5. CHARCOAL AS A FIRE PROXY

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Introduction

Charcoal analysis of lake sediments is used to reconstruct long-term variations in fire occurrence that can complement and extend reconstructions provided by dendrochronological and historical records. In the last 15 years, several papers have reviewed the methods for charcoal analysis of lake-sediment cores and its use as a tool for studying fire history (e.g., Tolonen, 1986; Patterson et al., 1987; MacDonald et al., 1991; J. S. Clark, 1988a; J. S. Clark et al., 1998; Long et al., 1998; Whitlock & Anderson, in review). In most cases, pollen and charcoal data from the same cores are used to examine the linkages among climate, vegetation, fire, and sometimes anthropogenic activities in the past. The growing use of charcoal analysis reflects a heightened interest within the paleoecological community to consider fire as an ecosystem process operating on long and short time scales, as well as an increasing need on the part of forest managers to understand prehistoric fire regimes. In this chapter, we discuss issues of site selection, chronology, and methodology in charcoal analysis, based on recent advances in the discipline. We also review the theoretical and empirical basis for charcoal analysis, including assumptions about the charcoal source area and the processes that transport and deposit charcoal into lakes.

Fire reconstructions based on lake-sediment records are derived from three primary data sources: particulate charcoal that provides direct evidence of burning; pollen evidence of fluctuations in vegetation that can be tied to disturbance; and lithologic evidence of watershed adjustments to fire, such as erosion or the formation of fire-altered minerals. Charcoal analysis quantifies the accumulation of charred particles in sediments during and following a fire event. Stratigraphic levels with abundant charcoal (so-called charcoal

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peaks) are inferred to be evidence of past fires. Pollen analysis is used to detect past fires on the assumption that fire and post-fire succession will alter somewhat the local plant community and its pollen representation in the sediments. Lithologic analyses supplement charcoal data by detecting changes in the input of allochthonous sediment and evidence of soil mineral alteration due to heating. The lithologic record has been used to deduce the location of a fire within a watershed and also fire intensity.

Charcoal production, transport, and deposition

Charcoal is produced when a fire incompletely combusts organic matter. The rate at which charcoal accumulates in a lake depends on the characteristics of the fire (e.g., how much charcoal is produced) and the processes that transport and deliver charcoal to the lake (Fig. 1). *Primary* charcoal refers to the material introduced during or shortly after a fire event. *Secondary* charcoal is introduced during non-fire years, as a result of surface run-off and lake-sediment mixing. The relationships between fire characteristics and the accumulation of primary charcoal and between taphonomic processes and the deposition of secondary charcoal are discussed separately, but it is important to remember that both sources comprise the sedimentary charcoal record.

Fire size, intensity, and severity all affect charcoal production and aerial transport, although little information is known about these relationships. Because charcoal particles can be carried aloft to great heights and transported great distances (Radtke et al., 1991; Andreae, 1991), the source of the charcoal may be from regional (distant) fires, extralocal (nearby but not within the watershed) fires, or local (within the watershed) fires. The distance that charcoal is carried during a fire has been discussed in several papers, including Swain (1978), Tolonen (1986), Patterson et al. (1987), J. S. Clark (1988a), Whitlock & Millspaugh (1996); J. S. Clark & Royall (1995, 1996), J. S. Clark et al. (1998), and Gardner & Whitlock (2001). Simple Gaussian plume models suggest that particles $>1000\,\mu$m diameter are released relatively close to the ground and deposited in near a fire (J. S. Clark & Patterson, 1997). These models predict that particles $<100\,\mu$m in size travel well beyond 100 m, and very small particles are lofted to great heights and travel long distances. Theoretical models also suggest a “skip distance” between the base of the convective column and the site of deposition. In principle, few charcoal particles smaller than 200 μm in diameter should be deposited within 6 km of the convection column (Fig. 2).

Four studies following modern fires confirm model predictions by showing a decrease in charcoal abundance away from the source. In one study, charcoal accumulation in small lakes following the 1988 fires in Yellowstone National Park indicated that charcoal particles $>125\,\mu$m diameter were abundant in sites <7 km from the fire (Whitlock & Millspaugh, 1996); beyond that distance the accumulation of such particles declined sharply. A more comprehensive study of the upper sediment of 35 lakes followed a 1996 fire in the Cascade Range of Oregon (Gardner & Whitlock, 2001). Levels of $>125\,\mu$m-sized charcoal were compared for the upper two core samples (0–2 cm and 2–4 cm depth) in burned sites and sites located within few kilometers upwind and downwind of the fire. Cores from the burned sites had statistically greater charcoal abundance in the top sample than those from unburned sites, and the peaks (i.e., difference between the top and second sample) were better defined than in unburned sites. Sites downwind of the fires had more charcoal in

