Holocene fire activity as a record of past environmental change

Cathy Whitlock and Patrick J. Bartlein

Department of Geography, University of Oregon, Eugene, OR 97403, USA; whitlock@oregon.uoregon.edu; bartlein@uoregon.edu

Introduction

Fire is the dominant form of natural disturbance in temperate forests, and, as such, it serves as a process that modulates forest susceptibility to climate change, disease, and other forms of disturbance. Fire has been identified as an important catalyst of vegetation change during rapid climate shifts in the past (e.g. T. Clark *et al.*, 1996; Swetnam & Betancourt, 1998), and it has been implicated as the primary agent of ecosystem change in the future (e.g. Overpeck *et al.*, 1990, 2003; Watson *et al.*, 2000). At the global scale, biomass burning is considered an important but poorly understood process in the global carbon cycle, one that releases greenhouse gases, aerosols, and particulates to the atmosphere but also sequesters carbon as inert charred matter and ash (Cofer *et al.*, 1997; Watson *et al.*, 2000). At the regional scale, fire plays an essential role in maintaining the integrity of forest ecosystems (MacNeil, 2000; Mills & Lugo, 2001; Nature, 2000). Because of fire's importance as an ecosystem process at large and small scales, it is necessary to understand: (1) the response of fires to past, present, and future climate change for global change assessments; and (2) the role of fire in maintaining forest health and promoting ecosystem change for better forest management.

Like many types of paleoenvironmental data, information on past fires can be interpreted in climatic terms as well as used as an indicator of how particular ecosystems respond to known climate changes. The ultimate objective of paleoenvironmental research is to do both – understand the cause and ecological consequences of climate change. Two sources of paleoecological data provide information on fire-climate interactions. One source, dendrochronological data, includes records of fire-scarred tree-rings and maps showing the distribution of forest-stand ages following fire (see Agee, 1993; Johnson & Gutsell, 1994, for information on methods). Dendrochronological methods provide highly resolved spatial reconstructions of past fire activity, but they are limited by the age of living trees, which spans only the last few centuries in most places. This relatively short duration makes it difficult to examine the role of fire during periods of major climate change. Moreover, tree-ring records are best suited to reconstruct low-intensity ground fires that do not kill trees and often offer little information on the frequency of stand-replacing crown fires, which have become more widespread in western forests in the last two decades.

The second data source is the record of particulate charcoal deposited in lakes and wetlands during and shortly after a fire (see Whitlock & Anderson, 2003; Whitlock & Larsen, 2002, for information on methods). Fire occurrence is identified by sedimentary layers with abundant or above-background levels of charcoal particles. The size and exact location of fires cannot be resolved with the specificity of dendrochronological studies, but charcoal records have the advantage of providing a fire reconstruction that spans thousands of years and encompasses periods of major climate change and vegetation reorganization. Annually resolved fire reconstructions are possible, but in most cases fire history is described in terms of fire episodes (one or more fires) during a time span of years to a few decades.

Fire was recognized as a past and present link between climate change and vegetation response in one chapter (Davis, 1965) of the review volume for the VII Congress of the International Association for Quaternary Research (Wright & Frey, 1965). Since 1965, research in fire history has undergone a renaissance that has improved the use of fire data as both a paleoclimatic and paleoecologic tool. Recent studies consider fire as a proximal cause of vegetation changes and also recognize that vegetation patterns (both spatially and temporally) help shape fire regimes. The role of climate as the ultimate control of both vegetation composition and fire regimes is also widely recognized. In this chapter, we discuss some of the recent advances, including efforts to: (1) better understand the processes that introduce charcoal into lakes and wetlands; (2) refine the methods to interpret these deposits; and (3) evaluate the response of fire to climate and vegetation controls operating on different time scales based on paleoecological evidence, paleoclimate simulations, and modern assessments. We focus this review on research in North America.

Refinements in Charcoal Analysis

The use of charcoal data to reconstruct fire history in North America began in the late 1960s and early 1970s when microscopic charcoal particles (generally $<100\,\mu$m in diameter) were tallied as part of routine pollen analysis. Early on, Swain (1973, 1978) developed a fire reconstruction based on peaks in the ratio of charcoal-to-pollen accumulation in varved-sediment lakes in Wisconsin. Since then, numerous studies have tallied microscopic charcoal particles, sometimes referred to as pollen-slide charcoal, and included the time series on pollen diagrams. Because small particles are carried aloft during a fire and may travel long distances, the source of microscopic charcoal is generally ascribed to regional fires, i.e. fires occurring in the region but not necessarily in the local watershed. The initial research, nicely summarized by Tolonen (1986) and Patterson *et al.* (1987), demonstrates the value of microscopic charcoal for regional fire reconstructions, and Smith & Anderson (1992), Fall (1997), Delcourt

DEVELOPMENTS IN QUATERNARY SCIENCE
VOLUME 1 ISSN 1571-0866
DOI:10.1016/S1571-0866(03)01022-4

© 2004 ELSEVIER B.V.
ALL RIGHTS RESERVED

et al. (1998), Reasoner & Huber (1999) and Carcaillet *et al.* (2001a) provide recent examples of this approach.

Macroscopic Charcoal Analysis

Interest in fire history has shifted from general descriptions of regional-scale incidence or frequency of regional fires to more spatially specific reconstructions of local fires. Local fire records are based on the interpretation of macroscopic particles (generally $>100\,\mu$m in diameter) recovered in sieved residues (e.g. Carcaillet *et al.*, 2001b; Long *et al.*, 1998) and on petrographic thin-sections (e.g. Anderson & Smith, 1997; Clark, 1988b, 1990) from contiguous core samples. Studies that use macroscopic charcoal, emphasize the fire history of the local watershed, and regional reconstructions are based on networks of local records. The attention on local fire reconstructions has necessitated a better understanding of charcoal taphonomy, i.e. the processes that introduce and deposit charcoal to a lake or wetland. The principles of particle motion physics have been used to describe the transport of charcoal particles from a point source, suggesting that particles $>1000\,\mu$m in diameter are deposited near a fire, particles $<100\,\mu$m travel well beyond 100 m, and very small particles are carried great distances before settling (Clark, 1988a; Patterson *et al.*, 1987). Studies of recent fires indicate a sharp decline in macroscopic charcoal beyond the fire margin (Anderson *et al.*, 1986; Clark *et al.*, 1998; Gardner & Whitlock, 2001; Ohlson & Tryterud, 2000; Whitlock & Millspaugh, 1996), and charcoal abundance displays a negative logarithmic distribution away from the source area (Fig. 1A). Within the burned region, charcoal continues to accumulate in lakes in the years after a fire as a result of secondary material transported and deposited from burned slopes and lake margins (Bradbury, 1996; Whitlock & Millspaugh, 1996) (Fig. 1B). These processes of sediment focusing as well as bioturbation may account for the fact that charcoal peaks in sediment cores often span several centimeters.

Calibration of charcoal records comes from comparing the age of charcoal peaks with the timing of known fire events. In the case of varved-sediment records, the correspondence between peaks and known fires may be accurate to the year (Clark, 1990). Macroscopic charcoal records in non-laminated sediments are dated with ^{210}Pb and AMS ^{14}C methods. Charcoal peaks in these sediments match the age of known fire events but with less precision; the best results come from regions with infrequent, high-severity fires that produce abundant charcoal (Millspaugh & Whitlock, 1995; Mohr *et al.*, 2000).

