

A 14,300-year-long record of fire–vegetation–climate linkages at Battle Ground Lake, southwestern Washington

Megan K. Walsh ^{a,*}, Cathy Whitlock ^b, Patrick J. Bartlein ^a

^a Department of Geography, University of Oregon, Eugene, OR 97403, USA

^b Department of Earth Sciences, Montana State University, Bozeman MT 59717, USA

Received 14 November 2007

Available online 16 July 2008

Abstract

High-resolution macroscopic charcoal analysis was used to reconstruct a 14,300-year-long fire history record from the lower Columbia River Valley in southwestern Washington, which was compared to a previous vegetation reconstruction for the site. In the late-glacial period (ca. 14,300–13,100 cal yr BP), *Pinus/Picea*-dominated parkland supported little to no fire activity. From the late-glacial to the early Holocene (ca. 13,100–10,800 cal yr BP), *Pseudotsuga/Abies*-dominated forest featured more frequent fire episodes that burned mostly woody vegetation. In the early to middle Holocene (ca. 10,800–5200 cal yr BP), *Quercus*-dominated savanna was associated with frequent fire episodes of low-to-moderate severity, with an increased herbaceous (i.e., grass) charcoal content. From the middle to late Holocene (ca. 5200 cal yr BP to present), forest dominated by *Pseudotsuga*, *Thuja*-type, and *Tsuga heterophylla* supported less frequent, but mostly large or high-severity fire episodes. Fire episodes were least frequent, but were largest or most severe, after ca. 2500 cal yr BP. The fire history at Battle Ground Lake was apparently driven by climate, directly through the length and severity of the fire season, and indirectly through climate-driven vegetation shifts, which affected available fuel biomass.

© 2008 University of Washington. All rights reserved.

Keywords: Fire history; Macroscopic charcoal; Pollen; Late-glacial; Holocene; Lower Columbia River Valley; Washington

Introduction

Little is known about the presettlement fire history of the interior valleys of the Pacific Northwest (PNW), including the Puget Lowland and lower Columbia River Valley (LCRV) of Washington and the Willamette Valley of Oregon. Historical data and tree-ring studies spanning the last several hundred years suggest that the low- to mid-elevation ecosystems, including wet and upland prairie, *Quercus garryana* (Oregon oak) savanna and woodland, and *Pseudotsuga menziesii* (Douglas-fir)-dominated forests, are adapted to fires of varying frequency and severity, and rely on it for their perpetuation (Thilenius, 1968; Franklin and Dyrness, 1988; Agee, 1993). Summer drought, which typically extends from July through September,

often leads to conditions appropriate for late-summer wildfires (Gedalof et al., 2005). However, as a result of effective fire suppression since the 1930s (Morris, 1934) and considerable human alteration of the region's ecosystems (Hulse et al., 2002), fires rarely occur. In an effort to reduce hazardous fuel build-up and restore native plant communities, fire's reintroduction into many ecosystems is underway (Pendergrass et al., 1998; Maret and Wilson, 2005), but information regarding its role in maintaining prairie, savanna, woodland, and forest ecosystems in prehistoric times is needed.

Paleoecological studies provide an opportunity for understanding the long-term environmental history of the interior valleys of the PNW. In the LCRV, late Quaternary pollen records are available from Fargher Lake, WA (Heusser and Heusser, 1980; Grigg and Whitlock, 2002) and Battle Ground Lake, WA (this site—Barnosky, 1985; Whitlock, 1992). In this paper, we supplement our understanding of the region by presenting a 14,300-year-long fire history record from Battle Ground Lake, WA. High-resolution macroscopic charcoal,

* Corresponding author. Department of Geography, University of Oregon, Eugene, OR 97403, USA. Fax: +1 541 346 2067.

E-mail address: mwalsh2@uoregon.edu (M.K. Walsh).

sedimentological and new palynological analyses provide information on the long-term fire and vegetation history of southwestern Washington and the influence of natural controls and anthropogenic activities on those histories. The reconstruction was compared with records from other low-elevation sites across the PNW in order to assess regional trends in fire–vegetation–climate interactions.

Site description

Battle Ground Lake (BGL), WA, ($45^{\circ}08.00'N$, $122^{\circ}49.17'W$, 154 m a.s.l.), is located approximately 30 km north of the city of Portland, OR (Fig. 1). The 13.5-ha lake lies in a remnant

volcanic crater of late Pleistocene age in the Boring Lava field (Wood and Kienle, 1990). Maximum depth is 16 m, drainage area is 1.6 times the size of the lake, and its rim rises approximately 72 m above the lake surface and the surrounding valley floor. The climate of the area is influenced by the seasonal shift in the position of the polar jet stream and the northeastern Pacific subtropical high-pressure system, leading to warm, dry summers and cool, wet winters (Mitchell, 1976; Mock, 1996). For the period of AD 1971–2000, the city of Battle Ground weather station (located approximately 4 km SW of BGL) recorded an average July temperature of $17.9^{\circ}C$ and an average January temperature of $3.8^{\circ}C$ (Western Regional Climate Center, 2007). During that period, an average total of 1349

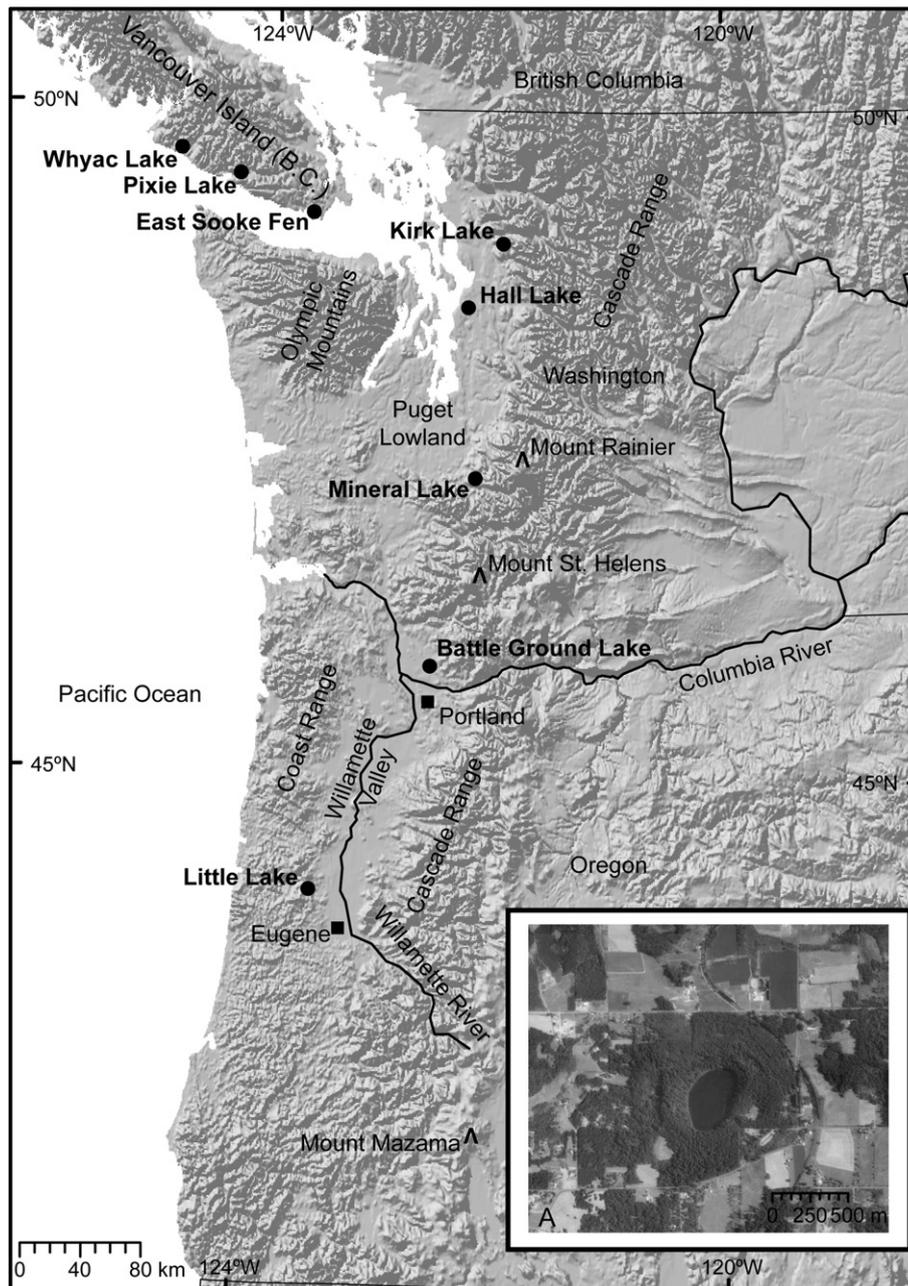


Figure 1. Map of the Pacific Northwest and the location of the study site Battle Ground Lake and other sites mentioned in the text. Inset A shows an aerial photograph of the site taken in 1990 (photo: USGS).

mm of precipitation fell annually, approximately 73% of it between November and April, mostly as rain (Western Regional Climate Center, 2007). The site is also influenced by an occasional cold wintertime easterly flow emanating from the Columbia Gorge (Sharp and Mass, 2004).

The vegetation surrounding BGL is a closed, second-growth forest of mostly *Pseudotsuga menziesii* and *Thuja plicata* (western red cedar), with scattered *Tsuga heterophylla* (western hemlock), *Abies grandis* (grand fir), and *Picea sitchensis* (Sitka spruce). Other common trees and shrubs found in the crater include *Alnus rubra* (red alder), *Acer macrophyllum* (big-leaf maple), *Fraxinus latifolia* (Oregon ash), *Salix* spp. (willow), *Corylus cornuta* (beaked hazel), *Cornus nuttallii* (Pacific dogwood), and *Spiraea douglasii* (hardhack), with an understory of *Polystichum* (sword fern) and other ferns. *Pteridium* (bracken fern), a heliophyte, grows in forest openings. Botanical nomenclature follows Hitchcock and Cronquist (1973). *Pseudotsuga*-dominated forests of the PNW typically experience stand-replacing fires at >100-year intervals, although this estimate varies considerably across the region and probably includes fires that have resulted from both human- and lightning-caused ignitions (Agee, 1993). Euro-American settlement of the BGL area began after the establishment of nearby Fort Vancouver (AD 1825); the population remained low throughout the 19th century, but increased rapidly in the early part of the 20th century (Allworth, 1976). The local forest near BGL was logged in the late 1800s and the only recorded historical fire in the crater was the Yacolt Fire of AD 1902 (Allworth, 1976).

