to increase fire activity in the interior Pacific Northwest (Heyerdahl et al., 2008), but has yet to be linked to fire activity in western Oregon. Even so, our lack of an understanding of El Niño variability (i.e., frequency, strength) during the middle-to-late Holocene makes it impossible to assess its influence on past fire activity. Furthermore, because of the decadal resolution of the charcoal record, we are unable to discern if fires at Beaver Lake during the middle-to-late Holocene occurred in summer (as is typical at present), or if they occurred during drier-than-present fall conditions caused by ENSO variability. Therefore, it remains possible that increased fire frequency at Beaver Lake over the last 9000 years was the result of regional climate variability in the Pacific Northwest. H3) Although the pollen data suggest no major shifts in the vegetation composition near Beaver Lake over the last 9000 years, shifts in vegetation (i.e., fuel) structure, which are not well registered in the pollen record (Carcaillet et al., 2001), could have increased the likelihood that lightning strikes ignited dry summer vegetation. However, the generally similar charcoal content (i.e., fuel type) of middle-to-late Holocene fires suggests that if changes in vegetation structure did occur (and therefore a different fuel type was burned), that these changes were insufficient to explain the total increase in fire frequency on their own. The clear exceptions to this occurred in Zone BL05B-3 (ca 5000–3500 cal yr BP), Zone BL05B-5 (ca 600 cal yr BP), and Zone BL05B-6 (ca 100–50 cal yr BP), when a large amounts of lattice-type charcoal (probably from leaves and other non-woody material) and lesser amounts of herbaceous charcoal (i.e., from grass) burned, leading to generally higher fire frequency during those times. H4) Greater intensity of human activity may have increased the number of ignitions near Beaver Lake during the middle-to-late Holocene and is discussed in the next section, as well as the possibility that the increased fire frequency was the result of some combination of climatic, ecological, and human influences.

5.2. Anthropogenic influences on the Beaver Lake record

Relatively little is known about the Holocene human history of the Willamette Valley, but the discovery of Clovis projectile points suggests habitation since ca 13 000 years ago (Aikens, 1993; Waters and Stafford, 2007). Early-Holocene evidence of habitation is sparse (Cheatham, 1984, 1988), either because repeated flooding of the Willamette River and its tributaries removed or buried archaeological sites (Aikens, 1993), or because the highly mobile lifeways of the Kalapuyans (the collective name for the native peoples of the Willamette Valley) left few cultural remains (Connolly, 2009). High magnetic susceptibility values and numerous sand, silt, and clay layers present in the Beaver Lake record prior to ca 9000 cal yr BP suggest the lake was located on a floodplain and intermittently inundated by floodwater in the early Holocene. This flooding would have made the area surrounding the site inhospitable for permanent settlement and unlikely that human ignitions were important at that time.

Middle Holocene archaeological sites in the Willamette Valley are more abundant than earlier and are dominated by pit ovens containing the charred remains of *Camassia quamash* (camas lily) bulbs, hazelnut shells, and oak acorn meats (O'Neill, 1987; O'Neill et al., 2004; Connolly, 2009). This change likely signals an intensification of food processing, and as a result, Kalapuyan groups may have seasonally occupied or managed the area around Beaver Lake to harvest local resources such as acorns, hazelnuts, and camas bulbs. Both *Quercus* and *Corylus* pollen remained relatively abundant in the Beaver Lake record through the middle-to-late Holocene, and although no *Camassia*-type pollen was found (unlike at Battle Ground Lake; Whitlock, 1992), modern plant associations place it within lowland riparian forest and wet-prairie ecosystems (Christy, 2004). Increasingly frequent fires at Beaver Lake during middle-to-late Holocene cooling may have been an attempt by the Kalapuya to maintain this vegetation and increase productivity of important food resources.

Further evidence suggests at least a partial human explanation for the increased fire activity at Beaver Lake during the middle-to-late Holocene. A shift from a period of highly variable fire-episode magnitude to a one of small-magnitude fires near Beaver Lake occurred ca 5000 cal yr BP and persisted until ca 1500 cal yr BP. A greater proportion of lattice charcoal in the record also occurred at this time, indicating that a different type of fuel was burned as compared to before. The timing of this shift coincides with increases in human populations in the Willamette Valley (Cheatham, 1988;

Connolly et al., 1997; O'Neill et al., 2004) and the establishment of cooler, effectively wetter conditions typical of present day. This change in climate greatly altered the seasonal availability of food resources and necessitated food storage, which in turn led to a semi-sedentary lifestyle where seasonal camps were frequently re-used or inhabited for extended amounts of time (Prentiss and Chatters, 2003; O'Neill et al., 2004). Population pressure and resource competition between neighboring groups may have decreased the amount of land available to each community, thus necessitating the use of fire as a management tool. The small magnitude of the fire episodes during this period suggests that climatic conditions were too wet for large fires to spread, or that small surface fires were used to enhance the growth of desired food sources.

