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Long-term relations among fire, fuel, and climate in the north-western US based on lake-sediment studies

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Abstract. Pollen and high-resolution charcoal records from the north-western USA provide an opportunity to examine the linkages among fire, climate, and fuels on multiple temporal and spatial scales. The data suggest that general charcoal levels were low in the late-glacial period and increased steadily through the last 11 000 years with increasing fuel biomass. At local scales, fire occurrence is governed by the interaction of site controls, including vegetation, local climate and fire weather, and topography. At subregional scales, patterns in the long term fire-episode frequency data are apparent: The Coast Range had relatively few fires in the Holocene, whereas the Klamath–Siskiyou region experienced frequent fire episodes. Fire regimes in the northern Rocky Mountains have been strongly governed by millennial- and centennial-scale climate variability and regional differences in summer moisture. At regional scales, sites in present-day summer-dry areas show a period of protracted high fire activity within the early Holocene that is attributed to intensified summer drought in the summer-dry region. Sites in summer-wet areas show the opposite pattern, that fire was lower in frequency than present in the early Holocene as result of strengthened monsoonal circulation then. Higher fire-episode frequency at many sites in the last 2000 years is attributed to greater drought during the Medieval Climate Anomaly and possibly anthropogenic burning. The association between drought, increased fire occurrence, and available fuels evident on several time scales suggests that long-term fire history patterns should be considered in current assessments of historical fire regimes and fuel conditions.

Additional keywords: charcoal data, fire history, Holocene, pollen data, western US.

Introduction

The western USA is currently experiencing dramatic environmental changes in the form of recent drought, rapid glacial recession, and severe wildfires (Gedalof *et al.* 2005; Westerling *et al.* 2006; Pederson *et al.* 2007). Recent attention on wildfires began in 1988 with the large area burned in Yellowstone National Park (600 000 ha), and this event has been followed by several years of record-setting fires in the western US and Canada (National Interagency Fire Center data, http://www.nifc.gov, accessed 4 January 2008). With each conflagration, the issue of historical precedence is raised: have fires of this scale occurred before, what are the prospects for ecological recovery, and are these events a predictable consequence of climate changes or fire-related management practices? To address these questions requires information on fire history and a clear understanding of how humans and climate have interacted to shape present forest ecosystems through the disturbance of fire.

Fire-history information comes from two primary sources. Dendrochronological records, including fire-scars on tree-rings and forest stand-age structure data, comprise one source and are available for most western forests (see the National Oceanic and Atmospheric Administration National Climatic Data Center (NOAA NCDC) International Multiproxy Paleofire Database for available data: http://www.ncdc.noaa.gov/paleo/impd/paleofire.html, accessed 4 January 2008). Tree-ring records are spatially specific and also temporally precise, and it is possible to identify individual years and even seasons of burning. Their primary limitation is that the oldest trees are relatively young, generally <500 years, which does not provide a good analogue for projected changes in climate as a result of increased greenhouse gases (IPCC 2007).

The second source of fire-history information comes from stratigraphic records of charcoal preserved in the sediments of lakes and wetlands and other geologic deposits. This charcoal is produced during a forest fire, carried aloft, deposited on the lake surface, and eventually buried in the sediments. Information on modern fires as well as theoretical and modelling studies provide the basis for interpreting charcoal data in terms of past fire (e.g. Whitlock and Millspaugh 1996; Peters and Higuera 2007). The geographic coverage of charcoal records in western USA is less extensive than that of tree-ring data, and they lack the spatial resolution or temporal precision. They do extend fire

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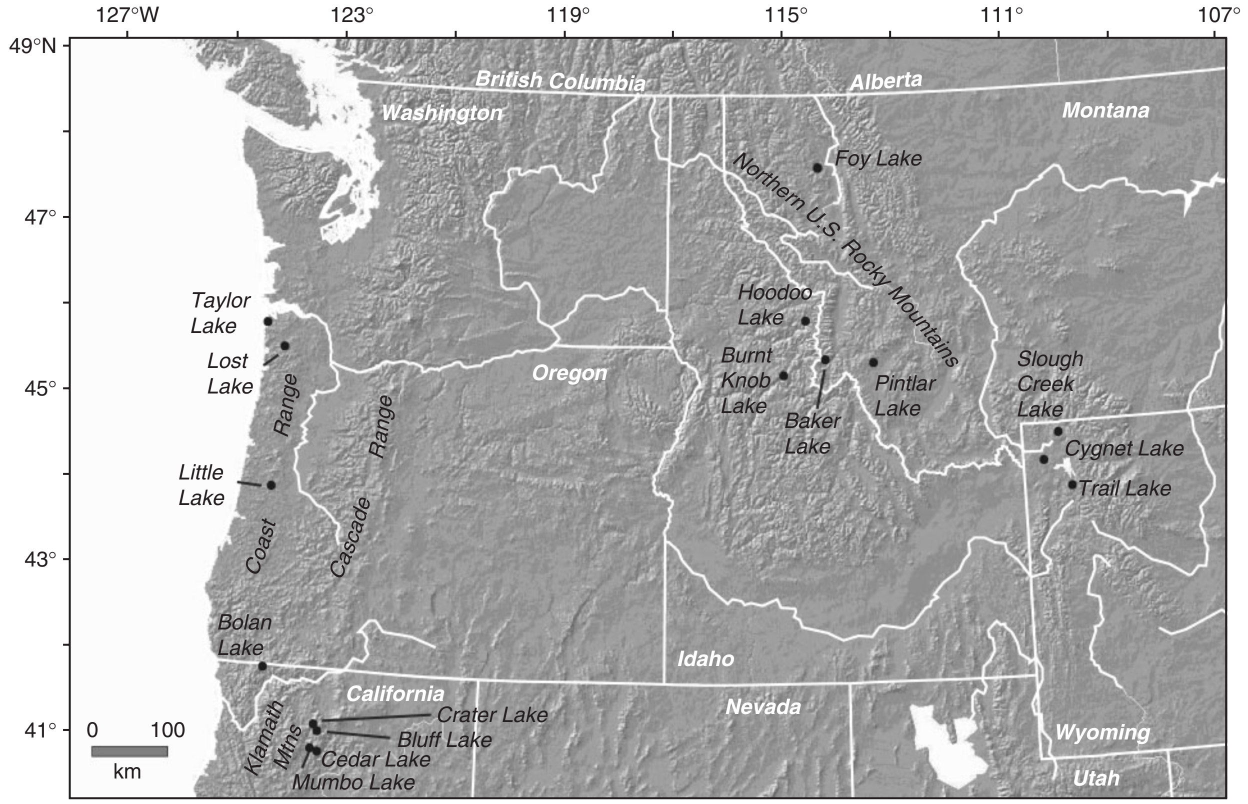

Fig. 1. Location of study sites in the north-western USA. Site information is available in Table 1.

reconstructions back thousands of years (i.e. the age of many western lakes). In addition, it is possible to compare charcoal and pollen records from the same cores to examine the interactions between fire and vegetation during periods of major environmental reorganisation. Thus, the insights gained from these long records have direct bearing on our understanding of current fire regimes in the face of changing climate.

The objective of the present paper is to compare the fire and vegetation history of the north-western USA based on charcoal and pollen records from 15 lake-sediment records. Other high-resolution fire records are available from the region and used for comparison (e.g. Hallett *et al*. 2003; Daniels *et al*. 2005; Gavin *et al*. 2006; Minckley *et al*. 2007), but our focus here is on the 15 sites as representative examples. We describe (1) the methods used for high-resolution fire-history studies; (2) the fire history of specific subregions of the north-western USA; and (3) a regional comparison of the temporal trends in charcoal data. We then discuss the implications of these long fire records for understanding present-day fire regimes and consider the importance of this information in current forest management.