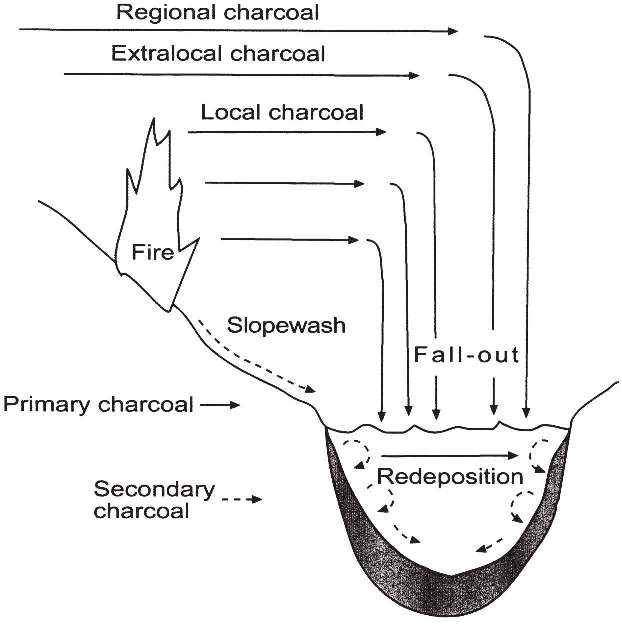

Figure 1. Schematic diagram of illustrating the sources of primary and secondary charcoal in a watershed.

the top sample than did sites upwind. The results suggest that lakes that received highest charcoal inputs lay inside the burned perimeter or just downwind of the site.

In a third study, J. S. Clark et al. (1998) described the abundance and particle size of charcoal collected in a series of traps during a prescribed fire in Siberia in 1993. Charcoal abundance dropped off sharply at the edge of the burned margin. In both the Siberian and Cascade studies, the observed sharp decline was not consistent with the presence of a skip distance (i.e., a zone of no charcoal deposition at the base of the convective column), although charcoal accumulation at great distances was not evaluated. In the Siberian study, particle size distributions were the same in traps from the burned area as they were for those located 80 m beyond the burn.

The fourth study examined 704 charcoal traps distributed within, and up to 100 meters outside, of three separate experimental fires in boreal Scandinavia (Ohlson & Tryterud, 2000). Traps within the burned area contained 56× more large particles (i.e., >0.5 mm diameter) than traps outside the fire perimeter. Moreover, large particles were found in about 80% of the traps inside the fire perimeter, in about 25% of traps located 0.1 to 0.9 meters outside the perimeter, and in <5% of the traps located 1 to 100 meters of the fire. These results confirm that macroscopic charcoal is not transported far from the fire margin.

Emissions of particulate matter vary depending on the fire and fuel conditions that affect combustion efficiency. Fires of low intensity (i.e., low heat release per unit time) are known to produce high emissions of particulate matter, because of their low combustion efficiency (Pyne et al., 1996). However, large particles are often associated with high-

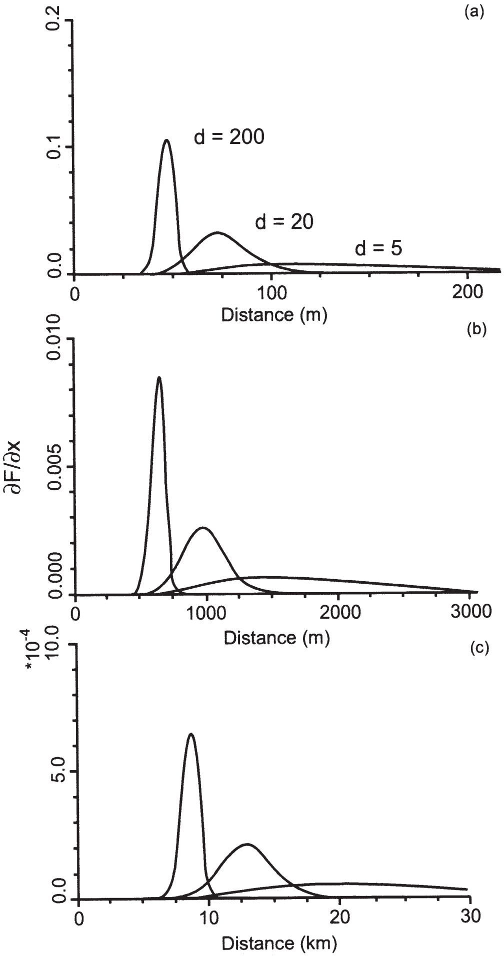

Figure 2. Relationship between distance from the base of a fire's convective column and the amount of charcoal deposited as determined by theoretical models for charcoal particles with diameters of 200, 20 and 5 μm and convective columns with a height of (a) 10 m, (b) 100 m, and (c) 1000 m. (after J. S. Clark, 1988a). Notice a theoretical "skip distance" between the fire and the first deposition of charcoal.

