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Fire–fuel–climate linkages in the northwestern USA during the Holocene

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Abstract: Variations in fire regimes can be inferred from changes in the abundance of sedimentary charcoal found in lake and bog sediments. When analysed with pollen data, inferences can be made about past vegetation dynamics and climate as well. The analysis of high-resolution charcoal records generally involves the decomposition of charcoal influx into (a) a slowly varying 'background' component that provides information about long-term changes in regional fire activity, biomass and/or depositional processes, and (b) a 'peaks' component that represents local fire events. In this study, 15 high-resolution charcoal records from the northwestern USA and associated pollen data were examined to describe the variations and controls of charcoal influx and background trends. Late-Holocene charcoal influx levels at each site were compared with late-Holocene sedimentation rates, vegetation and fire frequency, and with modern climate and physical site characteristics to better understand the spatial variability in charcoal abundance. Charcoal abundance was largely determined by physical site characteristics (eg, lake and watershed size) and the proportion of woody taxa. Background trends displayed regional similarities, and the subcontinental scale trend based on all records correlated closely with woody taxa proportions in the pollen spectra. Background charcoal and woody taxa proportions increased together from minima in the Late Glacial to maxima in the late Holocene. The strong similarity in these trends suggests that background charcoal influx is a function of fuel characteristics, which in turn are governed by climate and vegetation. Variations in sedimentation rate and fire frequency had little influence on background charcoal trends.

Key words: Fire history, fire frequency, fuel, climate, palaeofire, charcoal analysis, background charcoal, pollen, northwestern USA, Holocene.

Introduction

Holocene fire-history reconstructions based on charcoal in lake-sediment cores have been used to improve our understanding of past fire regimes in many forested regions (eg, Carcaillet and Richard, 2000; Huber and Markgraf, 2003; Lynch *et al.*, 2003). An analysis of closely sampled macroscopic charcoal particles (> 125 μm in diameter) provide high-resolution records of past fire activity that span several millennia. These data are usually presented as charcoal accumulation rates (CHAR = area or number of particles/cm^2 per yr) (Clark and Royall, 1995b; Whitlock and Bartlein, 2004; Whitlock *et al.*, 2003b). Local fire events or episodes (ie, more than one fire occurring during a brief time interval) are inferred from 'peaks' in CHAR. This interpretation or inference is based on assumptions that fire events produce a large number of charcoal particles, and larger (macroscopic) particles generally travel relatively short distances before deposition (Clark, 1988; Whitlock and Millspaugh, 1996; Ohlson and Tryterud, 2000). CHAR data also display slowly varying trends, referred to as 'background' charcoal (BCHAR). BCHAR trends have been ascribed to changes in regional fire incidence (Clark and Royall, 1995a) and biomass (Long *et al.*, 1998; Whitlock *et al.*, 2003a), as well as to non-fire-related processes, such as mass-wasting, redeposition (eg, from lake-level fluctuations; Lynch *et al.*, 2004), sedimentation rates and bioturbation (Millspaugh and Whitlock, 1995; Carcaillet *et al.*, 2002). Disentangling the multiple potential sources of BCHAR is necessary to improve our ability to reconstruct fire histories, because identification of charcoal peaks, and thus past fire-episode frequency, depends on how BCHAR is defined.

The objective of this study was to better understand the factors controlling spatial and temporal variability in charcoal abundances and to assess the potential of BCHAR as an independent source of fire-history information. We analysed 15 high-resolution charcoal records and associated pollen data from the northwestern USA (Figure 1) to assess the

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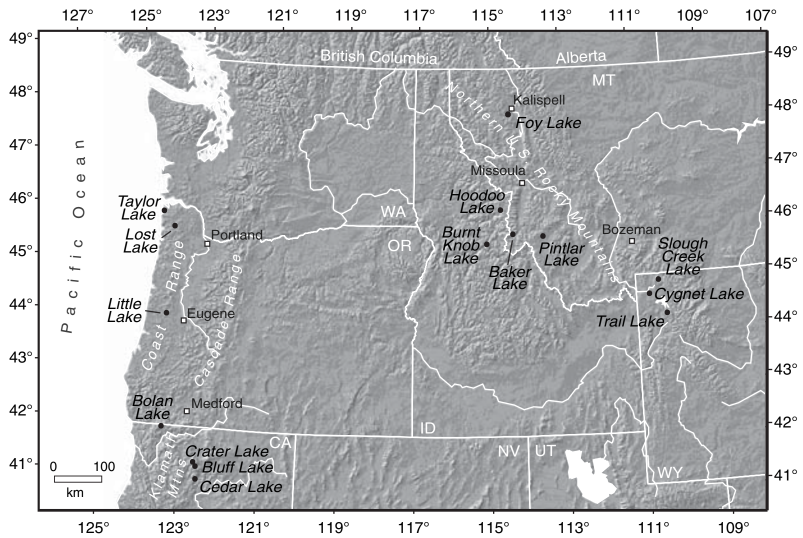

Figure 1 Map of the northwestern USA showing locations of fire history study sites

relationships between charcoal accumulation and sedimentation rates, fire-episode frequency and the abundance of woody vegetation. We compared late-Holocene (last 4000 years) BCHAR with present-day climate and site characteristics to better understand how physical site-specific variables influence mean charcoal accumulation. Holocene trends in the charcoal data were also examined in light of long-term changes in sedimentation rates, fire-episode frequency and woody fuel biomass. The results from this investigation help refine our interpretation of charcoal records and identify a long-term relationship between fire, fuels and climate in forests of the northwestern USA.

Study area and sites

The study area encompassed sites in the Oregon Coast Range (OCR), the Klamath-Siskiyou mountains (K-S) and the Northern Rocky Mountains (NRM) (Table 1), and covered over 500 000 km^2 of varied topography, climate and vegetation. Taylor, Lost and Little lakes in the OCR were lowest in elevation (6–449 m elevation) and received the highest annual precipitation. These sites are located in closed rainforest of *Tsuga heterophylla* (western hemlock), *Pseudotsuga menziesii* (Douglas-fir), *Picea sitchensis* (Sitka spruce) and *Alnus rubra* (red alder) (Long *et al*., 1998; Long and Whitlock, 2002; Long, 2003) and experience high-severity fires with frequencies that average two to seven fire episodes per 1000 years at present (Long, 2003).

Four sites (Bolan, Crater, Bluff and Cedar lakes) in the K-S are from intermediate elevations (1683–2288 m elevation) with high winter precipitation and diverse conifer forests of *Pinus monticola* (western white pine), *P. albicaulis* (whitebark pine), *P. contorta* (lodgepole pine), *P. Jefferyi* (Jeffery pine), *Pseudotsuga menziesii*, *Abies magnifica* (red fir), *Abies concolor* (white fir), *Calocedrus decurrens* (incense cedar) and many other conifers (Mohr *et al*., 2000; Briles *et al*., 2005). The K-S sites have a mixed-severity fire regime at present, with both surface and crown fires (Mohr *et al*., 2000; Whitlock *et al*., 2004).