Methods

In 2004, an 8.04-m-long sediment core (BG04A) was collected from the deepest part of the lake with a modified Livingstone piston corer (Wright et al., 1983) lowered from a floating platform (water depth = 16 m). Core segments were wrapped in cellophane and foil and refrigerated in the laboratory at the University of Oregon. In 2005, a 0.67-m-long short core (BG05B) was collected using a Klein piston corer, which recovered the sediment–water interface. The short core was sampled in the field at 0.5-cm intervals. BG04A long-core segments were split longitudinally, photographed, and the lithologic characteristics were described. Magnetic susceptibility was measured at contiguous 1-cm intervals on the intact core using a Sapphire Instruments magnetic coil. Samples of 1-cm³ volume were taken at 1-cm intervals for the upper 3 m and at 5-cm intervals for the lower 5 m of the core for loss-on-ignition analysis, which determines the water, organic, and carbonate content of the sediment (Dean, 1974).

Contiguous 1-cm³ samples were taken for charcoal analysis at 1-cm intervals for the upper 3 m and at 0.5-cm intervals for the lower 5 m of the long core. From the short core, contiguous 1-cm³ samples were taken at 0.5-cm intervals for charcoal analysis. Charcoal samples were soaked in a solution of 5% sodium hexametaphosphate for >24 hours 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. Only charcoal particles >125 μm in minimum diameter were tallied because previous studies indicate that large particles are not transported far from the source and thus are an indicator of local fire activity (Whitlock and Millspaugh, 1996; Whitlock and Larsen, 2001). Charcoal particles were identified and tallied as either woody or herbaceous based on their appearance and comparison to burned reference material collected at the study site (Fig. 2). Charcoal particles that were flat and displayed stomata within the rows of epidermal cells were counted as herbaceous charcoal and were assumed to come from grasses or other monocots (see Jensen et al., 2007). The ratio of herbaceous/total charcoal provided information on the fuel type and severity of fire events, and allowed for a comparison of fire activity in different sections of the core (see Whitlock et al., 2006). Plant macrofossils, such as needles and twigs, were also identified whenever possible and provided material for AMS ¹⁴C dating. Charcoal counts were converted

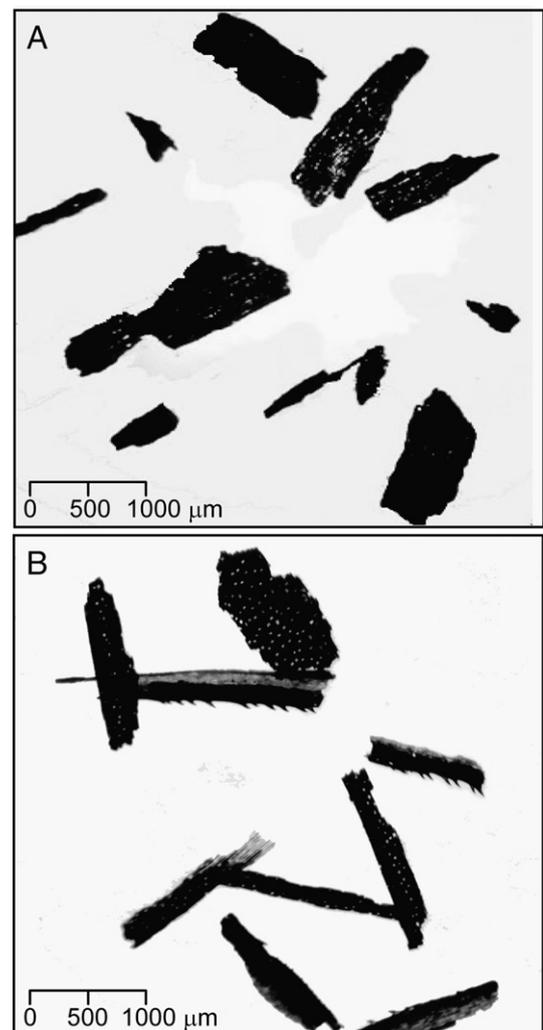


Figure 2. Photos of (A) woody charcoal particles and (B) herbaceous (i.e., grass) charcoal particles.

to charcoal concentration (particles/cm³) by dividing by the volume of each sample.

Charcoal accumulation rates (CHAR; particles/cm²/yr) were obtained by interpolating the charcoal data to constant 10-yr time steps, which represented the median temporal resolution in the core; the data were not log-transformed. The CHAR data series was decomposed into a “background” and “peaks” component. The background component has been discussed at length (see Millspaugh and Whitlock, 1995; Long et al., 1998; Carcaillet et al., 2002; Whitlock et al., 2003). Marlon et al. (2006) attributed CHAR background variation to slow changes in charcoal production associated with changing fuel types, and Higuera et al. (2007) concluded that at large temporal scales (i.e., 10 x mean fire return interval) it correlates well with area burned within the entire charcoal source area. The peaks component represents inferred “fire episodes” (i.e., one or more fires occurring in the duration of a peak) (Long et al., 1998). Charcoal analysis for core BG05A followed methods outlined in Higuera et al. (2008) and used the program CharAnalysis (Higuera et al., 2008; <http://CharAnalysis.googlepages.com>).

The CHAR background component was described using a robust (Lowess) smoother with a 500-yr window width, and the CHAR peaks component was taken as the residuals after background was subtracted from the interpolated time series. The threshold value separating fire-related from non-fire related variability in the peaks component was set at the 95th percentile of a Gaussian distribution modeling noise in the CHAR peaks time series. Sensitivity analysis of window widths between 300 and 1000 years showed that the signal-to-noise ratio (i.e., the measure of the separation between peaks and non-peak values) was maximized at 500 years. All CHAR peaks were screened to eliminate those that resulted from statistically insignificant variations in charcoal counts (Gavin et al., 2006). If the maximum charcoal count from a peak had a >5% chance of coming from the same Poisson-distributed population as the minimum count within the preceding 75 years, then it was identified as not significant (Higuera et al., 2008).

The CHAR time series was plotted on a log-transformed scale in order to facilitate comparison between different

sections of the core (Fig. 5). The significant peaks (i.e., fire episodes) were also plotted and used to calculate smoothed fire frequency, mean fire return interval, and fire-episode magnitude. Fire frequency (episodes/1000 yr) is the sum of the total 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. Fire-episode magnitude (particles/cm²) is the total charcoal influx in a peak and is related to fire size, severity, and taphonomic processes (Whitlock et al., 2006; Higuera et al., 2007).

Twelve 1-cm³ pollen samples were taken from core BG05B at 5-cm intervals (ca. 50–100 yr intervals) and processed following 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 types were assigned based on modern phytogeography, the presence of identified macrofossils, and previous macrofossil identification on an earlier core (Barnosky, 1985; Whitlock, 1992). Pollen counts were converted to percentages of the total terrestrial pollen and spores in each sample. Pollen accumulation rates (PAR; grains/cm²/yr) were calculated by dividing pollen concentrations by the deposition time (yr/cm) of the sample.

Results

Chronology and lithology

The age model for core BG04A was developed using seven AMS-¹⁴C age determinations and the identification of four dated tephra (Table 1). ¹⁴C dates were converted to calendar years before present (cal yr BP) using Calib 5.0.2 html (Stuiver and Reimer, 2005). Median ages were selected and rounded to the nearest decade when appropriate. The long core contained seven tephra of known age (Juvigné, 1986; Mullineaux, 1986), but only four had reliable enough dates to include in the age model. Tephra ages based on ¹⁴C age determinations were also converted to cal yr BP using Calib 5.0.2 html and median ages were used. Because the deposition of tephra is likely a rapid

Table 1
Age–depth relations in long core (BG04A) for Battle Ground Lake, Washington

Depth (cm below mud surface)	Lab number	Source material	Age (¹⁴ C yr BP) ^a	Age (cal yr BP) ^b
3		St. Helens D tephra		–30
67	AA65507	conifer needle	569±81	600 (506–679)
94	AA65739	conifer needle	911±52	830 (731–927)
144	AA65740	Twig	1585±68	1470 (1336–1620)
271	AA65741	Twig	3339±60	3570 (3442–3716)
333	AA65508	conifer needle	4159±42	4700 (4569–4833)
401	AA65742	conifer needle	4907±66	5650 (5577–5756)
512		Mazama O tephra		7627 (7577–7777) ^c
646.5	AA69495	bulk sediment	8671±52	9630 (9533–9778)
710		St. Helens J (upper) tephra	10490±360 ^d	12260 (11243–13058)
770		St. Helens J (lower) tephra	11280±590 ^d	13180 (11600–14771)

^a ¹⁴C age determinations were completed at the University of Arizona AMS Facility.

^b Calendar ages determined using Calib 5.0.2 html (Stuiver and Reimer, 2005). Median ages rounded to the nearest decade with 2σ range are reported.

^c Age as reported in Zdanowicz et al. (1999).

^d Age as reported in Juvigné (1986).

event, the thickness of individual layers was subtracted from the true core depth to create an adjusted depth. Probability density functions for each ^{14}C age determination were plotted in Figure 3 to show the uncertainty of individual calendar ages, and clearly illustrate the greater uncertainty of the tephra ages as compared to the AMS- ^{14}C age determinations. The resulting age model for core BG04A was best described by a 4th-order polynomial, suggesting a basal date of 14,300 cal yr BP for the core (Fig. 3A).