Identification of fire episodes from charcoal record generally involves decomposing the influx data into a background component and a "peaks" component (Clark & Patterson, 1997). The background component is considered to represent secondary material introduced to the lake during intervals between fires, or to measure variations in fuel availability and characteristics, or changes in charcoal delivery processes to the lake. The peaks component represents the charcoal introduced into the lake sediments during and immediately after a particular fire in the "charcoal catchment" of the lake. The sequence of charcoal peaks is the inferred record of fire episodes, from which fire frequency and the inverse, fire return intervals (or time between fires), are calculated. Two approaches have been proposed for the decomposition. Some researchers use a Fourier-series filter (Press *et al.*, 1992) to define the background component, and identify the peaks as positive deviations of the influx series from the background component (e.g. Carcaillet *et al.*, 2001b; Clark & Royall, 1996). The background series is assumed to be composed of many slowly varying sinusoidal components, and a filter used in a particular application can be designed to remove specific long-term variations in the charcoal influx. Another strategy uses a locally weighted moving average to define the background and a threshold ratio to identify peaks (e.g. Brunelle & Anderson, 2003; Hallett & Walker, 2000; Long *et al.*, 1998) (Fig. 2) The first approach is a "global" one in the sense that the background component is determined using information from the entire record, whereas the second is obviously a "local" one that allows for changes in the structure (the variability of the time series of charcoal influx and the shape of its spectrum) over time. Other approaches for performing the decomposition can be envisioned and in practice no single approach may be optimal for all cases.

Other Proxy Indicators of Fire

Other fire proxies complement charcoal-based fire reconstructions and have been used to infer the location and sometimes the size or severity of past fires. Gavin *et al.* (2002) examined charcoal in soil profiles in coastal British Columbia to better identify the location of past fire events recorded by lake-sediment charcoal. The location and the time-since-fire, determined by the age of charcoal particles in the soil sites, varied in wet and dry settings within the watershed. Some wet north-facing exposures, for example, had not burned since the warm, relatively dry conditions of the early Holocene.

Close correspondence between charcoal peaks and changes in key pollen taxa (Green, 1981; Patterson & Backman, 1988; Swain, 1973) or assemblages of pollen taxa that represent different stages of forest succession (Larsen & MacDonald, 1998; Rhodes & Davis, 1995) has been used to infer fire severity. Cross-correlations between pollen taxa and charcoal have helped identify vegetation responses to past fire events. For example, cross-correlation results from a site in northern Alberta revealed increases in the abundance of particular pollen taxa after peaks in pollen-slide charcoal. The succession of pollen types was used as a guide for identifying local fire events and post-fire recovery (Larsen & MacDonald, 1998). On longer time scales, change in abundance of fire-adapted and fire-sensitive taxa in the pollen record have also matched general trends in fire frequency through the Holocene (J. Clark *et al.*, 1996; Hallett & Walker, 2000; Long *et al.*, 1998).

Sugita *et al.* (1997) tried to evaluate the source area of the charcoal signal through the use of computer models that simulate pollen source area. The magnitude of stratigraphic

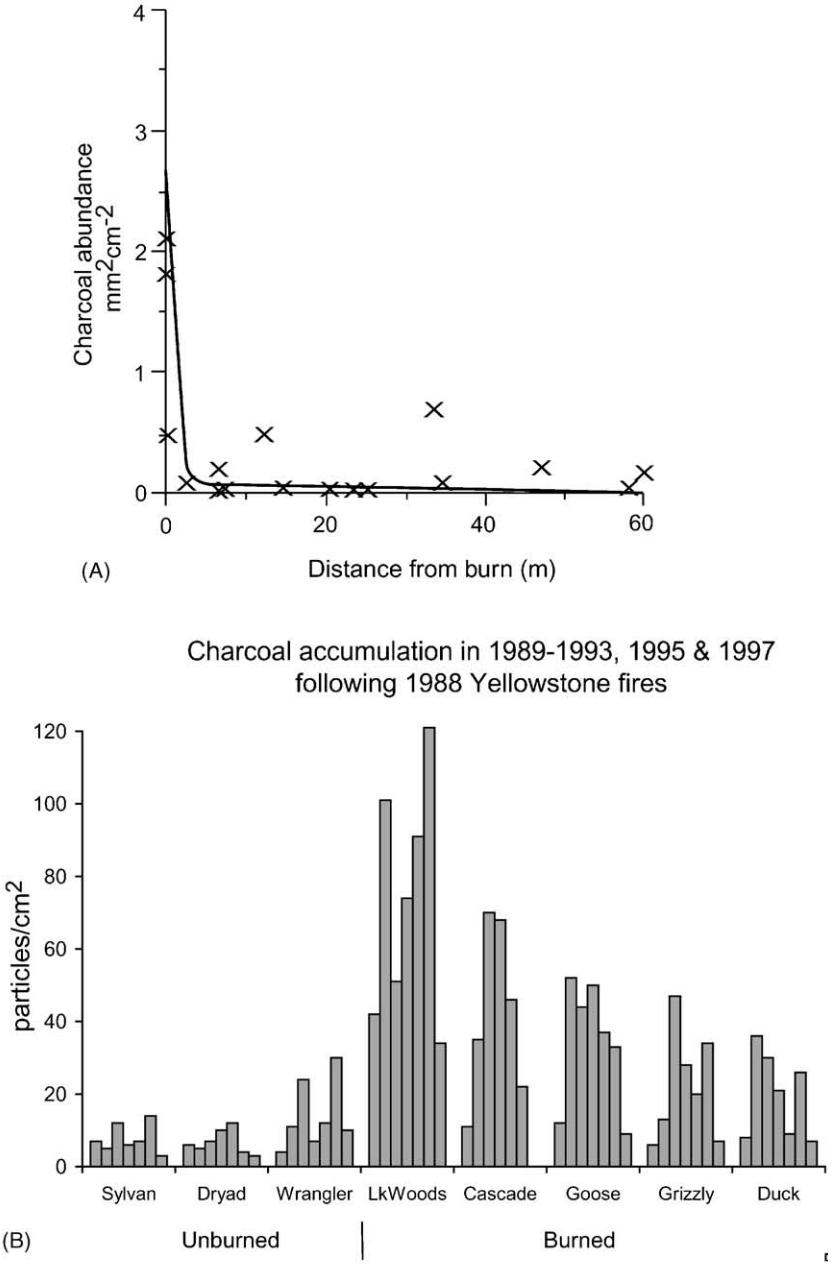
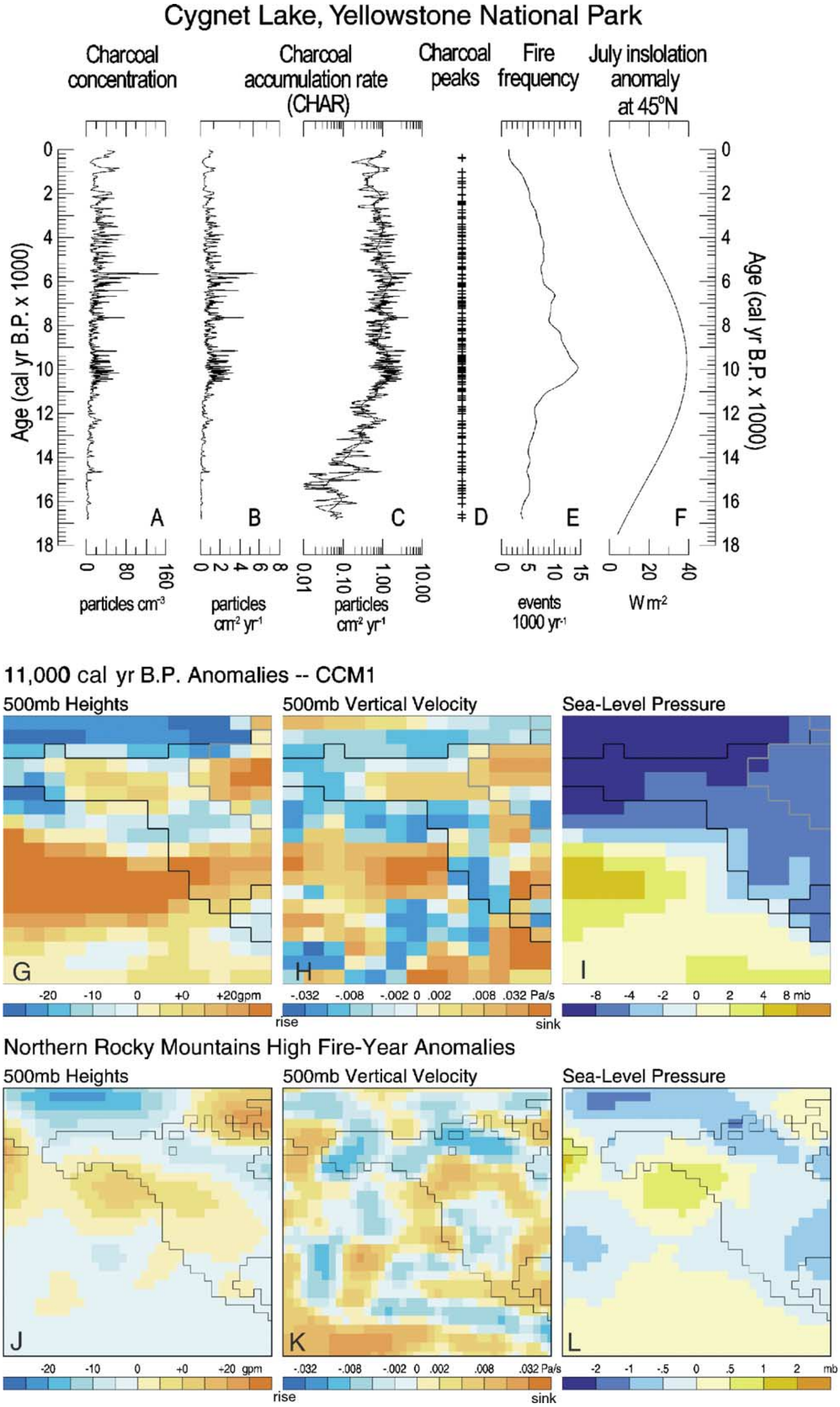


Fig. 1. Relationship between distance from a fire and the deposition of charcoal. A. Empirical evidence from Siberia, which shows that large charcoal particles display a negative exponential distribution away from their source and thus provide information on local watershed fires (after Clark et al., 1998). B. Charcoal accumulation (macroscopic particle abundance in the upper 2 cm of deep-water sediments) into lakes in Yellowstone National Park following the 1988 fires (data from 1989–1993, 1995 and 1997). Lakes in burned and unburned watersheds received charcoal during and immediately after the fire, but burned sites continued to accrue charcoal in the few years after the fire, and levels declined by 1997 (Whitlock & Millspaugh, 1996; unpublished data).

changes in particular fire-sensitive pollen taxa was used to infer the size and location of the fire. The assumption was that local fires would register a change in pollen abundance, but the magnitude of the response would depend on the fire size and distance from the lake and the lake size. These modeling approaches hold great promise for improving the spatial specificity of the fire reconstruction based on charcoal data.

Lithologic variations have also been used to infer the intensity of the fires and confirm their location within a watershed. Peaks of high-magnetic susceptibility in lake-sediment and wetland records have been used to detect pulses of erosion associated with fires and the formation of ferromagnetic minerals (Gedye *et al.*, 2000; Millspaugh & Whitlock, 1995). Fire-induced erosion has also been inferred from increases in the content of aluminum, vanadium, and silt in sediment associated with charcoal peaks (Cwynar, 1978) and increases in varve thickness (Clark, 1990; Larsen & MacDonald, 1998). The usefulness of sediment magnetism and geochemistry as fire proxies depends on the fire location, fire type and intensity, and soils and substrate type.

In summary, the use of charcoal data to reconstruct past fires has become grounded by studies of modern charcoal transport and deposition. High-resolution charcoal analysis of contiguous samples in varved- and non-laminated sediment records provide detailed time series that can be used to reconstruct fire frequency. Microscopic charcoal records offer information on fire activity at the regional scale, whereas macroscopic charcoal data reveal the frequency of local fires. Both approaches have been used to study vegetation and climate change. In addition, explicit consideration of the


Cygnet Lake, Yellowstone National Park
Charcoal concentration
Charcoal accumulation rate (CHAR)
Charcoal peaks
Fire frequency
July insolation anomaly at 45°N
Age (cal yr B.P. x 1000)
0
2
4
6
8
10
12
14
16
18
A
B
C
D
E
F
0 80 160
particles cm-3
0 2 4 6 8
particles cm2 yr-1
0.01 0.10 1.00 10.00
particles cm2 yr-1
0 5 10 15
events 1000 yr-1
0 20 40
W m2
11,000 cal yr B.P. Anomalies -- CCM1
500mb Heights
500mb Vertical Velocity
Sea-Level Pressure
G
H
I
-20 -10 0 +0 +20gpm
-.032 -.008 -.002 0 .002 .008 .032 Pa/s
rise
sink
-8 -4 -2 0 2 4 8 mb
Northern Rocky Mountains High Fire-Year Anomalies
500mb Heights
500mb Vertical Velocity
Sea-Level Pressure
J
K
L
-20 -10 0 +0 +20 gpm
-.032 -.008 -.002 0 .002 .008 .032 Pa/s
rise
sink
-2 -1 -.5 0 .5 1 2 mb

components that comprise charcoal records has improved fire reconstructions. The trends in macroscopic charcoal time-series provide information on changes in biomass and fuel availability through time, while the high-frequency signal denotes variations in fire frequency. As a result of these advances, charcoal and related fire proxy data are effective tools for studying both fire-vegetation and fire-climate relations in the past.

Modern and Past Fire-Climate Linkages

Fire Weather and Fire Climate

A better understanding of fire weather and fire climatology offers opportunities to refine the use of fire history data to discern fire-climate relationships in the past. Like many other environmental events (e.g. floods, avalanches), fires reflect both concurrent and antecedent conditions. *Fire weather* is the assemblage of specific meteorological conditions that vary on hourly and daily time scales and control the ignition, spread, and suppression of individual fires; *fire climate* consists of atmospheric circulation configurations and the attendant surface-climate anomalies that persist over time spans of weeks to seasons to years. The likelihood of fire in a given year is determined by particular weather conditions and their influence on fuel moisture, precipitation, relative humidity, lightning, air temperature, and wind (Pyne *et al.*, 1996; Weber & Flannigan, 1997). These weather conditions are embedded in large-scale climate anomalies, involving the strength of subtropical high-pressure systems, the location of upper-level ridges and troughs (and the moisture fluxes and vertical motions they govern), and the specific location of convectional storms during the fire season (Johnson & Wowchuk, 1993; Nash & Johnson, 1995; Skinner *et al.*, 1999, 2002).

Specific mechanisms link both large-scale and secondary circulation features with what happens at the surface in a particular region. This link has been described for specific regions in North America (e.g. Skinner *et al.*, 1999, 2002; Weber & Flannigan, 1997) to infer: (1) the anomalous components of mid-tropospheric flow, which in turn enhance or deflect the flow of moisture into a region; (2) the location of persistent ridges and troughs, which enhance or suppress precipitation through their influence on vertical motions; and (3) the effects of these components on cloudiness and surface energy balances, which influence soil and fuel moisture. Some studies have attempted to bridge these scales by considering statistical relationships between synoptic-scale atmospheric circulation patterns and specific fire-related meteorological variables (Flannigan & Harrington, 1988; Klein *et al.*, 1996; Roads *et al.*, 2000). Others have considered the remote controls of regional climate anomalies (e.g. North Pacific sea-surface temperatures) and regional area burned (Flannigan *et al.*, 2000).

Modern studies disclose the nature of fire-climate linkages on short time scales. On inter-annual time scales, fire activity inferred from dendrochronological data in many areas of North America is correlated with climate variations arising from atmosphere/ocean interactions, like the El Niño-Southern Oscillation (ENSO) (Swetnam & Betancourt, 1990, 1992; Veblen *et al.*, 2000). Likewise, decades of higher-than-normal precipitation (and fuel build-up) are often associated with significant fires when they are interrupted by drought episodes that reduce fuel moisture (Swetnam & Betancourt, 1998). Shifts between El Niño and La Niña phases or in the decadal-scale climate variability determine drought severity during a particular fire season or years, as well as the accumulation of fuels in previous years. This alternation of wet and dry episodes has been shown to be important in shaping the fire regime of the last few centuries, especially in low-elevation conifer forests (e.g. Clark, 1988c; Grissino-Mayer & Swetnam, 2000) and grasslands (Clark *et al.*, 2002).

Fire-Climate Linkages on Holocene Time Scales

On century and longer time scales ($>10^2$ years), large-scale changes in the climate system caused by variations in the seasonal cycle of insolation, atmospheric composition, and atmosphere-ocean interactions emerge as important controls of the fire regime. Variations in the seasonal cycle of insolation on orbital time scales (10^3–10^5 years) govern the slowly varying components of the climate system, and these apparently shape the long-term fire regime and vegetation. High-resolution charcoal records provide an opportunity to examine changes in fire activity in response to changes in the large-scale controls. For example, a record from Cygnet Lake in Yellowstone National Park was examined to reconstruct the fire history of the last 17,000 years, and compare it with changes in summer insolation that varied the intensity of

←

Fig. 2. A–F. Cygnet Lake, Yellowstone National Park (Millspaugh et al., 2000) provides an example of the charcoal decomposition approach of Long et al. (1998). A. Charcoal concentration calculated in contiguous samples; B. Data re-expressed as charcoal accumulation rates; C–D. Data decomposed into background trend (smooth curve) and charcoal peaks above background (Peaks are inferred to be fire episodes); E. Locally weighted frequency of charcoal peaks per 1000 years; F. Summer insolation anomaly. (Comparison of E and F suggests that time of maximum fires and the broad rise and fall of fire frequency is governed by the influences of the insolation anomaly.) G–L. Climate patterns shown in GCM simulations and modern NCEP data provide an explanation for high-fire activity noted at Cygnet Lake. G–I. 11,000 cal yr B.P.-minus-present anomalies of July 500 mb heights, vertical velocity, sea-level pressure, as simulated by a GCM Kutzbach et al. (1998; see also Bartlein et al., 1998). J–L. Composite anomalies for same variables in NCEP data (Kalnay et al., 1996; Kistler et al., 2001) for recent years of large-area burned in Montana.

drought in the region (Millspaugh *et al.*, 2000) (Fig. 2). The record suggested that fire frequency in the early Holocene (between 10,000 and 11,000 cal yr B.P.) reached a maximum of 10–15 episodes/1000 years, in contrast to frequencies of <5 episodes/1000 years over the last few thousand years (Millspaugh *et al.*, 2000).

A comparison of modern climate during high-area burned years with paleoclimate model simulations produced by general circulation models elucidates the large-scale climate features that give rise to fires in the region, both at present and in the early Holocene (Fig. 2). Despite the radical difference in the boundary conditions between the present and 11,000 cal yr B.P. (most notably the still-large ice sheet and greater-than-present summer insolation at 11,000 cal yr B.P.), the anomaly patterns look broadly similar. They are also similar in scale and patchiness, suggesting that the large-scale settings of years (or millennia) with frequent fires are similar (see figure legend for further discussion). In this example, the large-scale control – variations in summer insolation – affected past fire activity through changes in the same features of atmospheric circulation that influence the intensity of summer aridity and fire occurrence at present. The similarity suggests the intriguing hypothesis that circulation patterns that characterized the mean climatic state during the early Holocene resemble anomalous circulation patterns that occur as components of inter-annual circulation variations at present.

In the western U.S., Holocene fire reconstructions have been used to study the fire and climate histories of two precipitation regimes that are evident in the climate at present. One regime is centered in the Pacific Northwest and receives little precipitation in summer and hence the summer-to-annual precipitation ratio is low. In this summer-dry regime, summer conditions are influenced by the northerly position of the northeast Pacific subtropical high-pressure system, which brings dry stable conditions. Cygnet Lake lies in this precipitation regime. In contrast, the summer-wet regime receives relatively high summer precipitation at present as a result of the influence of monsoonal precipitation. This regime is well developed in the American Southwest, but summer precipitation maxima are also evident in the Great Plains and parts of the northern Rockies. During the early Holocene, these two precipitation regimes intensified in the western U.S. as a result of greater-than-present insolation in summer (Bartlein *et al.*, 1998; Fall *et al.*, 1995; Mock & Brunelle-Daines, 1999; Whitlock & Bartlein, 1993). Areas under the influence of the subtropical high became drier as summer insolation directly increased temperatures and decreased effective moisture and indirectly strengthened the subtropical high. In the summer-wet regime, temperatures were higher as a result of the direct effects of greater insolation, and summer precipitation increased as a result of stronger onshore flow.

Shifts in long-term fire frequency in summer-dry and summer-wet regions probably reflect variations in fuel moisture as a result of shifts in the relative importance of winter and summer precipitation. The influence of a stronger-than-present subtropical high in the early Holocene is evident in fire reconstructions from the summer-dry regions of the Pacific Northwest and northern Rockies. Fire frequency was high before and at ca. 7000 cal yr B.P., coincident with the timing of maximum summer drought, and declined to present day as the climate became wetter (Fig. 3A). Fire activity declined in the late Holocene as the climate became cooler and wetter and present vegetation was established. This response is also registered at sites in the mixed conifer forests of the Klamath Mountains of northern California, although less clearly because fires are generally more frequent there and the sedimentation rates of the lakes are very slow. Especially high periods of fire activity took place at ca. 8000, 4000, and 1000 cal yr B.P. (Fig. 3A). The number of fire episodes (charcoal peaks) varied among regions depending on the fuel conditions and severity of drought. For example, fires were less frequent in the relatively wet Coast Range, more common in the summer-dry regions of the Rocky Mountains, and very common in the dry forests of the Klamath region. Despite differences in fire frequency among summer-dry regions, the temporal trends in fire occurrence, governed by large-scale circulation features, show similarities.

The summer-wet sites of the northern Rockies (Pintlar and Baker lakes) and in Yellowstone National Park (Slough Creek Lake) featured low fire occurrence in the early Holocene and highest fire activity in the late Holocene. This shift in fire frequency is consistent with the effects of the amplification of the seasonal cycle of insolation in areas strongly influenced by the summer monsoon. Higher-than-present summer precipitation suppressed fires in the early Holocene as a result of stronger onshore flow; as summer insolation decreased and monsoons weakened in the middle and late Holocene, fire activity increased. The summer-wet sites also record high fire frequency in the late-glacial period, perhaps in response to higher-than-present summer insolation but weaker monsoonal circulation than in the early Holocene.