intensity fires, because turbulent winds move such particles beyond the combustion zone (Ward & Hardy, 1991). As a result, fires of high intensity (with long flame length) often produce proportionately larger particles than do low intensity, smoldering combustion fires (Ward & Hardy, 1991). The composition of the charcoal also changes with temperature. In experiments run at high temperatures (>500 °C), early combustion of grass and leaf material resulted in a high representation of wood charcoal (Umbanhowar & McGrath, 1998). Wood particles also become denser and more fractured at high temperatures, which makes them more prone to waterlogging and settling (Vaughn & Nichols, 1995). In forests in the western

United States, particulate charcoal in lake-sediment records consists of predominately wood particles, suggesting a bias towards preserving the record of high-intensity convection-driven fires. Fire regimes characterized by frequent and efficient ground fires do not produce much charcoal, partly because such fires are often small, and charred particulates are not carried aloft. Prairie fires, which are generally cool and fast, produce significant amounts of charred herbaceous material (Umbanhowar, 1996; Pearl, 1999).

If fire processes were the only factors involved, sedimentary charcoal would all be primary and thus a direct measure of biomass burning. However, because the record is composed of both primary and secondary sources, estimating fire size, severity, or intensity is possible only in the most general terms. Studies of modern charcoal accumulation in lakes indicate that charcoal deposition can take place several years after the actual fire. For example, Whitlock & Millspaugh (1996) observed that lakes in both burned and unburned watersheds in Yellowstone received charcoal during the 1988 fires, but the amounts continued to increase significantly for five years in burned watersheds. Anderson et al. (1986) described accrual of charcoal into a lake in Maine for several decades following a 1910 fire. Patterson et al. (1987) report steady increases in microscopic charcoal for several decades after a watershed fire in 1947. The secondary charcoal in these cases may have been introduced from standing burned snags and downfallen trees along the lake margin. Surface run-off may also have delivered charcoal in the few years following a fire, but the importance of this process diminishes as the watersheds became revegetated.

Another source of secondary charcoal, noted in the Yellowstone study (Whitlock & Millspaugh, 1996), was the accumulation of particles that landed on the lake during the fire and were blown to the shore and deposited in the littoral zone. In the years after the fire, this material was refocused to deep water. Bradbury (1996) documented similar movement of littoral charcoal in Elk Lake, a 1.01 km^2 lake in north-central Minnesota. By associating the charcoal peaks in the deep-water core with changes in the diatom record, Bradbury (1996) demonstrated that shallow-water charcoal was mobilized in the lake during spring circulation. In both the Yellowstone and Elk Lake studies, the focusing of charcoal to deep water occurred within a few years of the fire event. In the case of most sites, this refocused material would be part of the charcoal peak. Thus, it is important to note that a charcoal peak in the stratigraphic record is probably composed of particles deposited during and after a fire. For this reason, it may be difficult to infer levels of fire intensity or fire size in the past based on charcoal abundance in lakes.

Site selection

Fire history reconstructions, like most paleoecological procedures, are time consuming, and it is important that sites are chosen carefully. The characteristics of both the watershed and the lake should be considered. Large watersheds provide a large source area for charcoal, because fires can occur over a large area, both near and close to the lake. A site with a large watershed relative to the lake size will magnify the allochthonous inputs (Birks, 1997). For example, in Whitlock & Millspaugh (1996), lakes with large watersheds relative to their size had higher amounts of macroscopic charcoal after a fire than did lakes with small watersheds. Rhodes & Davis (1995) chose a lake in Maine specifically because it had a small surface area and a 50× larger watershed. The large ratio between watershed size and lake surface area magnified the limnological signal of each disturbance event. Such sites, however, also increase the introduction of secondary charcoal, which might distort fire history interpretations.