In the NRM, Foy Lake is located at the lower forest-steppe margin (1006 m elevation) in the Flathead Valley of Montana. It is surrounded by steppe and forests of *Pseudotsuga menziesii*, *Pinus ponderosa* and *Larix occidentalis* that support frequent fires (40–70 episodes/1000 yr) and a mixed-severity fire regime (Power, *et al*., 2005). Four lakes in subalpine (Burnt Knob, Baker and Hoodoo lakes) and montane forest (Pintlar Lake) (1770–2250 m elevation) of northwestern Montana and northern Idaho support infrequent, stand-replacing fires (3–9 episodes/1000 yr). The montane forest around Pintlar Lake (1921 m elevation) is dominated by *P. contorta*. Hoodoo Lake (1764 m elevation) is surrounded primarily by *P. contorta* and *P. menziesii*. Baker Lake (2300 m elevation) lies in subalpine forest dominated by *P. albicaulis* and *Larix lyalli* (subalpine larch) on dry slopes, and *Abies bifolia* (subalpine fir) and *Picea englemannii* (Englemann spruce) on wetter slopes. *A. bifolia*, *P. albicaulis*, and *P. contorta* are the dominant species around Burnt Knob Lake (2250 m elevation). Slough Creek, Cygnet and Trail lakes lie in montane forest and at the lower forest-steppe margin (1884–2530 m) in Yellowstone National Park (YNP). Slough Creek Lake (1884 m elevation) is located within *Artemisia tridentata* (sagebrush) steppe and open forests of *Pseudotsuga menziesii*. The site experiences relatively frequent, low-severity fires (20–50 episodes/1000 yr) (Millspaugh, 1997). *P. contorta* forest surrounds Cygnet Lake (2530 m elevation) (Millspaugh *et al*., 2000) and *P. menziesii*, *P. contorta*, *Abies bifolia* and *P. engelmannii* are present at Trail Lake (2362 m elevation) (C. Whitlock and R. Sherriff, unpublished data, 1997). The latter two sites have infrequent stand-replacing fires at present (2–5 episodes/1000 yr).

The seasonality of precipitation is an important site characteristic related to long-term changes in fire activity and fire-episode frequency (Whitlock and Bartlein, 2004; Brunelle *et al*., 2005). The sites can be grouped into two categories according to the ratio of summer to annual precipitation (Whitlock and Bartlein, 1993). ‘Summer-dry’ sites lie in the region where summer precipitation is currently suppressed by the northeastern Pacific subtropical high-pressure system. This high-pressure system causes widespread subsidence over the northwestern USA, leading to especially dry summer conditions in the OCR, K-S and parts of the NRM. ‘Summer-wet’ sites exist where monsoonal circulation has a stronger influence–to the east of the Continental Divide. In such areas, moisture is drawn northward from the Gulf of Mexico and eastern subtropical North Pacific into the Southwest and farther north into the NRM during the summer. At present, most locations (11 out of the 15 sites) exhibit summer-dry patterns, whereas three are summer-wet (Baker, Pintlar and Slough Creek lakes) and one is transitional (Foy Lake).

Table 1 Physical and climatic site characteristics and reconstructed 4000-yr mean sedimentation rates, CHAR, fire frequency and arboreal pollen percentages

Site	Latitude, longitude	Elev. (m)	Lake area (ha)	Watershed area (ha)	Mean watershed slope (deg)	4 kyr mean sed. rate (cm/yr)	4 kyr mean fire freq. (events/1000 yr)	4 kyr mean AP (%)	4 kyr mean CHAR (p/cm^2 per yr)
Cedar L., CA[h]	41.21°N, 122.50°W	1740	2.6	116	17	0.028	6.658	0.901	0.36
Bluff L., CA[g]	41.35°N, 122.56°W	1921	1.2	12	24	0.023	4.858	0.909	0.69
Crater L., CA[g]	41.40°N, 122.58°W	2288	2.5	92	22	0.050	6.511	0.953	0.35
Bolan L., OR[a]	42.02°N, 123.46°W	1637	5.0	59	19	0.069	8.309	0.921	3.64
Little L., OR[d]	44.16°N, 123.58°W	212	3.3	597	23	0.201	5.911	0.943	21.82
Lost L., OR[c]	45.81°N, 123.57°W	449	5.7	33	14	0.069	5.984	0.948	3.06
Taylor L., OR[f]	46.08°N, 123.90°W	6	3.5	68	14	0.068	5.129	0.930	4.72
Burnt Knob L., ID[b]	45.70°N, 114.99°W	2250	1.1	11	15	0.028	4.632	0.943	0.11
Hoodoo L., ID[b]	46.32°N, 114.65°W	1770	2.5	57	18	0.053	5.221	0.905	0.68
Foy L., MT[h]	48.16°N, 114.36°W	1006	85.0	502	9	0.057	13.642	0.961	14.88
Cygnet L., WY[f]	44.66°N, 110.62°W	2530	5.3	744	4	0.027	5.881	0.790	0.73
Trail L., WY[i]	44.28°N, 110.17°W	2362	35.3	263	12	0.130	8.162	0.853	0.88
Baker L., MT[b]	45.89°N, 114.26°W	2300	2.2	47	20	0.032	3.384	0.915	0.30
Slough Cr. L., WY[j]	44.92°N, 110.35°W	1884	2.9	145	29	0.058	11.313	0.663	3.10
Pintlar L., MT[b]	45.84°N, 113.44°W	1921	4.3	428	9	0.166	9.448	0.877	3.05

[a]Briles *et al.*, 2005; [b]Brunelle-Daines, 2002; [c]Long, 2003; [d]Long and Whitlock, 2002; [e]Long *et al.*, 1998; [f]Millspaugh, 1997; [g]Mohr *et al.*, 2000; [h]Power *et al.*, 2006; [i]C. Whitlock, unpublished data, 1997; [j]C. Whitlock and R. Sheriff, unpublished data, 2000.

Site	Jan. temp. (°C)[k]	July temp. (°C)[k]	MTCO (°C)[k]	MTWA (°C)[k]	Mean ann. precip. (cm)[k]	Jan./July precip. ratio[k]	AE/PE[k]
Cedar L., CA	– 2.5	15.4	– 2.5	15.4	91	17.36	0.632
Bluff L., CA	– 1.6	15.6	– 1.6	15.6	90	16.82	0.583
Crater L., CA	– 3	14.9	– 3	14.9	90	14.83	0.617
Bolan L., OR	0.3	15.4	0.3	15.4	94	19.90	0.468
Little L., OR	5.1	16.6	5.1	16.9	119	15.53	0.660
Lost L., OR	3.7	14.4	3.7	14.9	160	9.41	0.788
Taylor L., OR	5.4	15	5.4	15.4	153	8.97	0.707
Burnt Knob L., ID	– 7.1	16.4	– 7.1	16.4	46	2.52	0.436
Hoodoo L., ID	– 5.7	17.3	– 5.7	17.3	41	2.43	0.476
Foy L., MT	– 6.3	17.3	– 6.3	17.3	40	1.48	0.533
Cygnet L., WY	– 11.7	13.4	– 11.7	13.4	46	1.36	0.615
Trail L., WY	– 10.5	14.5	– 10.5	14.5	39	1.36	0.513
Baker L., ID	– 7.7	16.2	– 7.7	16.2	34	1.06	0.437
Slough Cr. L., WY	– 9.1	15.9	– 9.1	15.9	37	0.97	0.474
Pintlar L., MT	– 6	17.4	– 6	17.4	31	0.97	0.494

[k]P.J. Bartlein and S.L. Shafer, unpublished data, 2000.

Data and methods

Physical site characteristics

Lake and watershed characteristics were examined to assess their influence on recent BCHAR levels (Table 1). Digital elevation models (DEMs) and georeferenced topographic quadrangle images (DRGs) from the US Geological Survey (USGS) (http://data.geocomm.com, last accessed September 2006) and Digital Orthophoto Quadrangles (DOQs) from the Oregon Geospatial Data Clearinghouse (OGDC) provided a basis for determining lake elevation, watershed area and mean watershed slope, and for digitizing lake shorelines and calculating lake-surface areas.