Charcoal records from 30 sites in Quebec also disclose variations in summer precipitation through the Holocene (Carcaillet & Richard, 2000; Fig. 4). Examination of recent years of high area burned in eastern Canada suggests that the fire seasons are associated with the development of an anomalous upper-level ridge immediately over and upstream of east-central Canada (Skinner *et al.*, 1999, 2002). During these years, more meridional circulation deflects moisture-bearing systems away from southern Quebec. The records show higher fire incidence in the early Holocene, followed by a shift to fewer fires after 8000 cal yr B.P. (Carcaillet & Richard, 2000). Fire activity increased after 3000 cal yr B.P. and remained high to the present at several sites. Early-Holocene drought is attributed to the effects of higher-than-present summer insolation and locally dry conditions at the margin of the ice sheet. Inferred greater dominance of humid Atlantic air masses over Canada in middle Holocene summers led to fewer fires than before. More frequent incursion of dry Pacific air or cool Arctic air in summers resulted in more fires after 3000 cal yr B.P. The fire regime shifts occur independently of the vegetation changes, suggesting the control of climate for fire conditions is different from that for vegetation change (Carcaillet *et al.*, 2001a).

Fire variations on centennial scales are evident in dendrochronological and lake-sediment records across

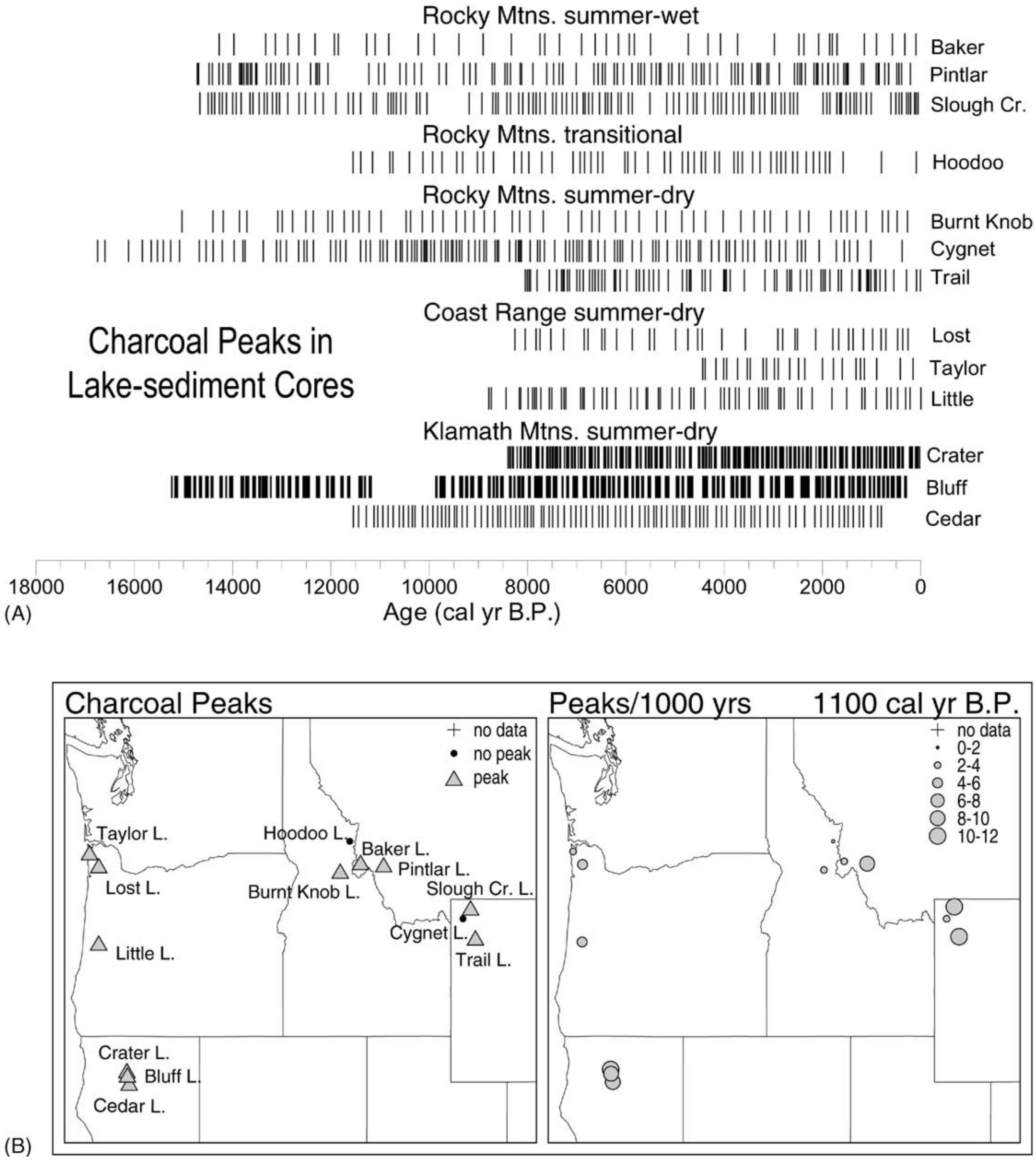


Fig. 3. A. Macroscopic charcoal peaks in lake-sediment records from summer-wet and summer-dry climate regions in the northwestern United States. Charcoal peaks are the occurrence of charcoal accumulation values above background values and interpreted as "fire episodes" within the watersheds of the lakes. B. Sites with fire activity at ca. 1100–1200 cal yr B.P. as shown by the presence of charcoal peaks. This period falls within the so-called Medieval Warm Period when fire frequency was high at many sites, as evidenced by the number of charcoal peaks/1000 years. Reference to lake sites: Baker, Pintlar, and Hoodoo lakes (Brunelle, 2002); Burnt Knob Lake (Brunelle & Whitlock, 2003); Slough Creek Lake (Millspaugh & Whitlock, 2003); Cygnet Lake (Millspaugh et al., 2000); Trail Lake and Cedar Lake (Whitlock, R. Sherriff, and T. Minckley, unpublished data); Taylor Lake (Long & Whitlock, 2002); Lost Lake (Long, 2003); Little Lake (Long et al., 1998); Crater and Bluff lakes (Mohr et al., 2000).

North America. For example, increased fire activity is noted between 800 and 1200 cal yr B.P. – the so-called Medieval Warm Period – in Yellowstone National Park (Meyer *et al.*, 1995; Millspaugh & Whitlock, 2003), the Sierra Nevada (Swetnam, 1993; Brunelle & Anderson, 2003), the Klamath Mountains (Mohr *et al.*, 2000), and the northern Rocky Mountains (Brunelle, 2002; Hallett & Walker, 2000) (Fig. 3B). Synchronization of fire activity across regions that display different climate responses on millennial time scales suggests that short-term variations in climate can override the long-term controls. The situation is not unlike recent years (e.g. 1988, 1996, and 2000) when large areas burned in the West as a result of anomalous drought and fuel buildup.

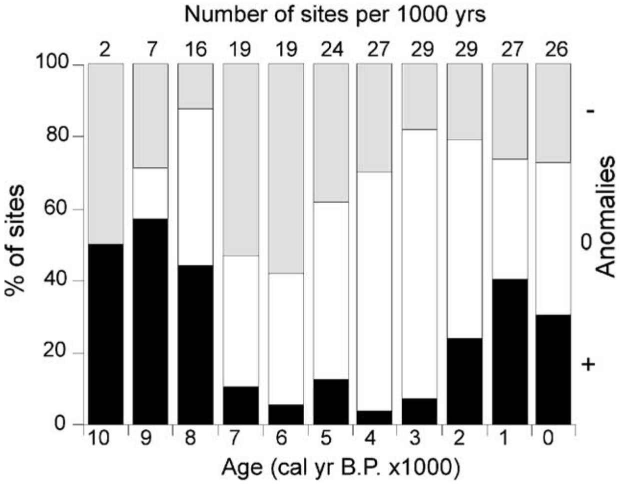


Fig. 4. Variations in fire activity during the Holocene based on microscopic charcoal records from Quebec. The data are presented as charcoal abundance anomalies calculated at 1000-year intervals, in which charcoal influx at a particular interval is compared with the mean charcoal influx over entire Holocene at each site. Below average fire activity is gray; above average is black (based on Carcaillet & Richard, 2000).

Discussion

The growing network of high-resolution fire reconstructions, based on charcoal analysis of lake-sediment records, offers a new proxy by which to study climate change and climate variability in the Holocene. The strength of charcoal data as a paleoclimatic tool rests on understanding the controls of fire regimes and the climate and weather conditions that accumulate and dessicate fuels and create ignitions. In grassland regions, wet years give rise to frequent fires because they allow build-up of fine fuels necessary to spread fires, whereas in forested regions, fire activity increases in dry seasons when fuels dry out. In xeric forests, previous years or seasons are as critical in determining the fire regime as is the season of fire occurrence; in mesic forests, fire events correlate best with climate anomalies of the fire season, with little antecedent influence (Westerling *et al.*, 2003). In other words, one rule does not apply to all fire-climate systems, and this complexity makes the reconstruction of past climate conditions from fire history information particularly challenging.

Charcoal analysis has undergone considerable refinement in the recent decades with improvements in the understanding of charcoal taphonomy and the interpretation of charcoal data. Local fire histories of relatively high precision are obtained from an examination of macroscopic charcoal records, and these records are used to infer variations in fire episodes through time. Microscopic charcoal data also provide fire-history information, but at a more generalized regional scale. Additional fire proxies, including high-resolution pollen data, soil charcoal, and lithologic and geochemical information, enhance fire-history interpretations. The growing network of charcoal records from North America shows variations in fire history that are fairly coherent within climate regions and reasonable in light of our understanding of changes in climate and vegetation during the Holocene.

Better appreciation of the climate conditions that give rise to fires on daily-to-annual time scales has furthered fire-history research from the standpoints of description (Where did fires occur and when?) and hypothesis testing (How does the fire history record provide a series of natural experiments to test fire-climate relationships under different climatic controls?). Modern climate data help reveal the large-scale atmospheric circulation features that promoted large severe fires in recent years. With the use of paleoclimate model simulations, it is possible to examine the frequency of such conditions through the Holocene and ascertain how past variations in fire frequency are related to droughts on annual-to-decadal times scales (e.g. ENSO and PDO [Pacific Interdecadal Oscillation]) and on centennial time scales (e.g. Medieval Warm Period). On longer time scales, the role of more slowly varying components of the climate system, such as changes in the seasonal cycle of insolation, atmospheric composition, sea-surface temperatures and ice-sheet size, on fire regimes comes into play.

Current collaborations among fire historians, climatologists, and paleoclimatologists promise to lead to the development of new conceptual models that explain the causes of variations in fire incidence on different spatial and temporal scales. Insights gained from understanding fire-climate-vegetation relations in the past are an essential part of this effort. For example, information on the climate conditions conducive to past fires helps assess the role of fire in the face of projected changes in climate resulting from global warning. Moreover, close comparison of fire and other paleoecological records discloses the ecological consequences of changing fire regimes and plant communities, and this information can help guide management decisions that consider the role of natural disturbance in current and future forests. Examination of a network of fire-history records that span a range of past conditions will help discern the relative importance of fuel build-up vs. climate change during current fire years. Thus, the paleoecological perspective provides an understanding of the ecological and environmental conditions that promote individual fires, create particular fire regimes and determine the natural range of variability in this important ecosystem process.

Summary

Recent advances in fire-history research have enabled the use of charcoal records both as a proxy of climate change and as a tool for examining the response of ecosystems to disturbance. High-resolution charcoal records, obtained from the sediments of lakes and wetlands, are available from several sites in North America and provide information on changes in fire regime occurring on annual-to-millennial time scales during the Holocene. Such reconstructions are supported by studies of recent fires that identify the charcoal source area and processes of charcoal deposition, as well as modern fire-climate-vegetation interactions. When charcoal time series are decomposed, it is possible to distinguish between a slowly varying component that represents variation in fuel composition and hydrology, and charcoal peaks that signify fire episodes. Associated pollen records complement the reconstruction by disclosing past changes in vegetation following individual fires, the role of vegetation in shaping fire regimes, and the long-term consequences of changes in the fire regime on vegetation. The influence of large-scale controls of climate on fire patterns, including variations in summer insolation during the Holocene, is evident in the temporal and spatial variations in fire reconstructions in western and northeastern North America and from an analysis of atmospheric circulation features that give rise to fires.

Acknowledgments

The research described in this paper was supported by grants from the National Science Foundation (ATM-0117160, EAR-9906100). We appreciate the use of unpublished data provided by Colin Long, Tom Minckley, and Rosemary Sherriff, and the help of Andrea Brunelle and Jennifer Marlon in assembling the charcoal database. We thank Bryan Shuman and an anonymous reviewer for helpful comments on the manuscript.

References

Agee, J.K. (1993). *Fire Ecology of Pacific Northwest Forests*. Washington, DC, Island Press, 493 pp.

Anderson, R.S., Davis, R.B., Miller, N.G. & Stuckenrath, R. (1986). History of the late- and post-glacial vegetation and disturbance around Upper South Branch Pond, northern Maine. *Canadian Journal of Botany*, **64**, 1977–1986.

Anderson, R.S. & Smith, S.J. (1997). The sedimentary record of fire in montane meadows, Sierra Nevada, California, USA: A preliminary assessment. *In*: Clark, J.S., Cachier, H., Goldammer, J.G. & Stocks, B. (Eds), *Sediment Records of Biomass Burning and Global Change*. Berlin, Springer Verlag, NATO ASI Series 1: Global Environmental Change, **51**, 313–328.

Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb, R.S., Webb, T., III & Whitlock, C. (1998). Paleoclimate simulations for North America over the past 21,000 years: Features of the simulation climate and comparisons with paleoenvironmental data. *Quaternary Science Reviews*, **17**, 549–585.

Bradbury, J.P. (1996). Charcoal deposition and redeposition in Elk Lake, Minnesota, USA. *The Holocene*, **6**, 339–344.

Brunelle, A. (2002). Holocene changes in fire, climate and vegetation in the northern Rocky Mountains of Idaho and western Montana. Ph.D. dissertation. Eugene, University of Oregon.

Brunelle, A.R. & Anderson, R.S. (2003). Sedimentary charcoal as an indicator of late-Holocene drought in the Sierra Nevada, California, and its relevance to the future. *The Holocene*, **13**, 21–28.

Brunelle, A. & Whitlock, C. (2003). Postglacial fire, vegetation, and climate history in the Clearwater Range, Northern Idaho, USA. *Quaternary Research* (in press).

Carcaillet, C. & Richard, P.J.H. (2000). Holocene changes in seasonal precipitation highlighted by fire incidence in eastern Canada. *Climate Dynamics*, **16**, 549–559.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S. & Prairie, Y.T. (2001a). Change of fire frequency in the eastern Canadian boreal forests during the Holocene: Does vegetation composition or climate trigger the fire regime? *Journal of Ecology*, **89**, 930–946.

Carcaillet, C., Bouvier, M., Larouche, A.C. & Richard, P.J.H. (2001b). Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. *The Holocene*, **11**, 476–547.

Clark, J.S. (1988a). Particle motion and the theory of stratigraphic charcoal analysis: Source area, transport, deposition, and sampling. *Quaternary Research*, **30**, 67–80.

Clark, J.S. (1988b). Stratigraphic charcoal analysis on petrographic thin sections: Applications to fire history in northwestern Minnesota. *Quaternary Research*, **30**, 81–91.

Clark, J.S. (1988c). Drought cycles, the 'Little Ice Age' and fuels: A 750 yr record of fire in northwestern Minnesota. *Nature*, **334**, 233–235.

Clark, J.S. (1990). Fire and climate change during the last 750 years in northern Minnesota. *Ecological Monographs*, **60**, 135–159.

Clark, J.S. & Patterson, W.A. (1997). Background and local charcoal in sediments: Scales of fire evidence in the paleorecord. *In*: Clark, J.S., Cachier, H., Goldammer, J.G. & Stocks, B. (Eds), *Sediment Records of Biomass Burning and Global Change*. Berlin, Springer Verlag, NATO ASI Series 1: Global Environmental Change, **51**, 23–48.

Clark, J.S. & Royall, P.D. (1996). Local and regional sediment charcoal evidence for fire regimes in presettlement northeastern North America. *Journal of Ecology*, **84**, 365–382.

Clark, J.S., Royall, P.D. & Chumbley, C. (1996). The role of fire during climate change in an eastern deciduous forest at Devil's Bathtub, New York. *Ecology*, **77**, 2148–2166.

Clark, J.S., Lynch, J., Stocks, B. & Goldammer, J. (1998). Relationships between charcoal particles in air and sediments in West-central Siberia. *The Holocene*, **8**, 19–29.

Clark, J.S., Grimm, E.C., Donovan, J.J., Fritz, S.C., Engstrom, D.R. & Almendinger, J.E. (2002). Drought cycles and landscape responses to past aridity on prairies of the northern Great Plains, USA. *Ecology*, **83**, 595–601.

Clark, T.L., Jenkins, M.A., Coen, J. & Packham, D. (1996). A coupled atmosphere-fire model: Convective feedback on fire-line dynamics. *Journal of Applied Meteorology*, **35**, 875–901.

Cofer, W.R., Koutzenogii, K.P., Kokorin, A. & Excurra, A. (1997). Biomass burning emissions and the atmosphere. *In*: Clark, J.S., Cachier, H., Goldammer, J.G. & Stocks, B.

(Eds), *Sediment Records of Biomass Burning and Global Change*. Berlin, Springer Verlag. NATO ASI Series 1: Global Environmental Change, **51**, 169–188.

Cwynar, L.C. (1978). Recent history of fire and vegetation from annually laminated sediment of Greenleaf Lake, Algonquin Park, Ontario. *Canadian Journal of Botany*, **56**, 10–12.

Davis, M.B. (1965). Phytogeography and palynology of northeastern United States. *In*: Wright, H.E., Jr. & Frey, D.G. (Eds), *The Quaternary of the United States*. Princeton New Jersey, Princeton University Press, 377–401.

Delcourt, P.A., Delcourt, H.R., Ison, C.R., Sharp, W.E. & Gremillion, K.J. (1998). Prehistoric human use of fire, the eastern agricultural complex, and Appalachian oak-chestnut forests: Paleoecology of Cliff Palace Pond, Kentucky. *American Antiquity*, **63**, 263–278.

Fall, P.L. (1997). Fire history and composition of the subalpine forest of western Colorado during the Holocene. *Journal of Biogeography*, **24**, 309–325.

Fall, P.L., Davis, P.T. & Zielinski, G.A. (1995). Late Quaternary vegetation and climate of the Wind River Range, Wyoming. *Quaternary Research*, **43**, 393–404.

Flannigan, M.D. & Harrington, J.B. (1988). A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada 1953–1980. *Journal of Applied Meteorology*, **27**, 66–72.

Flannigan, M., Todd, B., Wotton, M., Stocks, B., Skinner, W. & Martell, D. (2000). Pacific sea surface temperatures and their relation to area burned in Canada. *Third Symposium on Fire and Forest Meteorology*. Boston, Massachusetts, American Meteorological Society, 151–157.

Gardner, J.J. & Whitlock, C. (2001). Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. *The Holocene*, **11**, 541–549.

Gavin, D.G., Brubaker, L.B. & Lertzman, K.P. (2002). Holocene fire history of a coastal temperate rainforest based on soil charcoal radiocarbon dates. *Ecology* (in press).

Gedye, S.J., Jones, R.T., Tinner, W., Ammann, B. & Oldfield, F. (2000). The use of mineral magnetism in the reconstruction of fire history: A case study from Lago di Origlio, Swiss Alps. *Palaeogeography, Palaeoclimatology, and Palaeoecology*, **164**, 101–110.

Green, D.G. (1981). Time series and postglacial forest ecology. *Quaternary Research*, **15**, 265–277.

Grissino-Mayer, H.D. & Swetnam, T.W. (2000). Century-scale climate forcing of fire regimes in the American Southwest. *The Holocene*, **10**, 213–220.

Hallett, D.J. & Walker, R.C. (2000). Paleoecology and its application to fire and vegetation management in Kootenay National Park, British Columbia. *Journal of Paleolimnology*, **24**, 401–414.

Johnson, E.A. & Gutsell, S.L. (1994). Fire frequency models, methods and interpretations. *Advances in Ecological Research*, **25**, 239–287.

Johnson, E.A. & Wowchuk, D.R. (1993). Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Canadian Journal of Forest Research*, **23**, 1213–1222.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R. & Joseph, D. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, **77**, 437–472.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R. & Fiorino, M. (2001). The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation. *Bulletin of the American Meteorological Society*, **82**, 247–267.

Klein, W.H., Charney, J.J., McCutchan, M.H. & Benoit, J.W. (1996). Verification of monthly mean forecasts for fire weather elements in the contiguous United States. *Journal of Climate*, **9**, 3317–3327.

Kutzbach, J.E., Gallimore, R., Harrison, S., Behling, P., Selin, R. & Laarif, R. (1998). Climate and biome simulations for the past 21,000 years. *Quaternary Science Reviews*, **17**, 473–506.

Larsen, C.P.S. & MacDonald, G.M. (1998). An 840-year record of fire and vegetation in a boreal white spruce forest. *Ecology*, **79**, 106–118.

Long, C.J. (2003). Holocene fire and vegetation history of the Oregon Coast Range. Ph.D. dissertation. Eugene, University of Oregon.

Long, C.J. & Whitlock, C. (2002). Fire and vegetation history from the coastal rain forest of the western Oregon Coast Range. *Quaternary Research*, **58**, 215–225.

Long, C.J., Whitlock, C., Bartlein, P.J. & Millspaugh, S.H. (1998). A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Canadian Journal of Forest Research*, **28**, 774–787.

MacNeil, J.S. (2000). Forest fire plan kindles debate. *Science*, **289**, 1448–1449.

Meyer, G.A., Wells, S.G. & Jull, A.J.T. (1995). Fire and alluvial chronology in Yellowstone National Park: Climatic and intrinsic controls on Holocene geomorphic processes. *Geological Society of America Bulletin*, **107**, 1211–1230.