Steep slopes may increase the introduction of secondary charcoal through erosion (Swanson 1981, Meyer et al., 1995). High rates of erosion following fire are generally attributed to unvegetated ground, hydrophobic soils, and reduced infiltration, but the effects last only a few years. A study from the Colorado Rockies showed a 1000-fold increase in surface soil movement following a stand-replacement fire. Erosion rates remained ten times greater than pre-fire rates for up to four years (Morris & Moses, 1987). Meyer et al. (1995) presented evidence from Yellowstone National Park to suggest that significant amounts of charcoal were transported soon after a fire by large mass-wasting events triggered by intense rains; surface run-off contributed very little to the charcoal record. The presence of riparian vegetation at the lake margin may trap some of this material and thus limit the input of secondary charcoal (Whitlock & Millspaugh, 1996; Terasmae & Weeks, 1979). In this way, a riparian fringe may enhance the resolution of the primary fire signal, particularly if it has existed through the duration of the record. Lakes chosen for fire-history studies should also have small or no inflowing streams that could transport secondary charcoal.

Chronology issues

Adequate chronological control is necessary for any high-resolution time series. Varved sediment records provide the option of seasonal to coarser temporal resolution, and thus they are preferred for fire-history reconstructions. In sites with non-varved sediments, the chronology for the fire reconstruction is based on ^{210}Pb dating of sediments that span the last 200 years and AMS ^{14}C dating of charcoal and terrestrial macrofossils from the remainder of the core. Radiocarbon years should be converted to calendar years using standard calibration programs (e.g., Stuiver et al., 1998) in order to calculate true charcoal accumulation rates. In developing an age-depth model for homogeneous sediment types, it is important to use as smooth a regression curve as possible to avoid sharp discontinuities in deposition time that will influence the charcoal accumulation rates. Of course, sharp changes in sediment type suggest discontinuities in deposition and may justify changing the age-depth model.

Variations in sedimentation rate usually make it difficult to sample a core at equally spaced time intervals. Such changes are not a problem when annually laminated sediments are used; however, in non-varved records, variations in sedimentation rate affect the calculation of charcoal accumulation rates and fire frequency. For this reason, charcoal records from nonlaminated sediments should be converted to intervals that are regularly spaced in time. Because direct interpolation of charcoal data to a constant time interval may not conserve the quantity of charcoal within the intervals, concentration values and deposition times should be interpolated to pseudo-annual intervals. Those values may be integrated over broader intervals (e.g., ten years, but ideally that of the temporally longest subsample) and then divided by the average deposition time over those intervals to produce a series of charcoal accumulation rates (number, area, or mass of charcoal cm^{-2} yr^{-1} = CHAR) spaced at broader (i.e., decadal) intervals (see Long et al., 1998).

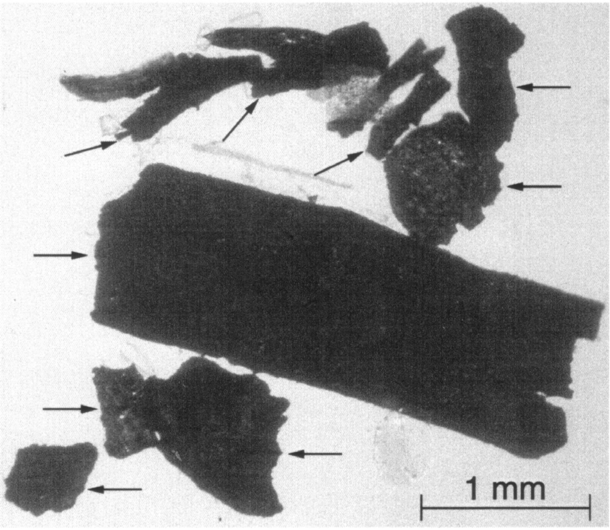

Figure 3. Macroscopic charcoal particles (arrow) left after washing sediment through a 250 μm screen.

Methods

Charcoal is produced between temperatures of 280 and 500 °C (Chandler et al., 1983). Higher temperatures convert the material to ash through glowing combustion and lower temperatures may lightly scorch the material, but not char it. Charcoal particles are visually recognizable as opaque, angular and usually planar, black fragments (Fig. 3). Other black particles in sediments, such as minerals, plant fragments, and insect cuticles, may sometimes be confused with charcoal. Minerals are, however, distinguishable by their crystalline form, such as the octahedral or cubic shape of pyrite, or by their birefringence in polarized light (Clark, 1984). Insect cuticles are thinner than charcoal. Dark plant fragments can be distinguished from charcoal by applying pressure to the particles using a dissecting needle. Charcoal particles fracture under pressure into smaller angular fragments, whereas plant fragments impale or compress.

The visual and physical characteristics of charcoal may be learned by looking at and breaking experimentally created charcoal (Umbanhower & McGrath, 1998) and by examining published photographs (Clark, 1984; Sander & Gee, 1990). