Comparison of charcoal and tree-ring records of recent fires in the eastern Klamath Mountains, California, USA

Cathy Whitlock, Carl N. Skinner, Patrick J. Bartlein, Thomas Minckley, and Jerry A. Mohr

Abstract: Fire-history reconstructions are based on tree-ring records that span the last few centuries and charcoal data from lake-sediment cores that extend back several thousand years. The two approaches have unique strengths and weaknesses in their ability to depict past fire events and fire regimes, and most comparisons of these datasets in western conifer forests have focused on sites characterized by high-severity crown fires. Tree-ring and charcoal data spanning the last 300 years in four watersheds in the montane forests of the Klamath Mountains provided an opportunity to compare the records in a fire regime of frequent low- to moderate-severity surface events. The charcoal data were obtained from small lakes, and tree-ring records were derived from fire-scar chronologies at multiple sites within each watershed. The comparison indicates that the tree-ring records detected individual fires not evident in the lake-sediment profiles, whereas the charcoal data disclosed variations in fuel loading and general levels of burning at broader spatial scales. Regional burning in the late 19th and early 20th centuries was evident in the lake-sediment records, and both datasets registered a decline in fire activity in the late 20th century. Thus, the two types of data provide complementary as well as supplementary information on past fire conditions.

Résumé : Les reconstitutions historiques des feux sont basées sur des séries dendrométriques qui s'étendent sur les derniers quelques siècles et sur les données fournies par le charbon de bois présent dans les carottes de sédiments lacustres qui couvrent plusieurs milliers d'années. Les deux approches ont des forces et des faiblesses particulières dans leur capacité à mettre en évidence les feux et les régimes de feu passés. La plupart des comparaisons de ces ensembles de données dans les forêts de conifères de l'Ouest ont mis l'accent sur des sites caractérisés par des feux de cime de sévérité élevée. Des séries dendrométriques et des données tirées du charbon de bois couvrant les 300 dernières années dans quatre bassins situés dans les forêts alpestres des monts Klamath fournissent une occasion de comparer ces données pour un régime de feu caractérisé par de fréquents feux de surface de sévérité faible à modérée. Les données tirées du charbon de bois ont été obtenues à partir de petits lacs, et les séries dendrométriques ont été dérivées à partir de chronologies de blessures causées par le feu à plusieurs endroits dans chaque bassin. La comparaison indique que les séries dendrométriques ont détecté des feux qui n'étaient pas évidents dans les profils de sédiments lacustres tandis que les données fournies par le charbon de bois ont révélé des variations dans la quantité de combustibles et les niveaux généraux de brûlage à des échelles spatiales plus larges. Des incendies régionaux survenus à la fin du 19^{e} siècle et au début du 20^{e} siècle étaient évidents dans les sédiments lacustres. Les deux groupes de données montrent qu'il y a eu une diminution des feux à la fin du 20^{e} siècle. Par conséquent, les deux types de données fournissent des informations complémentaires et supplémentaires sur les situations passées concernant les feux.

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Introduction

The size and severity of recent fires in the conifer forests of the western United States have raised questions about the occurrence of such events prior to the implementation of current forest management practices, including active fire suppression. Information on fire conditions prior to Euro-American settlement comes from dendrochronological records of the last few centuries and lake-sediment charcoal records that span the Holocene period. Both datasets have intrinsic strengths

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C. Whitlock,[1,2] P.J. Bartlein, T. Minckley,[3] and J.A. Mohr.[4] Department of Geography, University of Oregon, Eugene, OR 97403, USA.
C.N. Skinner. U.S. Forest Service, Pacific Southwest Research Station, Redding, CA 96002, USA.

[1] Corresponding author (e-mail: whitlock@montana.edu).
[2] Present address: Department of Earth Sciences, Montana State University, Bozeman, MT 59717, USA.
[3] Present address: Department of Geography, Geology, and Anthropology, Indiana State University, Terre Haute, IN 47809, USA.
[4] Present address: College of Forestry, Oregon State University, Corvallis OR 97443, USA.

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and shortcomings, and fire-history research strives to integrate the findings of both datasets in fire reconstructions (Whitlock et al. 2003). Despite this goal, few studies have critically compared the reconstructions provided by tree-ring and charcoal records to assess their effectiveness at describing past fire activity. Because the underlying assumptions and approaches used in each method differ, questions arise about their relative abilities to resolve past fire conditions and provide comparable, or supplemental, fire reconstructions.

Dendrochronological information on past fires is based on fire-scarred tree-ring chronologies developed from living trees and remnant materials and from establishment ages of trees following fire (Madany et al. 1982; Agee 1993). In most forests, these chronologies extend back about 500 years. Cross-dated fire scars yield reconstructions that are geographically resolved (i.e., known fire location) and temporally precise (i.e., annual resolution) and that describe conditions not lethal to the tree (i.e., surface burns). Stand ages provide fire reconstructions that are spatially specific yet less temporally precise (i.e., decadal resolution) than dated fire scars. In stand-age analysis, the detection of older fires is hampered by the fact that old trees are eliminated from the record by younger fires (Agee 1993). Moreover, because fires may kill all trees in some stands and few in others, structural and age diversity in forested landscapes is often related to variations in past fire severity. Stands that have experienced high-severity crown fires are even aged or several aged, with stems in relatively few age-classes, whereas those that experience low- and moderate-severity burns have stems in a wide range of age-classes, because fires kill few trees in the stand (Agee 1993; Taylor and Skinner 1998). How best to extrapolate point data from fire-scarred trees to other parts of the landscape is a topic of considerable discussion, and it becomes an issue when researchers try to infer the size and severity of the fire (Baker and Ehle 2001).

Fire reconstructions from the analysis of charcoal and other proxy fire indicators preserved in lake sediments make use of the fact that lakes are repositories of paleoenvironmental information. During and following a fire, particles of charred plant debris (i.e., charcoal) are introduced to the lake through airborne fallout, streamflow, and surficial processes and are incorporated into the sediments. Recent refinements in charcoal analysis have improved our ability to reconstruct past fire events from lake-sediment records (see Whitlock and Larsen 2002 and references therein). The chronology for charcoal records is based, in most cases, on interpolating ages between a series of radiocarbon and ^{210}Pb dates, and it is less temporally precise than tree-ring reconstructions. The ^{210}Pb dating method is based on the decay of radioactive ^{210}Pb in sediments, following its formation in the atmosphere and burial in the sediments. The short half-life of this isotope is useful for dating sediments less than 200 years old. Radiocarbon dating is also based on radioactive decay and provides a chronology for organic materials that are about 500 – 40 000 years old. Radiocarbon dates must be converted to calendar years by calibration (e.g., Stuiver et al. 1998) before they can be compared with tree-ring and ^{210}Pb chronologies. With both radiocarbon and ^{210}Pb dating methods, the analytical error increases exponentially with age, and most lake-sediment fire reconstructions have decadal accuracy at best.

Lake-sediment cores collected in the western United States have charcoal particles in most samples, and the identification of a fire episode requires decomposing the charcoal-influx record into a background or trend component and a residual component, in which large positive values define charcoal peaks that are thought to represent fire episodes. A charcoal peak may span a few centimetres of the core and thus represent several years of accumulation. In areas of frequent fires, an individual peak may represent charcoal accumulation from one or more fires. The background charcoal trend reflects other characteristics of the fire regime, including changes in production, transport, and delivery of charcoal to the site (Whitlock and Larsen 2002). Variations in background levels are associated with changes in vegetation and (or) hydrology, whereas variations in the frequency of peaks represent changes in the occurrence of fire episodes through time (Long et al. 1998).

Theoretical and empirical studies have shown that macroscopic particles (>100 μm in diameter) do not travel far from their source and provide a record of past fires within or near a watershed. Following the 1988 fires in Yellowstone National Park, charcoal particles of >125 μm diameter were abundant in sites <7 km from the fire (Whitlock and Millspaugh 1996); beyond that distance, the accumulation of such particles declined sharply. A study of the uppermost sediment of 36 lakes following a 1996 fire in the Cascade Range of Oregon showed that particles of >125 μm diameter were statistically more abundant in burned sites than in unburned sites within 2 km of the burn (Gardner and Whitlock 2001). Similarly, Clark et al. (1998) observed that charcoal abundance and size dropped off within metres of the burned margin of an experimental fire in Siberia. Another modern charcoal study examined 704 charcoal traps distributed within and up to 100 m outside three experimental fires in boreal Scandinavia (Ohlson and Tryterud 2000). Charcoal particles of >0.5 mm diameter were found in about 80% of the traps inside the burned area, about 25% of the traps located 0.1–0.9 m outside the fire perimeter, and <5% of the traps located 1–100 m outside the fire perimeter.

Simple Gaussian-plume models also predict that particles >1000 μm in diameter, released relatively close to the ground, are deposited within 100 m of a fire (Clark and Patterson 1997). Theoretically, particles of <10-μm diameter could travel well beyond 100 m, and very small particles could be transported long distances. These modeling studies confirm empirical observations that macroscopic charcoal abundance falls off sharply beyond the fire margin. An examination of particles in this size range thus provides information on events in and near the immediate watershed. Selection of small lakes (<10 ha) with little inflow, simple bathymetry, and small watersheds further constrains the fire location, because these physical characteristics tend to reduce the introduction of postfire or secondary charcoal by fluvial and surficial processes (Gardner and Whitlock 2001).

Dendrochronological data have been used to calibrate charcoal records in terms of fire size and proximity, with varying degrees of success (e.g., Clark 1990; MacDonald et al. 1991; Millspaugh and Whitlock 1995). In mesic and high-elevation conifer forests of the western United States and Canada, charcoal peaks have closely matched the age of large or severe fires, and the correspondence has been best for fires in small to intermediate-sized watersheds (e.g., Millspaugh and Whitlock 1995; Larsen and MacDonald 1998; Hallett et al. 2003). Stand-replacing fires in such forests seem to produce a lot of charred plant debris, and the convective uplift associated with such fires helps transport charcoal to lakes. Fires located upwind of lakes have been shown to deposit significantly more charcoal than those downwind, confirming the importance of airborne transport (Millspaugh and Whitlock 1995; Gardner and Whitlock 2001). In other regions, macroscopic charcoal peaks have closely matched years of low-severity fires in mixed hardwood–conifer forests, and peaks in microscopic charcoal (<100-μm-sized charcoal particles) have been used to detect regional fires (e.g., MacDonald et al. 1991; Tinner et al. 1998).

Most charcoal studies to date have been directed at reconstructing high-severity burns, whereas most dendrochronological investigations have focused on low-severity fire regimes. We examined the tree-ring and charcoal records of the last 300 years in four small watersheds in the eastern Klamath Mountains of northern California to assess how these two approaches register past fire events in an environment characterized mostly by frequent, generally small burns. The results of this study contribute to our understanding of charcoal transport and the relative ability of lake-sediment and tree-ring data to record past fires.

Site description

The Klamath region is noted for its high diversity of conifer species and unique mixtures of taxa from the Pacific Northwest, California, and Great Basin. The vegetation in the Klamath Mountains reflects gradients in temperature and precipitation, as well as the influence of the ultramafic (serpentine) bedrock. Dense forests are dominated by *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir), *Pinus ponderosa* Laws. (ponderosa pine), *Pinus lambertiana* Dougl. (sugar pine), *Abies concolor* (Gord. & Glend.) Lindl. (white fir), and *Calocedrus decurrens* (Torr.) Florin (incense-cedar). *Quercus kelloggii* Newb. (California black oak) occurs at elevations below about 1000 m above sea level (a.s.l.) in nonserpentine areas (Sawyer and Thornburgh 1988). *Pinus jeffreyi* Grev. & Balf. (Jeffrey pine) replaces *P. ponderosa* with increasing elevation or on ultramafic soils. Upper montane forests (>1400 m a.s.l.) on mesic sites consist of dense to open mixed stands over a continuous layer of sclerophyllous shrubs (Keeler-Wolf 1990*a*), whereas areas underlain by serpentine feature relatively bare or discontinuous shrub cover.

Past fires have helped to structure the montane forests of the Klamath region. Tree-ring data indicate median fire intervals of generally <35 years at a scale of 1–2 ha, although fires have occasionally burned many sample sites over large watersheds (Agee 1991; Taylor and Skinner 1998, 2003). The fires of the region have been generally frequent, occasionally large, and generally low- or moderate-intensity surface burns. Typical burns have been mainly low or moderate in severity and patchy enough to allow *A. concolor* to grow to a fire-resistant size (e.g., Agee 1993). Resulting forest stands are mostly multiaged, often with many stems >250 years old, and commonly include older stems of *A. concolor* (Taylor and Skinner 1998, 2003). Tree-ring and lake-sediment data indicate that fires in this region have been more frequent and less severe than in the Pacific Northwest but less frequent than in the central Sierra Nevada (Wills and Stuart 1994; Taylor and Skinner 1998; Mohr et al. 2000). Recent large fire episodes include the extensive lightning-caused 1987 fire (155 000 ha; Biswell 1989), 1999 fire (71 000 ha; Omi and Martinson 2002), and 2002 Biscuit Fire (186 000 ha; USDA Forest Service 2003).

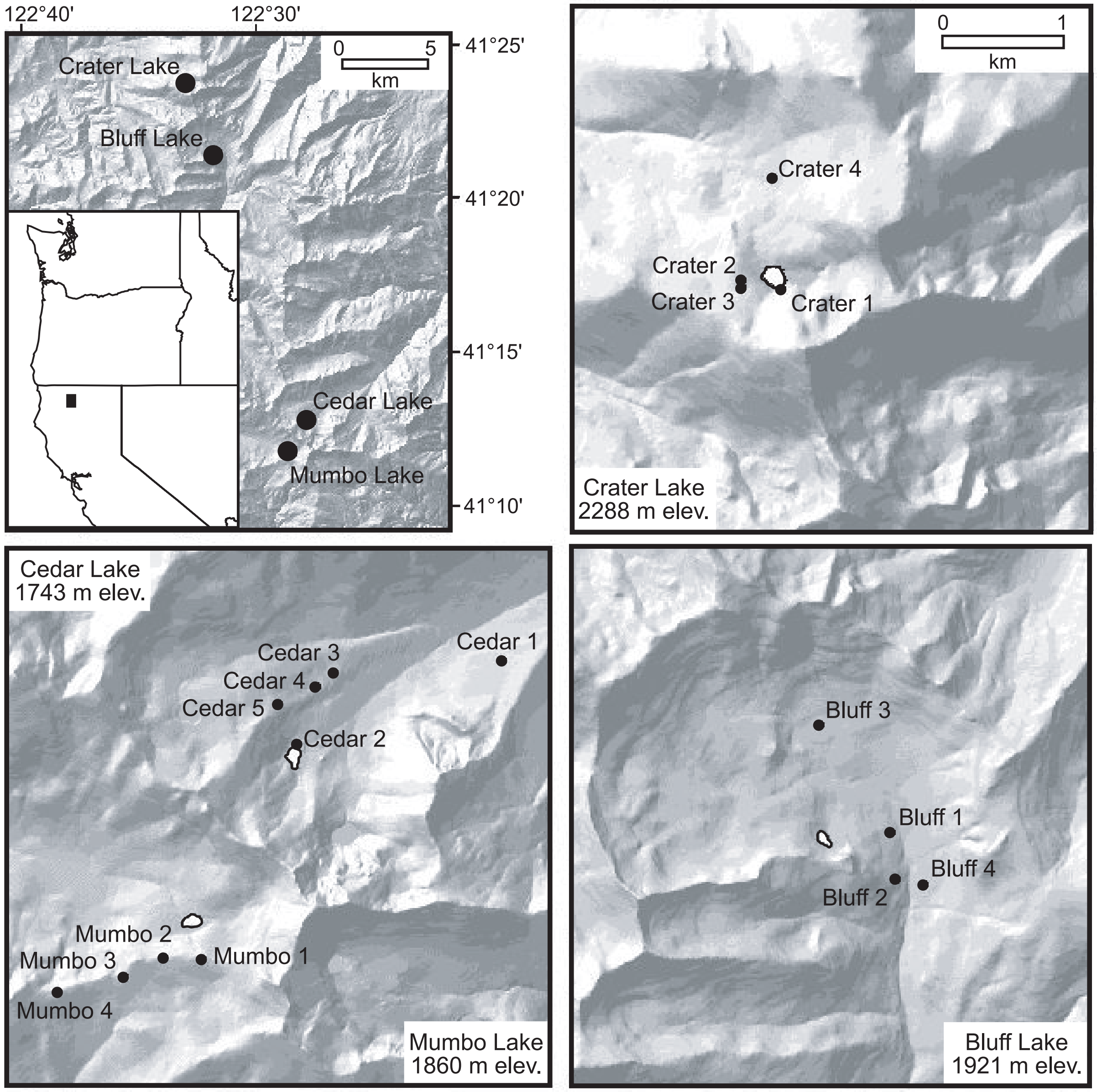
In contrast to the more common forest conditions and fire regimes of the Klamath Mountains just described, the upper montane and subalpine environments in this study region are characterized by rocky outcrops, screes, wet seeps and meadows, and riparian zones intermixed with forest stands, woodlands, and shrubfields on shallow soils derived from ultramafic substrates. These factors combine to break up fuel continuity. Individual fires are likely limited in extent under all but the most severe conditions. Heavy snow packs lasting into the early to mid-summer in many years contribute to a very short fire season. Fuel beds are generally compact, and except in unusual circumstances, they promote slowly spreading, mostly smoldering fires. Fuel buildup is slow because of the limited growing season. High-intensity fires are mostly associated with pockets of fuel created by tree falls, thinning of dense younger stands, insect-related mortality, avalanches, snow or ice crushing, or the death of larger trees as late-successional conditions are achieved (Skinner et al., in press). Thus, evidence of extensive fire activity (i.e., multiple trees and sites scarred in the same year) is not necessarily evidence of large or intense fires. Rather, it may simply be evidence of several fires in years that were more conducive to fire occurrence (e.g., warm and dry).

Four watersheds were chosen for the study (Fig. 1). Crater Lake (41°24′N, 122°35′W, elevation 2288 m a.s.l., water depth 12.15 m) lies behind a glacial moraine on the northwest-facing slope of China Mountain. It is the site with the highest elevation, and the climate is correspondingly cooler and wetter than at other sites. It is surrounded by *Pinus balfouriana* Grev. & Balf. (foxtail pine), *Pinus albicaulis* Engelm. (whitebark pine), *Pinus contorta* Loud. (lodgepole pine), *Pinus monticola* Dougl. (western white pine), *P. jeffreyi*, *Abies magnifica* var. *shastensis* Lemm. (Shasta red fir), and *Tsuga mertensiana* (Bong.) Carr. (mountain hemlock) (Keeler-Wolf 1987). The understory is sparse but dominated by *Ceanothus prostratus* Benth. (mahala mat), and *Arctostaphylos patula* Greene (greenleaf manzanita).

Bluff Lake (41°20′N, 122°33′W, elevation 1921 m a.s.l., water depth 1.70 m) lies in a southeast-facing valley on the south side of South China Mountain. It is located in open forest composed of *P. jeffreyi*, *P. contorta*, *P. monticola*, *A. concolor*, *C. decurrens*, and *P. menziesii*. *Pinus lambertiana* grows at elevations below the lake, and *Pinus attenuata* Lemm. (knobcone pine) is present on ridges. *Quercus vaccinifolia* Kellogg (huckleberry oak), *C. prostratus*, and *Arctostaphylos* species are present in the shrub understory.

Mumbo Lake (41°11′27″N, 122°30′36″W, elevation 1859 m a.s.l., water depth 3.2 m) lies in a small west-facing cirque-like depression. Open conifer forests of *P. contorta*, *P. monticola*,

Fig. 1. Location maps of the four study watersheds in the Klamath Mountains, showing lakes and tree-ring sites.



P. jeffreyi, *A. concolor*, and *A. magnifica* var. *shastensis* surround the lake. *Pinus lambertiana* also grows near the site, and *T. mertensiana* is present on higher slopes. The understory is generally sparse and includes *Q. vaccinifolia*, *Arctostaphylos uva-ursi* (L.) Spreng. (kinnikinnik), *Amelanchier alnifolia* (Nutt.) Nutt. (Saskatoon serviceberry), and *Spiraea* spp. The region has been logged since the 1950s.

Cedar Lake (41°12′N, 122°27′W, elevation 1950 m a.s.l., water depth 2.60 m) features a dense bottomland forest, strongly dominated by *Chamaecyparis lawsoniana* (A. Murr.) Parl. (Port-Orford-cedar) on the south and east margins. The relatively open stands on the north and west sides of the lake are composed of *P. jeffreyi*, *P. monticola*, *P. contorta*, *P. lambertiana*, *A. concolor*, *C. decurrens*, and *P. menziesii*. Important shrubs include *Q. vaccinifolia*, *C. prostratus*, *Ceanothus velutinus* Dougl. ex Hook (snowbrush ceanothus), *A. patula*, *Arctostaphylos nevadensis* A. Gray (pinemat manzanita), *Amelanchier pallida* Greene (western serviceberry), and *Holodiscus discolor* (Pursh) Maxim. (oceanspray). The upper montane forest that surrounds Cedar Lake is composed of *A. magnifica* var. *shastensis*, *P. monticola*, *P. contorta*, and *T. mertensiana*. The shrub layer is dominated by the endemic *Arctostaphylos klamathensis* S.W. Edwards, Keeler-Wolf & W. Knight (Klamath manzanita) (Keeler-Wolf 1990*a*, 1990*b*).

Materials and methods

The tree-ring sampling strategy was designed to maximize the completeness of an inventory of fire dates within each site over as long a period as possible (Swetnam and Baisan 2003) while also collecting samples from sites spatially dispersed within the first- and second-order watersheds. (We define the first-order watershed as the drainage area above the lake and the second-order watershed as the catchment area above and below the lake.) From the studies of charcoal transport and deposition described above, we assumed that the distance between the tree-ring sites and the lakes was small enough that years of high fire activity recorded in the tree-ring sites would also be registered as increased charcoal accumulation in the sediments of a particular lake. Although we may have not detected all small fires in these basins, the sampling pattern allows us to identify years of more extensive fire activity that would be likely to contribute to increased production and aerial transport of charcoal to the lakes.

The species used in this study rarely exhibited a record of external fire scars without the open wound having rotted. Instead, the fire record is most often found in trees that healed rapidly after the fires, and the scars are buried in the trees (see Taylor and Skinner 2003; Skinner et al., in press). It was necessary to gather samples from relatively sound, dead material, especially stumps and downed logs whose fire scars were preserved and not rotted. None of the first-order watersheds had been logged, but such materials were available in the second-order watersheds. With the exception of Crater Lake, the first-order watershed area above the lakes also had generally sparse tree cover, with little available source of fire-scarred material. Most evidence available from live trees in the first-order watersheds was of species that exhibited considerable rot interior to the last fire (*A. concolor*, *A. magnifica*, *P. monticola*, and *P. contorta*). Of the dead material, most was too rotten to use, with the exception of the *P. albicaulis* at Crater Lake.

After extensive field reconnaissance, fire-scar samples were collected from three to five sites within a 2-km radius of each lake. The sites were 1–2 ha and located in mixed-species stands. The exception was Cedar 2 (one of the five Cedar Lake sites), which was located in a stand dominated by *C. lawsoniana*. Full and partial cross sections were cut with a chainsaw from stumps, downed logs, and snags with externally visible fire scars from each collection site (Arno and Sneck 1977). Each wedge or cross section was sanded and polished to a high sheen (320 grit) so that tree rings and fire scars could be readily distinguished under a microscope. Fire scars were identified by the characteristic disruption and healing patterns of radial tree-ring growth (McBride 1983; Dieterich and Swetnam 1984). The precise year of each fire was determined by cross-dating tree rings with standard dendrochronological techniques (Stokes and Smiley 1977; Swetnam et al. 1985).

Most specimens were cross-dated by visually comparing them with nearby chronologies (Briffa and Schweingruber 1983*a*, 1983*b*; Graumlich 1985; Buckley 1988) obtained from the International Tree-Ring Data Bank (Grissino-Mayer and Fritts 1998). The program COFECHA was used to facilitate cross-dating of specimens (Holmes 1983) that we were not able to cross-date visually. Only successfully cross-dated specimens were used to determine fire-scar dates. After fire dates were determined, the fire-history data for each site were summarized with FHX2 software (Grissino-Mayer 2001).

Composite fire chronologies were developed for each site and watershed (Dieterich 1980; Agee 1993). Composite fire-scar filters for each watershed were (1) all fires; (2) years when fires were recorded on at least two trees anywhere in the watershed; (3) years when fires were recorded on at least two sites in the watershed; and (4) years when fires were recorded on a minimum of two trees on at least two sites. The most inclusive filter (filter 1) captured all years in which fires were found, including those on only a single tree somewhere in the watershed. The most restrictive filter (filter 4) disclosed years when fires were more extensive and likely burned more biomass that could contribute charcoal to the lakes.

In each lake, a metre-long sediment core was taken to recover the mud–water interface intact and provide a sedimentary record that spanned at least 300 years. Cores were extruded vertically from the top of the tube at 1.0-cm intervals. Subsamples were stored in plastic bags and refrigerated when returned to the laboratory. At Crater and Bluff lakes, radiocarbon ages were converted to calendar years, and the age–depth relation based on these ages was used to calculate the age of the uppermost sediments (Mohr et al. 2000). At Mumbo and Cedar lakes, a series of samples weighing 0.2–2.0 g were taken from the top 20 cm of the cores for ^{210}Pb dating, and we extrapolated that age model to assign ages to deeper sediments. The Little Glass Mountain volcanic ash, dated at 915 (A. Sarna-Wojcicki, personal communication), was present in the Mumbo and Cedar lake cores and provided another age determination.

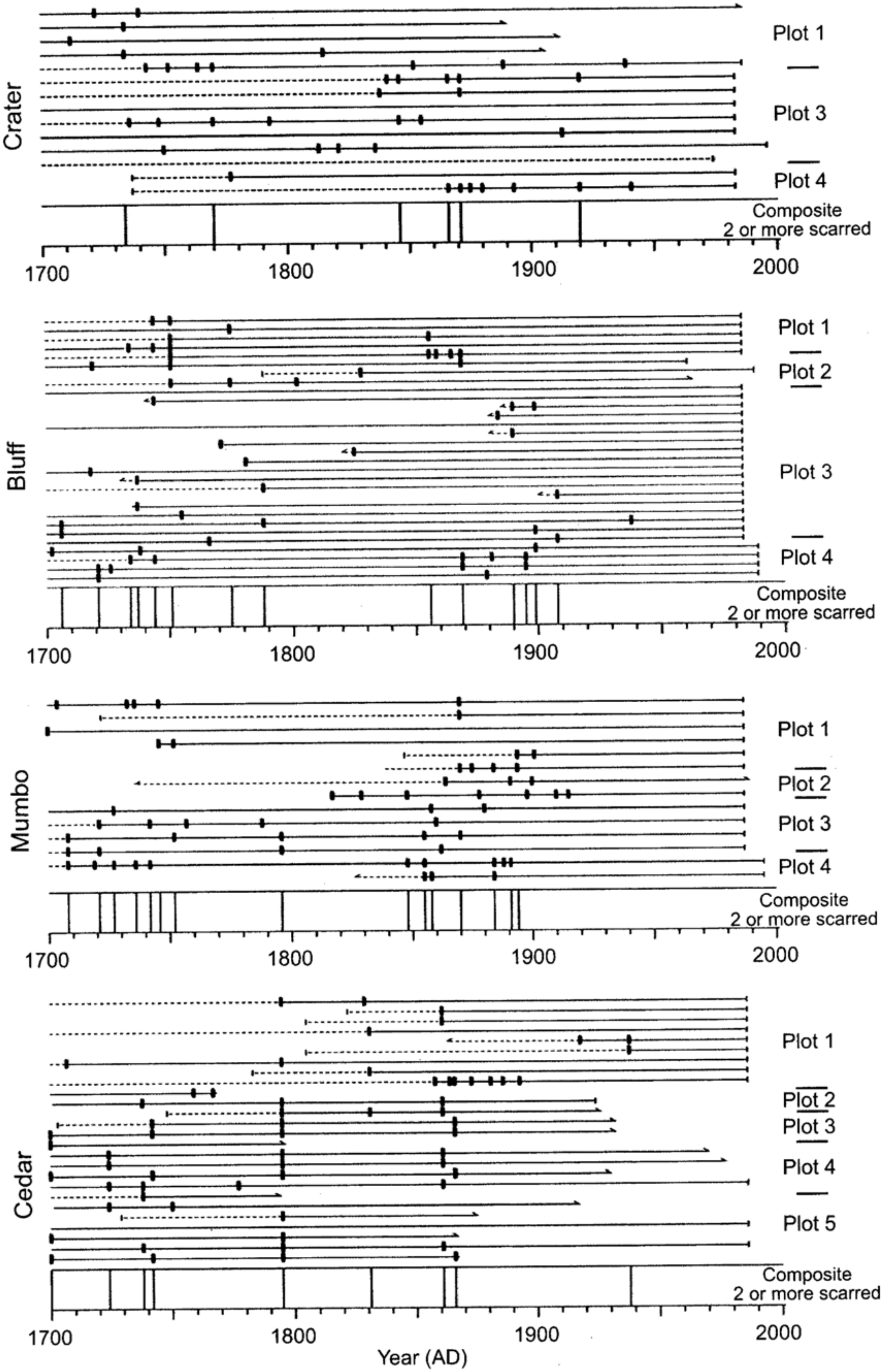
Charcoal analysis was performed on 1-cm-thick contiguous samples; for each sample, 5 cm^3 was disaggregated in a 5% solution of sodium hexametaphosphate for 3 days. The residue was wet-sieved through a nested series of metal screens with mesh sizes of 250 and 125 μm. Each sample was placed in a gridded Petri dish, and the charcoal in each size-class was tallied under a stereomicroscope at × 50 magnification. The counts were converted to charcoal concentrations (particles·cm^{-3}). Because the two size-classes showed the same trend, the counts were combined. Charcoal accumulation rates (particles·cm^{-2}·year^{-1}) were calculated by dividing the charcoal concentrations by the deposition time (years·cm^{-1}) for each sample. Charcoal peaks were identified by visual inspection as instances in which the charcoal influx stood above the general background trend.

Results

Ages of fire-scarred tree rings are presented in Fig. 2, which also gives a composite time series showing years when two or more trees were scarred (filter 2). Figure 3, which summarizes the composite time series for all filters, shows that the number of fires equaling or exceeding filter 3 or filter 4 was achieved rarely. The age models for each lake-sediment record are presented in Table 1. Figure 4 shows the charcoal stratigraphy at each location, plotted by age, as well as the fire years when at least two trees were scarred in the watershed (filter 2).

Of the four tree-ring sites near Crater Lake, three sites (Crater 1, Crater 2, and Crater 3) were close to the lake on the south side, and the fourth site (Crater 4) was 1 km to the north and downstream of the lake. The three specimens collected at Crater 2 (two *P. monticola* and one *T. mertensiana*) could not be cross-dated and were not used to determine fire

Fig. 2. Tree-ring record of fire activity for the four lake basins. Each horizontal line is an individual tree, and each vertical dash is a dated fire scar. The composite at the bottom of each chart represents the years when fires were recorded on at least two trees in the watershed (filter level 2).



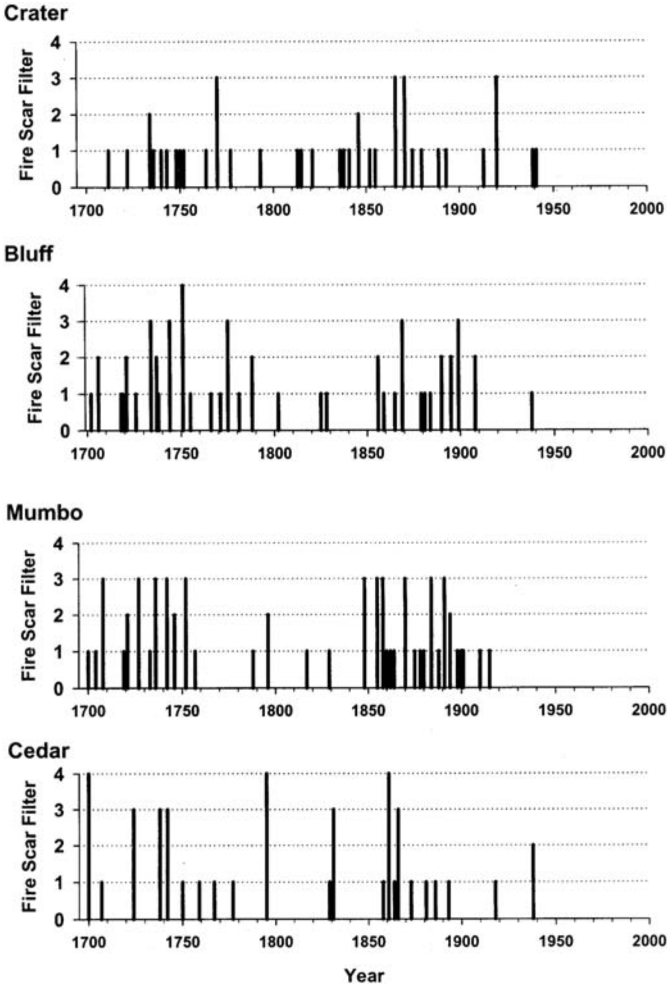


Fig. 3. Composite time series of tree-ring records of fire events for each lake basin, using different filters. Composite fire-scar filters for each watershed were (1) fires recorded on a single tree; (2) fires recorded on at least two trees in the watershed; (3) fires recorded on at least two sites in the watershed; and (4) fires recorded on a minimum of two trees on at least two sites.

history. Crater 4 had few scars concurrent with those at Crater 1 and Crater 3. Data from individual sites indicated that most fire events affected only single trees. Concurrent scars on trees at more than one of the sites suggested large (or multiple) fires in 1920, 1871, and 1770. Data that showed more than one tree scarred at a single site added 1840 and 1734 to the list of years with high fire activity (Figs. 2 and 3).

At Crater Lake, the age model for the short core was based on a series of radiocarbon dates from the long core that spanned the entire Holocene (Mohr et al. 2000); correlation between cores was based on lithologic similarities (Table 1). Each centimetre spanned 8–17 years, and charcoal accumulation rates ranged between 0.046 and 0.51 particles·cm^{-2}·year^{-1}. High charcoal abundance occurred in 1953–1970, 1869–1936, and 1774–1835, with a pronounced peak at 1953–1970 and 1774–1788 (Fig. 4).

Four tree-ring sites were analyzed near Bluff Lake. Three sites — Bluff 1, Bluff 2, and Bluff 4 — were down valley to the east and southeast of the lake. Bluff 3 was located 1 km north of the lake, at a similar elevation. We collected more specimens at this site than at others because it was in a wet meadow area, and most samples had interior rot before the last one or two scars. Years when more than one site featured fire scars were 1899, 1869, 1775, 1751 (at all sites), 1744, and 1738. Years when more than one tree was scarred at individual sites included 1908, 1895, 1890, 1856, 1788, 1734, 1721, and 1706 (Figs. 2 and 3). Two specimens of *P. jeffreyi* and one of *C. decurrens* could not be cross-dated.

The age model at Bluff Lake was developed from a series of radiocarbon dates from the longer core (Table 1) (Mohr et al. 2000). Samples spanned 5–12 years, and charcoal accumulation rates ranged from 0.37 to 2.63 particles·cm^{-2}·year^{-1}. High charcoal levels were noted at 1980–1986, 1955–1962, 1944–1950, 1903–1933, 1870–1891, 1775–1787, and 1703–1751. Prominent peaks were dated at 1992–1995, 1944–1950, 1927–1933, 1909–1915, 1870–1891, and 1739–1751 (Fig. 4).

Four tree-ring sites near Mumbo Lake were located on the ridge to the south of the lake, and all recorded past fire events. Years when more than one site recorded fires included 1891, 1884, 1870, 1858, 1855, 1848, 1752, 1742, 1736, 1727, and 1708. Years when more than one tree was scarred at individual sites were 1894, 1796, 1746, and 1721 (Figs. 2 and 3).

At Mumbo Lake, a second-order polynomial regression was used to fit an age model to the series of ^{210}Pb dates and the age of the Little Glass Mountain ash (Table 1). Deposition time ranged between 2 and 26 year·cm^{-1}, and charcoal accumulation rates ranged between 0.029 and 1.43 particles·cm^{-2}·year^{-1}. High levels of charcoal occurred at 1920–1936 (when a series of high peaks occurred), 1914–1916 (another high peak), 1900–1909, 1881–1888, 1862–1872, and 1710–1738 (Fig. 4).

Five tree-ring sites were examined at Cedar Lake: Cedar 1 was located on a ridge 2 km to the east; Cedar 2 lay in *Chamaecyparis* forest along the east shore of the lake and had two specimens that we were unable to cross-date; and Cedar 3–Cedar 5 were located north of the site along the ridge that forms the watershed divide. Fire years at more than one site included 1866, 1861 (registered at all sites in several trees), 1831, 1795 (registered at all sites in several trees), 1742, 1738, 1724, and 1700. In addition, fires in 1938 were recorded by more than one tree at Cedar 1, but the event was not registered at the other sites (Figs. 2 and 3).

As we did for Mumbo Lake, we fitted the age-versus-depth model for the Cedar Lake short core with a polynomial curve based on ^{210}Pb dates and the age of the Little Glass Mountain ash, and deposition times were 8 years·cm^{-1} at the top and 33 years·cm^{-1} at the base (Table 1). Charcoal accumulation rates ranged between 0.028 and 3.36 particles·cm^{-2}·year^{-1}, with peaks at 1941–1956 and 1892–1923 and a smaller peak at 1844–1862. No distinct peaks before 1862 were noted (Fig. 4).

Discussion

Comparison of the four records reveals variations in charcoal accumulation rates, in terms of both background trends and the occurrence of charcoal peaks that seem to reflect site-to-site differences in physical setting, vegetation, and local fire history. The presence of charcoal in every centimetre of the short cores suggests low levels of charcoal accrual, even in nonfire years, interspersed with periods of high charcoal

Table 1. Radiometric ages used to develop an age–depth model for the study sites.

Site	Depth (cm)/date (AD year)	Depth (m)/calibrated age (years BP*)	Comments
Crater Lake			
(Mohr et al. 2000)		0.62/1 462	Radiocarbon chronology from long core used to construct short core chronology; calibration based on Reimer and Stuiver (1993) and Stuiver et al. (1998)
		1.59/2 581	
		2.61/5 907	
		3.37/6 415	
		4.07/8 125	
Crater Lake age model: Age = $-3.1156 \times \text{depth}^4 - 19.6547 \times \text{depth}^3 - 198.644 \times \text{depth}^2 = 1689.57 \times \text{depth}$			
Bluff Lake			
(Mohr et al. 2000)		0.37 /1 609	Radiocarbon chronology from long core used to construct short core chronology; calibration based on Reimer and Stuiver (1993) and Stuiver et al. (1998)
		0.66 /2 786	
		1.13 /4 740	
		1.41 /6 451	
		1.93 /8 810	
		2.27 /9 985	
		3.13 /11 065	
		3.64 /13 471	
Bluff Lake age model: Age = $-319.068 \times \text{depth}^3 + 1087.91 \times \text{depth}^2 + 3599.49 \times \text{depth}$			
Mumbo			
	2/1980		^{210}Pb dates provided by University of Wisconsin – Milwaukee, Center for Great Lakes Research; age of Little Glass Mountain tephra at 43 cm (Sarna-Wojcicki, personal communication)
	4.75/1958		
	7/1941		
	9/1926		
	11/1910		
	17/1864		
	20.5/1837		
	24.5/1807		
	51.5/915		
Mumbo Lake age model: Age = $-0.0299 \times \text{depth}^3 + 0.9605 \times \text{depth}^2 - 14.203 \times \text{depth} + 1996$			
Cedar Lake			
	1/1996		^{210}Pb dates provided by University of Wisconsin – Milwaukee, Center for Great Lakes Research; age of Little Glass Mountain tephra at 43 cm (Sarna-Wojcicki, personal communication)
	5.5/1989		
	6.5/1982		
	7.5/1975		
	8.5/1968		
	9.5/1962		
	10.5/1955		
	12.5/1941		
	14.5/1926		
	16.5/1913		
	18.5/1899		
	20.5/1886		
	22.5/1872		
	24.5/1858		
	26.4/1844		
	43/915		
Cedar Lake age model: Age = $-0.0266 \times \text{depth}^3 + 0.7742 \times \text{depth}^2 - 9.1763 + 1996$			

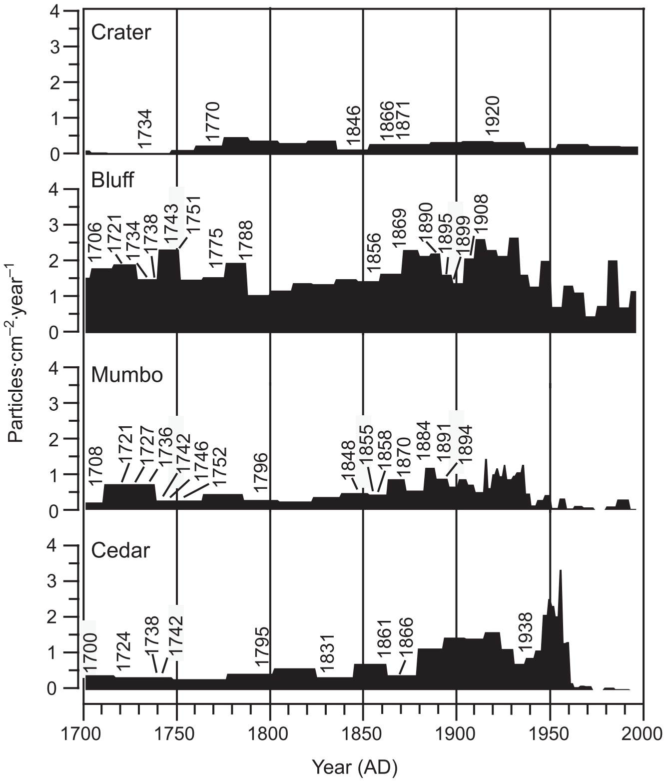
*Before present (1950).

accumulation. Past fire years (as registered in the tree-ring data) provide a basis for interpreting variations in the charcoal time series at each site.

Crater Lake, located at the highest elevation and in the most sparsely forested watershed, had the lowest accumulation rates, whereas Bluff and Cedar lakes featured the highest rates of charcoal accumulation, consistent with their lower, more forested settings. At Crater Lake, the tree-ring record suggests that past fires seldom affected more than single trees or stands. Little charcoal production during such fires probably accounts for the relatively low charcoal accumulation rates at this site.

Charcoal abundance at Mumbo Lake was nearly as low as that at Crater Lake for much of the record. Mumbo's first-order

Fig. 4. Time series of charcoal accumulation rates for the study lakes. Chronology was based on age models presented in Table 1. Fire years satisfying filter level 2 or higher in the tree-ring record are plotted next to each charcoal time series. (See Fig. 3 for descriptions of filters.)



watershed is defined by a prominent, sparsely vegetated ridge, and the second-order watershed is small, steep, and west trending (Fig. 1). The confined watershed may have protected the site from dry north and northeast winds that often influence fire spread in this region (e.g., the Megram and Jones fires of 1999) (Skinner et al., in press), restricting the charcoal input to local fires. Moreover, the tree-ring data from near Mumbo Lake featured only a few years when fires were recorded on more than two trees at a site or at more than two sites by single trees, and small fires would have produced relatively low levels of charcoal.

Bluff and Cedar lakes lie in larger watersheds that are slightly wetter than those of Mumbo and Crater lakes. The increased fire severity in these watersheds is reflected by the greater number of scarred trees per site, as well as by the greater number of tree-ring sites recording the same fire year. The higher rates of charcoal accumulation than at Crater or Mumbo lakes also attest to the fact that fires in the first- and second-order watersheds were likely larger and probably burned more biomass in these settings. Compared with the other sites, the higher charcoal accumulation rates may be explained by more continuous fuel cover, as well as by a broader charcoal source area.

The charcoal peaks in the records likely represent multiple fires occurring over several years, because the sedimentation rates in these relatively unproductive lakes are slow. The combination of frequent fires and slow sedimentation rates smooths the fire-related peaks in the record. Studies in sparsely vegetated watersheds elsewhere suggest that charcoal transport and deposition can continue years after a fire event (Patterson et al. 1987; Whitlock and Millspaugh 1996). This phenomenon may well explain the breadth of some peaks, as well as the lag between some charcoal peaks and fire years in the Klamath data. For example, a series of fires at the end of the 19th century at Bluff Lake was probably responsible for the broad charcoal peak dating between 1903 and 1933, which suggests charcoal deposition for several years after the fires and possibly inaccuracy in the lake-sediment chronology. A local fire at the shores of Cedar Lake in 1938 may have been responsible for the charcoal peak dating between 1941 and 1956. Likewise, several fires between 1848 and 1894 at Mumbo Lake possibly contributed to the broad peaks of charcoal dated at 1862–1872, 1881–1895, and 1900–1909.