Charcoal data

The original published fire-history studies employed similar data collection and analysis methods. Sediment cores were sampled at contiguous 1-cm intervals in all cases except Foy Lake, which was laminated and thus sampled at 3 to 5 mm intervals (Power *et al.*, 2006). Sediment was gently washed through a 125 μm mesh sieve, and the remaining charcoal particles were counted under a dissecting microscope at 20–32× magnification. Charcoal abundances were tallied from each sample and converted into concentration data (particles/cm^3). An age versus depth curve (age model) was created for each record with ^{14}C and ^{210}Pb dates, dendrochronological evidence of known fires and stratigraphic markers of known ages (see original publications for details). Radiocarbon dates were calibrated to years before present (cal. yr BP) using CALIB 4.1 (Stuiver *et al.*, 1998) and all subsequent ages discussed in the text are based on calibrated dates.

The original records were analysed using the decomposition technique of Long *et al.* (1998), which is described again here. Concentration values (particles/cm^3) and deposition times (yr/cm) were interpolated into annual values. Annual values were averaged over intervals that ranged from 8 to 30 years (bins). Binned concentration values were then divided by average deposition times of the binned interval to obtain time series of charcoal accumulation rates (CHAR) (particles/cm^2 per yr). CHAR time series were logarithmically transformed for variance stabilization (Log(CHAR + 1)) before being decomposed into background and peaks components (CHAPS software, P. Bartlein, unpublished data, 2003). A locally weighted mean was used to estimate the background component of the CHAR data. The peaks component (or fire-episode series) was derived as the positive deviations from a local mean that exceeded a certain threshold value. The peaks data were smoothed to produce a summary of fire-episodes through time (expressed as number of events/1000 years). Independent evidence of known fires in the watershed or the present-day mean fire-return intervals (Agee, 1993) was used to help decide (a) the width of the temporal window used to calculate the locally weighted mean (and hence the smoothness of the background component), and (b) the threshold used to identify peaks in the CHAR. The CHAR data were partially standardized for this study, which is described in the analysis.

Pollen data

Fossil-pollen data are available from Crater and Bluff lakes (Mohr *et al.*, 2000), Cedar Lake (C. Whitlock, unpublished data, 2004), Bolan Lake (Briles *et al.*, 2005), Little Lake (Worona and Whitlock, 1995), Lost Lake (Long, 2003), Taylor Lake (Long and Whitlock, 2002), Burnt Knob Lake (Brunelle and Whitlock, 2003), Hoodoo, Pintlar and Baker lakes (Brunelle *et al.*, 2005), Cygnet Lake (Millspaugh *et al.*, 2000), Trail Lake (C. Whitlock, unpublished data, 1997), Foy Lake (Power *et al.*, 2006) and Slough Creek Lake (Millspaugh *et al.*, 2004). Descriptions of vegetation history and methods are available in the original publications. Pollen percentages of trees and shrub taxa were summed and interpolated to 10-yr intervals for each pollen profile to estimate changes in woody or arboreal (AP) taxa. This proxy was considered a measure of woody fuel levels.

Climate data

Modern climate data provided a means of characterizing the different sites at present (Table 2), and for extrapolating climatic differences among sites during the last 4000 years. Although climate has not been static during this period, relative climatic differences between sites have probably been maintained. Mean monthly temperature and mean monthly precipitation were interpolated from a gridded (10-min) data set from the Climate Research Unit (CRU) (New *et al.*, 2002; http://www.cru.uea.ac.uk/cru/data/tmc.htm, last accessed September 2006) using the following methods. Long-term monthly means (1961–1990) for temperature, precipitation and percent possible sunshine were used to calculate local lapse rates for these variables by fitting a locally weighted trend-surface regression model to the data within the neighbourhood of each grid point. The regression model was a third-order polynomial based on latitude and longitude, with elevation as a covariate. Inverse-distance squared weighting was used within a search radius of 500 km. The lapse rates at each 10-min grid point were used to adjust the CRU values to the elevation of study sites, and then the adjusted values were interpolated to the sites using geographically weighted bilinear interpolation. Bioclimatic variables for each site, including growing-degree days (GDD) using a 5°C base, the Priestly-Taylor moisture index (the ratio of actual to potential evapotranspiration (AE/PE)), and mean temperature of the coldest and warmest month of the year (MTCO and MTWA), were calculated from the basic climate variables using a program (bioclim.for) originally from Prentice *et al.* (1992).

Analysis

The possibility always exists that changes in sedimentation rate alone, and not charcoal production and deposition, could generate patterns of variation in CHAR time series (Clark *et al.*, 1996b). To test for this possibility, we examined the age versus depth curves (age model), sedimentation rates, charcoal concentration and influx data for each site, as well as CHAR, BCHAR, peaks and fire-episode frequency data. In order to facilitate comparisons, two components of the decomposition analysis were standardized. The bin-width used to interpolate concentration values into equally spaced time intervals was standardized to 10 years. Similarly, the background-smoothing window-width used to identify long-term trends in the interpolated CHAR data was standardized to 500 years. The threshold value used to identify peaks and infer fire-episode

Table 2 Results from multiple linear regression

Variable	Coefficient	*p*-value
Intercept	−23.26	0.01
Elevation	−0.01	0.00
Lake area	0.08	0.01
Watershed area	0.02	0.00
Watershed slope	0.54	0.00
Arboreal pollen%	21.04	0.02
Adjusted R-squared: 0.92		
F-statistic: 35.05 on 5 and 9 df		
p-value: 0.00		

frequency variations was not standardized, because it was based on local calibration data at each study site.

In order to identify factors that influence the charcoal accumulation rates in a lake, we calculated the mean CHAR value for each record over the last 4000 years (Table 1) and performed a multiple linear regression with a variety of potential predictor variables. Although an average based on 4000 years is a coarse summarization of the varying BCHAR time series, it seemed appropriate for comparing against site differences that probably did not change substantially during the late Holocene (Clark *et al.*, 1996a). The variables analysed in the regressions included modern lake and watershed size, mean watershed slope, watershed-to-lake area ratio, elevation, GDD, AE/PE, mean annual precipitation, MTCO, MTWA and the ratio of winter to summer precipitation (Table 2). 4000-yr averages for sedimentation rate, fire-episode frequency and arboreal pollen percentages were also included as potential predictors of BCHAR. While these variables have changed over the late Holocene, the differences within a record during the last 4000 years are generally less than differences between records. The regression model used was chosen by examining the R^2_{adj} and Mallow's C_p statistics for all possible combinations of variable subsets (Weisberg, 1985). Two models had $R^2_{adj} > 0.90$ and C_p values $\approx p$. One included AE/PE and the other did not. We chose the model without AE/PE for simplicity but recognize that AE/PE may be an important factor in determining average CHAR nonetheless. For the remaining analyses the data were normalized by log-transforming the values (Log(CHAR + 1)). To facilitate comparisons across sites, the data were also standardized (Carcaillet and Richard, 2000; Haberle and Ledru, 2001).

In order to explore regional patterns in the BCHAR trends, records that had similar climates were grouped together. Modern climate variables, such as mean annual temperature and precipitation, MTCO, MTWA, GDD and whether a site was summer-wet or summer-dry were used to create groups (Table 2). In the westernmost region, the greatest differences among the sites were found in the seasonal precipitation ratios. Cedar, Bluff, Crater, Bolan and Little lakes shared high January/July precipitation ratios, whereas Lost and Taylor lakes had lower ratios and were clearly the wettest in terms of mean annual precipitation. In the NRM, Burnt Knob, Hoodoo and Foy lakes had the highest January/July precipitation ratios and were substantially warmer than the other NRM sites in terms of GDD, MTCO and MTWA. Pintlar Lake was the driest site and had a low January/July precipitation ratio, but it was more similar to Burnt Knob, Hoodoo and Foy in terms of GDD, MTCO and MTWA, as well as geographically. As a result, we chose to group Pintlar Lake with Burnt Knob, Hoodoo and Foy lakes. Cygnet, Trail and Slough Creek lakes were similar in terms of both seasonal precipitation and warmth, although Slough Creek received slightly more precipitation than Cygnet and Trail lakes in the summer months. Baker Lake was placed in the YNP/high-elevation climate group (despite being closer to the northern NRM sites) because it was more similar to the YNP sites in terms of both precipitation and temperature.

A subcontinental scale analysis was performed on the charcoal records in order to examine potential controls on long-term trends in background charcoal. We grouped all 15 of the charcoal and pollen records together to determine whether any similarities were apparent between background charcoal, fire-episode frequency, AP percentages and sedimentation rates. For each summary curve (ie, sedimentation rate, BCHAR, fire-episode frequency and AP), a simple mean was calculated at 10-yr intervals based on all 15 BCHAR records, using a 4000-yr base. The fire-episode frequency and sedimentation rate curves were smoothed with a 200-yr window. For the purposes of discussion, time periods are defined as follows: Late Glacial period (14 000–11 000 cal. yr BP); early Holocene (11 000–7000 cal. yr BP), middle Holocene (7000–4000 cal. yr BP) and late Holocene (4000 cal. yr BP to present).

Results

Sedimentation rates

A visual comparison was made between sedimentation rates, concentration and CHAR for each record (Figure 2). The records are organized first by region (K-S and OCR records in the left column and NRM records in the right-hand column) and then by January/July precipitation. Comparisons revealed no consistent temporal relationships between sedimentation rates and charcoal data. For example, sedimentation rates, concentration and CHAR increased together at Cedar Lake from *c.* 11 500 to 8000 cal. yr BP, but changed in opposite directions after 8000 to 7000 cal. yr BP. Lost Lake sedimentation rates trended upwards from 8000 to 4000 cal. yr BP, while charcoal concentration and CHAR trended downwards. The opposite was true at Little Lake, where sedimentation rates, charcoal concentration and CHAR all increased together from ~5000 to 2000 cal. yr BP. At Hoodoo Lake, a relationship between sedimentation rates, charcoal concentration and CHAR was clear at *c.* 1500 cal. yr BP, but this is due to a sharp change in age–depth relations that affected the age model, sedimentation rates and CHAR data, and represents a unique case (A. Brunelle, personal communication, 2006). Overall, the standardized trends in CHAR and BCHAR do not appear to be artefacts of the lake system or data analysis methods.

A relationship exists, however, between spatial variations in average sedimentation rate and fire-episode frequency. For example, sedimentation rates were low at Burnt Knob and Baker lakes (0.03 cm/yr over the last 4000 years; Table 1) and so were inferred fire-episode frequencies (4.6 and 3.4 episodes/1000 yr during the last 4000 years, respectively; Table 1), whereas Pintlar and Trail lakes had relatively high sedimentation rates (0.17 cm and 0.13 cm, respectively) and relatively high fire-episode frequencies (9.4 episodes/1000 yr for Pintlar, and 8.2 episodes/1000 yr for Trail during the last 4000 years; Table 1). High sampling resolution (eg, Foy Lake) and small background smoothing window width (eg, Bluff, Crater and Cedar lakes, discussed below) also caused fire-episode frequencies to appear higher than they would otherwise. However, within individual records there is no relationship between the variation in sedimentation rate and fire-episode frequency over time (Figures 2 and 3).

Standardization

The standardized charcoal data, including CHAR, BCHAR, peaks and fire-episode frequency, are shown for all 15 sites in Figure 3. Background data were smoothed using a 500-yr window width, and fire-episode frequency was smoothed with a 2000-yr window. The original values of the threshold ratio, which determines how much charcoal above background is required for a peak, were retained. The original (non-standardized) fire-episode frequency curves (but not peaks or background) are also shown for comparison. CHAR and BCHAR were plotted on logarithmic scales, whereas fire-episode frequency was plotted on linear scales. For most records, standardization did not significantly alter the charcoal data; however, records from Cedar, Bluff and Crater lakes were an

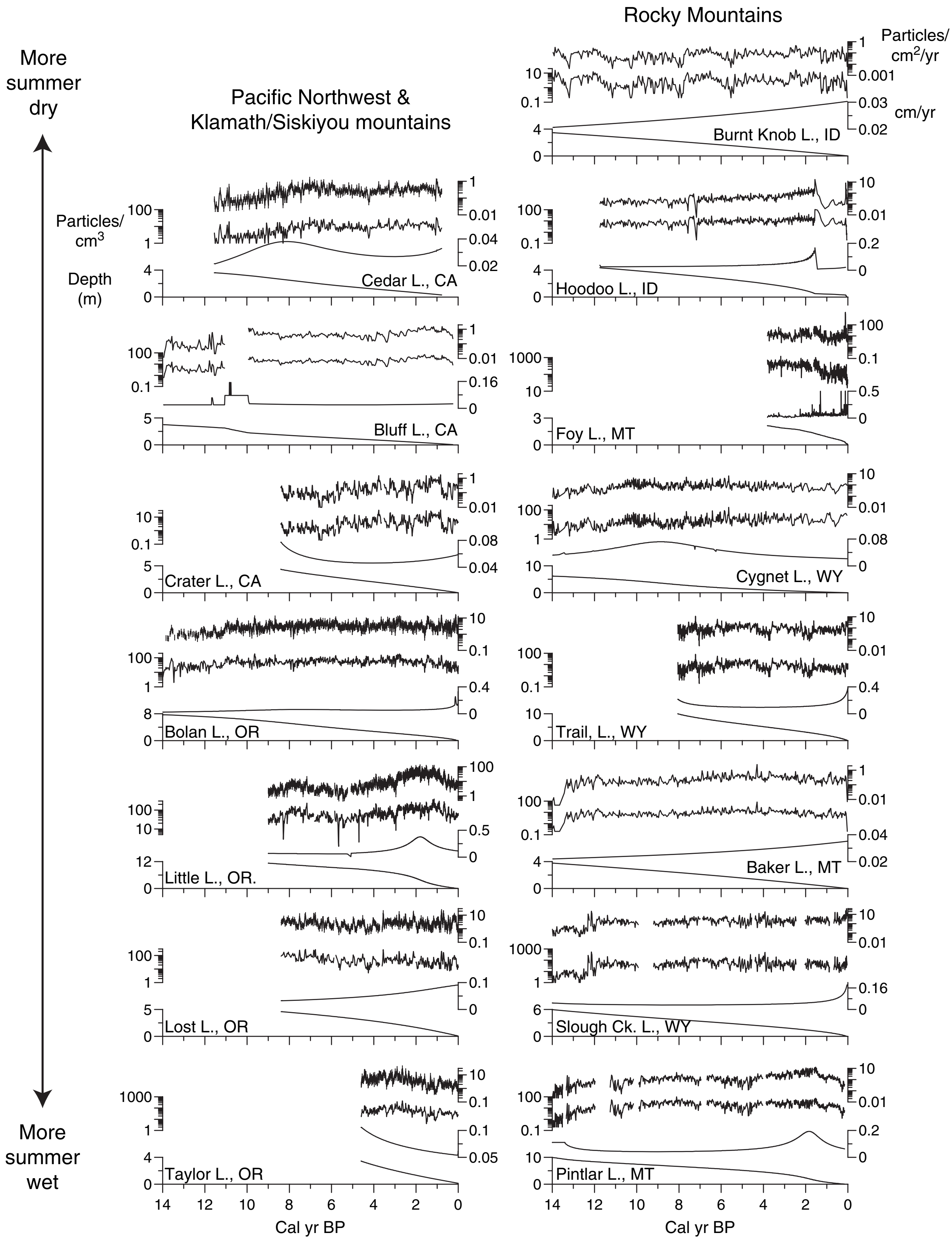

Figure 2 For each site, from bottom to top, the data are: sediment core depth (m), sedimentation rate (cm/yr), concentration (particles/cm^3), and influx (particles/cm^2 per yr). Records were organized by region (Klamath-Siskiyou and Oregon Coast Range records in the left column and Northern Rocky Mountain records in the right-hand column), and by Jan/July precipitation ratios within regions. Data sources: Cedar Lake, CA (C. Whitlock, unpublished data, 2004); Bluff and Crater lakes, CA (Mohr *et al*., 2000); Bolan Lake, OR (Briles *et al*., 2005); Taylor Lake, OR (Long and Whitlock, 2002); Lost Lake, OR (Long, 2003); Little Lake, OR (Long *et al*., 1998); Foy Lake, MT (Power *et al*., 2006); Cygnet Lake, WY (Millspaugh *et al*., 2000); Trail Lake, WY (C. Whitlock, and R. Sherriff, unpublished data, 1997); Slough Creek Lake, WY (Millspaugh *et al*., 2004); Burnt Knob (ID) (Brunelle and Whitlock, 2003); Baker (MT), Hoodoo (ID) and Pintlar (MT) lakes (Brunelle *et al*., 2005)

exception. Standardized BCHAR became less variable at Cedar, Bluff and Crater lakes (not shown) because the original data were smoothed using a very small window-width (120 yr). The attendant fire-episode frequency, which was calculated from the peaks in CHAR, also became less variable than in the original study. Peak frequency was generally lowered by

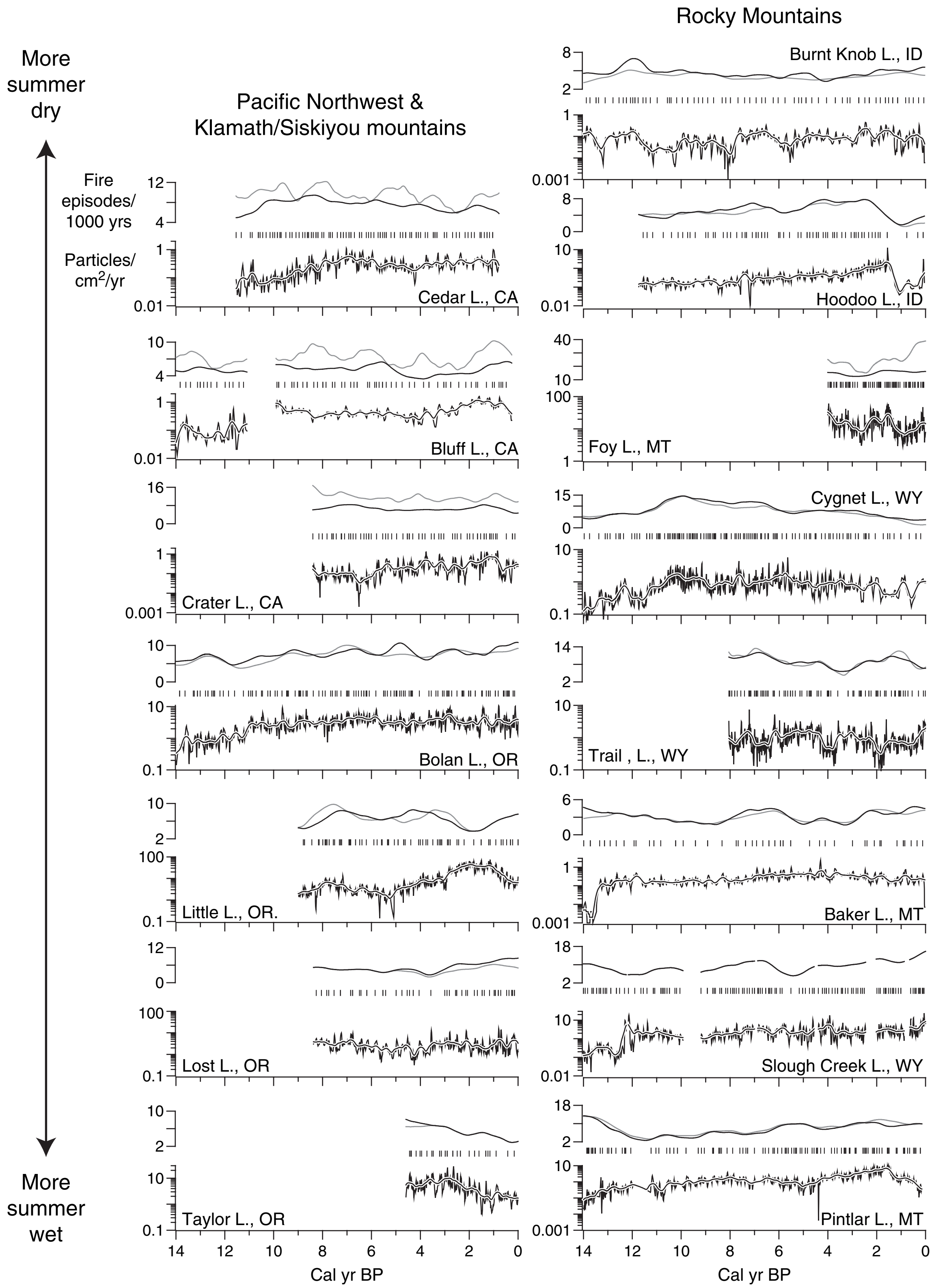

Figure 3 For each site, from bottom to top, the data are: standardized CHAR overlaid with BCHAR (particles/cm^2 per yr), peaks (tic marks) and fire-episode frequency (episodes/1000 yr). Non-standardized (original) fire-episode frequency (grey line) is overlaid on the standardized fire-episode frequency. Data sources: Cedar Lake, CA (C. Whitlock, unpublished data, 2004); Bluff and Crater lakes, CA (Mohr *et al.*, 2000); Bolan Lake, OR (Briles *et al.*, 2005); Taylor Lake, OR (Long and Whitlock, 2002); Lost Lake, OR (Long, 2003); Little Lake, OR (Long *et al.*, 1998); Foy Lake, MT (Power *et al.*, 2006); Cygnet Lake, WY (Millspaugh *et al.*, 2000); Trail Lake, WY (C. Whitlock, and R. Sherriff, unpublished data); Slough Creek Lake, WY (Millspaugh *et al.*, 2004); Baker (MT), Burnt Knob (ID) (Brunelle and Whitlock, 2003); Baker (MT), Hoodoo (ID) and Pintlar (MT) lakes (Brunelle *et al.*, 2005)

standardization of these K-S sites, because the smoother background component caused multiple small peaks to be counted as single larger peaks. The new parameters seem appropriate because the deposition time in these sediment cores was relatively slow (averaging 30 yr/cm), and recent charcoal peaks in the K-S records incorporate charcoal input from multiple fires (Whitlock *et al.*, 2004). The standardized Foy Lake record also differed substantially from the original results (Power *et al*., 2006), which were done at high resolution and using a small interpolation bin.

Controls on average charcoal accumulation

Mean CHAR values (during the last 4000 years) at each lake differed by several orders of magnitude (Table 1). Foy and Little lakes had the most charcoal on average, whereas Crater, Bluff and Cedar lakes had the least. Results from multiple regression analysis revealed that lake area, mean watershed slope, watershed area, elevation and AP percentages explained much of the difference in average BCHAR among sites ($R^2_{adj} = 0.92, p < 0.001$) (Table 2). A statistically significant relationship ($p < 0.001$) was found between average BCHAR and each of the five variables, meaning that lakes at low elevations, with high AP percentages, large lake-surface or watershed area and/or steep watershed slopes had greater charcoal abundance than those at lower elevations, with lower AP percentages, smaller lake or watershed areas and/or with lower-gradient watersheds. The regressions also indicated that fire frequency and sedimentation rates were not related to mean charcoal abundance.

Regional background charcoal trends

Distinct patterns in the standardized BCHAR and AP data were apparent within each regional climate group (Figure 4).

OCR and K-S climate group

Standardized BCHAR from Little, Bolan, Crater, Bluff and Cedar lakes generally showed low levels of charcoal accumulation in the Late Glacial period and early Holocene, intermediate levels in the middle Holocene and higher charcoal accumulation during the late Holocene (Figure 4A). Variability in BCHAR was higher in the early and middle Holocene than in the late Holocene. Maximum BCHAR levels generally occurred between *c*. 2000 and 1000 cal. yr BP, and values declined to present after 1000 cal. yr BP. Averaged AP percentages for these five records increased during the Late Glacial period and then remained relatively constant until ~2500 cal. yr BP. AP percentages generally declined from ~2500 to 250 cal. yr BP, when they decreased sharply and then increased to present.

Records from Lost and Taylor lakes (less than 40 km apart) showed some synchronous BCHAR variations during the last

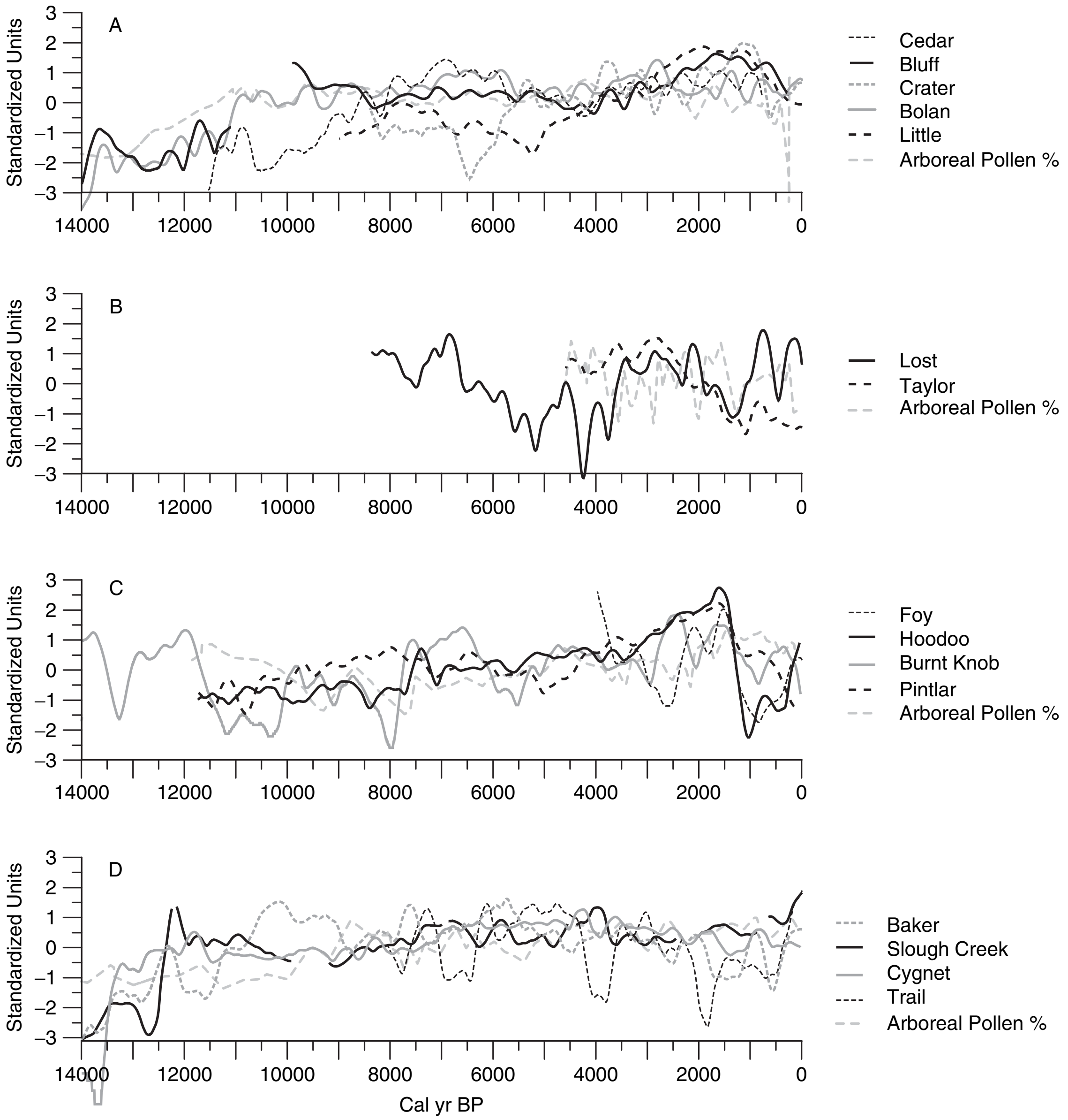

Figure 4 Regional trends in background charcoal data and arboreal pollen percentages. Records were grouped based on their geographic proximity and climatic similarity

~4000 years (Figure 4B). For example, standardized BCHAR were relatively high at *c*. 3000 cal. yr BP and relatively low at *c*. 1500 cal. yr BP. The record from Lost Lake showed fluctuations during the last ~8000 cal. yr, and BCHAR at Taylor Lake declined from ~4000 cal. yr BP to present (Long, 2003). Average AP percentages showed no clear trend.

NRM climate group

Standardized BCHAR data from Foy, Hoodoo, Pintlar and Burnt Knob lakes showed similar patterns (Figure 4C). Trends and variability in the Hoodoo and Pintlar lake records in particular were similar through the Holocene, and BCHAR from Foy Lake followed the same general pattern during the past ~ 2500 years. BCHAR from Burnt Knob Lake showed a more irregular pattern than at Hoodoo or Pintlar lakes, but BCHAR levels in general increased from *c*. 11 000 to 1600 cal. yr BP. BCHAR at Foy, Hoodoo, Pintlar and Burnt Knob lakes reached their Holocene maxima at *c*. 1600 cal. yr BP, followed by a substantial decline until *c*. 1000 cal. yr BP. BCHAR was variable at all four lakes during the last 1000 years but was generally lower than previously. Mean AP percentages for these four sites were relatively high in the Late Glacial and late-Holocene periods. Mean AP and BCHAR both displayed gradual increases from the beginning of the middle Holocene to the middle of the late Holocene.

YNP/high-elevation climate group

Baker, Slough Creek, Cygnet and Trail lakes are located in different environmental settings; however, they tended to show increasing BCHAR during the Late Glacial period and high BCHAR in the middle Holocene. BCHAR at Baker and Trail lakes decreased in the late Holocene, whereas that at Cygnet and Slough Creek lakes remained high. During the last few centuries, Baker, Slough Creek and Trail lakes showed sharply increasing BCHAR. Average AP percentages increased with BCHAR in this region from the Late Glacial period to the middle Holocene, but AP remained high during the late Holocene while BCHAR at Baker and Trail lakes declined.

