A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study

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Abstract: High-resolution analysis of macroscopic charcoal in sediment cores from Little Lake was used to reconstruct the fire history of the last 9000 years. Variations in sediment magnetism were examined to detect changes in allochthonous sedimentation associated with past fire occurrence. Fire intervals from ca. 9000 to 6850 calendar years BP averaged 110 ± 20 years, when the climate was warmer and drier than today and xerophytic vegetation dominated. From ca. 6850 to 2750 calendar years BP the mean fire interval lengthened to 160 ± 20 years in conjunction with the onset of cool humid conditions. Fire-sensitive species, such as *Thuja plicata* Donn ex D. Don, *Tsuga heterophylla* (Raf.) Sarg., and *Picea sitchensis* (Bong.) Carr., increased in abundance. At ca. 4000 calendar years BP, increases in allochthonous sedimentation increased the delivery of secondary charcoal to the site. From ca. 2750 calendar years BP to present, the mean fire interval increased to 230 ± 30 years as cool humid conditions and mesophytic taxa prevailed. The Little Lake record suggests that fire frequency has varied continuously on millennial time scales as a result of climate change and the present-day fire regime has been present for no more than 1000 years.

Résumé : Une analyse fine du charbon macroscopique a été réalisée dans les carottes de sédiments du lac Little, en vue de reconstituer l'histoire des feux des 9000 dernières années. Les variations du magnétisme des sédiments ont été examinées pour détecter les changements dans la sédimentation allochtone, associés avec l'occurrence passée des feux. Il y a environ 9000 jusqu'à 6850 ans calendriers BP, les intervalles entre les feux étaient, en moyenne, de 110 ± 20 ans, alors que le climat était plus chaud et plus sec qu'aujourd'hui et que la végétation xérophile dominait. L'intervalle moyen s'est allongé à 160 ± 20 ans entre environ 6850 et 2750 ans calendriers BP en rapport avec l'avènement de conditions fraîches et humides. Parallèlement, l'abondance des espèces sensibles au feu, comme le *Thuja plicata* Donn ex D. Don, le *Tsuga heterophylla* (Raf.) Sarg. et le *Picea sitchensis* (Bong.) Carr., a augmenté. Il y a environ 4000 ans calendriers BP, les augmentations en sédiments allochtones ont provoqué un apport secondaire de charbon au site. Il y a environ 2750 ans calendriers BP jusqu'à présent, l'intervalle moyen s'est accru à 230 ± 30 ans, étant donné la prédominance des conditions fraîches et humides et des taxa mésophiles. Les données du lac Little suggèrent, qu'à l'échelle millénaire, la fréquence des feux a varié continuellement à cause des changements climatiques et que l'actuel régime des feux existe depuis, au plus, 1000 ans.

[Traduit par la Rédaction]

Introduction

Holocene vegetation changes in the Pacific Northwest (PNW) are well known from a network of pollen records, and on millennial time scales these variations have been explained as a response to large-scale changes in the climate system (e.g., Heusser 1977; Mathewes 1985; Whitlock 1992; Thompson et al. 1993; Hebda and Whitlock 1997). For example, the expansion of xerophytic species in western Washington and Oregon in the early Holocene epoch has been attributed to warmer than present summer temperatures and summer drought. These variations were the result of the amplification of the seasonal cycle of insolation and the influence of greater than present summer insolation on atmospheric circulation. The development of mesophytic forests in the late Holocene has been related to the onset of cool wet conditions as summer insolation decreased to present levels. Although such linkages between vegetation and climate seem clear on long time scales, we have little understanding of the proximal mechanisms by which Holocene vegetation change is accomplished (Green 1982).

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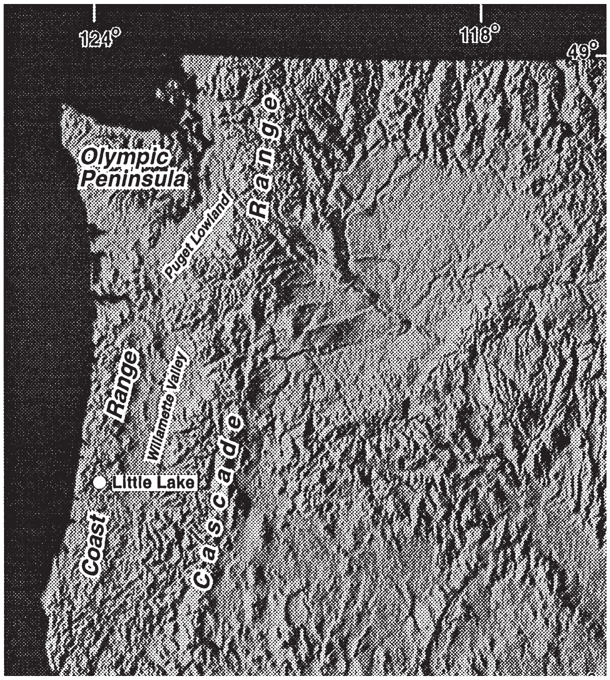
The role of fire in the temperate conifer rainforests of the PNW is best known from archival records, and forest stand-age and tree-ring data that span the last 300–500 years (e.g., Hemstrom and Franklin 1982; Teensma 1987; Morrison and Swanson 1990; Impara 1997). An alternative source of fire-history information comes from the analysis of particulate charcoal in dated lake-sediment cores (Patterson et al. 1987; Clark 1990; Millspaugh and Whitlock 1995). Fire reconstructions based on charcoal records lack the spatial specificity of dendrochronologic records, but they offer an opportunity to examine the role of fire over several millennia and during periods of major vegetation and climate change.

Previous studies of charcoal analysis in the PNW examined either microscopic charcoal particles, which provide a record of regional fires, or macroscopic charcoal sampled at wide intervals (Tsukada et al. 1981; Dunwiddie 1986; Cwynar 1987; Wainman and Mathewes 1987). From these studies it has been difficult to reconstruct local fire history or examine fire frequency variations. In this paper, we present a high-resolution

Fig. 1. Location of Little Lake and physiographic features mentioned in the text.



record of local fire history for the last 9000 years from Little Lake (44°10′N, 123°35′W, 210 m elevation) in the Oregon Coast Range. The record is based on an analysis of macroscopic charcoal particles in continuous 1 cm thick samples of an 11.33 m long sediment core. Rates of charcoal accumulation were analyzed to identify fire events and separate them from background trends in the data. A published pollen record from Little Lake (Worona and Whitlock 1995) provided information on past changes in forest composition that could be compared with the fire history reconstruction. We also examined the record of sediment magnetism to assess both the role of fire in triggering sedimentation events and the importance of surficial processes in delivering charcoal to the lake during nonfire years.

Little Lake is a landslide-dammed lake in the central Coast Range of Oregon, 45 km east of the Pacific Ocean (Fig. 1). It has a surface area of 1.5 ha and drains an area of 330 ha. The site is located within the *Tsuga heterophylla* Zone of western Oregon (Franklin and Dyrness 1988), which includes western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and western red cedar (*Thuja plicata* Donn), with occasional grand fir (*Abies grandis* (Dougl.) Lindl.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and western white pine (*Pinus monticola* Doug. ex D. Don.). Today the Little Lake watershed supports second-growth forest of Douglas-fir after extensive logging in this century. Hardwood species, such as red alder (*Alnus rubra* Bong.) and big-leaf maple (*Acer macrophyllum* Prush), are present in disturbed and riparian sites. Oregon white oak (*Quercus garryana* Dougl.) grows in nearby valleys and the Willamette Valley to the east. Understory trees and shrubs include vine maple (*Acer circinatum* Pursh), cascara (*Rhamnus purshiana* DC.), huckleberry (*Vaccinium* L.), sword-fern (*Polystichum munitum* (Kaulf.) Presl.), woodfern (*Dryopteris* spp. Adans.), and bracken (*Pteridium aquilinum* Gled.). Botanical nomenclature follows Hitchcock and Cronquist (1973).

The climate of the Coast Range is characterized by cool wet winters and warm dry summers (Hemstrom and Logan 1986). January and July mean monthly temperatures average 4.7°C and 18.0°C respectively. Mean annual precipitation at Little Lake is ca. 2000 mm, and 90% is received between October and May from westerly storms (Taylor 1993). Expansion of the eastern Pacific subtropical high in summer produces mild, dry weather favorable for burning. Coast Range fires are generally driven by strong easterlies associated with interior high-pressure cells. In the 19th and 20th century, logging activities have often provided an ignition source, but prior to that time fires in the Coast Range were probably started by lightning storms (Agee 1993).

Two fires were recorded in the Little Lake watershed in the 20th century in 1982 and 1929. Unfortunately, information on earlier fires was not available, and the fact that the watershed has been extensively logged limits the possibility of long dendrochronological records. Elsewhere in the Coast Range, journals and government land surveys document past fires as far back as the arrival of Euro-Americans in the region ca. 1800. Morris (1934) and Juday (1976) noted that large tracts (> 100 000 ha) of the Coast Range burned during the period from 1849 to 1902, but the first government survey of the Little Lake watershed did not report burned stands or dead timber (Gesner 1894). Impara (1997) described fire-scar and stand-age data from several locations in the central Coast Range, but suitable trees were not found within the Little Lake watershed. The study, however, recorded small fires (<300 ha) throughout the region during the last 500 years and particularly large fires in the late 19th century. All these records confirm that fires have been part of the coastal rainforest ecosystem in historic time and occasionally have burned large areas.

Fire-frequency reconstructions with charcoal accumulation rates

The application of charcoal accumulation rates (CHAR, particles·cm^{-2}·year^{-1}) as a means for reconstructing variations in fire events and the recurrence of fire events through time (i.e., fire frequency) requires both laboratory and data-analytical phases. The laboratory phase involves extracting and tallying charcoal particles from contiguous core intervals and converting these data to CHAR (see Methods). The data-analytical phase is necessitated by observations that the rate of inclusion of charcoal in lake sediments at a particular time depends on a number of interacting controls, only one of which is the occurrence of a charcoal-producing fire (MacDonald et al. 1991; Millspaugh and Whitlock 1995; Whitlock and Millspaugh 1996; Clark and Royall 1996). These taphonomic concerns are not at issue in dendrochronologic-based fire reconstructions, where individual fires are recorded directly by fire scars.

The rate at which charcoal accumulates in lake sediments depends on the amount of charcoal produced by a fire, which in turn depends on fuel load, standing biomass, and fire severity; the atmospheric and fluvial processes that entrain, transport, and deliver charcoal to a lake; and the sedimentologic processes that operate within a lake. Moreover, the charcoal produced by a particular fire may not be deposited at once in the deep-water sediments but, instead, may be introduced over a period of years (Whitlock and Millspaugh 1996; Bradbury 1996). Consequently, the challenge in the data-analytical phase is one of event detection or signal extraction to clearly separate the component of a CHAR time series that indicates the fire occurrence from that related to the joint effects of charcoal production and sedimentation. Here, as in Clark and Royall (1996), this objective is accomplished by statistically decomposing an individual CHAR time series into separate series that represent each of these components.

Motivation for a decomposition approach for analyzing CHAR

CHAR records can be described as consisting of two components: (1) a low-frequency or slowly varying background component and (2) a higher frequency or more rapidly varying component described usually as the peaks component, which is the particular record of fire that we seek to extract (Clark and Royall 1996). This two-component model for a time series of charcoal accumulation rates has arisen from (1) inspection of charcoal records and their correlation with historical and dendrochronologic records of fire (Clark 1990; Millspaugh and Whitlock 1995), (2) monitoring the inclusion of charcoal in lake sediments following observed fires (Whitlock and Millspaugh 1996), and (3) development of conceptual models that describe how charcoal data record fires (Patterson et al. 1987; Whitlock and Millspaugh 1996; Clark and Royall 1996).

The background component in this two-component model may consist of several subcomponents, which at present we are unable to separate distinctly. These subcomponents include (1) a general, but time-varying, level of CHAR that reflects the rate of charcoal production, (2) charcoal that is sequestered in the watershed and in the littoral zone of the lake for a protracted period before transportation and inclusion in deep-water sediments (secondary charcoal; see Whitlock and Millspaugh 1996), and (3) a regional component that represents the contribution of charcoal from fires within the region but not within or adjacent to the watershed of the lake (Clark and Royall 1996). The relative importance of the first two subcomponents should change considerably as characteristics of the vegetation (and consequently standing biomass and fuel load), watershed (hillslope hydrology and fluvial geomorphology), and lake (level, trophic status, and morphology) change. The third, regional subcomponent may also vary as vegetation and climate change.

The peaks component represents the contribution of charcoal produced by a single fire event in the "charcoal catchment" of a lake, which is generally the watershed of the lake (but sometimes fires in the adjacent watersheds are expressed as strongly in the lake of an unburned watershed as a fire within the watershed; see Millspaugh and Whitlock 1995; Whitlock and Millspaugh 1996). The peaks component also is assumed to consist of subcomponents, including (1) a major subcomponent that represents the input from a particular fire, and (2) a minor "noise" subcomponent that includes both the analytical error in CHAR determinations (Whitlock and Millspaugh 1996) as well as natural, random variations in CHAR. In practice, the noise subcomponent is not explicitly portrayed, but instead it is implicitly recognized by focusing attention only on the largest values of the peaks component (Clark and Royall 1996) or by defining a threshold value, which when exceeded by the peaks component, is assumed to signal a fire event (Millspaugh and Whitlock 1995).

Depending on the temporal resolution of the sedimentary record, a fire event in this context could be a single fire or a sequence of fires clustered in time. To detect individual fires, the sedimentary record would need to be sampled at shorter time intervals than the likely interval between fires. A key decision that must be made in sampling a record for charcoal analysis is therefore the selection of an appropriate (temporal) sampling resolution. If the selected interval is too coarse, then the charcoal accumulation rates in each interval may represent the production of charcoal from more than one fire, consequently blurring or integrating the record.

Although it is not our objective to do so here, a similar conceptual model and motivation for a decomposition approach could be constructed for sediment magnetism data (Thompson and Oldfield 1986). The background levels of magnetic minerals in the sediment are likely determined by pedologic and geomorphic processes that operate within the watershed, much as the background levels of CHAR reflect general characteristics of the vegetation, fire regime and charcoal taphonomy. Peaks in the magnetic-susceptibility record probably reflect individual geomorphic events, similar to the fire events recorded by peaks in CHAR data (Dearing and Flower 1982) (see Methods).

Decomposition of CHAR by locally weighted averaging

We implemented the decomposition of a "raw" CHAR time series by using a locally weighted (moving) average to define the background component and assigning a CHAR-value threshold to remove the noise subcomponent from the peaks component. Locally weighted averages were calculated by moving a "window" along the CHAR series, and at each point determining a weighted average of CHAR values for the points contained within the window. The weight assigned to each point was based on the distance of the point from the center of the window. This method of locally weighted averaging is related to the "lowess" or "loess" approach for smoothing scatter diagrams (Cleveland 1979). Weights were determined using the "tricube" weight function (Cleveland 1979), which is approximately bell shaped, and thus allows points closer to the center of the window to influence the weighted average more than points near the edges of the window.

The width of the window is one parameter value that must be selected in analyzing CHAR data. The width of the window controls the smoothness of the resulting background component. Windows that are too wide produce background components that do not adequately represent the true long-term variations in charcoal production, while windows that are too narrow produce a background component that essentially mimics the peaks component. The appropriate window width can usually be selected by visually comparing the resulting background component with the CHAR time series.

A second parameter value that must be selected in this decomposition approach is the CHAR threshold. The value is set or calibrated using the dendrochronologic or historical record to specify particular values of the peaks component that, when exceeded, indicate a fire event has occurred. In practice, it is convenient to define this parameter in terms of a threshold ratio, or the ratio of CHAR at a particular time to the background component. A threshold ratio of 1.0 would identify all

Table 1. ^{210}Pb dates for Little Lake short core.[a]

Depth (cm)	Age (AD)	Error of age (±1SD)	Sediment accumulation rate ($g \cdot cm^{-2} \cdot year^{-1}$)
0–1	1992	6.9	0.1199
1–2	1990	7.1	0.1558
2–3	1988	7.3	0.1730
4–5	1983	8.1	0.1165
5–6	1981	8.4	0.1705
6–7	1979	8.9	0.1407
7–8	1977	9.3	0.1598
8–9	1974	9.8	0.1682
9–10	1972	10.3	0.1929
12–13	1966	12.2	0.1596
15–16	1957	15.5	0.1125
18–19	1947	20.5	0.1017
21–22	1935	29.6	0.0641
24–25	1918	48.6	0.0624
27–28	1904	76.5	0.0671
30–31	1880	156.8	0.0391

[a] Data provided by D.R. Engstrom, St. Croix Watershed Research Station, Marine on St. Croix, Minn.

CHAR greater than the background level as a signal of a fire event.

Clark and Royall (1996) described a different approach for extracting the background component from a CHAR time series. They used a Fourier-series filter (Press et al. 1986), based on the variance spectrum of the CHAR series to describe the background component, and defined their peaks component as the positive deviations of the CHAR series from the background. This approach assumes that the background series is composed of many slowly varying sinusoidal components. As is the case with our locally weighted averaging approach, the smoothness of the background component in the Clark and Royall (1996) approach can be adjusted, in their case, by the choice of the width of the "spectral window" used in constructing a variance spectrum either through smoothing the periodogram or transforming an autocovariance function. Clark and Royall (1996) do not explicitly define a CHAR threshold for identifying fire events but by plotting only the positive residuals from the background component, such a threshold is implicitly defined: the low values of the noise component cannot be distinctly separated from the horizontal axis of their plots of the high-frequency or peaks component.