The age model for core BG05B was developed from 18 ^{210}Pb age determinations and one correlated AMS ^{14}C date from core BG04A (Table 2). Cores BG04A and BG05B were correlated based on charcoal peaks and tephra units present in both cores. The age model for BG05B was best described by a 4th-order polynomial for the upper 14 cm of the core, and a 2nd-order polynomial for lower 53 cm of the core (Fig. 3B). This shift in the sedimentation rate at ~14-cm depth was likely caused by increased slopewash following the Yacolt

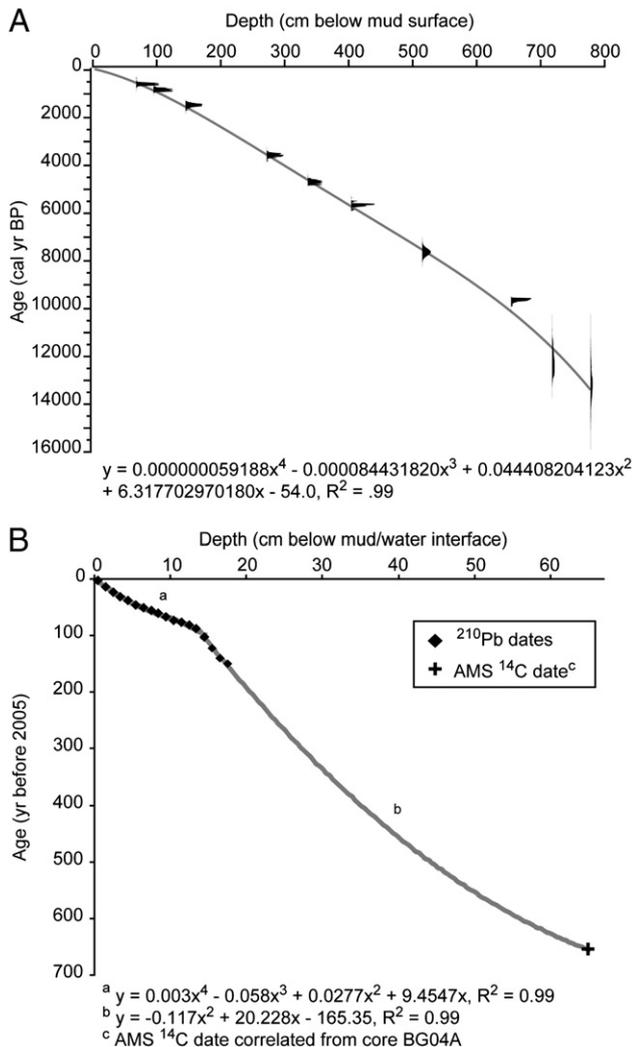


Figure 3. (A) Age-versus-depth model for long core BG04A (see Table 1 for ^{14}C and tephra dates). (B) Age-versus-depth model for short core BG05B (see Table 2 for ^{210}Pb dates). The radiocarbon date was correlated from the long core based on core stratigraphy (see Table 1 for ^{14}C date).

Table 2

Age–depth relations in short core (BG05B) for Battle Ground Lake, Washington

Depth (cm below mud surface)	^{210}Pb age ^a (yr before 2005)	Age (yr AD)
0–1	3.0	2002.0
1–2	14.1	1990.9
2–3	24.0	1981.0
3–4	31.7	1973.4
4–5	38.8	1966.2
5–6	46.3	1958.7
6–7	52.0	1953.0
7–8	56.1	1948.9
8–9	61.2	1943.8
9–10	68.3	1936.7
10–11	73.7	1931.3
11–12	77.6	1927.4
12–13	82.2	1922.8
13–14	87.9	1917.1
14–15	100.8	1904.2
15–16	122.0	1883.0
16–17	140.6	1864.5
17–18	149.4	1855.6
18–19 ^b	176.3	1828.7
19–20 ^b	253.0	1752.0

^a ^{210}Pb age determinations were completed by J. Budahn at the USGS Denver Federal Center, Colorado.

^b Age determinations for these samples were not used in the age-versus-depth model.

fire of AD 1902, which burned within the BGL crater. Core BG05B was composed entirely of fine detritus gyttja with the AD 1980 Mount St. Helens D tephra occurring at 2–3 cm depth.

Three lithologic units were observed in core BG04A. Silty organic clay extended from the bottom to 660-cm depth and was characterized by low organic (~5%) and relatively high magnetic susceptibility values (~0.0005 emu) (Fig. 4). Apparently, little ground cover resulted in large amounts of inorganic clastic material washing into the lake. Above 660-cm depth, organic values were ~60% and magnetic susceptibility values were less than 0.0001 emu, indicating a more productive lake system with little clastic input, except during the deposition of tephra units. From 660–360-cm depth, the sediment was laminated fine detritus gyttja, and above 360-cm depth, it was nonlaminated fine detritus gyttja. Clay layers of ~0.5-cm width were noted between 335 and 325-cm depth. Tephra from the Mt. Mazama eruption was found at a depth of 514–519-cm depth and is the only identified tephra in the core not from Mount St. Helens.

Charcoal and pollen records

The charcoal record for core BG04A was compared to a previous vegetation reconstruction for BGL and both were described using the pollen zonation of core BG80B (Barnosky, 1985) (Fig. 5 and Table 3). The age model for core BG80B was updated by calibrating the ^{14}C dates using Calib 5.0.2 html (Stuiver and Reimer, 2005) and using a newer age determination for the Mt. Mazama eruption (Zdanowicz et al., 1999). A 4th-order polynomial was used to develop an age-depth curve for core BG80B.

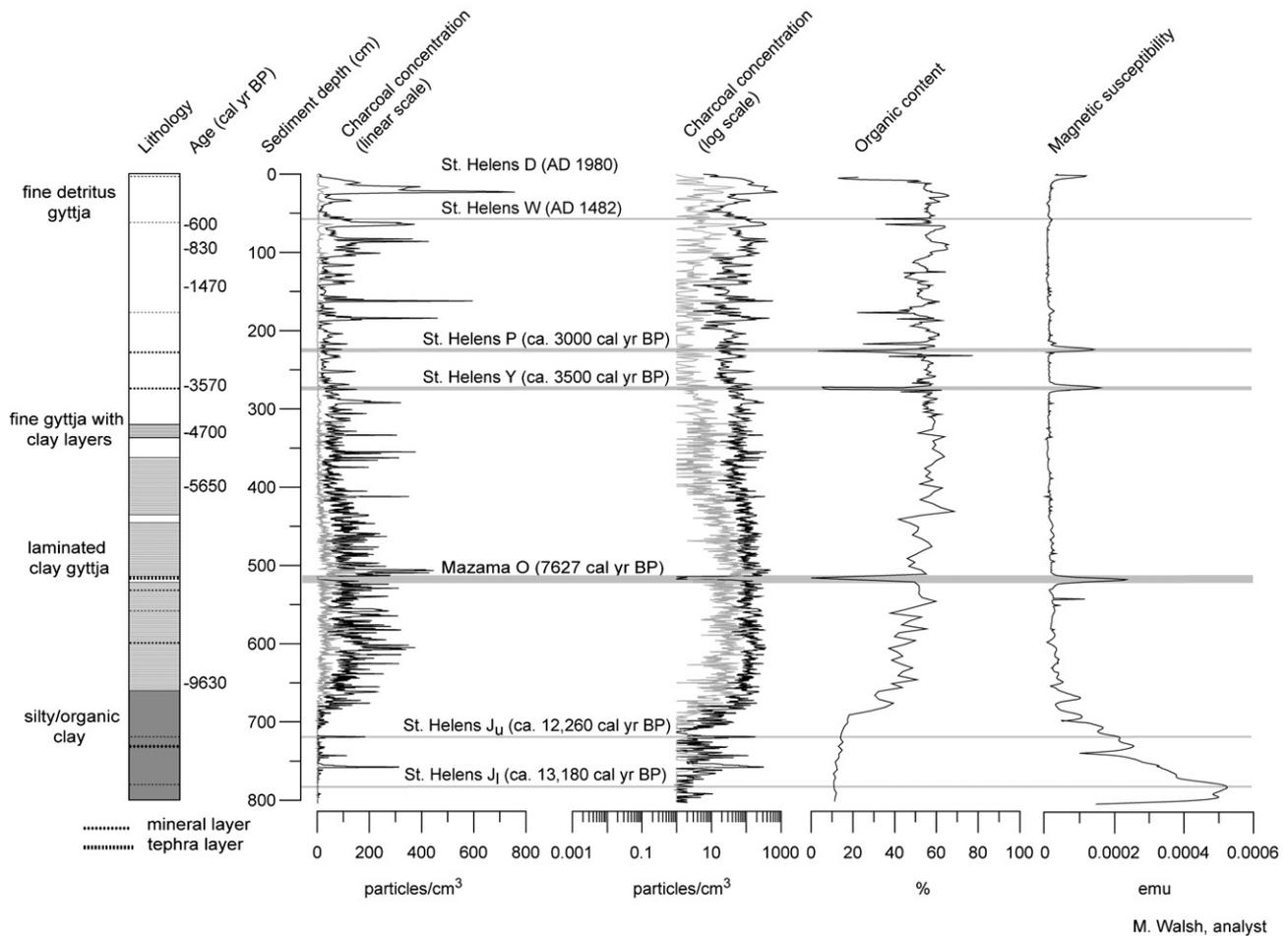


Figure 4. Battle Ground Lake long core BG04A lithology, charcoal concentration (linear scale), charcoal concentration (log scale), organic content (%), and magnetic susceptibility (emu) plotted against sediment depth (cm below mud surface). For the charcoal concentration curves, the black line is the total macroscopic charcoal >125 μm and the gray line is the herbaceous charcoal >125 μm . The gray horizontal bars indicate identified tephra layers in the core.

Zone BG2 (15,000–11,200 ^{14}C yr BP; 14,300–13,100 cal yr BP)

Charcoal concentration was low in this zone with an average of 1.5 particles/cm³. CHAR values ranged between 0–0.32 particles/cm²/yr with an average of 0.04 particles/cm²/yr. Average fire frequency was 2 episodes/1000 yr and only one significant charcoal peak was registered in this zone (fire-episode magnitude: 12 particles/cm²). The average herbaceous charcoal content for the zone was low (3.5%). The vegetation was an open forest or parkland of *Picea*, *Pinus contorta* (lodgepole pine), *Alnus sinuata* (Sitka alder), *Tsuga mertensiana* (mountain hemlock), *Artemisia* (sagebrush), and Poaceae.

Zone BG1c (11,200–9500 ^{14}C yr BP; 13,100–10,800 cal yr BP)

Charcoal concentration and CHAR were higher in this zone than in the previous one. Average charcoal concentration was 17.5 particles/cm³. CHAR values ranged from 0–10.3 particles/cm²/yr with an average of 0.7 particles/cm²/yr. Fire frequency increased from 4–11 episodes/1000 yr from the bottom to the top of this zone; mFRI was 149 yr. Fire-episode magnitude varied greatly from 0.3–785 particles/cm², with the largest of these episodes at ca. 12,800 cal yr BP. Another large charcoal

peak with a magnitude of 359 particles/cm² coincided with the Mount St. Helens J (upper) tephra. Average herbaceous charcoal content in this zone was low (5.6%). The vegetation was a *Pseudotsuga/Abies*-dominated forest with *Alnus rubra*-type and *Pteridium* in disturbed areas.