Broad-scale trends in background charcoal

Despite large differences in modern climate, vegetation, fire regimes and topography, the smoothed 15-record BCHAR mean displayed a long-term trend (Figure 5A). Mean BCHAR anomalies increased rapidly from 14 000 to *c*. 10 000 cal. yr BP, and recorded a distinct period of high BCHAR from *c*. to 11 600 cal. yr BP, which was coincident with the Younger Dryas (YD) interval (12 900 to 11 600 cal. yr BP; Alley *et al*., 1993). BCHAR gradually increased from *c*. 10 000 to 1600 cal. yr BP, with the exception of the interval from *c*. 8200 to 6800 cal. yr BP, when BCHAR increased sharply again. BCHAR fluctuated for the remainder of the Holocene, declining from *c*. 1600 to 1200 cal. yr BP, increasing from *c*. 1200 to 900 cal. yr BP, declining from *c*. 900 to 500 cal. yr BP and then increasing sharply in the last ~ 500 years. The addition of new records to the mean did not account for the overall increase in BCHAR towards present (see Figure 5A), inasmuch as notable increases from the early Holocene to the late Holocene were apparent in individual long records (ie, at Bluff, Crater, Little, Burnt Knob, Hoodoo, Foy, Baker, Slough Creek and Pintlar lakes; Figure 3). The increase in BCHAR towards present also did not match synchronous changes evident in multiple BCHAR records, such as the decline in charcoal abundance after *c*. 1600 cal. yr BP at Foy, Hoodoo, Burnt Knob and Pintlar lakes.

Smoothed means for AP percentages (Figure 5A), sedimentation rates (Figure 5B), and peak frequency (Figure 5B) were calculated to explore these factors as potential controls on BCHAR. Millennial-scale trends in AP percentages paralleled those of BCHAR, generally increasing at a rate similar to BCHAR from the Late Glacial period to the late Holocene. Centennial-scale variations between BCHAR and AP, however, were dissimilar. Likewise, trends in peak frequency and

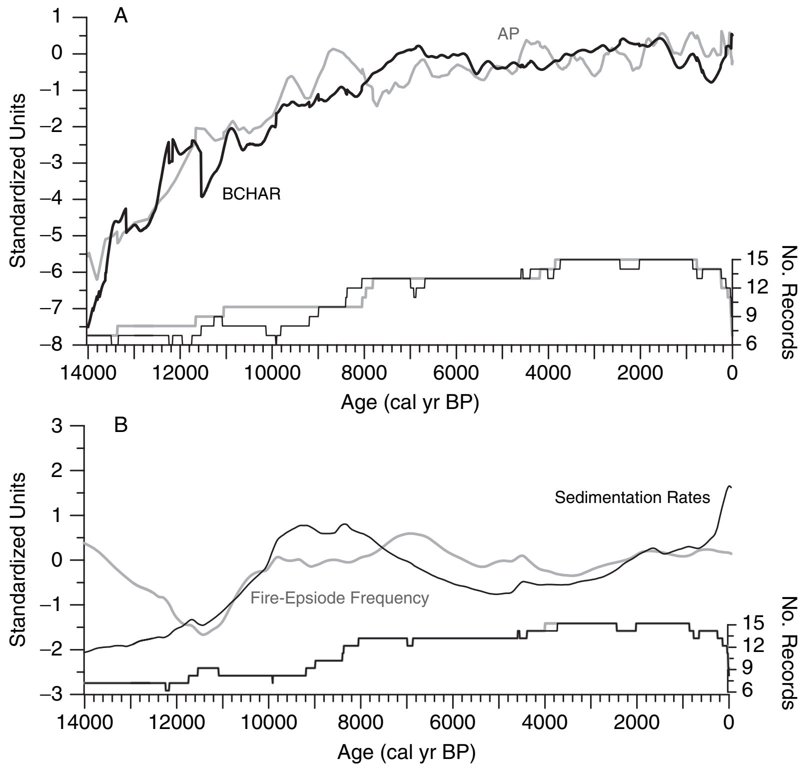

Figure 5 Holocene trends in (A) the smoothed mean of 15 standardized background charcoal records (thick black line) and arboreal pollen percentages (grey line) and (B) the smoothed sedimentation rate mean (black line) and fire-episode frequency mean (grey line) for 15 records. The numbers of records that make up the means at any given time are plotted below the trends in colours that correspond to the trend lines

sedimentation rate were not consistent with those of BCHAR, although some features of the trends matched mean BCHAR variations during particular time intervals. For example, both peak frequency and BCHAR were relatively high from *c*. 8000 to 6000 cal. yr BP. Visual comparisons between individual BCHAR and fire-episode frequency records (Figure 2) also revealed that these two components co-varied in some records for particular periods. For example, BCHAR and fire-episode frequency trends were similar at Cygnet and Taylor lakes throughout their records, and some sites (eg, Pintlar, Hoodoo and Baker lakes) showed relatively high fire-episode frequency at $\sim$2000 cal. yr BP, when BCHAR was highest.

Discussion

Controls on average charcoal abundance

Various potential controls on average charcoal have been recognized in previous fire-history studies. For example, climate and/or vegetation differences explained variations in macroscopic charcoal abundance in the northeastern USA (Clark and Royall, 1994, 1995b), and many studies have suggested that physical site characteristics are important as well (eg, Swain, 1973, 1978; Cwynar, 1987; Patterson *et al*., 1987; Whitlock *et al*., 1997; Carcaillet *et al*., 2002). However, few have analysed the relationships between physical site characteristics and mean charcoal abundance quantitatively (but see Whitlock and Millspaugh, 1996 and Gardner and Whitlock, 2001).

Understanding the controls on CHAR in a record helps determine the importance of charcoal production, transport and deposition. This, in turn, can provide insights as to which ecological processes contribute to variations in background charcoal levels, peak size and peak frequency. For example, if charcoal is entering a lake solely by aerial fallout, we might expect lake size to be an important factor in determining average charcoal abundance. A large lake, for example, would provide a large target area for charcoal transported by wind, and would be expected to have relatively high amounts of charcoal (Sugita *et al*., 1997). It is also possible, however, that a large lake will dilute the charcoal signal (eg, in Yellowstone Lake; Theriot *et al*., 2006), in which case we would expect lake size and mean CHAR to vary inversely. Alternatively, if charcoal were entering sediments via post-fire erosion and surface flows, watershed size and slope may be expected to be important.

Our regression analysis suggests that aerial and surficial transport processes were important controls on mean CHAR. That is, lake and watershed size as well as watershed slope were all positively correlated with average charcoal abundance. In addition, differences in elevation and woody taxa abundance were also important in accounting for the differences in mean charcoal abundance observed across sites. Elevation varied negatively with mean CHAR, and woody taxa abundance varied positively with charcoal abundance. Elevation may be important for a variety of reasons, because many aspects of climate and vegetation change vary with elevation. A plausible explanation for our study region is that the lowest elevation sites were located in coastal rainforest with the highest levels of fuel biomass of our study region. As a result, the negative relationship between elevation and charcoal abundance probably reflects the higher levels of fuels and thus charcoal production at low elevation sites in the study region.

Synchroneity of background charcoal trends

Much of the discussion about background charcoal in the fire-history literature has focused on determining its source area (Clark, 1988; Ohlson and Tryterud, 2000; Lynch *et al*., 2004). Theoretical and empirical studies suggest that macroscopic charcoal is primarily deposited from local fires because large particles settle rapidly. This observation suggests that variations in BCHAR should be local in origin. In other studies, however, background charcoal trends have been interpreted as a record of regional fire activity, even for macroscopic charcoal data (Clark and Royall, 1995b; Clark and Patterson, 1997; Whitlock *et al*., 2004), implying an extralocal or regional source for macroscopic charcoal (see also Tinner *et al*., 2006).