Mills, T.J. & Lugo, A.E. (2001). The long-term answer: Fight fire with research. *Nature*, **409**, 452.

Millspaugh, S.H. & Whitlock, C. (1995). A 750-year fire history based on lake sediment records in central Yellowstone National Park. *The Holocene*, **5**, 283–292.

Millspaugh, S.H. & Whitlock, C. (2003). Postglacial fire, vegetation, and climate history of the Yellowstone-Lamar and Central Plateau provinces, Yellowstone National Park. *In*: Wallace, L. (Ed.), *After the Fires: The Ecology of Change in Yellowstone National Park*. New Haven, Connecticut, Yale University Press (in press).

Millspaugh, S.H., Whitlock, C. & Bartlein, P.J. (2000). Variations in fire frequency and climate over the last 17,000 years in central Yellowstone National Park. *Geology*, **28**, 211–214.

Mock, C.J. & Brunelle-Daines, A.R. (1999). A modern analogue of western United States summer palaeoclimate at 6000 years before present. *The Holocene*, **9**, 541–545.

Mohr, J.A., Whitlock, C. & Skinner, C.J. (2000). Postglacial vegetation and fire history, eastern Klamath Mountains, California. *The Holocene*, **10**, 587–601.

Nash, C. & Johnson, E.A. (1995). Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. *Canadian Journal of Forest Research*, **26**, 1859–1874.

Nature (2000). Seeing the wood for the trees, **406**, 661.

Ohlson, M. & Tryterud, E. (2000). Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal. *The Holocene*, **10**, 519–525.

Overpeck, J.T., Rind, D. & Goldberg, R. (1990). Climate-induced changes in forest disturbance and vegetation. *Nature*, **343**, 51–53.

Overpeck, J.T., Whitlock, C. & Huntley, B. (2003). Terrestrial biosphere dynamics in the climate system: Past and future. *In*: Bradley, R.S. & Pedersen, T. (Eds), *Causes and Consequences of Past Climate Variations*. International Geosphere Biosphere Project Book Series: New York: Springer, 81–103.

Patterson, W.A., III, Edwards, K.J. & MacGuire, D.J. (1987). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews*, **6**, 3–23.

Patterson, W.A. III & Backman, A.E. (1988). Fire and disease history of forests. *In*: Huntley, B. & Webb, T. III (Eds), *Vegetation History*. Dordrecht, Kluwer Academic Publishers, 603–632.

Press, W.H., Flannery, B.P., Teukolsky, S.A. & Vetterling, W.T. (1992). *Numerical recipes*. Cambridge, Cambridge University Press, 963 pp.

Pyne, S.J., Andrews, P.L. & Laven, R.D. (1996). *Introduction to Wildland Fire*. New York, John Wiley and Sons, 769 pp.

Reasoner, M.A. & Huber, U.M. (1999). Postglacial palaeoenvironments of the upper Bow Valley, Banff National Park, Alberta, Canada. *Quaternary Science Reviews*, **18**, 475–492.

Rhodes, T.E. & Davis, R.B. (1995). Effects of late Holocene forest disturbance and vegetation change on acidic Mud Pond, Maine, USA. *Ecology*, **76**, 734–746.

Roads, J.O., Chen, S.-C., Fujioka, F.M. & Burgan, R.E. (2000). Development of a seasonal fire weather forecast for the contiguous United States. *Third Symposium on Fire and Forest Meteorology*. Boston Massachusetts, American Meteorological Society, 99–102.

Skinner, W.R., Stocks, B.J., Martell, D.L., Bonsal, B. & Shabbar, R. (1999). The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. *Theoretical and Applied Climatology*, **63**, 89–105.

Skinner, W.R., Flannigan, M.D., Stock, B.J., Martell, D.L., Wooton, B.M., Todd, J.B., Mason, J.A., Logan, K.A. & Bosch, E.M. (2002). A 500hPa synoptic wildland fire climatology for large Canadian forest fires, 1959–1996. *Theoretical and Applied Climatology*, **71**, 157–169.

Smith, S.J. & Anderson, R.S. (1992). Late Wisconsin paleoecologic record from Swamp Lake, Yosemite National Park, California. *Quaternary Research*, **38**, 91–102.

Sugita, S., MacDonald, G.M. & Larsen, C.P.S. (1997). Reconstruction of fire disturbance and forest succession from fossil pollen in lake sediments: Potential and limitations. *In*: Clark, J.S., Cachier, H., Goldammer, J.G. & Stocks, B. (Eds), *Sediment Records of Biomass Burning and Global Change*. Berlin, Springer Verlag, NATO ASI Series 1: Global Environmental Change, **51**, 387–412.

Swain, A.M. (1973). A history of fire and vegetation in northeastern Minnesota as recorded in lake sediments. *Quaternary Research*, **3**, 383–396.

Swain, A.M. (1978). Environmental changes during the past 2000 yr in north-central Wisconsin: Analysis of pollen, charcoal and seeds from varved lake sediments. *Quaternary Research*, **10**, 55–68.

Swetnam, T.W. (1993). Fire history and climate change in Giant Sequoia groves. *Science*, **262**, 885–889.

Swetnam, T.W. & Betancourt, J.L. (1990). Fire-Southern Oscillation relations in the Southwestern United States. *Science*, **249**, 1017–1020.

Swetnam, T.W. & Betancourt, J.L. (1992). Temporal patterns of El Nino/Southern Oscillation – wildfire teleconnections in the southwestern United States. *In*: Diaz, H.F. & Markgraf, V. (Eds), *El Nino: Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge, U.K., Cambridge University Press, 258–270.

Swetnam, T.W. & Betancourt, J.L. (1998). Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate*, **11**, 3128–3147.

Tolonen, K. (1986). Charred particle analysis. In: Berglund, B.E. (Ed.), *Handbook of Holocene Palaeoecology and Palaeohydrology*. New York, John Wiley and Sons, 485–496.

Veblen, T.T., Kitzberger, T. & Donnegan, J. (2000). Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecological Applications*, **10**, 1178–1195.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. & Dokken, D.J. (2000). *Land Use, Land-Use Change, and Forestry*. Intergovernmental Panel on Climate Change: Cambridge, UK, Cambridge University Press, 377 pp.

Weber, M.G. & Flannigan, M.D. (1997). Canadian boreal forest ecosystem structure and function in a changing climate: Impact on fire regimes. *Environmental Review*, **5**, 145–166.

Westerling, A.L., Gershunov, A., Brown, T.T., Cayan, D.R. & Dettinger, M.D. (2003). Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society*, May issue, 595–604.

Whitlock, C. & Anderson, R.S. (2003). Methods and interpretation of fire history reconstructions based on sediment records from lakes and wetlands. *In*: Swetnam, T.W., Montenegro, G. & Veblen T.T. (Eds), *Fire and Climate Change in the Americas*. New York, Springer, 3–31.

Whitlock, C. & Bartlein, P.J. (1993). Spatial variations of Holocene climatic change in the Yellowstone region. *Quaternary Research,* **39**, 231–238.

Whitlock, C. & Larsen, C. (2002). Charcoal as a fire proxy. *In*: Smol, J.P., Birks, H.J.B. & Last, W.M. (Eds), *Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators*. Dordrecht: Kluwer Academic Publishers, **3**, 75–97.

Whitlock, C. & Millspaugh, S.H. (1996). Testing assumptions of fire history studies: An examination of modern charcoal accumulation in Yellowstone National Park. *The Holocene*, **6**, 7–15.

Wright, H.E., Jr. & Frey, D.G. (1965). *The Quaternary of the United States*. Princeton, New Jersey, Princeton University Press, 377 pp.