Zone BG1b (9500–4500 ^{14}C yr BP; 10,800–5200 cal yr BP)

Charcoal concentration and CHAR were much higher in this zone than the previous zones. Average charcoal concentration was 116.7 particles/cm³. CHAR ranged from 0.2–24.3 particles/cm²/yr with an average of 6.4 particles/cm²/yr. Fire frequency generally increased throughout this zone to a maximum of 17 episodes/1000 yr at ca. 6700 cal yr BP. This was followed by a sharp decrease in fire frequency to its lowest point in the zone of 9 episodes/1000 yr at ca. 5400 cal yr BP. The mFRI for the zone was 87 yr. Fire-episode magnitude varied widely from 0.6 to 569 particles/cm² (average: 68 particles/cm²). Large-magnitude peaks occurred immediately following the deposition of Mazama ash and had a high herbaceous charcoal content (~30%). Average herbaceous charcoal content for the zone was 20.8%, with many values as high as 40–50%. The vegetation was savanna-like with *Quercus*, *Pseudotsuga*, and Poaceae dominating, and

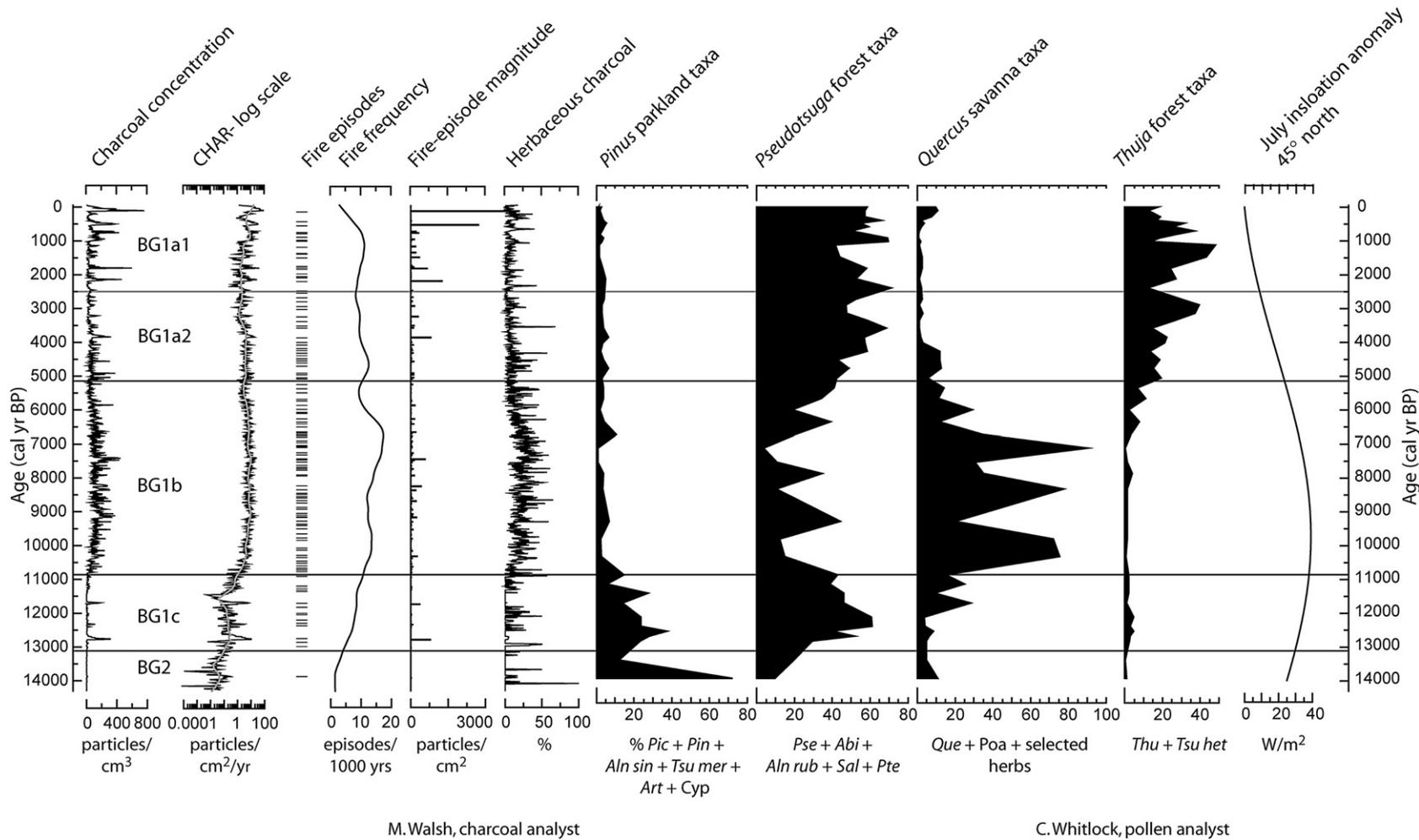


Figure 5. Battle Ground Lake long core BG04A charcoal concentration (particles/cm³), charcoal accumulation rate (CHAR-log scale) (particles/cm²/yr), fire episodes (black bars), fire frequency (episodes/1000 yr), fire-episode magnitude (particles/cm²), herbaceous charcoal (%), selected summed pollen percentages from the Battle Ground Lake core BG80B, and July insolation anomaly at 45° north plotted against an age scale (cal yr BP). Pollen data are from [Barnosky \(1985\)](#) (Pic = *Picea*, Pin = *Pinus*, Aln sin = *Alnus sinuata*, Tsu mer = *Tsuga mertensiana*, Art = *Artemisia*, Cyp = *Cyperaceae*, Pse = *Pseudotsuga menziesii*, Abi = *Abies*, Aln rub = *Alnus rubra*, Sal = *Salix*, Pte = *Pteridium*, Que = *Quercus*, Poa = *Poaceae*, Thu = *Thuja plicata*, Tsu het = *Tsuga heterophylla*). Insolation values are from [Berger and Loutre \(1991\)](#).

herbaceous taxa such as *Camassia*-type (either *Camassia quamash* (camas lily) or *Zigadenus venenosus* (death camas)), *Heuchera*-type (alumroot), Asteraceae (sunflower family) sub-family Tubuliflorae, and Apiaceae (carrot family) were also present.

Zone BG1a (4500 ¹⁴C yr BP–present; 5200 cal yr BP–present)

This zone was divided into two subzones based on fire activity: **Subzone BG1a2 (5200–2500 cal yr BP)** had an average charcoal concentration of 65.8 particles/cm³, average CHAR of 3.8 particles/cm²/yr, and average fire-episode magnitude of 97 particles/cm². Average fire frequency was 10 episodes/1000 yr (mFRI: 107 yr) and average herbaceous charcoal content was 8.8%. **Subzone BG1a1 (2500 cal yr BP–present)** had an average charcoal concentration of 88.6 particles/cm³ and average CHAR of 7.2 particles/cm²/yr. Average fire frequency was 9 episodes/1000 yr (mFRI: 124 yr) and herbaceous charcoal content was 7.6%. Most notably, the average fire-episode magnitude (533 particles/cm²) was the highest of the entire record.

Fire frequency initially increased in Zone BG1a to 13 episodes/1000 yr at ca. 4600 cal yr BP. This was followed by a general decrease until ca. 2500 cal yr BP. Fire frequency then increased again and was higher than the zone average of 11 episodes/1000 yr between ca. 1500 and 700 cal yr BP. The most recent portion of the record showed a sharp decrease in fire frequency (present-day value: 3 episodes/1000 yr). The vegetation of Zone BG1a was a closed forest dominated by *Pseudotsuga*, *Thuja*-type, *Tsuga heterophylla*, *Abies*, and *Alnus rubra*-type, with *Pteridium* and other herbaceous taxa present in disturbance-related openings.

The charcoal record for core BG05B registered three major fire episodes over the last ~700 years, at ca. AD 1350, ca. AD 1390, and the Yacolt fire of AD 1902 (Fig. 6). The large magnitude of the charcoal peaks and the high woody charcoal content suggests that these were high-severity crown fires. A smaller fourth peak at ca. AD 1930 probably represents re-burns associated with the AD 1902 Yacolt fire (Gray, 1990), or other fires burning outside the crater. The early 20th century was a period of high fire activity in the LCRV (Morris, 1934). The BG05B pollen record indicates the presence of a closed forest at BGL prior to ca. AD 1325, evidenced by high PAR of *Thuja*-type and *Pseudotsuga*. Early seral communities followed the fires at ca. AD 1350 and 1390, as evidenced by the increased PAR of *Pteridium*, *Alnus rubra*-type, and Poaceae at ca. AD 1425, and decreases in *Thuja*-type and *Pseudotsuga* PAR. Over the next four hundred years, *Thuja*-type and *Pseudotsuga* reestablished, although not to previous levels. Their PAR remained relatively high until the Yacolt fire of AD 1902, when *Pteridium* and then *Alnus rubra*-type increased. The decrease in *Thuja*-type and *Pseudotsuga* PAR after AD 1800 is consistent with the beginning of logging in the LCRV and the establishment of nearby Fort Vancouver (Allworth, 1976). Later declines in arboreal PAR indicate local logging in the late 1800s and are associated with an expansion of Poaceae. Poaceae PAR rose dramatically at ca.

Table 3

Average charcoal concentration, CHAR, fire frequency, fire return interval, fire-episode magnitude, herbaceous charcoal values, and fire regime description for Battle Ground Lake core BG04A

	Average charcoal concentration (particles/cm ³)	Average CHAR (particles/cm ² /yr)	Average fire frequency (episodes/1000 yr)	Average fire return interval (yr)	Average fire-episode magnitude (particles/cm ²)	Average herbaceous charcoal (%)	Fire regime	Vegetation description ^a
BG1a: 5200–present	77.0	5.4	10	113	282	8.2	Relatively frequent, moderate- to high-severity, understory and crown fires	<i>Pseudotsuga/Thuja</i> -dominated forest with openings
BG1a1: 2500–present ^b	88.6	7.2	9	124	533	7.6		
BG1a2: 5200–2500 ^a	65.8	3.8	10	107	97	8.8	Frequent, low- to moderate-severity, surface and understory fires	<i>Quercus</i> -dominated savanna with herbaceous understory
BG1b: 10,800–5200	116.7	6.4	13	87	68	20.8		
BG1c: 13,100–10,800	17.5	0.7	8	149	84	5.6	Infrequent, low- to moderate-severity, surface and understory fires	<i>Pseudotsuga/Abies</i> -dominated forest with openings
BG2: 14,300–13,100	1.5	0.04	2	N/A	12	3.5	Little to no fire	<i>Pinus/Picea</i> -dominated open forest or parkland

^a Vegetation reconstructions are from Battle Ground Lake core BG80B (Barosky, 1985; Whitlock, 1992).