A potential disadvantage of the Clark and Royall (1996) approach is that the variance spectrum and resulting filter are defined globally (i.e., using the entire record) as opposed to locally, implicitly assuming that the variance spectrum of CHAR does not vary or "evolve" through time. Our initial analyses of the Little Lake and other charcoal influx records suggest that the shape of the variance spectrum indeed varies over time in response to changing climate and vegetation. Consequently, we favor an approach wherein the background component may adapt to changes in the variability of the CHAR data.

As is the case for other paleoenvironmental indicators present in lake sediments (e.g., pollen, diatoms), CHAR and magnetic-susceptibility data are approximately lognormally distributed. Consequently, these data were log (base 10) transformed before analysis.

Methods

Core retrieval and field sampling

Overlapping sediment cores were collected in 1993 from the center of Little Lake with a 5-cm-diameter modified Livingstone sampler, to yield an 11.33 m-long sedimentary record (referred to as core 93). The sediments were extruded in the field, wrapped in cellophane and aluminum foil, and transported to the laboratory where they were refrigerated. A 0.45-m-long short core was also collected from the center of Little Lake, using an 8-cm-diameter gravity sampler that preserved the mud–water interface intact. The short core was extruded in the field at 1-cm intervals, stored in plastic bags, and also refrigerated.

Core chronology

Sixteen ^{210}Pb age determinations were used to establish a chronology for the short core (Table 1). Ages were plotted against core depth using linear interpolation to construct an age-versus-depth curve. This analysis indicated that the 45-cm short core spans the past 230 years.

Three lithologic units, separated by gradual transitions, were recognized in core 93. The lowest unit (8.88–11.33 m depth) consisted of dark gray (10YR 4/1) organic clay (ca. 11% organic matter). A volcanic ash layer at 10.44–10.46 m depth was attributed to the eruption of Mount Mazama in southwestern Oregon. The overlying unit (6.21–8.88 m depth) consisted of black (5 YR 2.5/1) organic silty clay (ca. 12% organic matter). The upper 6.21 m of the core consisted of sandy gyttja (ca. 12% organic matter), which was subdivided into a lower unit (2.60–6.21 m depth) of very dark gray (5YR 3/1) fine-detritus gyttja and an upper unit (0.00–2.60 m depth) of very dark grayish brown (10 YR 3/2) medium-detritus gyttja.

Age-versus-depth relations for stratigraphic intervals in core 93 were based on four accelerator mass-spectrometry (AMS) ^{14}C dates, one bulk sediment ^{14}C date, and the accepted ^{14}C age of the Mazama tephra (Bacon 1983). The ^{14}C dates were converted to calendar ages using the calibration program (CALIB 3.01) of Stuiver and Reimer (1993) (Table 2). A third-order polynomial regression (Table 2, model A) was used to describe the deposition time of sediments between 0.00 and 8.98 m depth and a second-order polynomial regression (model B) was used between 8.98 and 11.33 m depth (Fig. 2). These age models minimized abrupt changes in deposition time, but it should be noted that the age assignments were very similar to those of Long (1996), which used linear interpolation over the length of the record. Model B gave an extrapolated age of 8990 calendar years BP (calendar years before present) at 11.33 m depth.

Core 93 sampling

We chose a sampling interval of 1 cm, which represents a deposition of time of 8 years, because dendrochronologic estimates of fire frequency in the region suggest that this interval was sufficiently short to resolve fire events in the charcoal record. Subsamples of 2.5 cm^3 were taken from contiguous 1-cm intervals from the cores and disaggregated in a 5% solution of sodium hexametaphosphate for 24 h.

Macroscopic charcoal particles (>50 μm in diameter; Clark 1988) were analyzed because they are not transported long distances (Patterson et al. 1987; Clark 1990; Whitlock and Millspaugh 1996). Whitlock and Millspaugh (1996), for example, found that macroscopic charcoal particles (>125 μm in diameter) were abundant in lakes that lay within a 10-km radius of a recent fire but were scarce at greater distances. At Little Lake, sediment samples were gently washed through nested sedimentologic screens (mesh sizes of 63, 125, and 250 μm diameter), and particles were tallied under a stereomicroscope. The profiles of charcoal abundance in the different size fractions compared well in the upper metre, but the smallest size fraction

Table 2. Calibrated and uncalibrated ^{14}C dates used in the age models for Little Lake Core 93 and Core 91.

Depth (m)	Calibrated age[a] (calendar year BP ± 2SD)	Uncalibrated age (^{14}C year BP)	Material	Lab no. or reference
Core 93				
		Age Model A		
1.81–1.82	1070 (970–1200)	1 190 ± 60	Charcoal	Beta–78015
5.79–5.83	2580 (2470–2690)	2 500 ± 60	Charcoal	Beta–78016
7.95–7.97	3690 (3550–3840)	3 440 ± 60	Charcoal	Beta–7801
		Age Model B		
8.98–9.02	5240 (4970–5300)	4 490 ± 60	Charcoal	Beta–78018
10.44–10.46	7630 (7540–7700)	6 850 ± 50	Mazama ash	Bacon (1983)
11.00–11.09	8560 (8480–8760)	7 860 ± 70	Sediment	Beta–72030
Core 91				
		Age Model C		
3.45–3.55	2940 (2780–3110)	2 840 ± 70	Sediment	Beta–48600
5.45–5.55	4840 (4600–4780)	4 260 ± 70	Sediment	Beta–48601
7.74–7.75	7630 (7540–7700)	6 850 ± 50	Mazama ash	Bacon(1983)
8.75–8.85	9250 (9080–9390)	8 270 ± 80	Sediment	Beta–48602
10.35–10.45	12720 (12520–12900)	10 790 ± 80	Sediment	Beta–48603

Note: Age Model A (0.00–8.98 m depth): Age = 32 + 537 (depth–69 depth^2 + 8.19 (depth)^3;
Age Model B (8.98–11.33 m depth): Age = –13 809 + 2538 (depth) –46.4 (depth)^2;
Age Model C (0.00–10.45 m depth): Age = –3.3 + 994 (depth) –72.0 depth^2+9.02 (depth)^3.
[a]Calibration to calendar years based on Stuiver and Reimer (1993).

was difficult and extremely time consuming to count. Whitlock and Millspaugh (1996) also found that the 63–125 μm diameter size fraction conveyed the same information as the larger size classes. On these grounds, we focused our analysis on macroscopic particles >125 μm in diameter for the remainder of the core. Charcoal counts were converted to charcoal concentration (particles/cm^3), and then divided by sample deposition time (years/cm) to calculate CHAR (particles·cm^{-2}·year^{-1}).

These laboratory procedures differ from those used in other charcoal studies in the PNW in two ways. First, Dunwiddie (1986) in the Washington Cascades and Wainman and Mathewes (1987) in southwestern British Columbia, examined contiguous samples of 2- to 3-cm and 5-cm intervals, respectively, as compared with our 1-cm intervals, and Tsukada et al. (1981) and Cwynar (1987) in the Puget Lowland of Washington, analyzed samples spaced 5–20 cm apart. We believe that this coarser sampling resolution may not provide clear detection of individual fire events. Second, all macroscopic particles >125 μm in diameter were tallied in this study, whereas Dunwiddie (1986) examined larger sized particles (>710 μm), resulting in low particle counts and the possibility that small local fires were not detected. Tsukada et al. (1981) and Cwynar (1987) tallied microscopic charcoal particles (<50 μm in diameter) on pollen slides that may have come from distant fires.

Pollen analysis

Pollen analysis of Little Lake core 91 is described in Worona and Whitlock (1995). The pollen samples were assigned ages based on a third-order polynomial regression that used the depths of four calibrated ^{14}C-age determinations and the Mazama ash in core 91 (Table 2). Cores 91 and 93 were correlated by chronology to compare the pollen and charcoal records. The samples in the Worona and Whitlock (1995) study were widely spaced, ca. 160 to 600 years apart, and, consequently, the pollen data provide a general picture of vegetation change that is not fully compatible with the higher temporal resolution of the charcoal record.

Magnetic susceptibility analyses

Sediment magnetism has been used to infer changes in the minerogenic clastic input to a lake (Thompson and Oldfield 1986). Fires often remove the organic layer of soils, which can destabilize slopes (Swanson 1981; Benda 1994), and heat soils, which can increase the formation of paramagnetic minerals (Thompson and Oldfield 1986); both processes may increase the magnetic susceptibility of sediments deposited in a lake (Millspaugh and Whitlock 1995). However, variations in runoff, streamflow, and mass movement unrelated to fire can also produce changes in the magnetic susceptibility of sediments (Dearing and Flower 1982).

Magnetic-susceptibility readings were taken on an 8-cm^3 subsample from each 1-cm interval before the charcoal analysis was performed. Electromagnetic units per cubic centimetre (emu/cm^3) were divided by sample deposition time (years/cm) to calculate magnetic-susceptibility accumulation rates (emu·cm^{-2}·year^{-1}). The resulting data were analyzed in the same way as the CHAR data.

Decomposition of CHAR and magnetic-susceptibility time series

Subtle variations in sedimentation rate make it difficult (if not impossible) to sample a core at equally spaced time intervals. Although it is not an explicit requirement of our decomposition approach that the observations be regularly spaced in time, for practical purposes and for comparison with other records, such an arrangement is desirable. Because direct interpolation of CHAR to a constant time interval may not conserve the quantity of charcoal within intervals, we interpolated charcoal concentration values and deposition times to pseudo-annual intervals. We then integrated the concentration values over 10-year intervals and divided by the average deposition time over those intervals to produce a series of CHAR spaced at decadal intervals.

Window width and threshold-ratio parameters were determined (1) by examining the CHAR from the short core relative to the record of 20th century fires near Little Lake, and (2) by considering a variety of values for the two parameters used in the decomposition of the long record and comparing the results with information on present-day fire regimes in coastal forests of the PNW. The latter analysis provided indications of the robustness of the method and the sensitivity of the outcomes to the choice of parameter values. For display, we also

Fig. 2. Age-versus-depth relations for core 93 based on the age model information given in Table 2. Model A was applied from 0.00 to 8.98 m depth, and model B was used for 8.98 to 11.33 m depth. Error bars are 2 SDs of the calibrated ^{14}C years.

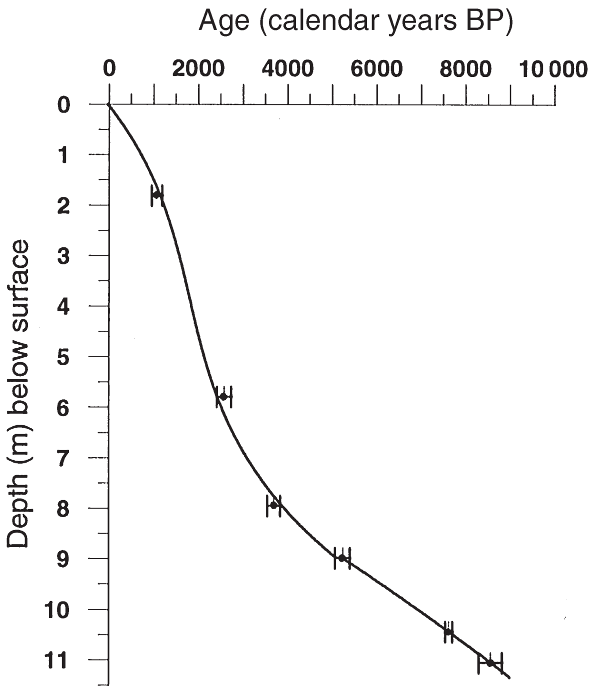
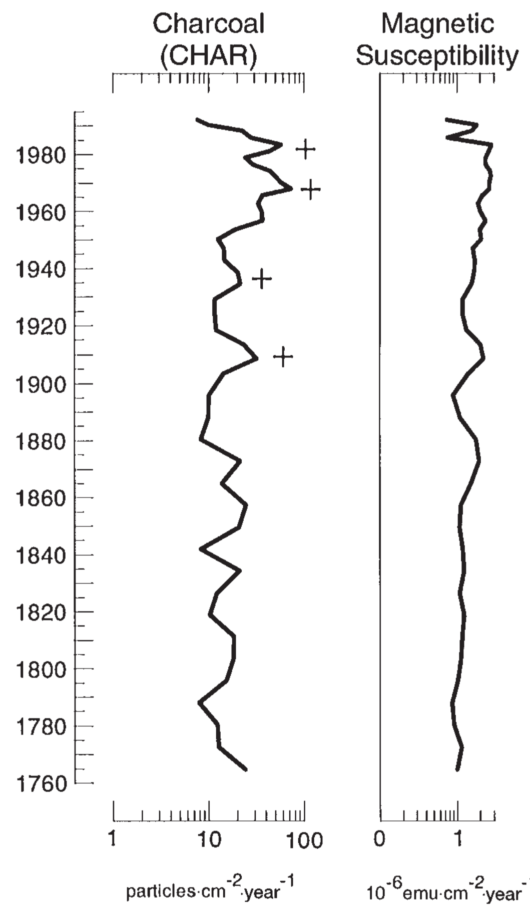


Fig. 3. Log-transformed charcoal (CHAR) and magnetic susceptibility accumulation rates plotted against age in the short core. Core intervals with a plus sign are associated with known or suspected watershed fires in 1982, 1967, 1934, and 1910.



produced a locally weighted mean frequency of peaks (number of peaks/1000 years). This peak-frequency series was obtained by smoothing a binary series of peaks (1, peak; 0, no peak) using a locally weighted average with a 2000-year window width.

Results

Record of 20th century fire events

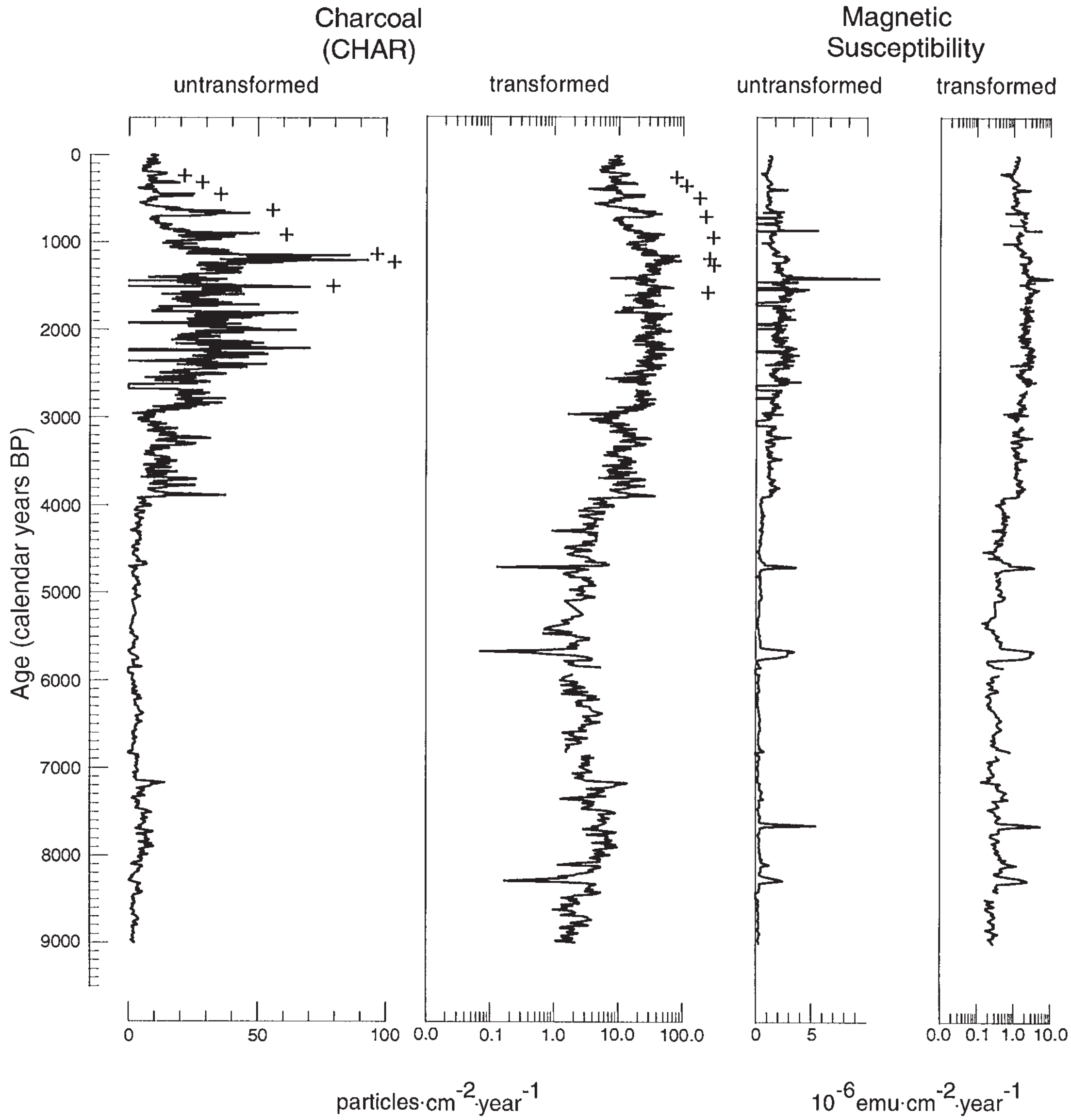
CHAR and magnetic-susceptibility data from the short core allow us to examine evidence of recent fires that occurred in and near the Little Lake watershed. Four accumulation-rate peaks in CHAR were apparent from visual inspection in the record (1982, 1967, 1936, and 1910) marked by the plus signs in Fig. 3). The 1982 peak may be associated with a 12-ha debris burn in the southwestern part of the watershed in that year (Bureau of Land Management 1992). The 1967 peak, as well as the general increase in CHAR since 1950, is attributed to increased slash burns following timber harvest. The 1934 peak may be from the 1929 Lake Creek fire in and north of the watershed (Oregon State Board of Forestry 1994); the difference in age lies within the uncertainty of ^{210}Pb-controlled chronology. Morris (1934) identified 1910 as a year in which numerous fires swept through western Oregon and Washington, and although no specific record was found for the Little Lake watershed, nearby fires are the likely source of the charcoal peak. A comparison of the CHAR peaks associated with observed fires and a general background level of about 15 particles·cm^{-2}·year^{-1} suggest that the peaks are two to five times larger than the background levels.

The magnetic-susceptibility record shows a relatively steady increase in level from 1760 to 1980 (Fig. 3). Increases in sediment magnetism in the 20th century may reflect increased erosion due to logging and road building (Jones and Grant 1996). It could be argued from the slight rise in magnetic-susceptibility values associated with a CHAR peak in 1910 and the generally high values in the intervals from 1960 to 1980 (which contains two prominent CHAR peaks) that erosional events are responsible for high values in both CHAR and magnetic susceptibility. This situation would certainly confound our use of CHAR peaks as indicators of past fires. We note, however, that the increase in magnetic-susceptibility accumulation rates is broad compared with the CHAR peaks, and the two records do not vary consistently. For example, there is no increase in magnetic susceptibility accumulation rates to match the CHAR peak in 1934 or the earlier fluctuations in CHAR values from 1760 to 1860, as might be expected with erosion after a fire (Swanson 1981; Meyer et al. 1995; Benda 1994). These observations lead us to assume that CHAR and magnetic susceptibility data register distinct aspects of fire and geomorphic disturbance in the watershed.

Analysis of core 93 and the selection of window-width and threshold-ratio values

The observed (i.e., not interpolated to constant time steps) and untransformed CHAR and magnetic-susceptibility records for Little Lake show values that vary over several orders of

Fig. 4. Comparison of untransformed and log-transformed Charcoal (CHAR) and magnetic-susceptibility accumulation rates plotted against age in core 93. Charcoal peaks assumed to be local fire events in the last 1500 years are marked with plus signs (see text for discussion). Values are not interpolated to a constant time step.



magnitude (Fig. 4). Between ca. 9000 and 4000 calendar years BP, both CHAR and magnetic-susceptibility values are low with frequent, but small, peaks that rise above background levels. After ca. 4000 calendar years BP, both increase dramatically and remain high until ca. 1200 calendar years BP. When log transformed, the increases in CHAR and magnetic-susceptibility data at ca. 4000 calendar years BP are muted, but the records still show distinct variations in background levels over time.

As demonstrated by the short-core record and other sedimentary charcoal studies (Clark 1990; Millspaugh and Whitlock 1995), CHAR peaks that represent local fires display a distinctive rapid rise in CHAR levels and an equally rapid return to low CHAR values. Eight CHAR peaks are evident in the last 1500 years in core 93 (marked by plus signs in Fig. 4). The success of different combinations of window width and threshold-ratio values in identifying the eight peaks was used as a criterion for selecting the particular values used in our analysis. This method of calibration was based on two considerations: (1) the eight CHAR peaks were easily distinguishable from background values by visual inspection, and (2) the peaks occurred at a time for which dendrochronologic data of fire were available from the PNW. Although, unfortunately, records were not available from the Little Lake watershed, these data provide estimates of fire frequency in coastal forests.

Window widths <300 years produced background components that tracked the CHAR so closely that none of the eight events registered as distinct peaks. Window widths >900 years generalized the background component and obscured what are probably meaningful differences between the early and late Holocene. Window widths between 300 and 900 years showed similar variations in the resulting background component, and an intermediate window width of 600 years was selected as optimal (Fig. 5).

Fig. 5. Comparison of window widths of 300, 600, and 900 years in defining background levels of log-transformed CHAR. Values interpolated to a constant time step. The intermediate width of 600 years was used for the fire-history reconstruction.

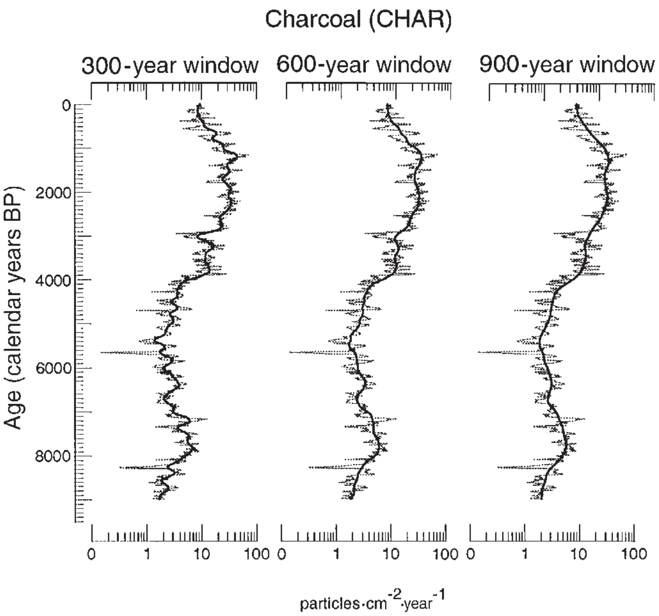
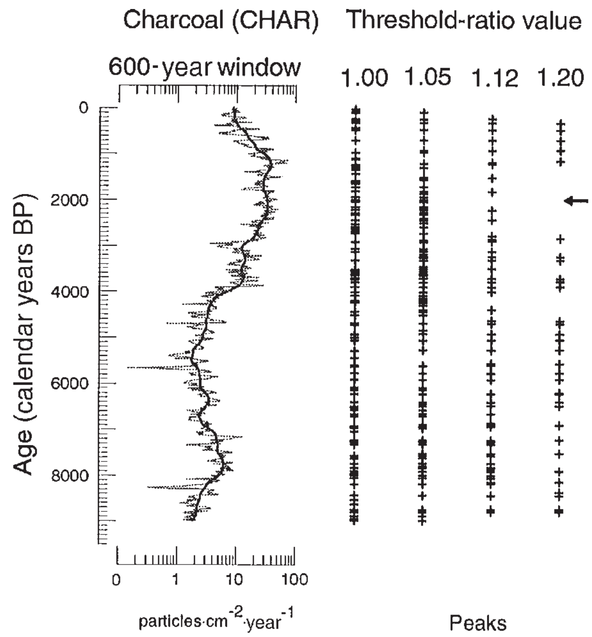


Fig. 6. Comparison of threshold-ratio values of 1.00, 1.05, 1.12, and 1.20 in the detection of peaks in log-transformed CHAR using a background window width of 600 years. Peaks (+) indicate a fire event. The arrow indicates the ca. 1700-year fire-free period discussed in the text. The threshold-ratio value of 1.12 was selected for the fire-history reconstruction.



A range of threshold-ratio values from 1.00 to 1.20 was evaluated to determine an appropriate value for identifying peaks with a 600-year background window (Fig. 6). The time between peaks was used to represent fire intervals or the time between successive fire events within the watershed. Threshold-ratio values of 1.00 and 1.05 identified the 8 peaks but also an additional 10 and 6 peaks, respectively, over that time period. This spacing of peaks suggest a mean fire interval (MFI; the arithmetic average of all fire intervals in a given space over a given time (Agee 1993)) of 110 years or less. These threshold-ratio values seem unlikely on the grounds that moist forests in the *Tsuga heterophylla* Zone of the Oregon Coast Range and Washington Cascade Range today have a longer MFI, on the order of 230 years or greater (Agee and Flewelling 1983; Agee 1990, 1993). In contrast, a threshold-ratio value of 1.20 identified only five of the eight peaks for the last 1500 years (MFI of 300 years). A value of 1.20 also produced a long fire-free interval (ca. 1700 years) (see arrow in Fig. 6) that seems unlikely given the fact that modern Sitka spruce forests growing in the coolest and wettest sites of the Olympic Peninsula, 500 km to the north (Fig. 1), have a MFI of 1150 years (Fahnestock and Agee 1983). A threshold-ratio value of 1.12 was selected because it identified the eight peaks and decreased the duration of the long fire interval to 400 years (Fig. 6).

Prehistoric CHAR and magnetic-susceptibility records

Visual inspection of the CHAR record suggested that it could be divided into three distinct zones: an early Holocene interval of relatively high peak frequency (ca. 9000 to 6850 calendar years BP; zone 3), a middle Holocene interval of intermediate peak frequency (ca. 6850 to 2750 calendar years BP; zone 2), and a late Holocene interval of low peak frequency (ca. 2750 calendar years BP to present; zone 1) (Fig. 7). The MFIs were as follows (rounded to decade): zone 3, 110 ± 20 years (mean ± SE); zone 2, 160 ± 20 years; zone 1, 230 ± 30 years. We performed an analysis of variance to test the null hypothesis that the MFI did not vary among zones. Prior to performing the analysis of variance, we tested the underlying assumption of homogeneity of group (i.e., zone) variances using Levene's test (Levene 1960). The null hypothesis that the variance of fire intervals across zones was homogeneous was not rejected ($L = 0.082$, $p = 0.92$). In contrast, the null hypothesis that the MFI was equal across zones was rejected, as we expected ($F = 4.85$, $p = 0.01$). The MFIs thus appear to vary significantly over time, while the within-zone variability of fire intervals do not.

During the early Holocene (ca. 9000 to 6850 calendar years BP), fire occurrence ranged from 5–8 events/1000 years, with a high of 10 events/1000 years at ca. 7500 calendar years BP. In the middle Holocene (ca. 6850 to 2750 calendar years BP) the record varied between eight and six events/1000 years. Fire incidence continued to decrease during the late Holocene (ca. 2750 calendar years BP to present) to a minimum of three events/1000 years by ca. 2000 calendar years BP. In the last 1000 years, the frequency has been constant at five events/1000 years.

Background CHAR levels were initially low (<2 particles·cm^{-2}·year^{-1}) and then increased to moderate levels (6 particles·cm^{-2}·year^{-1}) between 8000 and 7000 calendar years BP. They fell to low levels from ca. 7000 to 4000 calendar years BP (2–4 particles·cm^{-2}·year^{-1}), increased dramatically to about 37 particles·cm^{-2}·year^{-1} between ca. 4000 and 1200 calendar years BP, and then declined to present-day values of about 9 particles·cm^{-2}·year^{-1} (Fig. 7).

Peaks in magnetic susceptibility were probably the result of

Fig. 7. Log-transformed CHAR, background level, peaks, and inferred fire frequency for core 93, using a background window width of 600 years and a threshold-ratio value of 1.12. Horizontal lines denote boundaries between zone 3 (early Holocene, ca. 9000 to 6850 calendar years BP), zone 2 (middle Holocene, ca. 6857 to 2750 calendar years BP), and zone 1 (late Holocene, ca. 2750 calendar years BP to present).

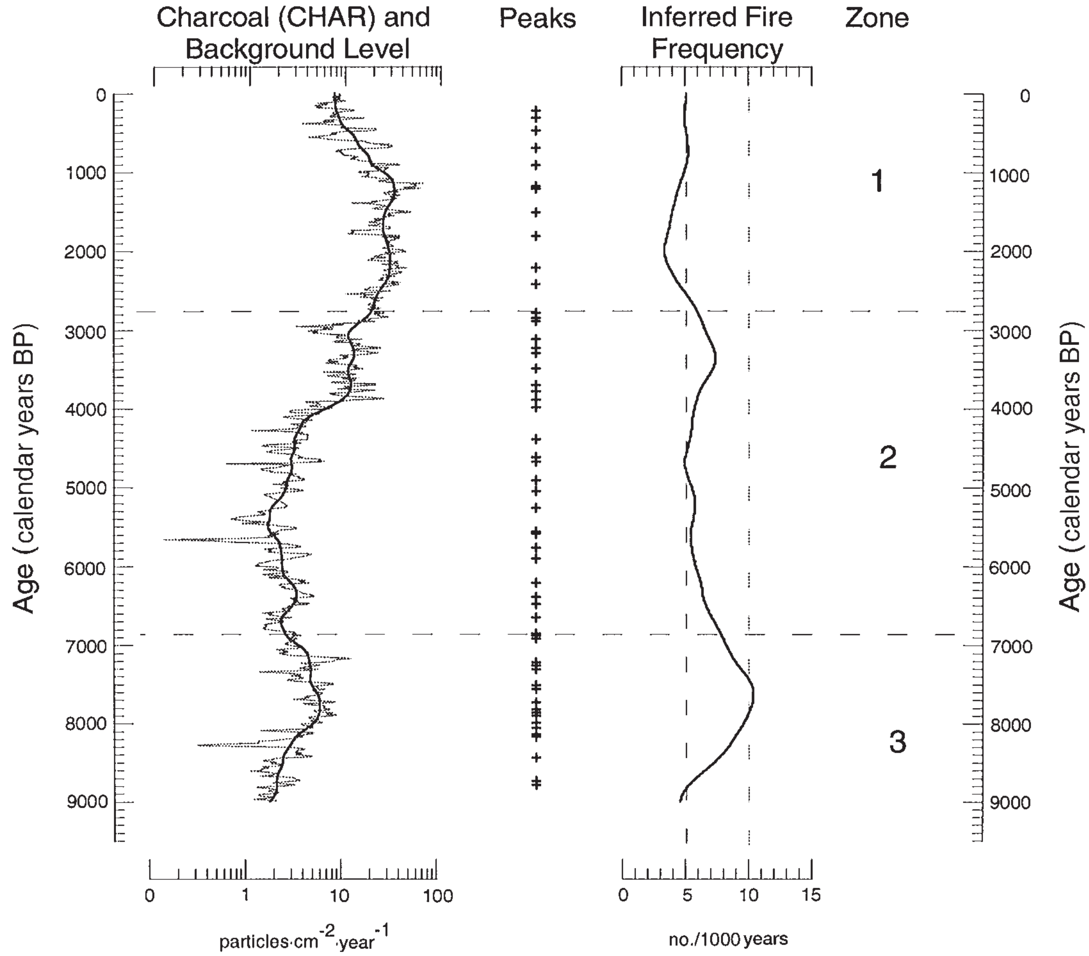


Table 3. Cross correlations among background and detrended CHAR and magnetic-susceptibility accumulation rate sseries.

	Cmean	Cdetrn	Mmean	Mdetrn
Cmean	1.000			
Cdetrn	–0.304	1.000		
Mmean	0.949	–0.318	1.000	
Mdetrn	–0.758	0.288	–0.843	1.000

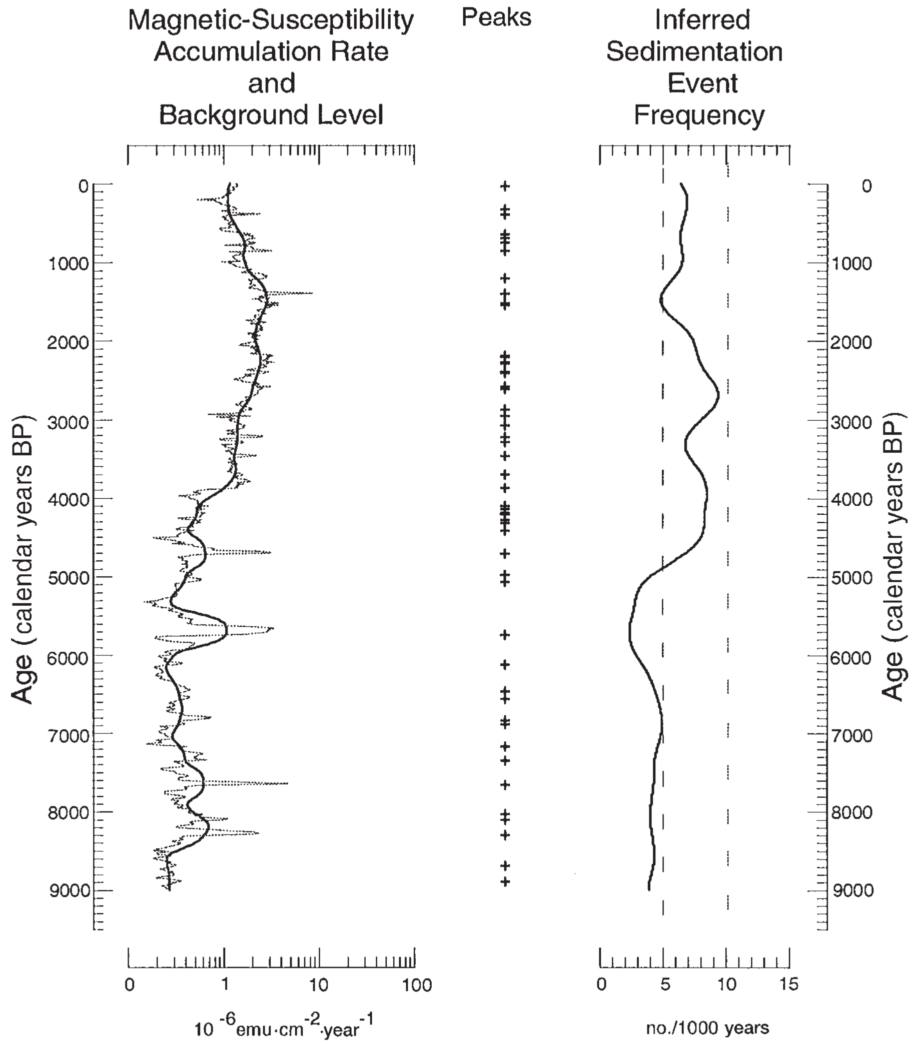
Note: Cmean = CHAR background values; Cdetrn = detrended CHAR values; Mmean = magnetic-susceptibility background values; and Mdetrn = detrended magnetic-susceptibility accumulation rates.

episodes of mass movement within the watershed caused by a variety of mechanisms, including fire (Benda 1994), storm-related precipitation (Reneau and Deitrich 1990) and earthquakes (Nelson et al. 1995). The inferred frequency of sedimentation events ranged between two and four events/1000 years from ca. 9000 to 5000 calendar years BP. It increased between ca. 5000 and 4500 calendar years BP from four to eight events/1000 years and remained high, from seven to nine events/1000 years, until ca. 2500 calendar years BP. The frequency of peaks decreased to five events/1000 years by ca. 1500 calendar years BP and has increased to six to seven events/1000 years since then (Fig. 8).

Changes in the background levels of magnetic susceptibility indicate general trends in clastic sedimentation through time. Values were low (between 0.25×10^{-6} and 1.00×10^{-6} emu·cm^{-2}·year^{-1}) from ca. 9000 to 3900 calendar years BP (Fig. 7). Elevated background levels occurred in association with peaks in magnetic-susceptibility values at ca. 8300, 5750, and 4700 calendar years BP and also with the deposition of Mazama ash (ca. 7630 calendar years BP). Background values increased to 2.90×10^{-6} emu·cm^{-2}·year^{-1} from ca. 3900 to 1500 calendar years BP and decreased to 1.15×10^{-6} emu·cm^{-2}·year^{-1} at the present day.

Cross correlation between charcoal and magnetic-susceptibility records was examined for detrended values (decadal CHAR and magnetic-susceptibility accumulation rates minus calculated background) and background values to determine if the two series were correlated and if the occurrence of sedimentation events was associated with charcoal peaks (Table 3). The lack of correlation (r = 0.288) between the detrended charcoal and magnetic-susceptibility values at Little Lake implies that introduction of clastic material to the lake was not closely associated with fire events. Correlations between the two sets of

Fig. 8. Log-transformed magnetic-susceptibility accumulation rates, background level, peaks, and inferred sedimentation event frequency for core 93, using a background window width of 600 years and a threshold-ratio value of 1.12.



data increased only slightly as 10-, 20-, 30-, 40-, and 50-year time lags were introduced (e.g., r = 0.304 at a 50-years time lag), suggesting that pulses of erosion did not follow fire events in a regular way. Unlike the findings of Millspaugh and Whitlock (1995) and Rummery (1983), sedimentation events at Little Lake do not seem to be directly related to fire events; instead they may signify precipitation events leading to mass movements, stream runoff, or earthquakes. In contrast, background levels of charcoal and magnetic susceptibility do show a strong correlation (r = 0.949), implying that background charcoal is composed of secondary material introduced to the lake as part of long-term variations in allochthonous sedimentation. At Little Lake, the background charcoal record likely reflects the local subcomponents that affect the production, transport, and incorporation of charcoal into the lake sediment. The fact that Little Lake is small and large charcoal particles are not transported long distances probably improved detection of local fire events and diminished the signal of regional fires at this site (see Methods).

Holocene vegetation, climate, and fire history

The pollen and charcoal records at Little Lake disclose changes in local vegetation, climate, and disturbance regime over the last 9000 years. This reconstruction can be compared with a network of paleoenvironmental records in the PNW and with paleoclimate model simulations produced by general circulation models (COHMAP Members 1988; Whitlock 1992; Thompson et al. 1993). In this way, the environmental history at Little Lake can be considered in light of large-scale changes in the climate system that affected the region as whole. On millennial and longer time scales, one important control of regional climate is the variations in the seasonal cycle of insolation, which occurred as a result of changes in the timing of perihelion and the tilt of the Earth's axis (Kutzbach et al. 1993). In the early Holocene, ca. 11 000 – 7000 calendar years BP, the Earth was closest to the Sun in July and the axial tilt was greater than today (Berger and Loutre 1991). As a result, summer insolation in the PNW was 8% higher than at present, and winter insolation was 8% less. Paleoclimate model simulations indicate that higher than present summer insolation led to increased summer temperatures and decreased effective moisture and indirectly to a strengthening of the eastern Pacific subtropical high, which further intensified aridity (Kutzbach and Guetter 1986; Kutzbach et al. 1993). Records throughout the PNW provide evidence of increased summer drought in the early Holocene consistent with the model results (Heusser 1977; Mathewes 1985; Barnosky et al. 1987; Thompson et al. 1993). In the middle and late Holocene, summer insolation decreased and summers became progressively cooler and wetter leading to the present climate. Superimposed on these millennial-scale variations are shorter changes in climate, which also must have affected vegetation and fire regimes, although the cause of these changes is less well known (see Bond et al. 1997).

The pollen record from Little Lake shows high percentages of *Quercus*, *Pseudotsuga*-type, *Alnus rubra*-type, and *Pteridium*-type in the early Holocene, prior to ca. 6850 calendar years BP (zone 3) (Fig. 9). The forest was apparently dominated by Douglas-fir with red alder in areas of frequent disturbance and oak on the driest sites. High percentages of *Pteridium aquilinum*, a heliophytic fern, suggest forest openings. The vegetation was probably similar to present-day forests in the dry regions of the *Tsuga heterophylla* Zone, such as at low elevations in the eastern Coast Range and the western Cascade Range (30–150 km to the east) (Fig. 1). A MFI of 110 ± 20 years is estimated for zone 3, which is consistent with that observed in these modern-analogue forests (Teensma 1987; Morrison and Swanson 1990). The vegetation and fire records therefore agree with regional evidence of warmer, drier conditions in the early Holocene and suggest that fires played an important role in maintaining open, xerophytic vegetation near Little Lake. Similar conclusions were reached in charcoal and pollen studies from the Puget Lowland (Cwynar 1987; Tsukada et al. 1981).

In general, background levels of CHAR and magnetic susceptibility in the early Holocene indicate little delivery of clastic material to the lake. Fires may have been small and not stand replacing and, thus, would not have produced much charcoal. In addition, mass movements may have been infrequent during a relatively dry period. It is noted, however, that background levels of CHAR and magnetic susceptibility increase somewhat during the period from ca. 8200 to 7500 calendar years BP within zone 3 (Figs. 7 and 8). The higher levels of CHAR suggest greater input of secondary charcoal as a result of changes in fuel conditions or fire severity. The increase in magnetic susceptibility background levels is associated with magnetic susceptibility peaks at 8300 calendar years BP and at ca. 7630 calendar years BP (the deposition of Mazama ash) and do not seem to reflect long-term changes in sediment delivery to the lake.

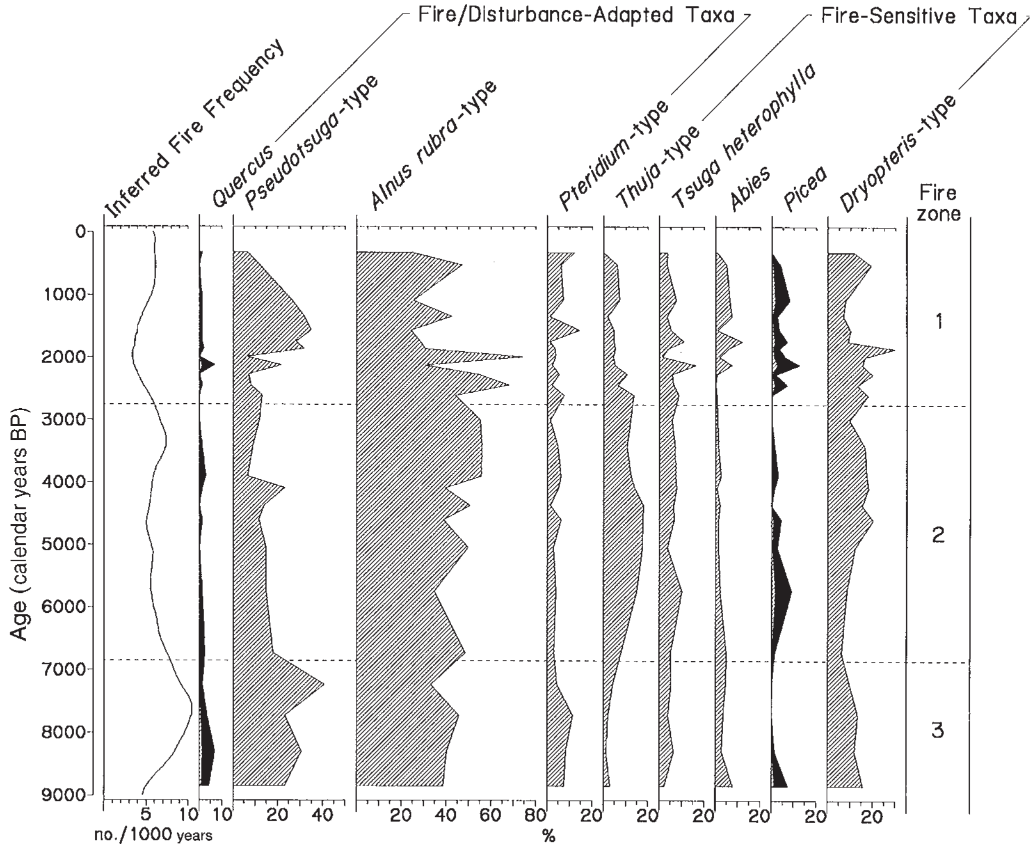
In the middle Holocene period (zone 2; ca. 6850–2750 calendar years BP), the pollen record registers decreased percentages of *Quercus*, *Pseudotsuga*-type, and *Pteridium*-type and increases in those of *Alnus rubra*-type, *Thuja*-type, *Tsuga heterophylla*, *Picea*, and *Dryopteris*-type (Fig. 9). The inferred changes in vegetation were not dramatic, but they imply an expansion of mesophytic and disturbance-sensitive taxa. This shift in forest composition is consistent with a trend towards less-severe summer drought as a result of decreasing summer insolation. The increase in western red cedar, western hemlock, and spruce near Little Lake suggests that the forest was becoming more closed, at least in some areas of the watershed. The high levels of *Dryopteris*-type spores, which are attributed to *Polystichum minutum* and *Dryopteris* spp., provide additional evidence; both are understory dominants of closed forests in the Coast Range today. The increase in red alder and the persistence of Douglas-fir through zone 2 indicates that parts of the watershed still experienced frequent disturbance. The charcoal record indicates a lengthening of MFI to 160 ± 20 years from ca. 6850 to 2750 calendar years BP, but fire occurrence probably varied within the watershed as a result of the different fire sensitivities of the plant communities.

The increase in background CHAR at ca. 4000 calendar years BP is consistent with higher amounts of woody fuel buildup associated with closed forests and suggests that increased fire severity produced greater amounts of charcoal during each event (Fig. 7). The concurrent increase in levels of background magnetic susceptibility indicates greater input of clastic material after 4000 calendar years BP (Fig. 8). The fact that peaks of CHAR and magnetic susceptibility do not coincide (Table 3), however, implies that individual fires did not immediately trigger a sedimentation event (i.e., within 50 years). After ca. 4000 calendar years BP, wetter conditions apparently led to more mass movements and greater stream run-off than before (Swanson 1981; Benda 1994; Meyer et al. 1995), which in turn delivered higher amounts of secondary charcoal and clastic material to the lake. Consistent with this model, Reneau and Dietrich (1990) present evidence of more mass movements in the Oregon Coast Range during the middle and late Holocene than before. They ascribed this geomorphic shift to increased winter storm activity.

The late Holocene period (zone 1; ca. 2750 calendar years BP to present) features increased values of *Pseudotsuga*-type (although a decrease in the uppermost levels), *Pteridium*-type, *Abies*, and *Picea* (Fig. 9). Pollen of *Alnus rubra*-type and *Thuja*-type decrease from previous values, and percentages of *Tsuga heterophylla* and *Dryopteris*-type remain relatively unchanged. This period records minor shifts in vegetation associated with continued regionwide cooling and increased moisture. At Little Lake, the increase in Douglas-fir and the persistence of red alder and bracken in zone 1 indicate the continued presence of xerophytic vegetation and forest openings, although the increase in spruce and fir imply an expansion of closed forests. As in the middle Holocene, the late-Holocene vegetation around Little Lake probably represents a mosaic of fire- and disturbance-adapted communities as well as fire-sensitive taxa. The charcoal record indicates a decrease in fire frequency in the late Holocene, with MFI dropping to 230 ± 30 years. Fire occurrence was lowest between ca. 2750 and 1500 years BP and has increased to about seven events in the last 1000 years. It must be remembered, however, that the identification of peaks in the last 1500 years was explicitly constrained as a means of selecting decomposition parameters for the rest of the record (see the Analysis of core 93 and the selection of window-width and threshold-ratio values section).

The Little Lake record extends our understanding of forest dynamics in the Coast Range to millennial time scales. Periods with frequent fires at Little Lake account for shifts in vegetation towards disturbance-adapted taxa, while millennia with few fires allowed the expansion of mesophytic, fire-sensitive species. This relation also is observed on shorter time scales. For example, at ca. 7500 calendar years BP, Douglas-fir, oak, and bracken were abundant, and spruce was scarce; fires at this time were frequent (Fig. 9). From ca. 6850 to 4500 calendar years BP, fire-sensitive taxa, like western red cedar, spruce,

Fig. 9. Inferred fire frequency from core 93 and pollen percentages of selected taxa from core 91 (Worona and Whitlock 1995). Black profile of *Quercus* and *Picea* is a 5% exaggeration. Taxa are grouped as fire or disturbance-adapted taxa or fire-sensitive after Agee (1993). Horizontal lines denote boundaries of charcoal-based zones.



and western hemlock expanded, and Douglas-fir became less abundant. This shift is accompanied by a steady decrease in fire occurrence. A period of increased fire frequency centered at ca. 3500 calendar years BP coincides with a peak abundance of red alder and declines in western red cedar and spruce. A notable period of infrequent fire centered at ca. 2000 calendar years BP was accompanied by an increase in grand fir, spruce, and Douglas-fir. The concurrent loss of red alder reflects a shift towards middle and late successional forests over much of the watershed.

The record also demonstrates linkages between changes in climate and fire regime on Holocene time scales. The early Holocene climate at Little Lake is part of a pattern of regional aridity associated with higher than present summer insolation. Warmer drier summers led to a regime of frequent fires, probably of low severity and small size. As the climate became cooler and wetter in the late Holocene, with the decrease in summer insolation, fires became less frequent but likely were more severe. This linkage between long-term variations in climate and fire frequency highlights the role of fire as the proximal cause of vegetation reorganization. As the climate varied, so too did the importance of fire as a catalyst of vegetation change.

The fire history at Little Lake also suggests that the frequency of fire events over the Holocene changed continuously over the last 9000 years. With the possible exception of the last 1000 years, the record shows no evidence of a prolonged fire cycle or mean return interval. Swetnam (1993) noted the noncyclic nature of fire occurrence over the last 2000 years in the Sierra Nevada, arguing that centennial-scale variations in fire history were a response to long-term changes in temperature. The record presented from Little Lake suggests that fire occurrence also tracks variations in temperature and effective moisture on millennial time scales in a nonstationary manner.

Conclusions

Little Lake provides a window on the long-term fire history of the Oregon Coast Range. The extent to which this record is representative of the regional fire history will become known as other long charcoal records are studied. Several conclusions are drawn from this study.

(1) Decomposition of the components that constitute a macroscopic charcoal record improves our ability to reconstruct local fire history from lake-sediment cores. At Little Lake, the background component of the charcoal record represents material introduced secondarily during nonfire years and variations in background provide information on changes in woody fuel biomass, sediment storage characteristics of the watershed and lake, and possibly the severity of fires. The peaks component represents fire events within or near the watershed. These interpretations are refined when other paleoenvironmental data are considered, including

evidence of changes in sedimentation, vegetation, and climate.

(2) High-resolution short-core studies provide information on recent fire history, although the results lack the spatial specificity and temporal resolution of dendrochronologic records. At Little Lake, we were able to identify peaks in the charcoal record that matched dates of recent fires in 1982, 1967, 1934, and 1910.

(3) Fire events at Little Lake were most frequent, with a MFI of 110 ± 20 years, in the early Holocene when warm, dry conditions existed. Fire frequency then decreased to a MFI of 160 ± 20 years as the climate became cooler and more humid in the middle Holocene. In the late Holocene a MFI of 230 ± 30 years was established with further cooling and increased precipitation. Increases in Douglas-fir, red alder, and other fire-resistant and disturbance-adapted species accompanied periods of high fire incidence. Fire-sensitive species, such as Sitka spruce and grand fir, were more abundant during periods of low fire frequency. These results suggest that variations in the frequency of fire have been important in shaping the composition and distribution of Coast Range forests through the Holocene and that changes in both vegetation and fire frequency were controlled by climate.

(4) The dramatic increase of secondary charcoal from ca. 4000 to 1200 calendar years BP is attributed to increases in burnable fuel biomass with the establishment of closed mesophytic forests. It is also explained by increased clastic sediment transport to the lake as a result of wetter conditions in the middle and late Holocene.

(5) Changes in climate on long time scales produced a nonstationary fire response at Little Lake over most of the last 9000 years. The record suggests that fire frequency has changed continuously with climate change and the present-day fire regime probably has no long-term history.

Acknowledgments

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