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).

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

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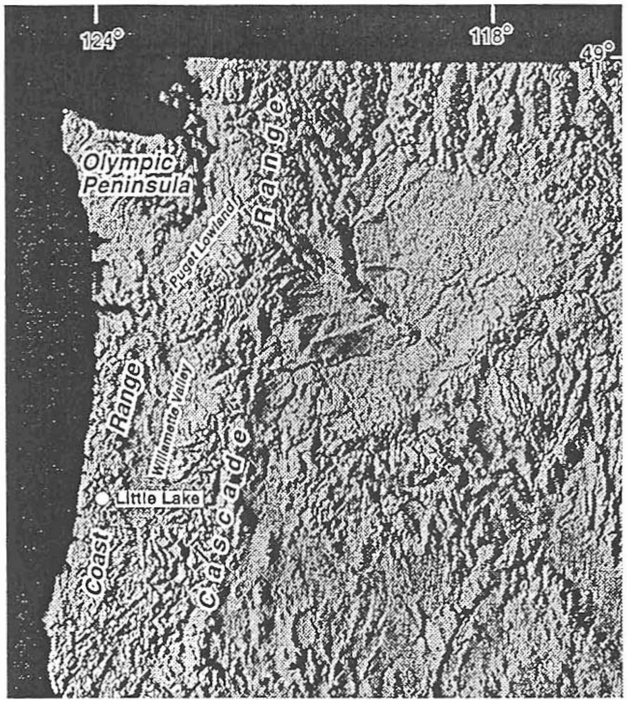
Fig. 1. Location of Little Lake and physiographic features mentioned in the text.



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.

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

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 + 904 (depth) –72.0 depth^2+0.02 (depth)^3

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.

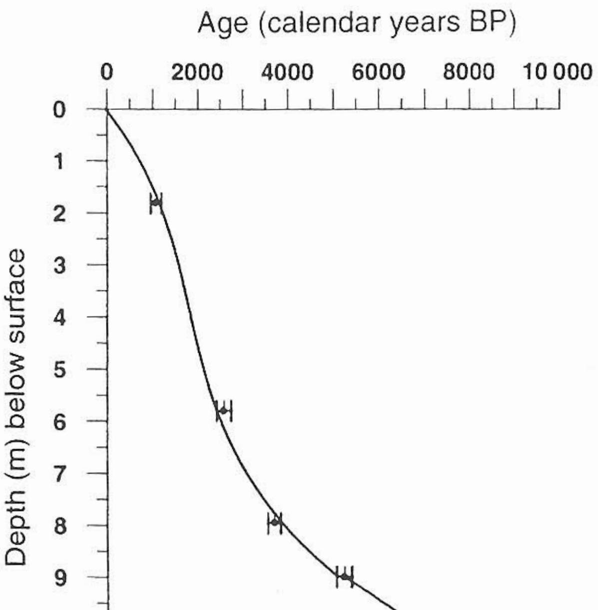


Fig. 3. Log-transformed charcoal (CHAR) and magnetic susceptibility accumulation rates plotted against age in the short core. Core intervals with a plus sign are associated with known or suspected watershed fires in 1982, 1967, 1934, and 1910.

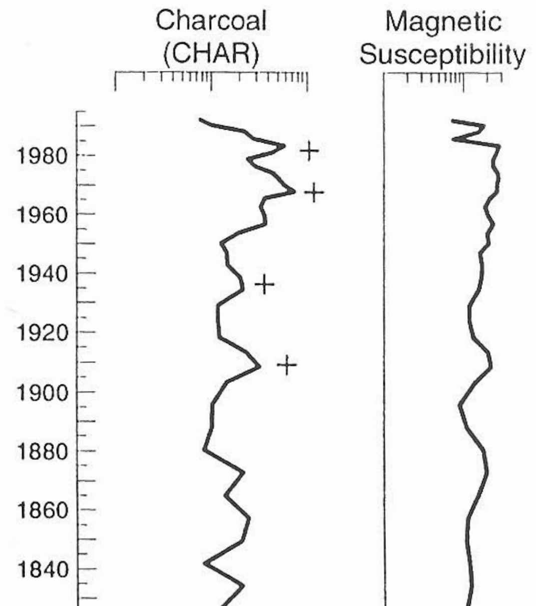


Fig. 4. Comparison of untransformed and log-transformed Charcoal (CHAR) and magnetic-susceptibility accumulation rates plotted against age in core 93. Charcoal peaks assumed to be local fire events in the last 1500 years are marked with plus signs (see text for discussion). Values are not interpolated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