The 15 sites are located in the Oregon Coast Range (OCR), the Klamath–Siskiyou Mountains (K-S), and the Northern Rocky Mountains (NRM) (Fig. 1; Table 1) and span an area of varied topography, geology, and present-day vegetation, climate, and fire regimes. Present-day vegetation ranges from temperate rainforest in the OCR to diverse conifer forests in the K-S, and lower steppe parkland communities to subalpine parkland in the NRM. The vegetation history includes periods of tundra, parkland, forest, and dry grassland over the last 17 000 years. Present fire regimes vary from infrequent high-severity (crown) fire in the OCR to mixed-severity fires in the K-S and NMR, and frequent low-severity (surface) fires at lower treeline in the NRM.

Seasonality of precipitation is an important site characteristic related to long-term changes in fire activity and fire-episode frequency in particular (Whitlock and Bartlein 2004; Brunelle *et al*. 2005). The sites can be broadly grouped into two categories according to the ratio of summer to annual precipitation. ‘Summer-dry’ sites lie in areas where summer precipitation is currently suppressed by the north-eastern Pacific subtropical high-pressure system. This high-pressure system causes widespread subsidence over the north-western USA, leading to especially dry summer conditions in the OCR, K-S and parts of the NRM. ‘Summer-wet’ sites exist east of the Continental Divide where recirculated monsoonal moisture is precipitated during mid–late summer convectional thunderstorms. In summer-wet 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. Twelve of the 15 sites exhibit summer-dry patterns, whereas three are summer-wet (Baker, Pintlar and Slough Creek Lakes), and the geographic location of these precipitation regimes does not seem to shift substantially during the last 11 000 years (the Holocene) (Whitlock and Bartlein 1993).

Table 1. Site information

Site	Latitude, longitude	Elevation (m)	Lake area (ha)	Reference
Summer-dry sites				
Cedar Lake, CA	41.21°N, 122.50°W	1740	2.6	C. Whitlock (unpubl. data)
Bluff Lake, CA	41.35°N, 122.56°W	1921	1.2	Mohr *et al.* (2000)
Crater Lake, CA	41.40°N, 122.58°W	2288	2.5	Mohr *et al.* (2000)
Bolan Lake, OR	42.02°N, 123.46°W	1637	5.0	Briles *et al.* (2005)
Little Lake, OR	44.16°N, 123.58°W	212	3.3	Long *et al.* (1998)
Lost Lake, OR	45.81°N, 123.57°W	449	5.7	Long (2003)
Taylor Lake, OR	46.08°N, 123.90°W	6	3.5	Long and Whitlock (2002)
Burnt Knob Lake, ID	45.70°N, 114.99°W	2250	1.1	Brunelle and Whitlock (2003)
Hoodoo Lake, ID	46.32°N, 114.65°W	1770	2.5	Brunelle *et al.* (2005)
Foy Lake, MT	48.16°N, 114.36°W	1006	85.0	Power *et al.* (2005)
Cygnet Lake, WY	44.66°N, 110.62°W	2530	5.3	Millspaugh *et al.* (2001)
Trail Lake, WY	44.28°N, 110.17°W	2362	35.3	C. Whitlock (unpubl. data)
Summer-wet sites				
Baker Lake, MT	45.89°N, 114.26°W	2300	2.2	Brunelle *et al.* (2005)
Slough Creek Lake, WY	44.92°N, 110.35°W	1884	2.9	Millspaugh *et al.* (2004)
Pintlar Lake, MT	45.84°N, 113.44°W	1921	4.3	Brunelle *et al.* (2005)

Charcoal analysis methods

The methods used to reconstruct past changes in fire activity were similar for all 15 sites discussed in the text. Sediment cores were collected from each lake and sediment samples and plant macrofossils, such as needles or pieces of wood, were taken from the cores and sent to a laboratory for radiocarbon (^{14}C) and lead-210 (^{210}Pb) dating. An age *v.* depth curve (age model) was created for each record based on a combination of ^{14}C and ^{210}Pb dates, dendrochronological or historical evidence of known fires, and stratigraphic markers of known ages (e.g. distinct tephra or ash layers associated with specific volcanic eruptions). Radiocarbon dates were calibrated (Stuiver *et al.* 1998) to years before present (cal yr BP) before the age model was constructed. The age model was used to assign estimated ages to specific samples or intervals throughout the core.

Samples of a known volume (e.g. 5 cm^3) were then taken at contiguous intervals (typically 1 cm) throughout the core to be processed for charcoal analysis. Samples were gently washed through a 125 μm-mesh sieve, and charcoal particles in the residue were counted under a dissecting microscope at 20–32× magnification. Charcoal abundances were counted from each sample and divided by the sample volume to obtain concentration values (particles cm^{-3}). Sedimentation rate (cm year^{-1}) was calculated by dividing the thickness of each sample by the time spanned by the sample (based on the age model), and deposition time (year cm^{-1}) was obtained as the inverse of the sedimentation rates.

In order to account for the influence of changing sedimentation rates on charcoal abundance and concentration, concentration values were converted into charcoal accumulation rate (CHAR; particles cm^{-2} year^{-1}), also described as charcoal influx. This was accomplished by interpolating concentration values (particles cm^{-3}) and deposition times (year cm^{-1}) into pseudo-annual values, averaging these annual values over a specified interval (e.g. 10 years), and then dividing the average concentration value by the average deposition time for the interval. This procedure preserves the total influx of charcoal, whereas direct interpolation of charcoal influx to particular target years does not. CHAR time series were then logarithmically transformed for variance stabilisation ($\log_{10}(\text{CHAR} + 1)$).

CHAR time-series are highly variable, and the rate of charcoal accumulation at any point in time is a result of multiple interacting controls (Long *et al.* 1998). Four primary controls are thought to account for most of the variability in CHAR records: (1) long-term changes in charcoal deposition resulting from shifts in vegetation composition and hence fuel load and charcoal production; (2) short-term increases in charcoal production due to individual fire events within the 'charcoal catchment' of a lake; (3) regional fire activity; and (4) noise arising from geomorphic, sedimentologic, and limnologic processes.

To identify fire episodes and describe the long-term variation in charcoal deposition, we decomposed the CHAR time series into two components (1) a *background component* that represents the long-term changes in deposition, which is estimated by a locally weighted mean; and (2) the deviations of CHAR about the background component. Positive deviations that exceeded a certain threshold value are thought to represent the signature of individual fires or fire episodes and are referred to as the *peaks component*. The binary time series of peaks was smoothed to produce a summary of fire episodes through time (expressed as number of episodes/1000 years). The resulting background trend and peak frequencies for an individual record are dependent on three key parameters: (1) the size of the window-width used to calculate the locally weighted mean (background window-width); (2) the threshold value; and (3) the fire-episode frequency smoothing window. The first two parameters interact: an overly large window-width that results in 'underfitting' of the background component, or a threshold parameter that is too small may result in the identification of many spurious peaks. Conversely, a window-width that is too small, thereby 'overfitting' the background component, or a threshold value that is too high, may result in the underdetection of real peaks. Similarly, a relatively small fire-episode frequency smoothing window will lead to increased variability in the fire-episode frequency reconstruction, whereas a larger window will lead to a less variable record of fire-episode frequencies.