^b The zones in gray are not based on vegetation zones (Barnosky, 1985).

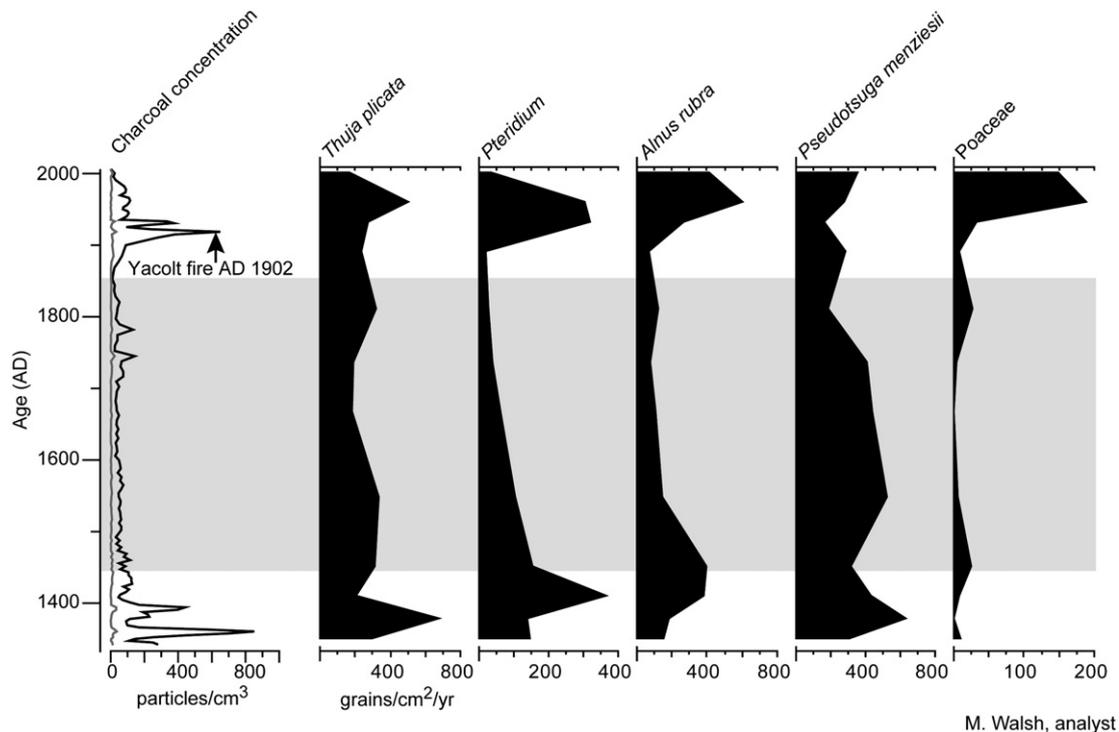


Figure 6. Charcoal concentration (particles/cm³) and selected pollen accumulation rates (PARs) for the Battle Ground Lake short core BG05B plotted on an age scale (AD). The black line on the charcoal concentration curve is the total number of charcoal particles >125 µm and the gray line is the number of herbaceous charcoal particles >125 µm. The gray shading shows the approximate dates of the Little Ice Age (ca. AD 1450–1850; Grove, 2001).

AD 1930 and again at AD 1950, marking extensive grass seed farming in the Willamette Valley and the LCRV.

Discussion

Fire–vegetation–climate linkages at Battle Ground Lake

In the late-glacial period (>14,300–13,100 cal yr BP), the regional climate was still likely cold and dry (Bartlein et al., 1998) and the vegetation surrounding BGL was an open forest or parkland dominated by *Pinus contorta* and *Picea*. The sparse vegetation and cold conditions supported little to no fire activity. As conditions warmed in the transition from the late-glacial to the early Holocene (Bartlein et al., 1998), *Pseudotsuga*, *Alnus rubra*, and *Abies* expanded at the expense of *Pinus contorta* and *Picea*, and a more closed forest developed at the site. After ca. 13,100 cal yr BP, fire episodes increased in frequency and size or severity, likely due to increased fuel biomass.

Influenced by greater summer drought in the early Holocene (i.e., ca. 11,000 cal yr BP) relative either to present or earlier (Bartlein et al., 1998), the vegetation at BGL shifted from a *Pseudotsuga/Abies*-dominated forest to a *Quercus*-dominated savanna, and fire activity increased dramatically (Fig. 5 and Table 3). Throughout the early and middle Holocene (ca. 10,800–6500 cal yr BP), frequent surface fires that burned mostly herbaceous (grass) biomass maintained the open vegetation. The ignition source for these fires may have been lightning strikes associated with increased convection during warmer summers because more subtropical moisture was likely advected into the western United States than at present (Bartlein

et al., 1998; Brown and Hebda, 2002a). It may also have come from human activities. Archaeological findings suggest human habitation of the PNW for at least the last 11,000 years (Ames, 2003). Evidence in the LCRV extends as far back as ca. 8000 yr BP, but is most abundant after ca. 2500 cal yr BP (Pettigrew, 1990; Aikens, 1993). No archaeological evidence has been found in the BGL crater or the immediate vicinity, although it is likely that the area was used by prehistoric peoples. Abundant *Camassia*-type pollen in the record is attributed to the presence of *Camassia quamash* near the site in the early to middle Holocene (Whitlock, 1992). Cultural records document the burning of this important root crop in the interior valleys of the PNW to enhance its growth (Turner and Kuhnlein, 1983; Boyd, 1986), consequently, human ignitions may be part of the fire signal at this time.

The largest or most severe fires of the early to middle Holocene occurred immediately after the eruption of Mt. Mazama. The 6 cm of tephra found in the core probably blanketed the landscape, damaging or killing the vegetation, providing additional fuel for several moderate-severity fires. Zobel and Antos (1997) reported that following the AD 1980 Mount St. Helens eruption, >2 cm of tephra was enough to kill many mosses and 15 cm killed most understory plants. The fires following the Mt. Mazama eruption, fueled by the dead or damaged shrubs and herbs, may have favored savanna taxa over forest as evidenced by increased abundance of *Quercus*, *Poaceae*, and other herbs at ca. 7500 cal yr BP.

The establishment of the modern forest at BGL, indicated by increased percentages of *Pseudotsuga*, *Thuja*-type and *Tsuga heterophylla* pollen, increased fuel loads and led to a rise in fire

activity between ca. 5400 and 4600 cal yr BP. The climate was transitional at this point, with winters becoming wetter, but with summers still sufficiently dry to support fires (Bartlein et al., 1998). The subsequent decrease in fire-episode frequency over the next 2500 years is consistent with cooler, wetter conditions in the late Holocene (Thompson et al., 1993) and the establishment of mesophytic forests in the PNW (Heusser et al., 1985; Whitlock, 1992). This period of lower fire frequency at BGL occurred during a period when glaciers were advancing on Mt. Rainier, ca. 4500–2000 cal yr BP (Crandall and Miller, 1974; Kaufman et al., 2004).

The data from the past 2000 years show the influence of centennial-scale climate variability, such as the Medieval Climatic Anomaly (MCA; ca. 1100–700 cal yr BP (AD 850–1250); Mann, 2002) and the Little Ice Age (LIA; ca. 500–100 cal yr BP (AD 1450–1850); Grove, 2001) on the fire and vegetation history at BGL. Evidence of the MCA in the western United States, usually in the form of increased aridity, 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). At BGL, fire frequency was higher than at any other time in the past 4000 years between ca. 1500 and 700 cal yr BP (Fig. 5), likely due to the warmer and/or effectively drier conditions associated with the MCA. Similar to the fire regime of the early and middle Holocene, these fires were relatively small in size or severity, as compared to fire episodes directly before and after this period. Several modern studies have shown that fire activity increases as summer temperatures increase and relative humidity decreases in the PNW (McKenzie et al., 2004; Gedalof et al., 2005). The higher fire frequency at BGL during the MCA was likely the result of extended summer drought (i.e., a longer fire season), which would have increased the probability that late-summer lightning strikes ignited the vegetation.

Regional evidence of cooler temperatures and greater precipitation associated with the LIA comes from tree-ring