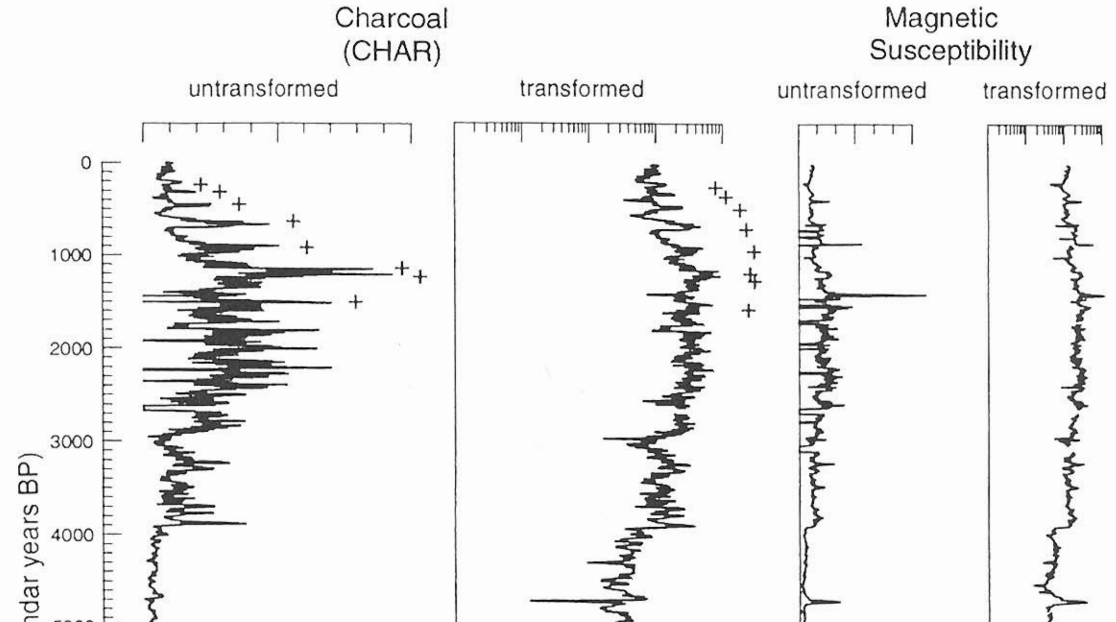


Fig. 5. Comparison of window widths of 300, 600, and 900 years in defining background levels of log-transformed CHAR. Values interpolated to a constant time step. The intermediate width of 600 years was used for the fire-history reconstruction.

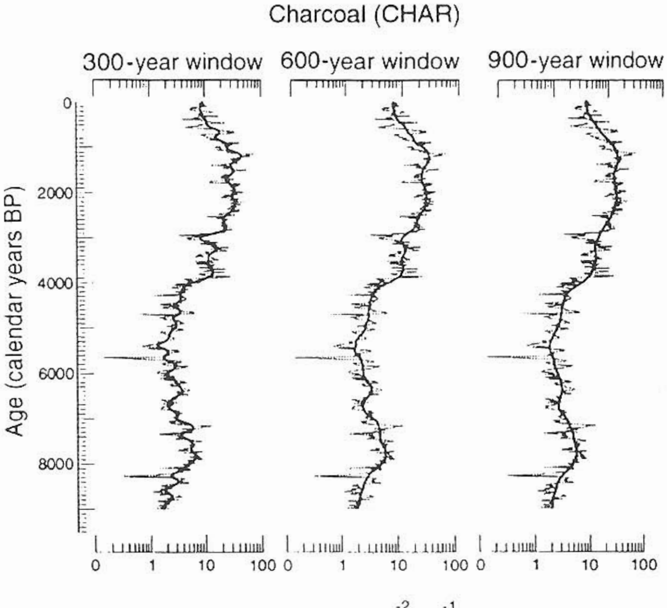


Fig. 6. Comparison of threshold-ratio values of 1.00, 1.05, 1.12, and 1.20 in the detection of peaks in log-transformed CHAR using a background window width of 600 years. Peaks (+) indicate a fire event. The arrow indicates the ca. 1700-year fire-free period discussed in the text. The threshold-ratio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

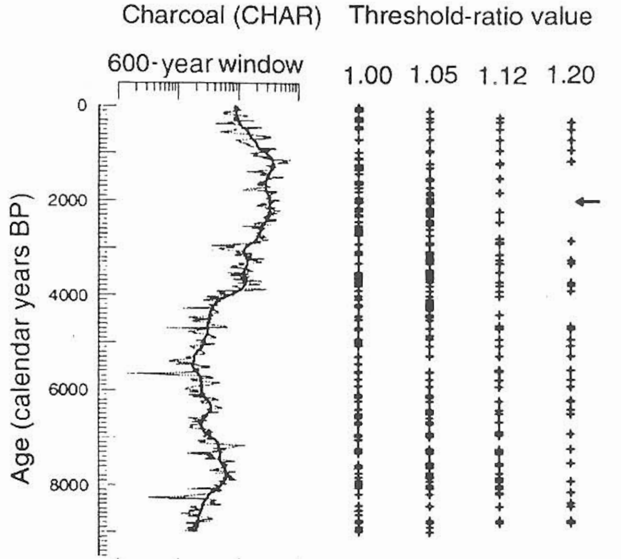


Fig. 7. Log-transformed CHAR, background level, peaks, and inferred fire frequency for core 93, using a background window width of 600 years and a threshold-ratio value of 1.12. Horizontal lines denote boundaries between zone 3 (early Holocene, ca. 9000 to 6850 calendar years BP), zone 2 (middle Holocene,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

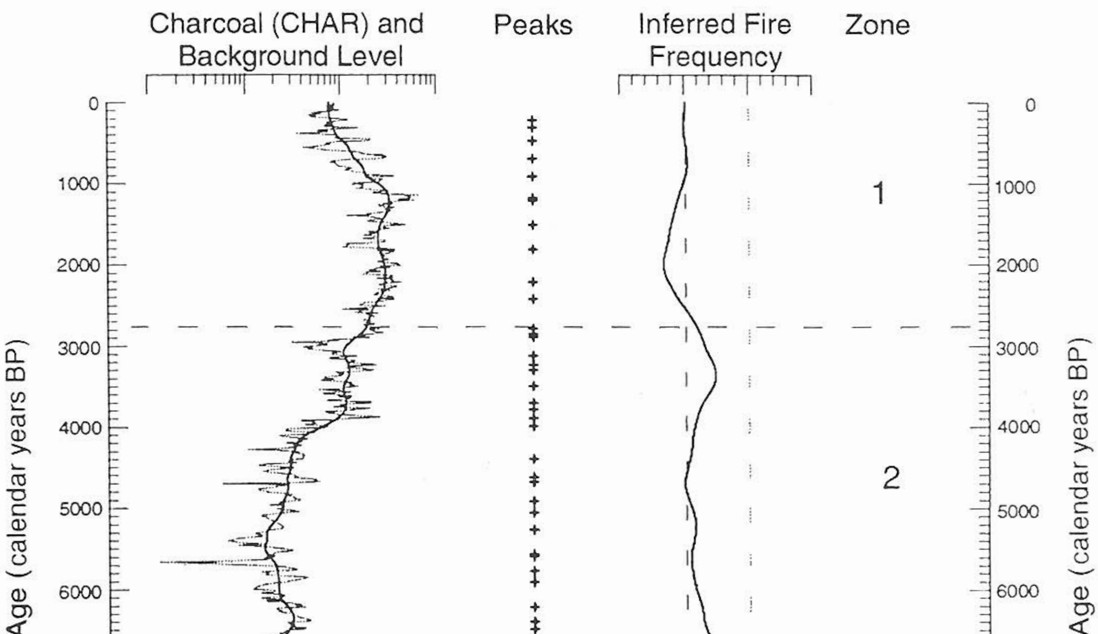
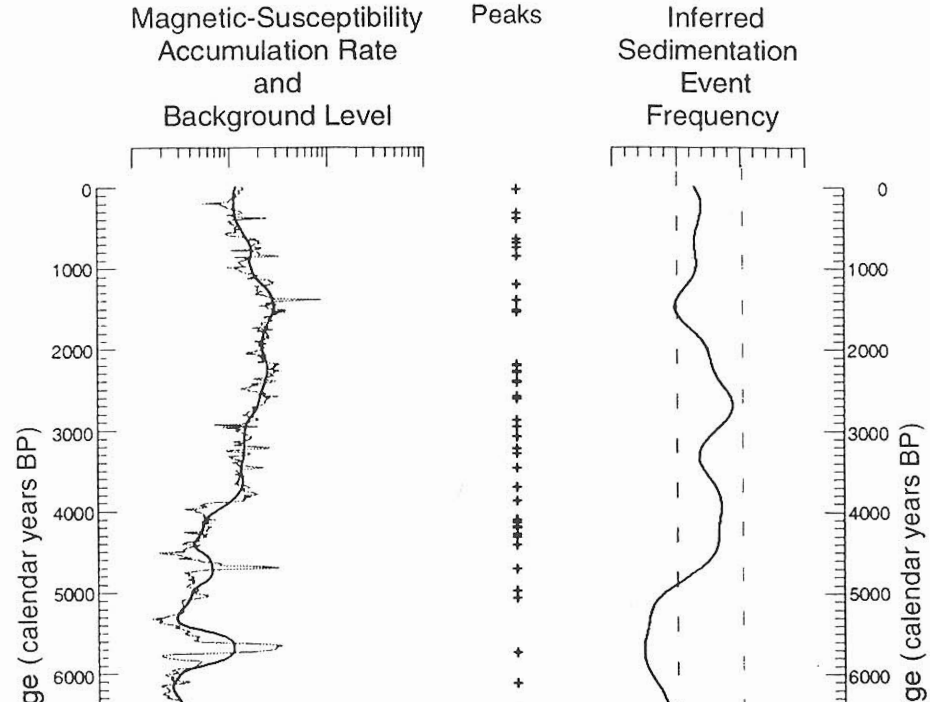


Fig. 8. Log-transformed magnetic-susceptibility accumulation rates, background level, peaks, and inferred sedimentation event frequency for core 93, using a background window width of 600 years and a threshold-ratio value of 1.12.

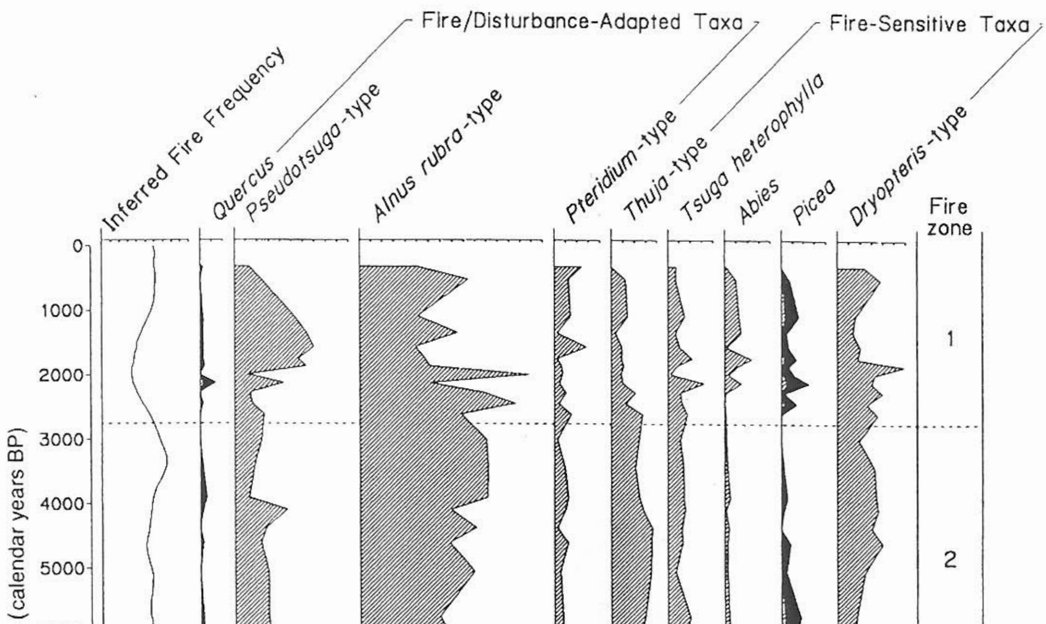


the PNW provide evidence of increased summer drought in the early Holocene consistent with the model results (Heusser 1977; Mathewes 1985; Barnosky et al. 1987; Thompson et al. 1993). In the middle and late Holocene, summer insolation decreased and summers became progressively cooler and wetter leading 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, ests 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

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.



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.

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