In order to ensure that the most appropriate decomposition parameters were chosen, independent evidence of recent fire activity was collected for each site and used to 'calibrate' the charcoal-based reconstruction. Each record was calibrated by comparing the dates of the most recent charcoal peaks with the dates of known fire events (e.g. based on historical documents or fire-scarred trees) in the watershed. Multiple iterations of comparisons were made using different combinations of parameters until a good fit was achieved between recent charcoal peak dates and dates of known fires in the area. In the absence of calibration data, present-day mean fire-return intervals (Agee 1993) were compared with modern peak frequencies to determine the most appropriate parameters.

The calibration step in the original data analyses ensured that each reconstruction was consistent with the recent, known fire history of the area. In each case, however, there were a range of possible parameters that could have been chosen that would have resulted in a good fit between the paleoecological fire-history reconstruction and the calibration data. Thus, when comparing multiple records across sites, it seemed prudent to minimise the differences in analytical methods by standardising the parameter values across sites, to the extent that each record remained consistent with the calibration data. We were able to standardise the interpolation bin to 10 years and the background window-width to 500 years without significantly altering the fire-episode frequency reconstructions or causing the modern reconstructed fire-episode frequencies to fall outside the range established by the independent fire-history evidence. The threshold-ratio parameters used in the original analyses, however, were retained, as these values proved essential to successful calibration (Marlon *et al.* 2006).

Subregional fire and vegetation histories

Oregon Coast Range

Three sites have been studied from the temperate coniferous rainforest of the Oregon Coast Range. Taylor, Lost and Little Lakes in the OCR are lowest in elevation (6 to 449-m elevation) and receive the highest annual precipitation. These sites lie within temperate rainforest of *Tsuga heterophylla* (western hemlock), *Pseudotsuga menziesii* (Douglas-fir), *Picea sitchensis* (Sitka spruce) and *Alnus rubra* (red alder) (Long *et al.* 1998, 2007; Long and Whitlock 2002). Fires tend to occur between June and mid-October in conjunction with dry summer conditions (Gedalof *et al.* 2005). Historic records of the past 150 years paint a picture of infrequent high-severity crown fires that burn large areas. For example, the Yaquina fire in 1868 burned ~51 000 ha in the central Coast Range and the Tillamook fire of 1933 burned ~106 000 ha in the northern Coast Range (Morris 1934; Juday 1977). Dendrochronologic data in the form of tree-rings (Impara 1997) and stand-age information (Juday 1977; Teensma *et al.* 1991) indicate that widespread high-severity fires have occurred throughout the Coast Range for the last ~500 years and have return intervals of between 150 and 350 years.

Little Lake is a landslide-dammed lake surrounded by *Pseudotsuga* forest in the central Coast Range of Oregon. An 11.33 m-long core, consisting of fine-detritus gyttja, was collected from the centre of the lake and used to reconstruct the fire history of the last 9000 years. Charcoal samples encompassed on average 8 years of sediment deposition, and the data were compared with the pollen record of Worona and Whitlock (1995), which was sampled at 200–400 year intervals in a different core. Four accelerator mass spectrometry (AMS)-^{14}C dates and the presence of Mazama ash were used to develop the age model and correlate charcoal and pollen records (Fig. 2).

During the early Holocene (9000 to 6700 calendar years before present (cal yr BP)), OCR forests were composed primarily of fire-adapted species such as *Pseudotsuga*, *Pinus*, and *Quercus* (oak), which likely grew on dry uplands, whereas riparian areas were occupied by *Alnus rubra*. Levels of CHAR were low but fire frequency was higher than at present (110 years between episodes). Apparently, fire episodes did not produce abundant charcoal, either because they were small or low-severity events (Long *et al.* 1998). During the middle Holocene (6700 to 2700 cal yr BP), increases in shade-tolerant species such as *Tsuga heterophylla*, *Thuja plicata* (western red cedar), and *Picea sitchensis* imply a shift to cooler or more mesic climate conditions in the Coast Range. The continued presence of *Pseudotsuga* suggests that some slopes still supported dry forest, but the overall decrease in fire frequency (150 years between episodes) is consistent with an increase in fire-sensitive mesophytic species. The late Holocene (2700 cal yr BP to present) featured further increases in the abundance of mesophytic species, including *Picea* and *Abies*. The persistence of *Pseudotsuga* and *Alnus* in the pollen record indicates strong moisture gradients in the upland vegetation as well as a well-developed riparian forest. The decrease in fire-episode frequency, averaging 210 years between episodes, and high CHAR levels mark the establishment of the present fire regime of infrequent widespread fires that consume abundant biomass (Long *et al.* 2007).

Klamath–Siskiyou Region

The floristically diverse forests of the Klamath Mountains are controlled by increasing moisture and decreasing temperature gradients with elevation, west-to-east decreases in moisture from the Pacific, and geologic substrates that affect soil nutrients. The Oak Woodland Zone (<800-m elevation) consists of *Pinus ponderosa* (ponderosa pine), *Pseudotsuga jeffreyi* (Jeffrey pine), *Quercus garryana* (Oregon white oak), *Q. kelloggii* (California black oak), *Calocedrus decurrens* (incense cedar), and *Pseudotsuga menziesii*. The Mixed-Evergreen Zone (800–1100-m elevation) is dominated by *Pseudotsuga menziesii* and *Lithocarpus densiflora* (tan oak). *Abies concolor* (white fire) and *Pseudotsuga menziesii* are common in the Mixed-Conifer Zone (1100 to 1300-m elevation), and *A. concolor* is the dominant species in its zone (1300 to 1900-m elevation). It is replaced upslope by *Abies magnifica* (red fir) (1900 to 2100-m elevation) and then *Tsuga mertensiana* (mountain hemlock) (2100 to 2300-m elevation) as conditions become cooler and wetter. Diorite soils dominate the region, but other soil types (e.g. ultramafics) pose severe nutrient limitations on community composition and foster areas of high endemism (Franklin and Dyrness 1988; Sawyer and Thornburgh 1988; Vasek and Thorne 1988). Fires in the Klamath region occur from June to September (Agee 1993) and help maintain the present vegetation diversity in the Klamath

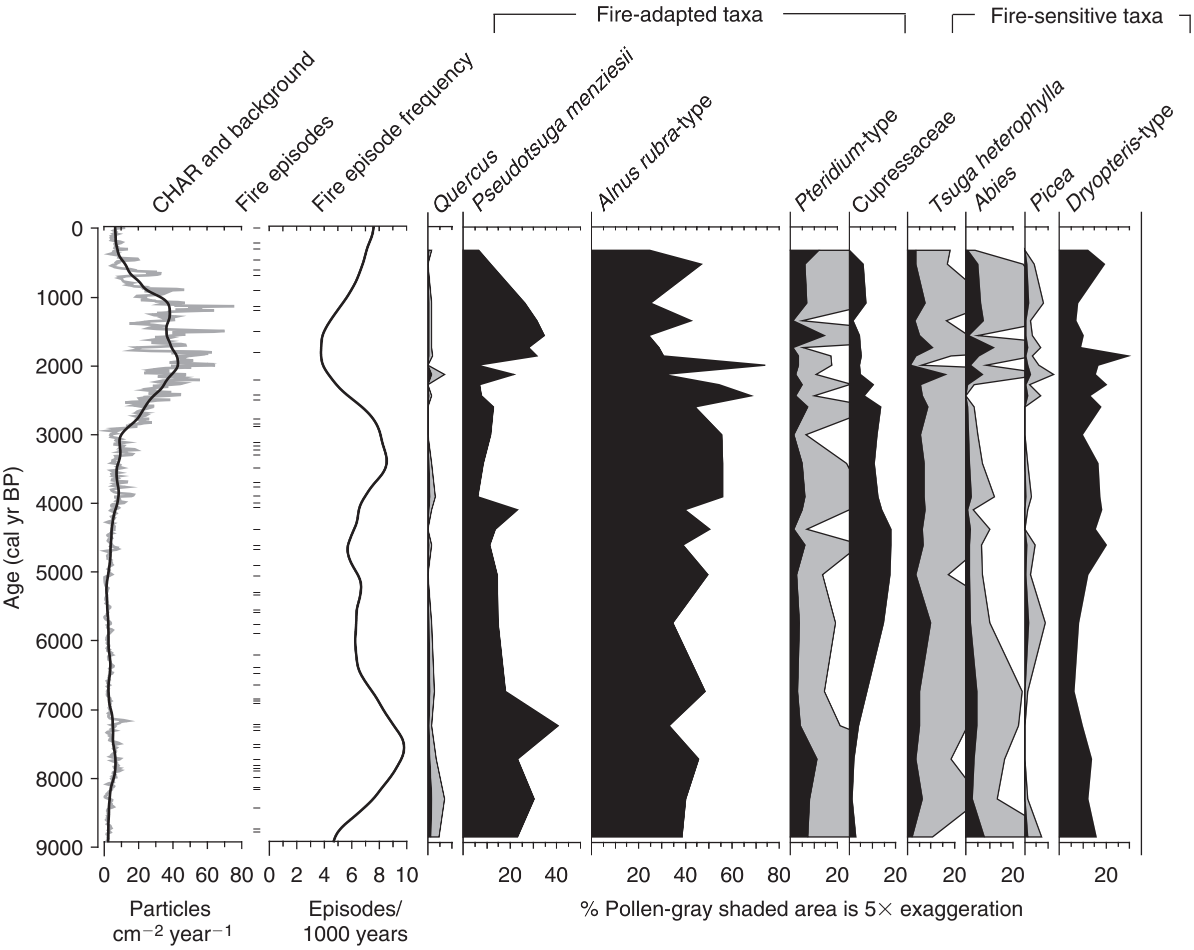

Fig. 2. Charcoal accumulation rate (CHAR) data showing background CHAR, fire events (peaks), and selected pollen percentage data for Little Lake, Oregon Coast Range (from Long *et al.* 1998).

Mountains. In oak woodlands, fire is frequent but of low intensity, and at higher elevations, it becomes less frequent and mixed severity. The lack of understorey fuels in many forests often limits fire size (Skinner and Chang 1996).

Fire and vegetation history studies have been conducted on five intermediate-to-upper elevation (1600 to 2200 m) sites, Bolan, Crater, Bluff, Mumbo, and Cedar Lakes (West 1989; Mohr *et al.* 2000; Briles *et al.* 2005; Daniels *et al.* 2005). Bluff and Crater Lakes are located in dry, ultramafic-rich settings in the eastern Klamath region. The records from Bolan, Mumbo and Cedar Lakes are representative of the vegetation history on nutrient-rich diorite soils.

Pollen and charcoal data from a 9 m-long sediment core from Bolan Lake, spanning the last 17 000 years, provide an example of the fire history of the Siskiyou Mountains (Fig. 3). The core contained inorganic clay before 14 500 cal yr BP, and fine-detritus clay gyttja with abundant plant macrofossils after that time. Nine AMS-^{14}C age determinations, a ^{210}Pb chronology, and the age of Mazama ash (7627 cal yr BP, Zdanowicz *et al.* 1999) were used to develop an age–depth model. The deposition time was 45 years cm^{-1} at the base and decreased to 3 years cm^{-1} at the top of the sediment core.

During the early late-glacial period (17 000 to 14 500 cal yr BP), the Bolan Lake area supported a subalpine parkland of *Pinus*, *Picea*, *Tsuga mertensiana*, *Artemisia* (sagebrush) and Poaceae when the climate was cooler than present. Charcoal data suggest infrequent fires during this period. Between ~14 500 and 13 000 cal yr BP, warmer conditions allowed conifer species to migrate upslope by 300–500 m in elevation, and fire activity increased. A cooler and/or wetter period (13 000 to 10 900 cal yr BP) is associated with an increase in *Picea*, *Abies*, *Artemisia* and *T. mertensiana* pollen and infrequent fires.

After 11 000 cal yr BP, open xerothermic forests of *Pinus*, *Quercus*, Cupressaceae and *Ceanothus* developed and fires became more frequent. The similarity of early Holocene vegetation to present-day mixed evergreen forests suggests that annual temperatures were ~1.5°C warmer than today. During the middle Holocene (7000–4500 cal yr BP), a closed forest of *Abies*, *Pseudotsuga*, Cupressaceae, *Alnus rubra*, *Ceanothus* and *Quercus* became established, and fire-episode frequency and CHAR levels were high. After 4500 cal yr BP, a closed forest with *Abies* and minor amounts of *Pinus*, *Picea*, *Tsuga mertensiana*, and *Pseudotsuga* developed. Cupressaceae, *Quercus vaccinifolia* (huckleberry oak) and *Ceanothus* were less abundant than in

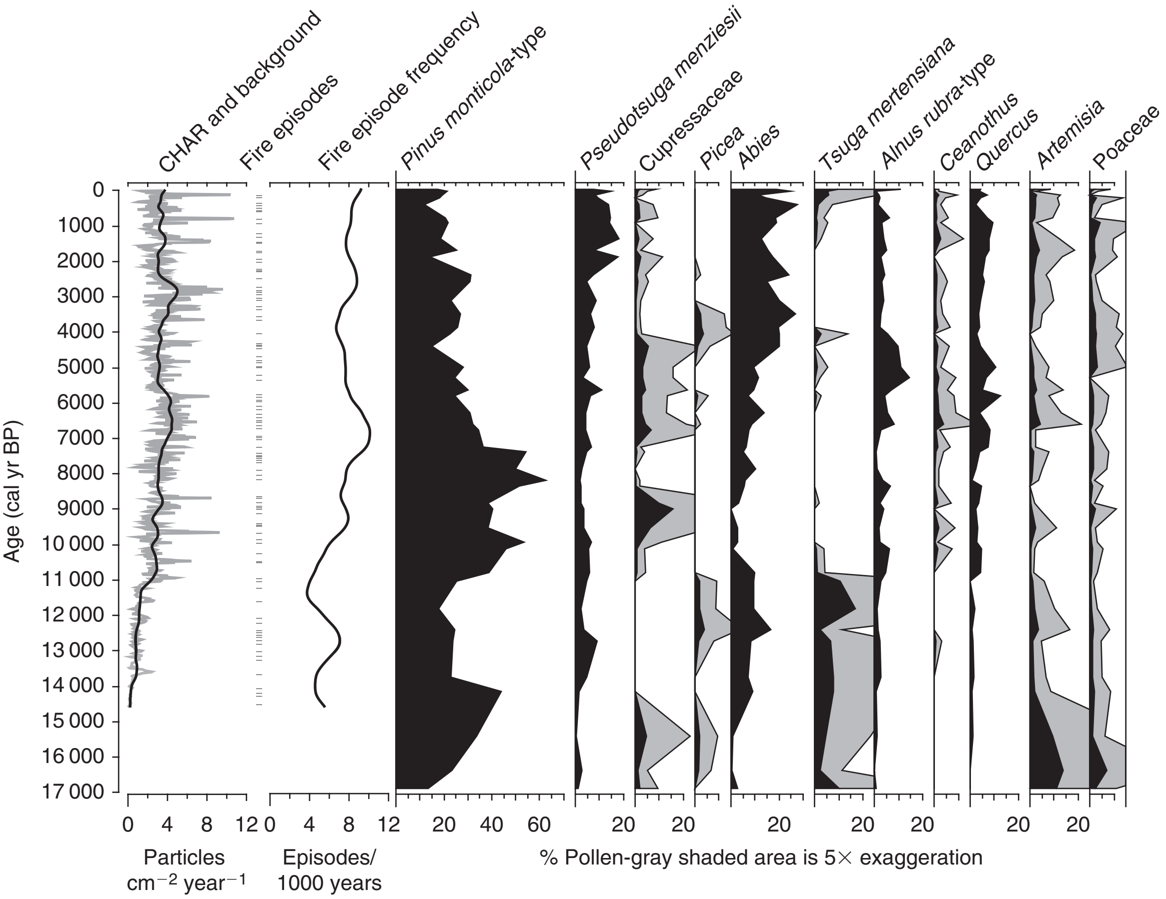

Fig. 3. Charcoal accumulation rate (CHAR) data showing background CHAR, fire events (peaks), and selected pollen percentage data for Bolan, Klamath–Siskiyou region (from Briles *et al.* 2005).

the early and middle Holocene and probably grew in openings. Fires became less frequent and CHAR levels declined slightly. The modern forests dominated by *Abies*, *T. mertensiana* and *Pseudotsuga* became established in the last 2000 years. High fire frequency occurred during the Medieval Climate Anomaly (700–1000 cal yr BP; Cook *et al.* 2004) and subsequently decreased in the last millennium.

The vegetation changes recorded at Bolan Lake show a close association with fire frequency variations on submillennial time scales. For example, from 10 900 to 12 500 cal BP, infrequent fires occurred when fire-sensitive *Abies*, *Picea* and *Tsuga mertensiana* were abundant. Likewise, in the late Holocene, a period of low fire frequency from 3000 to 5000 cal yr BP was associated with a high level of *Picea*. When conditions were warmer and drier in the early Holocene, high fire frequency coincided with an abundance of *Pseudotsuga*, Cupressaceae, and *Alnus rubra*.

Northern Rocky Mountains

In the NRM, Foy Lake is located at the lower forest–steppe margin (1006 m elevation) in the Flathead Valley of Montana and surrounded by *Artemisia* (sagebrush) steppe and forests of *Pseudotsuga menziesii*, *Pinus ponderosa* (ponderosa pine), and *Larix occidentalis* (western larch) (Power *et al.* 2006). At low elevations, surface fires occur in grassland and steppe regions approximately every 15 to 25 years, whereas stand-replacing crown fires occur approximately every 100 to 150 years (Barrett *et al.* 1997). Four sites lie in subalpine (Burnt Knob, Baker, and Hoodoo lakes) and montane forests (Pintlar Lake) (1770–2250-m elevation) of north-western Montana and northern Idaho where fires are infrequent (100–300 years apart) and often stand-replacing events. At intermediate elevations, Hoodoo and Pintlar lakes support mixed conifer forests. At high elevations, Burnt Knob (2250-m elevation) and Baker lakes (2300-m elevation) are located in open forests of *Larix lyallii* (subalpine larch), *Pinus albicaulis* (whitebark pine), *Picea engelmannii* (Engelmann spruce) and *Abies bifolia* (subalpine fir) (Brunelle and Whitlock 2003; Brunelle *et al.* 2005).

Baker Lake provides a fire and vegetation history from high elevations on the east side of the Bitterroot Range (Fig. 4). *Pinus albicaulis* (whitebark pine) and *Larix lyallii* (subalpine larch) grow on dry slopes, and *Abies bifolia* (subalpine fir) and *Picea engelmannii* (Engelmanni spruce) occur in wetter locations within the basin. *Pinus contorta* is also present in recently burned areas. A 4 m-long core from Baker Lake consisted of 4.5 m of fine-detritus gyttja (and an ~80 cm-thick deposit of Mazama ash) underlain by 20 cm of inorganic glacial clay. An age model based on nine AMS-^{14}C age determinations, a

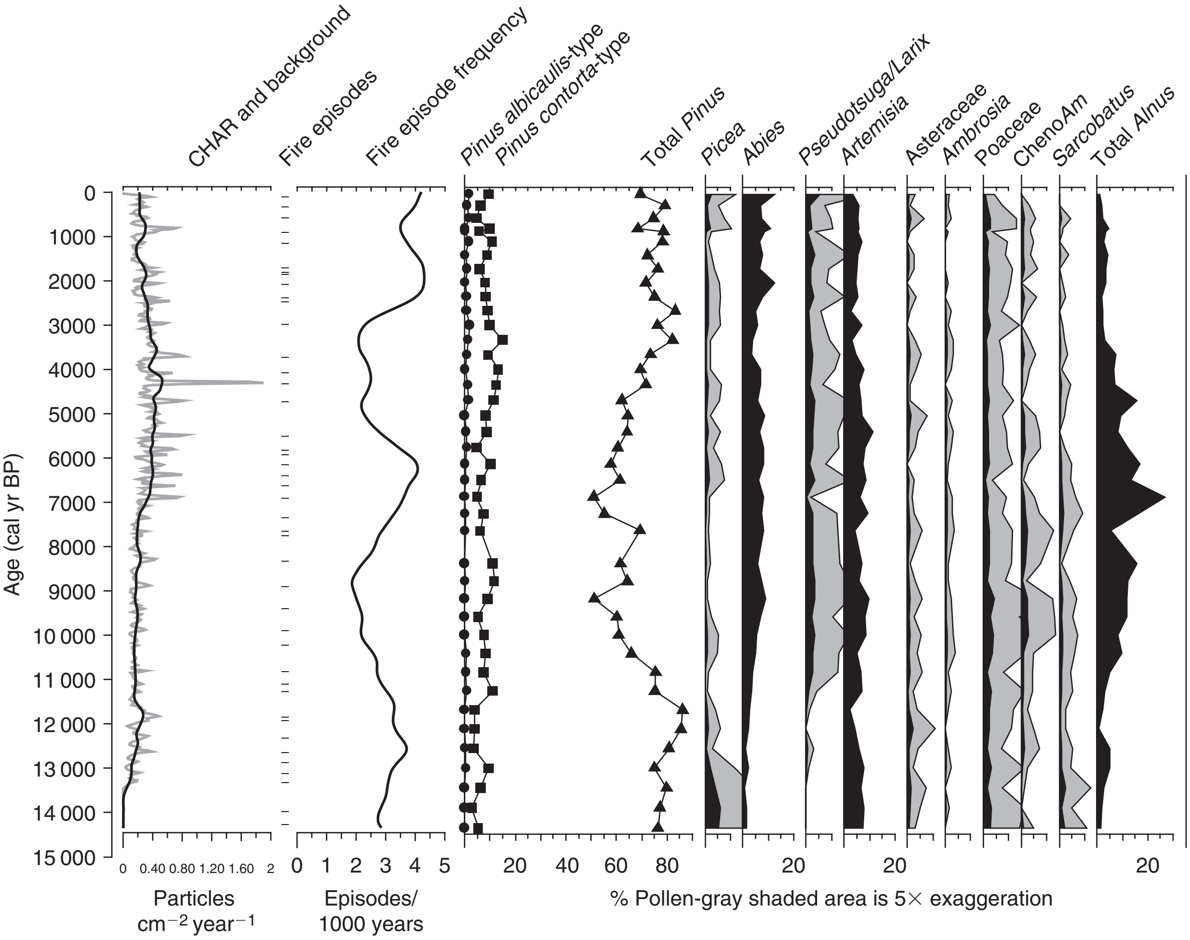

Fig. 4. Charcoal accumulation rate (CHAR) data showing background CHAR, fire events (peaks), and selected pollen percentage data for Baker Lake, Northern Rocky Mountains (from Brunelle *et al*. 2005).