Ca 1500–500 cal yr BP, fire episodes became much greater in magnitude than before (Fig. 7) and could be the result of regionally drier conditions associated with the Medieval Climate Anomaly (ca 1100–700 cal yr BP, AD 850–1250; Mann, 2002) (Graumlich and Brubaker, 1986). Four fire episodes with an average magnitude of 33 particles/cm^2 were recorded during the time of the Medieval Climate Anomaly, and a shift to less herbaceous charcoal (~16%) suggests fires burned more trees and shrubs (and were possibly more severe) than before. Two later fire episodes (ca 630 and 575 cal yr BP) are notable, not only because they were the last relatively high-magnitude fire episodes, but also because they were composed almost exclusively of lattice charcoal (60% and 85%, respectively). If lattice charcoal indeed comes from leaves and other non-woody material, then this may indicate that humans were burning material that typically did not burn in lightning strike-ignited fires.

At ca 500 cal yr BP, during another period of lower fire frequency, the fire regime at Beaver Lake shifted again, this time to low-magnitude fire episodes and the lowest charcoal concentration of the entire record. This decline in burning may have been the result of cooler, wetter conditions during the Little Ice Age (ca 500–100 cal yr BP, AD 1450–1850; Grove, 2001); five fire episodes with an average magnitude of 8 particles/cm^2 were registered during this time. However, this shift could also indicate human abandonment of the area due to lack of resources, or a reduction in population size due to introduced disease. Boyd (1990) estimated that as early as ca AD 1770 (ca 190 cal yr BP), disease had reached the Northwest Coast and had begun to reduce Native American populations. Others suggest that this may have occurred even earlier (Dobyns, 1983; Campbell, 1990), although there is no evidence to support this hypothesis. After ca AD 1875, fires at Beaver Lake are attributed to Euro-American settlement and land clearance (Figs. 6 and 7). A high proportion of lattice charcoal as compared to before indicates that these fires were anomalous to those of the previous 400 years. The largest magnitude post-settlement fire episode occurred ca AD 1890 (ca 60 cal yr BP) and was composed predominantly of lattice charcoal (~76%). No significant fire episodes were recorded at Beaver Lake over the last 45 years, and today, approximately half of the charcoal entering the lake is herbaceous and likely comes from annual burning of nearby grass seed fields.

6. Conclusions

Beaver Lake provides the first complete Holocene fire and vegetation history from the Willamette Valley. In the early Holocene, warmer, drier summers than at present and frequent flooding were responsible for relatively xeric woodland of *Quercus*, *Corylus*, and *Pseudotsuga*, with abundant *A. rubra* in disturbed areas. Riparian forest and wet-prairie habitat developed in the middle Holocene, likely a result of less frequent flooding and a shift to effectively cooler, wetter conditions than before. The vegetation at Beaver Lake remained relatively unchanged over the last 8000 cal yr; riparian forest and wet prairie grew around the lake and on the active floodplains, oak savanna existed on surrounding uplands, and conifer forest covered the foothills of the Coast and Cascade ranges. The exceptions to this were a brief period of inferred local drying/lowered lake level ca 2850–2300 cal yr BP, and the period Euro-American land clearance and agriculture after ca 160 cal yr BP.

High fire activity at Beaver Lake occurred ca 11 200–9300 cal yr BP in association with warm, dry conditions and the presence of xeric woodland near the site. Fires were likely frequent surface burns, although fire-episode magnitude and charcoal type suggests that at least a few of these were higher-severity burns. A decrease to the lowest fire frequency of the entire record occurred after 9300 cal yr BP, possibly the result of cooler, wetter climatic conditions. Subsequently, increased fire frequency during the middle and late Holocene, a period in which climatic conditions became wetter and cooler than before, could point to the importance of anthropogenic burning near Beaver Lake. This is supported by an increased abundance of archaeological sites interpreted to have been focused on food processing during this period. The middle and late Holocene fire history from Beaver Lake differs from other fire-history records at low-elevation sites in the Pacific Northwest, suggesting that the maintenance of wet prairie and oak savanna in the Willamette Valley, especially over the last 5000 years, was more so driven by local changes in vegetation structure and human land use, and to a lesser extent, regional climate variability.

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