In this study, similar patterns of variation were noted in BCHAR records from the same geographic region, and also from sites that were fairly distant but had similar climates (eg, Baker and Cygnet lakes). For example, a gradual increase in charcoal levels occurred at all sites but one (Taylor Lake) in the OCR and the K-S mountains from the Late Glacial period to the late Holocene. Late-Holocene background charcoal levels were also higher than previously in the NRM climate group, whereas the YNP/high-elevation climate group had highest background charcoal levels during the middle Holocene. Trends in AP percentages within the regional/climate groups did not always parallel the BCHAR variations. The similarity in BCHAR trends among nearby sites may indicate a large source area for BCHAR; however this seems unlikely given the relatively large distances between sites recording similar patterns. It seems more plausible that coherent BCHAR trends are reflecting shared fire regimes at related sites, implying that fire characteristics such as size (area burned), type (eg, crown fires) and severity (biomass consumed) exhibited some consistency across regions. In contrast, fire-episode frequency data are more site-specific (Whitlock *et al*., 2003b; Whitlock and Bartlein, 2004) and suggest that fire-episode frequency reconstructions, derived from macroscopic charcoal records, are more representative of local conditions or have more intrinsic error because of the high variability of fire patterns across small areas that results in a less reproducible signal (Gavin *et al*., 2006).

At the broadest spatial (subcontinental) and temporal scales, common trends in AP and BCHAR (Figure 5A) indicate that the abundance of woody taxa was increasing along with CHAR during the Holocene. Neither fire frequency nor sedimentation rate changes followed similar trajectories (Figure 5B). It is likely that increasing forest cover during the Holocene offered more woody fuels that produced more charcoal when burned. In addition, increased forest fires (as opposed to grass fires) might have led to incomplete combustion and more convectional uplift that carried charcoal particles aloft and increased their deposition into lakes (Clark, 1988; Whitlock and Larsen, 2001). However, it is also possible that a third factor, such as climate, was driving changes in both BCHAR and AP independently. This seems likely for certain time periods in particular. For example, during the late Holocene, discrepancies between BCHAR and AP trends within the OCR, K-S and NRM climate groups (Figure 4) suggest that fire regimes were responding to some broad-scale control besides changes in vegetation, such as changes in climate or human activity.

Broad-scale fire–fuel–climate linkages during the Holocene

At the subcontinental scale, the similar trajectories of BCHAR and AP can be explained in large part by postglacial changes in climate and vegetation, and their attendant influence on woody fuel development. The rapid increases in BCHAR and AP during the Late Glacial/early Holocene transition are consistent with warming conditions and forest development that would have increased woody fuels at that time (Barnosky *et al.*, 1987; Sea and Whitlock, 1995; Whitlock and Bartlein, 1997; Brunelle-Daines, 2002). High BCHAR during the YD interval may have been caused by a shift to drier conditions and larger or more severe fires during that time (Mathewes, 1993). The intermediate levels of BCHAR and AP during the middle Holocene may have been related to the generally cooler, wetter conditions, more fuels and greater charcoal production than in the early Holocene (Barnosky *et al.*, 1987; Thompson *et al.*, 1993: Bartlein *et al.*, 1998). A gradual shift to even cooler, moister climate conditions in the late Holocene (Mathewes, 1985; Mehringer, 1985; Hebda and Whitlock, 1997) led to further forest closure and fuel build-up. More severe large fires as a result of closed forests are consistent with the continuing increases in charcoal after 4000 cal. yr BP.

The fluctuations in BCHAR during the last ~2000 years were relatively large and rapid as compared with earlier Holocene changes. AP fluctuated but was generally higher than previously. Changes in vegetation composition inferred from pollen records show little variation during the last ~3000 years in the NRM (eg, Millspaugh *et al.*, 2000; Brunelle *et al.*, 2005), but OCR and K-S pollen records indicate a general expansion of closed forests in the Pacific Northwest and thus an overall increase in effective moisture during this period (Long *et al.*, 1998; Mohr *et al.*, 2000; Long and Whitlock, 2002; Briles *et al.*, 2005). Fire-episode frequency data suggest that fires were relatively common at most sites after ~2000 cal. yr BP, although Taylor, Hoodoo and Cygnet lakes registered very low fire occurrence. Several climate proxy records from western North America suggest dry conditions prevailed from ~1000 to 700 cal. yr BP (the Mediaeval Climatic Anomaly (Cook *et al.*, 2004)) (Graumlich, 1993; Stine, 1994; Mohr *et al.*, 2000), whereas cool moist conditions may have occurred from ~600 to 100 cal. yr BP (Luckman, 1993; Brunelle and Whitlock, 2003), coincident with the 'Little Ice Age' (Grove, 1988). These climate conditions seem to correspond with increases in BCHAR during the MCA and decreases in BCHAR during the LIA. No known climate changes at such broad spatial scales occurred between *c*. 1600 and 1200 cal. yr BP, however, when BCHAR was rapidly decreasing.

It is possible that changes in human populations or fire use contributed to the abrupt shifts in fire and fuels in the northwestern USA during the last two millennia. However, the scarcity of archaeological evidence and ethnographic records from the region makes it difficult to separate human versus climatic influences on fire regimes (Whitlock and Knox, 2002). Lepofsky *et al.* (2005) found a strong relationship between soil charcoal dates and archaeological ^{14}C dates from the southern coast of British Columbia, suggesting a human source for the period of elevated burning. However, a close examination of the archaeological and palaeoecological data demonstrated that even if there were greater levels of human-induced burning, the forests were too wet to burn in the absence of multiyear drought (Hallett *et al.*, 2003; Lepofsky *et al.*, 2005). Changes in Native American populations and land-use activities may have had a greater impact on fire regimes in the relatively drier forests of the western USA, and thus might help to explain some of the BCHAR variations during recent millennia. Additional examination of archaeological, climate and fire-history data is needed to determine whether this is likely.

During the last ~200 years, the sharp increases in BCHAR were due mostly to sharp increases in charcoal abundance at sites in the NRM (eg, Foy, Hoodoo, Slough Creek, Cygnet and Trail lakes). These changes probably reflect the large fires that occurred in this region near the turn of the twentieth century and in recent decades. In Idaho and Montana for example, three million acres burned in 1910, and more than 1.5 million acres burned in the YNP region in 1988 (National Interagency Fire Center, 2005). The large fires of 2000 and 2002 in Idaho, Montana and Oregon were not recorded in the BCHAR data because most of the records were collected prior to 2000. Although increased fuel build-up and larger fires in recent decades have sometimes been attributed to forest management practices such as fire suppression, fire-history and vegetation records from the northwestern USA suggest that periods of high fuels and large fires are not unprecedented in the late Holocene (Whitlock *et al.*, 2003b).

Conclusion

Analysis of charcoal accumulation rates and their relationship to sedimentation rates, site characteristics, climate, vegetation and fire-episode frequency data helped to clarify the interpretation of background charcoal trends for fire-history reconstructions. Local site characteristics, including both lake and watershed size, were important controls on the relative charcoal abundance at particular lakes, suggesting that both aerial and post-fire erosion are important mechanisms of charcoal transportation. Regional synchroneity that was not apparent in fire-episode frequency records was observed in the background charcoal records. Furthermore, these trends were not explained by variations in sedimentation rates. Thus, background charcoal trends may be more representative of regional fire activity than composites of local fire-episode frequency records. The regional coherence in background charcoal and similarities between background charcoal and woody taxa proportions suggest that changes in climate and forest cover that affected fire characteristics and fuel levels were important controls on Holocene trends in background charcoal.

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