^{210}Pb chronology, and the age of Mazama and Glacier Peak (13 155 cal yr BP; Carrara and Trimble 1992) ashes indicate that the core covered the last 14 500 years. Charcoal samples, analysed every centimetre, spanned on average 30 years. Pollen samples were taken every 10 centimetres and thus a spacing of 200 and 300 years.

A *Picea* parkland was present after ∼14 500 cal yr BP and replaced by a forest mostly composed of *Pinus albicaulis* at 12 750 cal yr BP. After ∼11 000 cal yr BP, *Abies* became a more significant forest component. The fire frequency reached four events/1000 years at ∼12 750 cal yr BP, and then declined into the early Holocene. Thermophilous taxa, including *Pseudotsuga/Larix*, Chenopodiineae and *Alnus*, became more abundant during the early Holocene indicating warmer conditions than before. Fire frequency decreased to three events/1000 years at 10 000 cal yr BP and two events/1000 years at 9000 cal yr BP. The low fire activity is interpreted as evidence of an invigorated monsoon in the early Holocene, which increased available moisture over that of earlier or later periods, thus suppressing fire activity (Brunelle *et al*. 2005).

By ∼7000 cal yr BP, *Pinus*, and particularly *P. albicaulis*, reached its lowest abundance. *Pinus* increased again and was as high as late-glacial levels by ∼3500 cal yr BP. Fire frequency increased to three events/1000 years at 7000 cal yr BP and reached highest values of more than four events/1000 years at 6000 cal yr BP before declining again. In the late Holocene (3500 cal yr BP to present), modern forests were established with the onset of cooler moister conditions than before. A distinctive peak of high fire activity (four events/1000 years) occurred at ∼2000 cal yr BP after which fire frequency dropped to a low at ∼800 cal yr BP (three events/1000 years). The present-day fire frequency of 3.5 events/1000 years was reached in the last few centuries.

Yellowstone Region

In Yellowstone National Park (YNP), fire histories are available from Slough Creek, Cygnet and Trail lakes in montane forest and at the lower forest–steppe margin (1884–2530 m) (Millspaugh *et al*. 2000, 2004; C. Whitlock and R. L. Sherriff, unpubl. data). Slough Creek Lake is surrounded by steppe and stands of *Pseudotsuga* and experiences relatively frequent, low-severity fires (Millspaugh *et al*. 2004). Trail Lake lies within a forest of *Pinus contorta*, *Abies bifolia*, and *Picea engelmannii* in southern YNP and Cygnet Lake is located within *Pinus contorta*

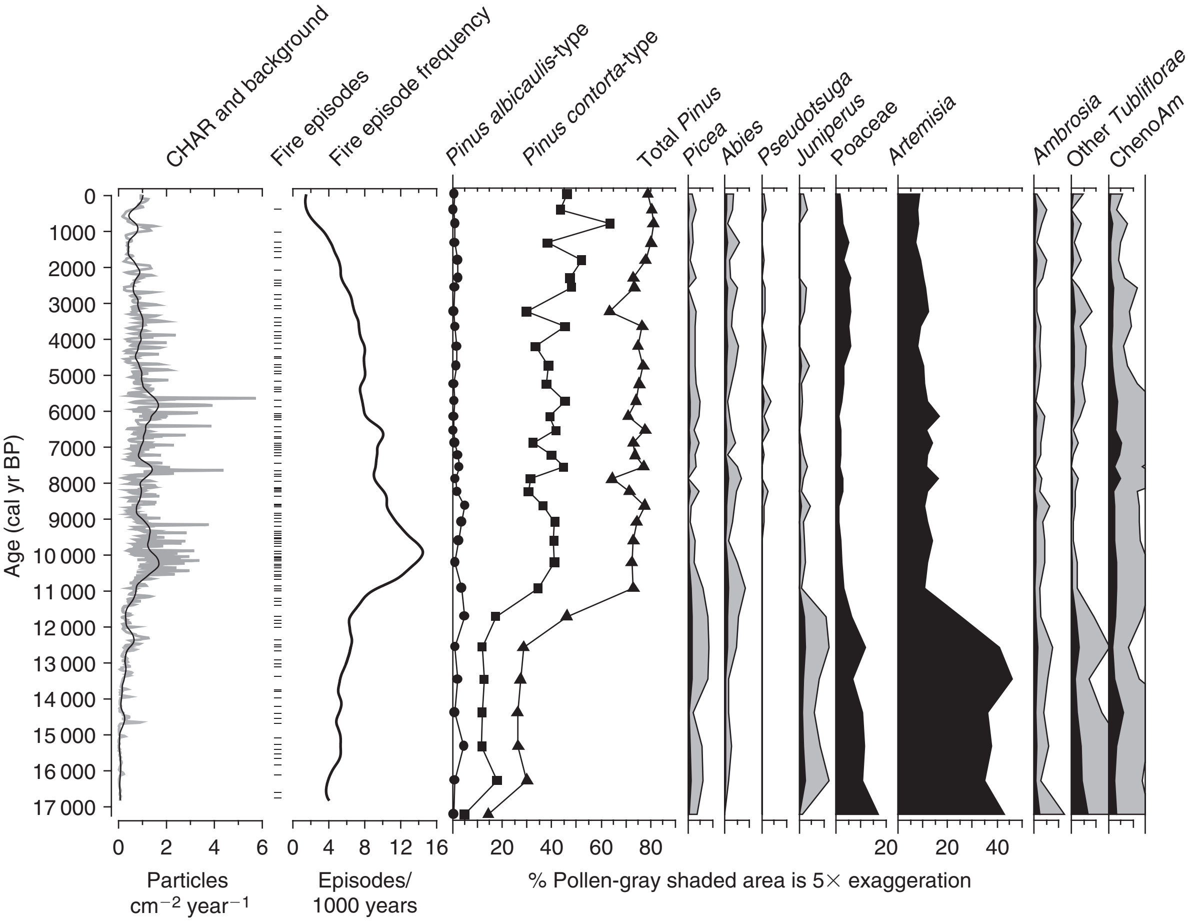

Fig. 5. Charcoal accumulation rate (CHAR) data showing background CHAR and fire events (peaks), and selected pollen percentage data for Cygnet Lake, Yellowstone National Park (from Millspaugh *et al.* 2000).

forest. Cygnet Lake and Trail Lake lie in present-day summer-dry areas, and Slough Creek Pond is located in the summer-wet region of northern YNP.

Pollen and charcoal data from Cygnet Lake in the Central Plateau Province (Fig. 5) provide a fire history of central YNP. At present, the plateau region supports uniform forest of *Pinus contorta*, despite experiencing climate conditions that are suitable for *Picea engelmannii*, *Abies lasiocarpa*, and *Pinus albicaulis*. In the last few centuries, large (>2500 ha), infrequent (200–400-year mean fire interval), stand-replacing fires resulted in a forest mosaic composed of different stand ages of *P. contorta* and little species diversity (Romme and Despain 1989). The strong edaphic control on the vegetation was confirmed by the pollen record, which showed little change over the last 11 000 years.

A 6.70 cm-long core was obtained, and 10 AMS-^{14}C age determinations and the age of Mazama and Glacier Peak ashes suggested that the record spanned the last 17 000 cal years. The lithology consisted of inorganic clay before 11 000 cal yr BP and fine-detritus gyttja after that time. Charcoal samples had an average deposition time of 20 years cm^{-1}, and the pollen samples taken from a core collected from the surrounding fen were spaced at 200–400 year intervals.

Pollen data from Cygnet Lake suggest that tundra or grassland grew in southern and central YNP following deglaciation (Whitlock 1993). In areas of southern and central YNP underlain by non-rhyolitic soils, *Picea* parkland developed between ~13 400 and 12 400 cal yr BP. This vegetation was replaced by *Picea–Abies–Pinus albicaulis* forest between ~12 400 and 11 000 cal yr BP. In contrast, the pollen record from Cygnet Lake indicates that *Picea*, *Abies* and *P. albicaulis* were uncommon in the Central Plateau Province, probably because they were unable to establish on infertile rhyolite substrates. Instead, tundra or meadow communities persisted until ~11 300 cal yr BP when *Pinus contorta* forest became widespread in southern and central YNP on both rhyolitic and non-rhyolitic substrates.

At Cygnet Lake, the frequency of local fires was initially low (approximately four events/1000 years) when tundra prevailed. July insolation at that time was similar to or slightly higher than present; however, summer conditions were cooler than today as a result of continental-scale circulation patterns and locally retreating glaciers. A gradual rise in fire frequency to six events/1000 years at 11 700 cal yr BP was most likely a response to increasing aridity during the summer insolation maximum. Increasing background CHAR probably corresponded with a change from open vegetation to parkland as *P. contorta* colonised the Central Plateau Province.

The incidence of fires increased rapidly around Cygnet Lake after ~11 700 cal yr BP when summers became warmer and drier in the Central Plateau Province. *Pinus contorta* forest was present in the watershed after 11 300 cal yr BP, and fire frequency rose to 15 events/1000 years. After 9900 cal yr BP, fire frequency gradually decreased to the present levels (<two to three events/1000 years). The trend of declining fire frequency in the middle and late Holocene paralleled decreasing summer insolation and a shift to cooler and effectively wetter conditions than before. Reduced drought in the late Holocene shortened the fire season (for example, by influencing the probability of ignition, fuel moisture, and fire weather) to its present length (July to mid-October) in any given year. CHAR remained relatively stable through the Holocene despite variations in the stand-age distribution (and thus, aboveground biomass) of the *P. contorta* forest. In the last two millennia, fire frequency has been lower (two to five events/1000 years) than at any time since the establishment of *P. contorta* forests. Protracted periods without fire probably have allowed *P. contorta* stands to mature, and forest structure to become more homogeneous. This type of landscape pattern has helped maintain the current fire regime, which features infrequent but large fires in dry years.

The period of maximum fire frequency in the Holocene differed between the Yellowstone–Lamar Province and the Central Plateau Province (Fig. 5). The fire record from Slough Creek Lake indicates high fire occurrence in the Yellowstone–Lamar Province occurred in recent millennia as a result of increasing drought conditions. In contrast, the fire record from Cygnet Lake suggests that fire frequency was highest on the Central Plateau between ~11 000 and 8000 cal yr BP when drought conditions prevailed there (Millspaugh *et al.* 2004).

Regional comparisons of fire-history records

Marlon *et al.* (2006) standardised background trends from the 15 target sites to examine the long-term changes in CHAR (Fig. 6*a*). The results showed that CHAR levels gradually increased from the late-glacial period to the late Holocene and decreased between 2000 and 1600 cal yr BP. Levels were particularly variable in the late-glacial period and during the last ~2000 years. Relatively high levels of CHAR occurred during the Younger Dryas cold interval (11 600–12 600 cal yr BP; Alley *et al.* 1993) and the Medieval Climate Anomaly, whereas relatively low CHAR levels were coincident with the Bølling-Allerød warm period and Little Ice Age.

General trends in Holocene fire activity (expressed by background CHAR levels) are controlled by climate and increasing levels of fuel biomass associated with post-glacial forest development. The long-term Holocene trend in background CHAR reflects gradually increasing fuel loads and more charcoal produced per fire as a result of the expansion of forests in the north-western USA (Marlon *et al.* 2006). On shorter time scales, different climate conditions, fuel loads, and fire regimes could account for similar fluctuations in background CHAR. For example, increases in charcoal levels could have arisen from cool dry conditions, high fuel loads, and few fires during the Younger Dryas cold interval and from warm dry conditions, low fuel loads, and frequent fires during the Medieval Climate Anomaly. The decline in charcoal levels between 2000 and 1600 cal yr BP is particularly striking in the northern Rocky Mountain sites and may also be related to increased anthropogenic burning in the valleys when Native American populations were at their highest levels (Power *et al.* 2006).

The fire frequency data are presented as anomalies based on the base period of last 4000 years, which is the period when the pollen data suggest that modern vegetation communities were established at the sites. Most records show extended periods of relatively high (positive anomalies) or low (negative anomalies) fire-episode frequency lasting several millennia before shifting to the opposite condition (Fig. 6*b*). Bolan Lake is an exception, alternating between periods of high and low fire-episode frequency every millennium or so for much of the Holocene. Eight of the 12 summer-dry records (Crater, Bluff, Cedar, Little, Cygnet, Burnt Knob, and Hoodoo and Trail lakes) reveal a period of high fire-episode frequency (positive anomalies) between the late-glacial and middle Holocene, from ~11 000 to 6000 cal yr BP, whereas two of the 12 summer-dry records (Bolan and Lost Lakes) had relatively low fire-episode frequencies (negative anomalies) during this interval. (Taylor and Foy lakes were not recording at this time.) It is noteworthy that these high anomalies are neither synchronous nor of the same duration or intensity at the sites.

The three summer-wet records, Pintlar, Baker and Slough Creek lakes, show a protracted period of lower-than-average fire-episode frequencies between the late-glacial and the middle Holocene. Fire-episode frequency began to increase only in the last few millennia. Thus, with the exception again of Bolan and Lost lakes, higher-than-average fire frequency occurred in the early Holocene at summer-dry sites, and lower-than-average fire-episode frequency occurred at summer-wet sites.

These and other published records from the north-western US indicate at least one major shift in fire-episode frequency during the last 2000–3000 years, although the direction of the shift varies from site to site, suggesting that fire regimes have been more variable in the recent past as compared with the early and middle Holocene. At no site is fire-episode frequency constant over the past two millennia. This evidence reinforces the observation that there is no stable fire regime on millennial time scales, because fire-episode frequency varies continuously as a consequence of long-term climate variations and their influence on vegetation (Whitlock *et al.* 2003). Based on dendrochronologic data from giant sequoia, Swetnam (1993) noted a lack of stationarity in fire occurrence on centennial time scales as well. These long tree-ring and charcoal time series suggest that including a recurrent fire-return interval in the definition of a fire regime is not appropriate for time spans of centuries or more, if at all (Whitlock 2004).

Equally evident in Fig. 6*b* are differences in the timing and duration of positive and negative fire anomalies among sites and subregions. These variations suggest that the large-scale controls of climate are just one factor in shaping fire history. Mesoscale climate, vegetation, and physical setting as well as the stochastic nature of fire occurrence in a particular location likely explain much of the fine-scale temporal and spatial variability. Although individual fire reconstructions may be just one realisation of many potential fire-history outcomes, the role of climate in fire

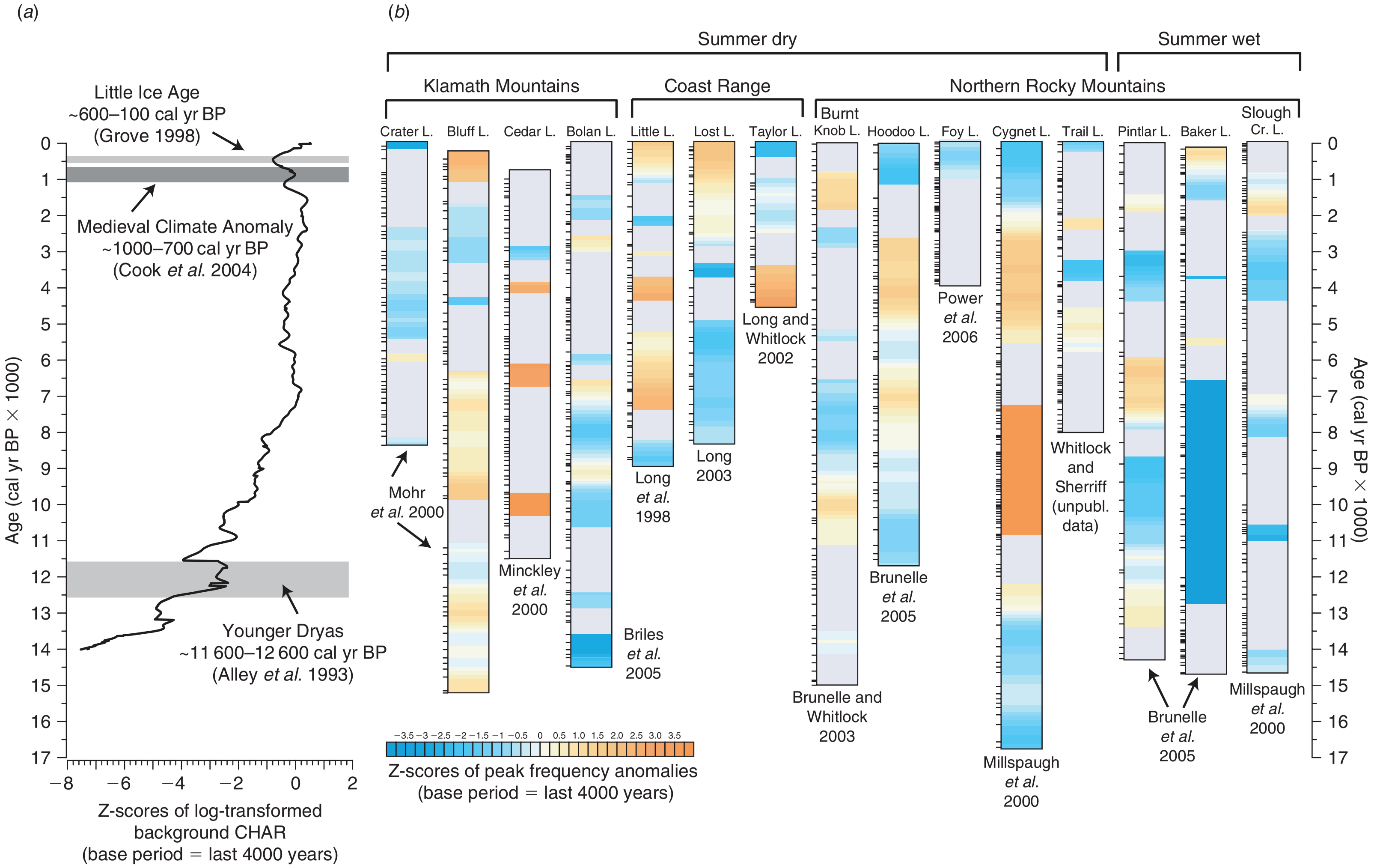

Fig. 6. (*a*) long-term trend in background charcoal accumulation rates summarised for 15 study sites. The trend was produced by calculating a simple mean of the Z-scores of the background components for all 15 background CHAR records at 10-year intervals. (Z-scores were based on the mean and standard deviation of the background component for the last 4000 years of each record.) (*b*) standardised fire-episode frequency anomalies for individual sites. Blue indicates lower-than-average fire-episode frequencies; orange indicates higher-than-average fire-episode frequencies. (Z-scores were based on the mean and standard deviation of the peak-frequency values for the last 4000 years of each record.)

history becomes apparent when similar responses are observed in different settings across the region. The relative importance of regional *v.* local controls may also have shifted through time as noted in a study of two closely spaced sites in south-central British Columbia (Gavin *et al.* 2006). The fire-episode frequency there showed more synchrony in the last 3000 years than in the preceding 3000 years, suggesting a stronger climatic control of fire activity than before.

Conclusions

Long-term records of fire history add a unique dimension to our understanding of fire–climate–vegetation linkages and should help discourage oversimplistic assumptions about current fire regimes and their stability. The following observations are noteworthy:

- Fires are part of natural ecosystem dynamics in the open and closed forests of the north-western USA and have been for millennia. Fire-history data indicate the presence of repeated fires in wet rainforests, subalpine forests, low-elevations forest, and steppe, as well as in tundra. These data confirm that large, stand-replacing fires are part of natural disturbance regimes in the western USA and not simply the result of forest management practices. Although the role of anthropogenic burning in prehistoric times cannot be ruled out in some areas (see Vale 2001), regional coherency in past fire occurrence suggests that climate is and has been the dominant driver of fire regimes at the regional scale (see also Bartlein *et al.* 2008).
- Levels of burned biomass have steadily increased in the last 11 000 years, although there is evidence at some sites of a decline at 2000 cal yr BP (Marlon *et al.* 2006). The close correspondence between long-term charcoal trends and Holocene forest development point to the joint importance of woody fuels and climate in the evolution of fire regimes. A challenge ahead is to identify the cause of the charcoal decline 2000 years ago, and its relationship to shifts in submillennial climate, vegetation and anthropogenic burning activities.
- The paleofire data support the idea that increased spring and summer temperatures and earlier spring snowmelt, observed at present and projected in the future, are likely to be accompanied by ever-greater fire activity (see Westerling *et al.* 2006). For example, a period of higher-than-present fire frequency before 6000 years ago is evident at most sites in the summer-dry regions of the north-western USA and agrees with pollen-based and other paleoclimatic reconstructions of increased summer drought then. The three records from summer-wet regions show the opposite relationship, namely wetter conditions and reduced fire activity during the early Holocene. The linkage between aridity and high forest fire activity in the past is quite convincing, and must have arisen from persistent circulation features as it does today (Trouet *et al.* 2006; Bartlein *et al.* 2008).
- Finally, an understanding of present fire regimes should be embedded in this longer time perspective. Some locations show little change in fire frequency during their entire history. Other sites arrive at present conditions along a trajectory of increasing fire frequency, whereas still others reach modern fire frequency as part of a long-term decline in activity from the early Holocene. Knowledge of the time since the last fire is not adequate to convey the fire history of even recent centuries in most cases. In contrast, fire reconstructions spanning the last 3000–4000 years are able to provide information on the development of the modern fire regime and its association with the establishment of present-day plant communities. Without supporting long-term paleoecologic data, short-sighted inferences about natural disturbance regimes and forest sensitivity are likely to be incorrect and unable to provide critical insights necessary to understand forest response to projected climate changes.

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