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HOLOCENE FIRE RECONSTRUCTIONS FROM THE NORTHWESTERN U.S.: AN EXAMINATION AT MULTIPLE TIME SCALES

C. Whitlock[1*] P. J. Bartlein[1], J. Marlon[1], A. Brunelle[2], and C. Long[1]

[1] Department of Geography, University of Oregon, Eugene OR
[2] Department of Geography, University of Utah, Salt Lake City, UT

1. INTRODUCTION

Information on past fire activity is provided by dendrochronological data and charcoal records from lake sediments (see Agee 1993; Patterson et al. 1987; Whitlock and Larsen 2002). These sources describe fire occurrence at different temporal and spatial scales of resolution, and together tree-ring and charcoal data offer a supplementary approach to fire reconstructions. Fire-scarred tree-ring and stand-age information is limited to living trees, and in most regions yields fire reconstructions that span the last 500 years or less. Fire-scarred tree rings register fire events that were not lethal to the tree, whereas stand establishment dates identify the minimum age of the last severe fire. Dendrochronological records offer a high level of spatial resolution in that the location of the fire is identifiable, and a combination of tree-ring and stand-age data makes it possible to discern identify locations of high-severity and low-severity fires. Tree-ring records are also temporally precise because scars can be dated to a particular growth ring and stand ages represent a minimum age of tree reestablishment after fire.

Examination of paleoenvironmental data preserved in lake-sediments provides more generalized information on past fire occurrence over much longer time spans (Long et al. 1998; Whitlock and Larsen 2002; Whitlock and Anderson 2003 for discussion of methods). Particulate charcoal, such as charred wood, bark, and leaves, is introduced into a lake through airborne fallout and delivery by streams and slopewash. Stratigraphic levels with abundant charcoal particles (so-called charcoal peaks) are considered evidence of past fire(s), and the frequency of peaks discloses past variations in fire frequency. The average abundance of charcoal through time, i.e., the charcoal background levels, offers information on changes in charcoal production and/or delivery, that result from changes in vegetation, hydrology, erosion, or fire size.

Charcoal records, by virtue of having a less well-defined source area and temporal resolution, reconstruct past fires with less temporal and spatial precision than tree-ring records. Inferences about source area are based on information on particle transport during modern fires, particulate-transport models, and pollen-transport models (Clark 1988; Whitlock and Millspaugh 1996; Clark et al. 1998; Sugita et al. 1998; Gardner et al. 2000). These studies have shown that macroscopic particles (>100 μm in minimum diameter) do not travel far from the fire perimeter and provide information on local events within the watershed, whereas microscopic charcoal (<100 μm in minimum diameter) may be transported long distances and thus offer insights into regional fire activity. Modern taphonomic studies indicate that charcoal particles accumulate in deep-water lake sediments for a few years after a fire (Whitlock and Millspaugh 1996). This delay tends to blur the exact age of a fire event because charcoal peaks can span several years of sediment accumulation. For that reason, charcoal peaks in a lake's record may represent more than one fire within the watershed and fires from more than one year.

Lakes with annually laminated (i.e., varved) sediment records permit the age of a fire to be established to the year (Clark 1990), but such lakes are rare in many parts of the U.S. In lakes where bioturbation and seasonal mixing result in non-laminated sediments, the fire chronology is established by a series of radiometric ages derived from ^{210}Pb and ^{14}C dating. Radiocarbon dates are converted to calendar years, and a polynomial regression is used to establish an age-depth model. With this level of chronologic resolution, past fires in coastal rainforests of the Pacific Northwest can be identified as distinct peaks because fire occurs infrequently and lakes in that region have relatively fast deposition times (decades cm^{-1}) (Long et al. 1998). In contrast, lakes in dry or unproductive settings and areas of frequent fires have less discrete charcoal peaks in their sedimentary records and individual fires are harder to identify (Whitlock et al., in review).

High-resolution fire chronologies are now available from lakes and wetlands in several regions. The records are high resolution in the sense that (1) contiguous sediment samples are examined (each sample representing a decade or so of deposition) enabling the detection of fire episodes, (2) several radiometric dates are used to develop a chronology, (3) accumulation rates (CHAR, particles cm^{-2} yr^{-1}) of macroscopic charcoal particles are used as the data source, and (4) charcoal records are interpreted in terms of the background trends and charcoal peak frequency. At each site, contiguous 1-cm core samples are washed through sieves and the charcoal particles are tallied under a binocular microscope. Charcoal concentration data (particles cm^{-3}) are divided by the deposition time (yr cm^{-1}) and the resulting accumulation rates are plotted at evenly spaced time intervals (Whitlock

*Corresponding author address: Cathy Whitlock, Department of Geography, University of Oregon, 1251 Univ. Oregon, Eugene OR, 97403-1251;
email: whitlock@oregon.uoregon.edu

and Larsen 2002).

Two components are immediately evident in the charcoal time series. One is the slowly varying component or long-term trend. Variations in this background component reflect changes in the levels of fuel biomass, the mechanisms that deliver charcoal to the lake through time, or fire size. In general, a region dominated by closed mixed-conifer forest with abundant woody fuel produces higher background levels of charcoal than an open parkland with less woody vegetation, although more research is needed to define the specific relationship between background charcoal, fuel biomass, and the spatial extent of fires. Likewise, surface transport of sediment may be more important during some climate and vegetation conditions and result in greater deposition of charcoal in the lake. The second component is the peaks above the background that represent fire episodes (i.e., one or more fires) during the time span. Given the sedimentation rate of most lakes in the western U.S., charcoal peaks can span a few decades or more of sediment accumulation. Decomposing the records into these components requires information on recent and historic fires to establish appropriate thresholds to distinguish a significant charcoal peak from background trends and random noise in the time series. Close collaboration with dendrochronologists has allowed us to use the age of known watershed fires to determine appropriate threshold levels and background window widths.

2. FIRE HISTORY DATABASE

A network of fire history records in the northwestern U.S. provides an opportunity to examine the linkages among changes in fire, climate, and vegetation during the Holocene (Fig. 1). The study sites are lakes (<10 ha diameter) with simple bathymetry and minimal or no inflowing streams. To date, research has focused on the fire history of middle- and high-elevation forests, because that is where most natural lakes and wetlands are located. These areas are characterized by stand-replacement fire regimes at present.

The most mesic sites in our study are Lost, Taylor, and Little lakes situated in temperate coastal rainforest, with Lost Lake as the wettest site. Burnt Knob and Baker lakes in the northern Rocky Mountains support subalpine forest and relatively wet conditions. Sites from both wet regions experience long fire-free intervals, with a century or more between large severe events. The driest sites, Crater, Bluff, and Cedar lakes, are located in the Klamath Mountains in forests characterized by frequent small fires. Slough Creek and Pintlar lakes lie at lower treeline in the northern Rocky Mountains, also in areas of frequent fires. Cygnet, Trail, and Hoodoo lakes are located in middle-elevation conifer forests with infrequent large stand-replacing fires and frequent smaller events.

The western U.S. can be divided into two regions based on precipitation characteristics that are evident in the present climate; these criteria provide another way of comparing fire history records (Whitlock and Bartlein 1993; Brunelle 2002; Shafer et al. 2003; Whitlock and Bartlein 2003). One regime, centered in the Pacific Northwest, receives little summer precipitation and hence the summer-to-annual precipitation ratio is low. In this so-called summer-dry regime, summer conditions are influenced by the northeast Pacific subtropical high-pressure system, which brings dry stable conditions to the Pacific Northwest and parts of the northern Rocky Mountains. Burnt Knob Lake on the west side of the Continental Divide in the Bitterroot Range in Montana; Cygnet and Trail lakes in central and southern Yellowstone National Park; Lost, Little, and Taylor lakes in the Oregon Coast Range; and Crater, Bluff, and Cedar lakes in the Klamath Mountains of northern California all lie in the summer-dry regime.

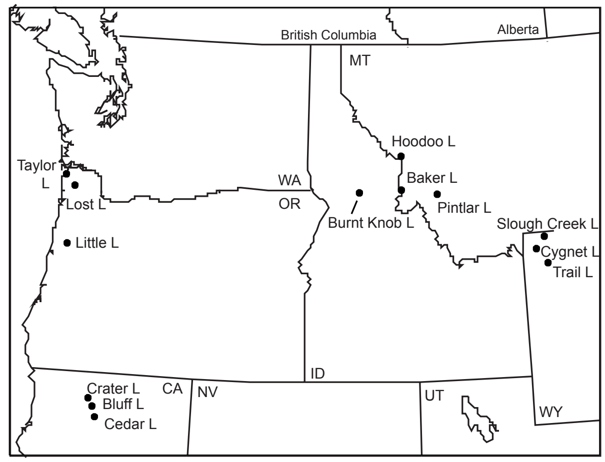

Figure 1. Location of fire history sites discussed in text. References: Baker, Hoodoo, and Pintlar lakes (Brunelle-Daines 2002); Slough Creek Lake (Millspaugh et al. 2003); Burnt Knob Lake (Brunelle and Whitlock 2003); Cygnet Lake (Millspaugh et al. 2000); Trail Lake (Whitlock and Sherriff, unpublished data); Lost Lake (Long 2003); Taylor Lake (Long and Whitlock 2002); Little Lake (Long et al. 1998); Crater and Bluff lakes (Mohr et al. 2000); Cedar Lake (Whitlock and Minckley, unpublished data).

The summer-wet regime receives relatively high summer precipitation at present as a result of the influence of summer monsoonal circulation patterns. It is best developed in the American Southwest, but summer precipitation maxima are also evident in parts of the northern Rocky Mountains where convectional storms bring significant levels of moisture and lightning. Sites that lie in this regime are Baker Lake on the east side of the Bitterroot Range crest, Pintlar Lake in the Pintlar Range of southwestern Montana, and Slough Creek Lake in northern Yellowstone National Park. At the transition between these regimes is Hoodoo Lake in the Bitterroot Range near the Continental Divide.

During the early Holocene, these two precipitation regimes intensified as a result of greater-than-present insolation in summer (Whitlock and Bartlein 1993; Bartlein et al. 1998). 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 stronger onshore flow. As summer insolation decreased in the middle and late Holocene, these patterns became attenuated. The summer-dry regions became effectively wetter than before and the summer-wet regions became drier than the early-Holocene period. Long-term changes in the intensity of these two precipitation regimes are clearly evident in the Holocene fire history.

2. RESULTS AND DISCUSSION

2.1 Trends in background charcoal

Long-term trends in background charcoal are evident in the average charcoal accumulation rates of all sites (Fig. 2). Gray lines represent z-score values of log-transformed background charcoal accumulation rates for each site. The length of time spanned by individual series ranges from 4 to 16 kyr. The running average of all records (black) reveals a gradual increase in charcoal accumulation from the late-glacial period to present. A decline in background levels is apparent at ca. 2 ka but the increase resumes a few hundred years before present. The addition of new records to the running average at various times throughout the Holocene does not account for the upward trend because most of the shorter records have below average accumulation rates. Background variability at particular sites can be caused by changes in the composition and distribution of vegetation (fuels), by hydrologic and erosional changes in the watershed that impact sedimentation rates, or by increases and decreases in the spatial extent of local fires. Coherent patterns in background charcoal that are evident at multiple sites and across broad temporal scales most likely reflect changes in charcoal production. For example, the upward trend in background accumulation rates observed at all sites (Fig. 2) suggests that charcoal production increased gradually with forest development and the evolution of associated fire regimes following glacial retreat. The relatively rapid decline in background accumulation at 2 ka may also be associated with biomass changes but the mechanisms behind such abrupt occurrences are more poorly understood and require further study.

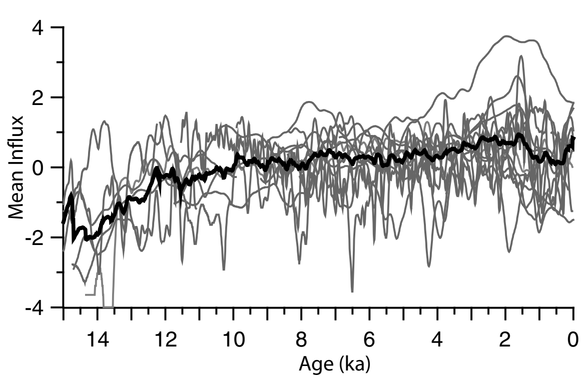

Figure 2. Long-term trends in background charcoal evident in the average charcoal accumulation rates. Gray lines represent z-score values of log transformed background charcoal accumulation rates for each site, and the running average of all records is shown by the black line.

2.2 Variations in peak frequency anomalies

Anomalies in the frequency of charcoal peaks relative to the last 1000 years provide a means of comparing variations in fire occurrence in different regions. The anomalies are based on a comparison of the peak frequency at any time with the mean peak frequency of each sites for the last 1000 years. Positive anomalies (purple) indicate when a site had more fires than the last 1000-year mean, while negative anomalies (green) are times when a site had fewer fires than the mean. The intensity of the color shows the magnitude of the anomaly.

The Holocene records can be compared in a number of ways. Sites in summer-wet and summer-dry regimes have contrasting fire anomaly patterns that reflect variations in the relative importance of winter and summer precipitation at different locations during the Holocene. The influence of a stronger-than-present subtropical high in the early Holocene is evident in the anomalous high peak frequency between 12 and 6 ka at several sites in the Pacific Northwest and northern Rocky Mountains. Cygnet Lake shows the most extreme anomaly with 10-15 more fires/1000 yr than during the last 1000 years. Anomalies became less positive in the middle and late Holocene at these sites as the summer insolation maximum wanes. Hoodoo Lake is located in an intermediate area beween summer-wet and summer-dry conditions and the anomalies were weakly positive in the early Holocene and weakly negative in the late Holocene. In the Klamath region, anomalies fluctuate between positive and negative values throughout the record, implying a muted response to millennial-scale shifts in insolation and a stronger response to centennial-scale climate variability. Especially high periods of fire activity, as expressed by the positive anomalies, took place at 8, 4, and 1 ka in the Klamath records.

The summer-wet sites feature negative frequency anomalies in the early Holocene and more positive (less negative) anomalies in the middle and late Holocene. The strongest expression is at Slough Creek and Pintlar lakes where fire activity is 10x lower in the early Holocene than in the last 1000 years. Apparently, a stronger summer monsoon in the early Holocene dampened fuels sufficiently to reduce fire occurrence. As summer insolation decreased and the monsoons weakened in the middle and late Holcoene, drier fuels allowed more frequent fires.

In general, peak frequency anomalies are strongest in the Rocky Mountains, where fire regimes are especially sensitive to seasonal moisture conditions. By contrast, Pacific Northwest and interior high-elevation sites show relatively muted anomalies. This may be explained by their wetter settings, which reduced the likelihood of fire even