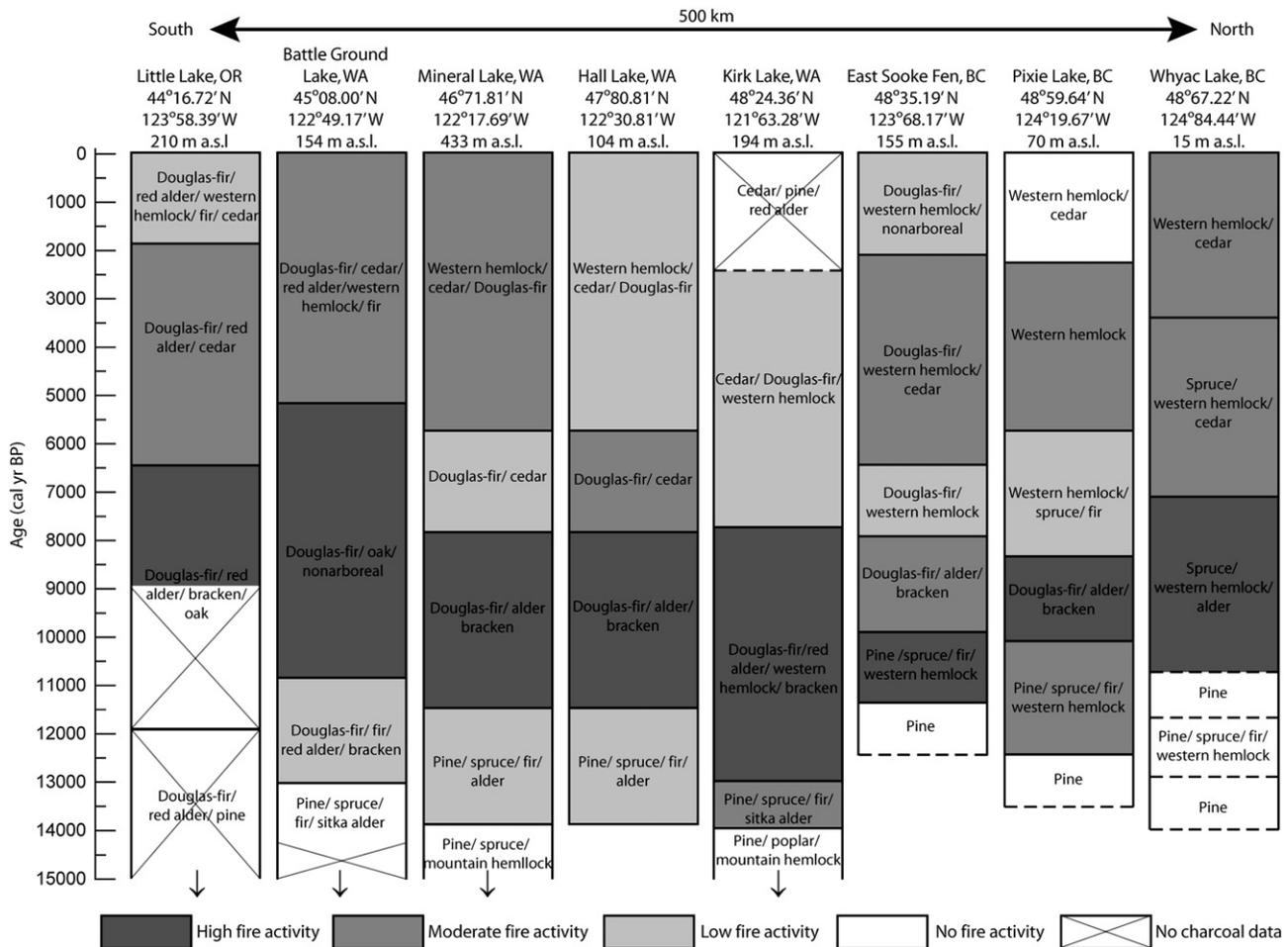


Figure 7. Pollen zones and inferred fire activity for eight low-elevation sites in the Pacific Northwest arranged from south (left) to north (right): Little Lake, OR (Worona and Whitlock, 1995; Long et al., 1998), Battle Ground Lake, OR (this study; Barnosky, 1985), Mineral Lake and Hall Lake, WA (Tsukada et al., 1981), Kirk Lake, WA (Cwynar, 1987), East Sooke Fen, Pixie Lake, and Whyac Lake, BC (Brown and Hebda, 2002a). Pollen zones were plotted based on the published information; all uncalibrated ages were calibrated to calendar years before present using Calib 5.0.2.html (Stuiver and Reimer, 2005), and median ages were chosen and rounded to the nearest century. The fire activity determinations for the pollen zones (box shading) are based on these author's interpretations of fire-episode frequency curves and CHAR values from Little Lake and Battle Ground Lake, charcoal fragment influx curves from Mineral Lake and Hall Lake, and CHAR curves and values from Kirk Lake, East Sooke Fen, Pixie Lake, and Whyac Lake, and are independently scaled for each site. The hatched lines indicate when the age of a vegetation zone was unknown by the author. The arrows indicate when the vegetation zone extends beyond the age scale of the figure.

dated glacial advances (Luckman, 1995; Wiles et al., 1999), tree-ring records (Graumlich and Brubaker, 1986; Weisberg and Swanson, 2003), and lake-sediment records (Brunelle and Whitlock, 2003). Between ca. 500–100 cal yr BP only two fire episodes were registered in the BGL long core (Fig. 5) and the short core shows little fire activity during this time (Fig. 6). The cooler temperatures and/or effectively wetter conditions of the LIA probably shortened the fire season and suppressed most summer fire ignitions. Although fire activity at BGL seems to have responded to the cooler conditions, the vegetation, as inferred from the pollen data, shows no dramatic changes due to the long life span of many PNW conifers. The pollen data do show a response to large-magnitude fire episodes, as evidenced by the increase in *Alnus rubra* and *Pteridium* following fires at ca. AD 1400 and 1900 (Fig. 6). Recovery from these events seems to have taken several hundred years based on the pollen changes.

In the late Holocene, settlement sites in the LCRV were strategically concentrated along the Columbia River and its tributaries to utilize abundant salmon and other resources (Boyd and Hajda, 1984; Pettigrew, 1990). Historical evidence suggests that at the time of Euro-American settlement in the LCRV, fire was used by the native inhabitants to promote the growth of many food sources, including nuts, berries, and root crops (Leopold and Boyd, 1999). Such fires were likely small and are not expressed in the BGL fire record. The close correspondence between the expansion of closed, mesophytic vegetation and the general decrease in fire frequency over the last ca. 5000 years argues against a sustained anthropogenic influence in the BGL area. Long-term cooling related to decreased summer insolation seems to have been the overriding control of fire and vegetation change in the late Holocene.

Regional comparison of low-elevation fire histories

Regional syntheses have shown that vegetation change in the PNW throughout the late-glacial and the Holocene has been nearly synchronous across multiple and environmentally diverse sites (Cwynar, 1987; Whitlock, 1992; Sea and Whitlock, 1995; Brown and Hebda, 2002a; Brown and Hebda, 2003). Similar shifts in fire regimes have been documented as well (Brown and Hebda, 2002b; Long and Whitlock, 2002; Hallett et al., 2003). Here we compare fire and vegetation reconstructions from several lowland sites (<500 m a.s.l.) in the region (Figs. 1 and 7). A wide array of charcoal analysis techniques were used in these studies; therefore, only general comparisons of fire activity could be made. The largest difference between the techniques is in the charcoal source area; macroscopic charcoal records tend to indicate local to watershed-scale fire activity (Whitlock and Millspaugh, 1996; Gardner and Whitlock, 2001), while microscopic charcoal records provide a more regional fire signal (Patterson et al., 1987) (see Whitlock and Bartlein (2004) for more a more detailed discussion). Fire frequency estimates are only available for the macroscopic charcoal records that used high-resolution sampling schemes and identified individual fire episodes.

Similar to the fire-history reconstruction at BGL, low-elevation sites across the PNW show little to no fire activity in

the late-glacial period and increased fire activity into the early Holocene (Fig. 7). A high-resolution macroscopic charcoal study at Little Lake (44°16.72'N, 123°58.39'W, 210 m a.s.l.) in the Oregon Coast Range, approximately 200 km southwest of BGL, shows highest fire frequency in the early Holocene between ca. 9000 and 6850 cal yr BP (Little Lake lacks charcoal data prior to this time). At Mineral Lake, WA (46°71.81'N, 122°17.69'W, 433 m a.s.l.), in the southern Puget Trough approximately 105 km northwest of BGL, and at Hall Lake, WA (47°80.81'N, 122°30.81'W, 104 m a.s.l.), in the central Puget Lowland approximately 220 km north of BGL, pollen-slide microscopic charcoal records show fire activity was low in the late-glacial period and greatest in the early Holocene, between ca. 11,500 and 8000 cal yr BP (Tsukada et al., 1981). At Kirk Lake, WA (48°24.36'N, 121°63.28'W, 194 m a.s.l.), in the northern Puget Lowland approximately 280 km north of BGL, a pollen-slide microscopic charcoal record suggests low fire activity before ca. 13,000 cal yr BP and highest fire activity between ca. 12,500 and 9500 cal yr BP (Cwynar, 1987). Disturbance-adapted species including *Pseudotsuga*, *Alnus rubra*, and *Pteridium*, were also highest at Kirk Lake in the early Holocene.

Approximately 330 km to the northwest of BGL, three sites on the southern part of Vancouver Island, British Columbia, provide macroscopic charcoal records: East Sooke Fen (48°35.19'N, 123°68.17'W, 155 m a.s.l.), Pixie Lake (48°59.64'N, 124°19.67'W, 70 m a.s.l.), and Whyac Lake (48°67.22'N, 124°84.44'W, 15 m a.s.l.) (Brown and Hebda, 2002a). Fire activity was low in the late-glacial period and increased in the early Holocene, although at slightly different times and to different magnitudes. Pixie Lake recorded a higher charcoal influx (particles/cm²/yr) in the early Holocene than the other two sites, but the increased abundance of disturbance-adapted taxa implies increased fire activity at all three sites (Brown and Hebda, 2002a).

Like BGL, all of the sites indicate decreased fire activity in the early and middle Holocene, but only at Little Lake and Hall Lake did this trend continue toward present (Kirk Lake lacks charcoal data after ca. 2500 cal yr BP). At Little Lake, fire episodes in the middle to late Holocene were larger or of higher severity, but less frequent than during the early Holocene. In contrast to the BGL record, Mineral Lake charcoal influx was higher in the middle to late Holocene, but the coarse sampling resolution makes specific fire interpretations difficult. On southern Vancouver Island, charcoal influx was variable among the sites in the middle and late Holocene. East Sooke Fen had higher charcoal influx between ca. 6400 and 5000 cal yr BP and after ca. 2000 cal yr BP. At Pixie Lake, charcoal influx was low between ca. 8500 and 6000 cal yr BP, and increased and remained high until ca. 2300 cal yr BP, when it dropped. At Whyac Lake, charcoal influx was low in the middle and late Holocene prior to ca. 2000 cal yr BP. The difference in charcoal accumulation between the sites is partially explained by their relative location along a moisture gradient (Brown and Hebda, 2002a). The rise in charcoal influx after ca. 2000 cal yr BP at East Sooke Fen and Whyac Lake, as well as at additional sites on Vancouver Island, is attributed to anthropogenic

burning (Brown and Hebda, 2002b). However, given the coarse sampling resolution of the records, the increase in charcoal influx may simply reflect changes in fuel biomass associated with increased moisture leading to larger, less frequent fires, not increased fire activity. A shift at Little Lake at ca. 2000 cal yr BP to even less frequent fire episodes but overall higher CHAR values indicates decreased fire activity throughout the most recent portion of the record (Long et al., 1998).

Charcoal and pollen records from these sites reveal relationships between fire and vegetation during the late-glacial and Holocene periods. Several sites indicate that increased fire activity lagged the change to more thermophilous vegetation by several centuries in the late-glacial period. For example, the shift to more frequent, greater magnitude fire episodes at BGL at ca. 12,500 cal yr BP occurred ~400–500 years after the rise of *Pseudotsuga*. At Kirk Lake, the expansion of *Pseudotsuga* and *Tsuga heterophylla* at ca. 12,900 cal yr BP preceded the rise in fire activity by ~500 years. Likewise, fire activity increased at Hall Lake ~750 years after the appearance of *Pseudotsuga* at ca. 11,500 cal yr BP. At Pixie Lake, the expansion of *Picea* at ca. 12,600 cal yr BP was followed ~500–700 years later by an increase in fire activity. Fire activity at Whyac Lake increased ~300–500 years following a rise in *Picea* at ca. 10,800 cal yr BP.

In all of these cases, the lag in the fire regime shift probably represents the time required for fuel to accumulate following the establishment of closed forests. The lag could, however, also indicate a lack of ignitions during the transition from the late-glacial to the early Holocene period, or possibly wetter conditions (see Mathewes, 1993) associated with the North Atlantic-focused Younger Dryas climate reversal (ca. 12,900–11,500 cal yr BP; Alley, 2000). The latter explanation seems less likely because vegetation change during the Younger Dryas was not uniformly registered across the PNW (Grigg and Whitlock, 1998; Vacco et al., 2005). The exception to the general occurrence of a lag in the shift in fire regime behind that of the vegetation is at East Sooke Fen, where fire activity seemingly increased simultaneously with rises in *Picea* and *Alnus* spp. at ca. 11,400 cal yr BP.

Shifts in vegetation and fire activity were more synchronous in the early Holocene. For example, as the climate warmed and dried, the shift from a closed forest to a savanna at BGL was accompanied by a concurrent shift in the fire regime. Additionally, fire activity dropped as *Thuja*-type increased at ca. 7000 cal yr BP at Little Lake and at ca. 5000 cal yr BP at Whyac Lake. At Pixie Lake, increased *Tsuga heterophylla* at ca. 8500 cal yr BP occurred as fire activity decreased. At East Sooke Fen, fire activity decreased as *Pseudotsuga* increased at ca. 9800 cal yr BP. It also seems that fire history cannot be linked to the history of a particular taxon. For example, at Little Lake, Kirk Lake, Mineral Lake, Hall Lake and Pixie Lake, fire activity rose with increased *Pseudotsuga* in the early Holocene. However, at East Sooke Fen, fire activity decreased with increased *Pseudotsuga* at ca. 9800 cal yr BP. Additionally, at Whyac Lake, fire activity increased along with *Tsuga heterophylla* at ca. 10,500 cal yr BP, but it decreased at Pixie Lake when *Tsuga heterophylla* increased at ca. 8500 cal yr BP.

Conclusions

The pollen and charcoal records from BGL suggest that the relationships between fire, vegetation, and climate in the late-glacial and Holocene changed, depending upon the time scale of investigation. On a millennial-time scale, fire activity seemed to track climate-induced vegetation change with varying degrees of lag on the order of a few decades to several hundred years. This finding has also been noted in regional comparisons of western North and South America (Whitlock et al., 2006, 2008). When the vegetation at BGL shifted from a cold, *Pinus/Picea*-dominated parkland to a warmer *Pseudotsuga/Abies*-dominated forest at ca. 13,100 cal yr BP, increased fire activity lagged ~500 years behind. This probably reflects a delayed response in the build up of fuel to support fires, but it may also be related to climate variations in the late-glacial period. Vegetation and fire activity shifts were more synchronous in the early and middle Holocene when xerophytic *Quercus*-savanna replaced a more closed forest at BGL. Apparently fuel levels were able to support the shift to more frequent, but less severe or smaller fires at this time. The lagged fire response in the late-glacial as compared with the more synchronous fire response to vegetation change in the Holocene is evident at other low-elevations sites in the PNW.

The BGL data also suggest a direct link between climate and fire activity on a centennial-time scale, in the absence of major vegetation change. For example, fire frequency was high during the MCA, while fire episodes were nearly absent during the LIA. The only responses in the vegetation were brief and expected shifts in seral status following individual fires. Evidently, it was the influence of these shorter-scale climatic shifts on the length and severity of the fire season that controlled fire frequency, not a climate-driven change in forest composition or structure.

Finally, although humans were present in the LCRV during the Holocene and quite likely burned the landscape near BGL, the charcoal record does not show a clear anthropogenic signal. The long-term trends in fire activity can be explained through known climate variations and attendant vegetation shifts, and are observed at other sites in the PNW. Even in the last 2500 years when human habitation in the LCRV was greatest, fire activity at BGL remained closely correlated with climate. Whether or not the fire history at BGL is representative of other parts of the LCRV and the Willamette Valley, where anthropogenic burning is thought to have been important prior to Euro-American settlement, remains to be seen.

Acknowledgments

This research was supported by grants from the Joint Fire Science Program (04-2-1-115) and National Science Foundation (ATM-0117160 and ATM-0714146), and in part by funds provided by the Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture. We thank J. Kertis and E. Heyerdahl for their support of this research. We also thank J. Budahn for ²¹⁰Pb dating and J. Pallister for assistance with tephra identification. J. Marlon, M. Power, C. Briles, V.

Rubinstein, S. Hineline, H. Van Vactor, S. Cohen, and T. Lancaster provided assistance in the field and laboratory. P. Higuera and D. Gavin provided assistance in data analysis.

References

- Agee, J.K., 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press, Washington, D.C.
- Aikens, M.C., 1993. *Archaeology of Oregon*. US Department of the Interior Bureau of Land Management, Portland.
- Alley, R.B., 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* 19, 213–226.
- Allworth, L.M., 1976. *Battle Ground...In and Around*. Taylor Publishing Company, Dallas.
- Ames, K.M., 2003. The Northwest Coast. *Evolutionary Anthropology* 12, 19–33.
- Barnosky, C.W., 1985. Late Quaternary vegetation near Battle Ground Lake, southern Puget Trough, Washington. *Geological Society of America Bulletin* 96, 263–271.
- Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb III, T., Whitlock, C., 1998. Paleoclimatic simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. *Quaternary Science Reviews* 17, 549–585.
- Berger, A., Loutre, M.F., 1991. Insolation values for the last 10 million years. *Quaternary Science Reviews* 10, 297–317.
- Boyd, R.T., 1986. Strategies of Indian burning in the Willamette Valley. *Canadian Journal of Anthropology* 5, 67–86.
- Boyd, R.T., Hajda, Y.P., 1984. Seasonal population movement along the lower Columbia River: the social and ecological context. *American Ethnologist* 14, 309–326.
- Brown, K.J., Hebda, R.J., 2002a. Origin, development, and dynamics of coastal temperate conifer rainforests of southern Vancouver Island, Washington. *Canadian Journal of Forest Research* 32, 353–372.
- Brown, K.J., Hebda, R.J., 2002b. Ancient fires on southern Vancouver Island, British Columbia, Canada: a change in causal mechanisms at about 2000 ybp. *Environmental Archaeology* 7, 1–12.
- Brown, K.J., Hebda, R.J., 2003. Coastal rainforest connections disclosed through a Late Quaternary vegetation, climate, and fire history investigation from the Mountain Hemlock Zone on southern Vancouver Island, British Columbia, Canada. *Review of Palaeobotany and Palynology* 123, 247–269.
- Brunelle, A., Whitlock, C., 2003. Postglacial fire, vegetation, and climate history in the Clearwater Range, Northern Idaho, USA. *Quaternary Research* 60, 307–318.
- Carcaillet, C., Almquist, H., Asnong, H., Bradshaw, R.H.W., Carrión, J.S., Gaillard, M.-J., Gajewski, K., Haas, J.N., Haberle, S.G., Hadorn, P., Müller, S.D., Richard, P.J.H., Richo, I., Rösch, M., Sánchez Goñi, M.F., von Stedingk, H., Stevenson, A.C., Talon, B., Tardy, C., Tinner, W., Tryterud, E., Wick, L., Willis, K.J., 2002. Holocene biomass burning and global dynamics of the carbon cycle. *Chemosphere* 49, 845–863.
- Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004. Long-term aridity changes in the western United States. *Science* 306, 1015–1018.
- Crandall, D.R., Miller, R.D., 1974. Quaternary stratigraphy and extent of glaciation in the Mount Rainier region, Washington. US Geological Survey Professional Paper 450-D, 59.
- Cwynar, L.C., 1987. Fire and the forest history of the north Cascade Range. *Ecology* 68, 791–802.
- Dean Jr., W.E., 1974. Determination of carbonate and organic matter in calcareous sediments by loss on ignition comparison with other methods. *Journal of Sedimentary Petrology* 44, 242–248.
- Faegri, K., Kaland, P.E., Krzywinski, K., 1989. *Textbook of Pollen Analysis*. John Wiley and Sons, New York.
- Franklin, J.F., Dymess, C.T., 1988. *Natural Vegetation of Oregon and Washington*. Oregon State University Press, Corvallis.
- Gardner, J.J., Whitlock, C., 2001. Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. *The Holocene* 11, 541–549.
- Gavin, D.G., Hu, F.S., Lertzman, K., Corbett, P., 2006. Weak climatic control of stand-scale fire history during the late Holocene. *Ecology* 87, 1722–1732.
- Gedalof, Z., Peterson, D.L., Mantua, N.L., 2005. Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. *Ecological Applications* 15, 154–174.
- Graumlich, L.J., 1993. A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quaternary Research* 39, 249–255.
- Graumlich, L.J., Brubaker, L.B., 1986. Reconstruction of annual temperature (1590–1979) for Longmire, Washington, derived from tree rings. *Quaternary Research* 25, 223–234.
- Gray, A., 1990. *Forest Structure on the Siouxi Burn, Southern Washington Cascades: Comparison of Single and Multiple burns*, M.S. thesis, University of Washington, Seattle.
- Grigg, L.D., Whitlock, C., 1998. Late-glacial vegetation and climate change in western Oregon. *Quaternary Research* 49, 287–298.
- Grigg, L.D., Whitlock, C., 2002. Patterns and causes of millennial-scale climate change in the Pacific Northwest during Marine Isotope Stages 2 and 3. *Quaternary Science Reviews* 21, 2067–2083.
- Grove, A.T., 2001. The “Little Ice Age” and its geomorphological consequences in Mediterranean Europe. *Climatic Change* 48, 121–136.
- Hallett, D.J., Lepofsky, D.S., Mathewes, R.W., Lertzman, K.P., 2003. 11,000 years of fire history and climate in the mountain hemlock rain forests of southwestern British Columbia based on sedimentary charcoal. *Canadian Journal of Forest Research* 33, 292–312.
- Heusser, C.J., Heusser, L.E., 1980. Sequence of pumiceous tephra layers and late Quaternary environmental record near Mount St. Helens. *Science* 210, 1007–1009.
- Heusser, C.J., Heusser, L.E., Peteet, D.M., 1985. Late-Quaternary climatic change on the American North Pacific Coast. *Nature* 315, 485–487.
- Higuera, P.E., Brubaker, L.B., Anderson, P.M., Brown, T.A., Kennedy, A.T., Hu, F.S., 2008. Frequent fires in ancient shrub tundra: implications of paleorecords for arctic environmental change. *PLoS One* 3, e0001744.
- Higuera, P.E., Peters, M.E., Brubaker, L.A., Gavin, D.G., 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. *Quaternary Science Reviews* 26, 1790–1809.
- Hitchcock, C.L., Cronquist, A., 1973. *Flora of the Pacific Northwest*. University of Washington Press, Seattle.
- Hulse, D., Gregory, S., Baker, J., 2002. *Willamette River Basin Planning Atlas: Trajectories of Environmental and Ecological Change*. Oregon State University Press, Corvallis.
- Jensen, K., Lynch, E.A., Calcote, R., Hotchkiss, S.C., 2007. Interpretation of charcoal morphotypes in sediments from Ferry Lake, Wisconsin, USA: do different plant fuel sources produce distinctive charcoal morphotypes? *The Holocene* 17, 907–915.
- Juvigné, E.H., 1986. Late-Quaternary sediments at Battle Ground Lake, southern Puget Trough, Washington. *Northwest Science* 60, 210–217.
- Kaufman, D.S., Porter, S.C., Gillespie, A.R., 2004. Quaternary alpine glaciation in Alaska, the Pacific Northwest, Sierra Nevada, and Hawaii. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), *The Quaternary Period in the United States*. Elsevier, Amsterdam, pp. 77–104.
- Leavitt, S.W., 1994. Major wet interval in White Mountains Medieval Warm Period evidenced in $\delta^{13}\text{C}$ of bristlecone pine tree rings. *Climatic Change* 26, 299–307.
- Leopold, E.B., Boyd, R.T., 1999. An ecological history of old prairie areas in southwestern Washington. In: Boyd, R.T. (Ed.), *Indians, Fire, and the Land in the Pacific Northwest*, pp. 94–138.
- Long, C.J., Whitlock, C., 2002. Fire and vegetation history from the coastal rain forest of the western Oregon Coast Range. *Quaternary Research* 58, 215–225.
- Long, C.J., Whitlock, C., Bartlein, P.J., Millsaugh, S.H., 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Canadian Journal of Forest Research* 28, 774–782.
- Luckman, B.H., 1995. Calendar-dated, early “Little Ice Age” glacier advance at Robson Glacier, British Columbia, Canada. *The Holocene* 5, 149–159.
- Mann, M.E., 2002. Medieval Climatic Optimum. In: MacCracken, M.C., Perry, J.S. (Eds.), *Encyclopedia of Global Environmental Change, Volume 1, The Earth System: Physical and Chemical Dimensions of Global Environmental Change*. John Wiley and Sons, Chichester, pp. 514–516.

- Maret, M.P., Wilson, M.V., 2005. Fire and litter effects on seedling establishment in western Oregon upland prairies. *Restoration Ecology* 13, 562–568.
- Marlon, J., Bartlein, P.J., Whitlock, C., 2006. Fire-fuel-climate linkages in the northwestern USA during the Holocene. *The Holocene* 16, 1059–1071.
- Mathewes, R.W., 1993. Evidence for Younger Dryas-age cooling on the north Pacific coast of America. *Quaternary Science Reviews* 12, 321–331.
- McKenzie, D., Gedalof, Z., Peterson, D.L., Mote, P., 2004. Climatic change, wildfire, and conservation. *Conservation Biology* 18, 890–902.
- Millsbaugh, S.H., Whitlock, C., 1995. A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. *The Holocene* 5, 283–292.
- Mitchell, V.L., 1976. The regionalization of climate in the western United States. *Journal of Applied Meteorology* 15, 920–927.
- Mock, C.J., 1996. Climatic controls and spatial variations of precipitation in the western United States. *Journal of Climate* 9, 1111–1125.
- Mohr, J.A., Whitlock, C., Skinner, C.J., 2000. Postglacial vegetation and fire history, eastern Klamath Mountains, California. *The Holocene* 10, 587–601.
- Morris, W.G., 1934. Forest fires in western Oregon and western Washington. *Oregon Historical Quarterly* 35, 313–339.
- Mullineaux, D.R., 1986. Summary of pre-1980 tephra-fall deposits erupted from Mount St. Helens, Washington State, USA. *Bulletin of Volcanology* 48, 17–26.
- Patterson III, W.A., Edwards, K.J., Maguire, D.J., 1987. Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* 6, 3–23.
- Pendergrass, K.L., Miller, P.M., Kauffman, J.B., 1998. Prescribed fire and the response of woody species in Willamette Valley wetland prairies. *Restoration Ecology* 6, 303–311.
- Pettigrew, R.M., 1990. Prehistory of the Lower Columbia and Willamette Valley. In: Suttles, W.P. (Ed.), *Handbook of North American Indians Volume 7, Northwest Coast*. Smithsonian Institution, Washington, D.C, pp. 518–529.
- Sea, D.S., Whitlock, C., 1995. Postglacial vegetation and climate of the Cascade Range, central Oregon. *Quaternary Research* 43, 370–381.
- Sharp, J., Mass, C.F., 2004. Columbia Gorge gap winds: their climatological influence and synoptic evolution. *Weather and Forecasting* 19, 970–992.
- Stine, S., 1994. Extreme and persistent drought in California and Patagonia during medieval time. *Nature* 369, 546–549.
- Stuiver, M., Reimer, P.J., 2005. CALIB Radiocarbon Calibration version 5.0.2 html. Available at <http://calib.qub.ac.uk/calib/>.
- Thilenius, J.F., 1968. The *Quercus garryana* forests of the Willamette Valley, Oregon. *Ecology* 49, 1124–1133.
- Thompson, R.S., Whitlock, C., Bartlein, P.J., Harrison, S.P., Spaulding, W.G., 1993. Climate changes in the western United States since 18,000 yr BP. In: Wright Jr., H.E., Kutzbach, J.E., Webb III, T., Ruddiman, W.F., Street-Perrott, F.A., Bartlein, P.J. (Eds.), *Global Climates Since the Last Glacial Maximum*. University of Minnesota Press, Minneapolis, pp. 468–513.
- Tsukada, M., Sugita, S., Hibbert, D.M., 1981. Paleocology in the Pacific Northwest I. Late Quaternary vegetation and climate. *Proceedings-International Association of Theoretical and Applied Limnology* 21, 730–737.
- Turner, N.J., Kuhnlein, H.V., 1983. Camas (*Camassia* spp.) and riceroot (*Fritillaria* spp.): two liliaceous “root” foods of the Northwest Coast Indians. *Ecology of Food and Nutrition* 13, 199–219.
- Vacco, D.A., Clark, P.U., Mix, A.C., Cheng, H., Lawrence Edwards, R., 2005. A speleothem record of Younger Dryas cooling, Klamath Mountains, Oregon, USA. *Quaternary Research* 64, 249–256.
- Weisberg, P.J., Swanson, F.J., 2003. Regional synchronicity in fire regimes of the western Cascades, USA. *Forest Ecology and Management* 172, 17–28.
- Western Regional Climate Center, 2007. Available at <http://www.wrcc.dri.edu>.
- Whitlock, C., 1992. Vegetational and climatic history of the Pacific Northwest during the last 20,000 years: implications for understanding present-day biodiversity. *Northwest Environmental Journal* 8, 5–28.
- Whitlock, C., Bartlein, P.J., 2004. Holocene fire activity as a record of past environmental change. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), *The Quaternary Period in the United States*. Elsevier, Amsterdam, pp. 479–490.
- Whitlock, C., Bianchi, M.M., Bartlein, P.J., Markgraf, V., Marlon, J., Walsh, M., McCoy, N., 2006. Postglacial vegetation, climate, and fire history along the east side of the Andes (lat 41–42.5°S), Argentina. *Quaternary Research* 66, 187–201.
- Whitlock, C., Larsen, C.P.S., 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), *Tracking Environmental Change Using Lake Sediments: Biological Techniques and Indicators Volume 2*. Kluwer Academic Publishers, Dordrecht, pp. 75–97.
- Whitlock, C., Marlon, J., Briles, C., Brunelle, A., Long, C., Bartlein, P., 2008. Long-term relations among fire, fuel, and climate in the north-western US based on lake-sediment studies. *International Journal of Wildland Fire* 17, 72–83.
- Whitlock, C., Millsbaugh, S.H., 1996. Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6, 7–15.
- Whitlock, C., Shafer, S.L., Marlon, J., 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest Ecology and Management* 178, 5–21.
- Wiles, G.C., Barclay, D.J., Calkin, P.E., 1999. Tree-ring-dated “Little Ice Age” histories of maritime glaciers from western Prince William Sound, Alaska. *The Holocene* 9, 163–173.
- Wood, C.A., Kienle, J., 1990. *Volcanoes of North America: United States and Canada*. Cambridge University Press, England.
- Worona, M.A., Whitlock, C., 1995. Late Quaternary vegetation and climate history near Little Lake, central Coast Range, Oregon. *GSA Bulletin* 107, 867–876.
- Wright Jr., H.E., Mann, D.H., Glaser, P.H., 1983. Piston cores from peat and lake sediments. *Ecology* 65, 657–659.
- Zdanowicz, C.M., Zielinski, G.A., Germani, M.S., 1999. Mount Mazama eruption: calendrical age verified and atmospheric impact assessed. *Geology* 27, 621–624.
- Zobel, D.B., Antos, J.A., 1997. A decade of recovery of understory vegetation buried by volcanic tephra from Mount St. Helens. *Ecological Monographs* 67, 317–344.