Regional fire years show up in the Klamath charcoal data, even when local fire activity is not registered in the tree-ring record. For example, large fires in 1955 that burned within 8 km to the south may have contributed to the charcoal peak at this time at Crater and Cedar lakes. Widespread fire activity in 1977 and 1987 in southwestern Oregon and northern California (Biswell 1989) provides an explanation for the rise in charcoal in the uppermost sediments of Bluff and Mumbo lakes. Apparently, anomalously large fires were able to disperse charcoal far beyond the immediate area of the burn. One way to test this assertion would be to monitor charcoal deposition in lakes located within burned and unburned watersheds following the Biscuit Fire of 2002, which was the largest ever recorded in the region.

In summary, the mixed correspondence between specific charcoal peaks and fire years in the tree-ring record might be explained in a number of ways. First, individual fire events recorded by the tree-ring record may have been small events that did not produce much charcoal. Second, the charcoal record may have detected local fires that were not sampled by the dendrochronological data, simply because the coverage of tree-ring sites was limited. Third, particular fire and taphonomic conditions may have contributed to the lack of congruence between the two datasets in some instances (e.g., surface burns producing little charcoal or lags in the input of charcoal following fires). The correspondence between tree-ring and charcoal records was best at sites where the forest supported a relatively dense understory and more continuous vegetation, for example, at Bluff and Cedar lakes. The coincidence of charcoal peaks and fires in the late 19th century at Bluff Lake may reflect times of better understory development that helped promote slightly larger or more severe charcoal-producing events than average. Fourth, the discrepancy between fire years and charcoal peaks may reflect error in the lake-sediment chronology of the order of a few years or decades.

The decadal trends in the charcoal accumulation rates show temporal variations in fire regime over the last 300 years. One signal at all sites was the increase in charcoal levels in the late 19th and early 20th centuries. At Bluff, Mumbo, and Cedar lakes, high charcoal accumulation rates were found at 1870–1933, 1862–1936, and 1892–1956, respectively. At Crater Lake, charcoal levels were high at 1869–1936. The timing of increased charcoal levels at all lakes coincided with the arrival and early activities of Euro-American settlers (Jackson 1964; Hoopes 1971) and with shifts in climate at the end of the Little Ice Age (Jacoby and D'Arrigo 1989; Taylor 1995; Wiles et al. 1996). It is difficult to determine the relative importance of these two factors in general (e.g., Stephens et al. 2003), and little information is available for directly assessing human as opposed to climatic impacts on Klamath forests. In terms of human activity, Aboriginal people of the Klamath Mountains are credited with managing fire for many different purposes (Lewis 1993; Pullen 1995); however, the spatial extent of their burning activities is not known and was probably limited (see Vale 2002). In contrast, extensive fires in the late 19th and 20th centuries were evident in many parts of the northwestern United States in association with early road-building, mining, and land-clearance activities (Agee 1993; Hessburg and Agee 2003; Weisberg and Swanson 2003). The tree-ring records in this study do not suggest alteration of the fire regime in the montane forests at this time (see also Taylor and Skinner 1998, 2003), but the rise in charcoal abundance in the lakes points to increased burning in the region, including at the four study sites. All the lakes show a decline in charcoal levels after the 1950s, when fire suppression efforts intensified and regional fire activity declined (Skinner et al., in press), and this reduction is also evident in the tree-ring data. Thus, background charcoal trends seem to provide a good index of changes in general burning levels and fuel conditions at a regional level.

Climate changes may also explain the increase in charcoal in the late 19th and early 20th centuries, and concurrent shifts in fire regimes have been described elsewhere (e.g., Stephens et al. 2003). Climate has generally warmed since the mid-1800s, and precipitation, although variable, was relatively high in the late 1800s and early 1900s and declined when fire suppression policies were implemented (Graumlich 1987; Hughes and Brown 1992; Earle 1993). The longer fire season (caused by higher temperatures) and the accumulation of burnable fuel biomass (as a result of increased precipitation) (Chang 1999; Swetnam and Baisan 2003) may have contributed to large fires or at least to more charcoal production during individual fires in the late 1800s and early 1900s.

Conclusions

This study advances our understanding of the source area of charcoal and the ability of charcoal peaks to register fire events within xeric montane forests. Previous studies by Whitlock and Millspaugh (1996), Clark et al. (1998), and Gardner and Whitlock (2001) were located in relatively mesic forests characterized by large stand-replacement fires that generated and delivered a lot of charcoal to lakes. Unlike the Klamath lakes, the lakes in other studies had rapid sedimentation rates relative to the fire return interval, and charcoal registered local stand-replacing events with fair fidelity. In contrast, the Klamath forests in these basins are characterized by mostly small, mixed-severity fires, which individually do not produce much charcoal. In addition, the relatively slow sedimentation means that each charcoal sample spans several years to a few decades and integrates the charcoal input from multiple fires.

The Klamath results suggest that charcoal records provide different types of information about past fire conditions, depending on the nature of the fire regime. In stand-replacing systems when fire activity is relatively infrequent, charcoal peaks can be used to indicate past fire events. In low- or mixed-severity fire regimes, where tree mortality may be limited to a few trees or shrubs, the likelihood that individual charcoal peaks will match past fires is greatly reduced, because such fires produce little charcoal. In the latter case, the trends in charcoal offer an opportunity to study decadal-scale variations in fire activity at a broader spatial scale.

Other studies support this observation: Tinner et al. (1998), working in the Swiss Alps, noted that intervals of abundant charcoal particles of >75-μm diameter in pollen slides correlated well with the area burned on decadal time scales within 20–50 km of the site. Long et al. (1998) found that charcoal peaks detected decades of local slash burning but not the individual small fires in seasonally dry forests of the Oregon Coast Range. In a comparison of charcoal in small forest hollows with tree-ring records in northwestern Washington, Higuera et al. (2005) concluded that high-severity fires were faithfully registered in the charcoal records but that less severe events were often not detected. Mohr et al. (2000) correlated decades of high charcoal accumulation in the last 200 years in the Klamath Range with periods of high fire activity inferred from the dendrochronological record. The background trends in these systems do not disclose individual fires; rather they disclose variations in fire occurrence and biomass burned.

The Klamath study underscores the value of comparing tree-ring and charcoal data from the same location. The tree-ring record provides fire-history information on individual fires over the last 300 years, whereas the charcoal data disclose variations in fuel loading and general levels of burning. The influence of fire suppression seems to be evident in both datasets, but the charcoal time series is a more regional depiction of the effects of this management policy. Interpretations based on charcoal data clearly need to consider the background trends in charcoal as an important component of the reconstruction, and tree-ring and charcoal comparisons should be an essential step in all long-term fire-history studies. The trick for paleoecologists will be to disentangle these signals on long time scales when the vegetation and fire regimes were changing in response to large-scale climate variations.

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