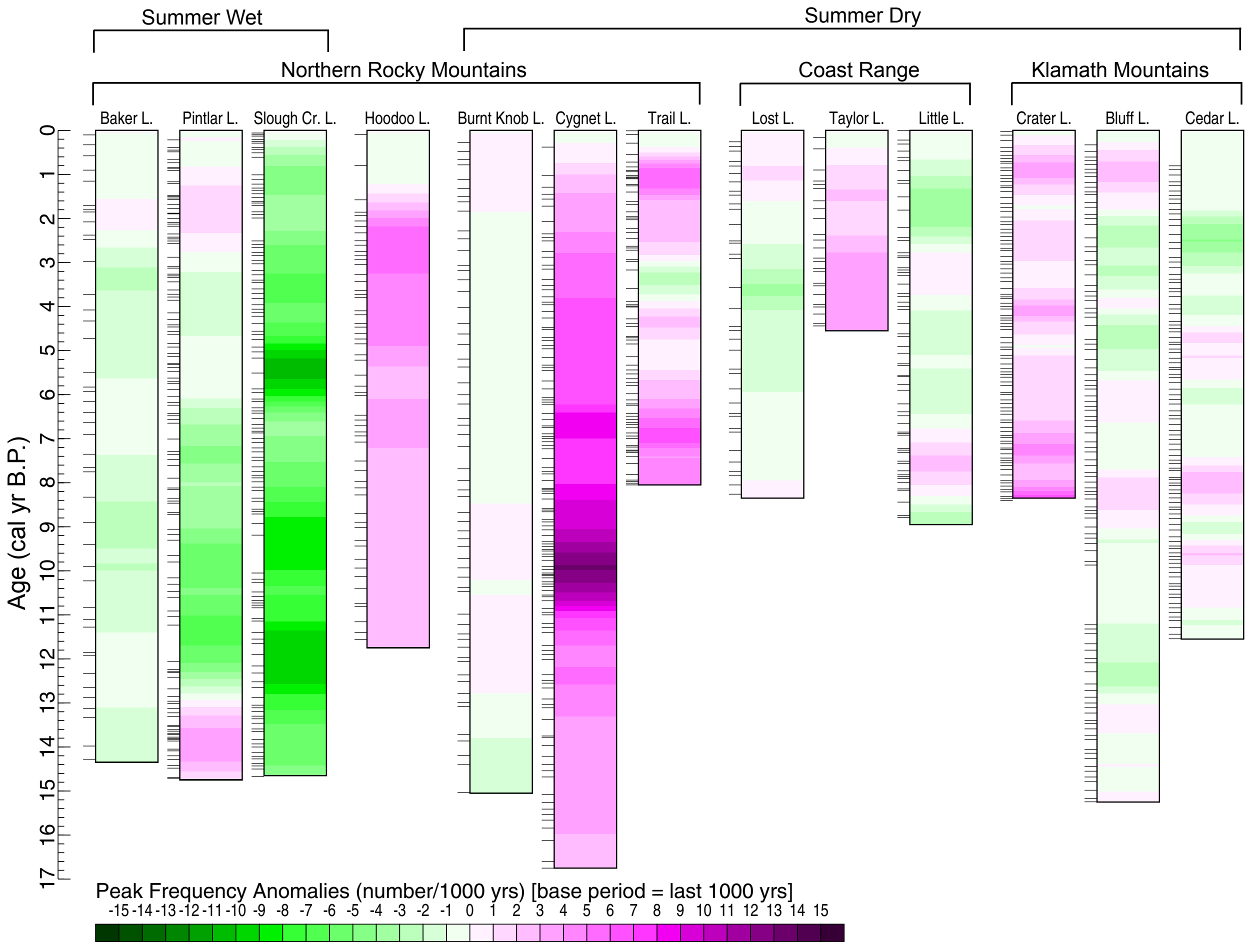

Figure 3. Comparison of the record of charcoal peaks at different sites for the last 17 kyr. Horizontal lines next to each site indicate charcoal peaks that denote fire events. Anomalies in the frequency of charcoal peaks are based on a comparison with the mean of the last 1000 years. Positive anomalies (purple) indicate more fires than the last 1000-year mean; negative anomalies (green) are times of fewer fires than the mean. Color intensity shows the magnitude of the anomaly. Baker, Pintlar, and Slough Creek lakes are in the summer-wet regime, and Burnt Knob, Cygnet, Trail, Lost, Taylor, Little, Crater, Bluff, and Cedar lakes are in the summer-dry regime. Hoodoo Lake is transitional.

during dry periods. The most mesic sites in both precipitation regimes show the least variability in frequency. Burnt Knob and Baker lakes in high-elevation forest show comparable fire anomalies, despite one being a summer-dry and the other a summer-wet site. Likewise, the wettest site, Lost Lake, shows very little change in fire activity during the last 9000 years, probably because the forests were relatively wet even in the early Holocene.

3. CONCLUSIONS

High-resolution charcoal records offer information on fire, vegetation, and climate changes on centennial and millennial scales, and thus supplement our understanding of fire history provided by dendrochronological data. Charcoal data are not merely an extension of the tree-ring chronologies; they provide an opportunity to study the role of fire during the large-scale reorganizations of the environment that take place in response to major shifts in the climate system. The slow increase in background charcoal from the late-glacial to ca. 2 ka provides a record of forest development and increasing levels of biomass following the last ice age. The sub-regional differences in fire event frequency during the Holocene disclose disturbance response to the intensification of present-day precipitation regimes during the early Holocene and to the weakening of these regimes in the middle and late Holocene. These spatial patterns in fire history are a result of the expression of precipitation regimes on a topographically complex landscape. Locational differences among sites also create persistent differences in fire history, as seen, for example, in the relatively muted fire anomalies in high-elevation sites. In addition, the timing and trends leading to the modern fire regime is highly individualistic, with some sites reaching modern conditions as a part of long-term trajectories towards increasing (or decreasing) fire activity, and others sustaining a modern fire regime for several centuries, with little change. These long-term records thus form an important element in understanding the natural variability of fires and should be considered in assessing the effects of human actions and forest management practices.

4. ACKNOWLEDGEMENTS

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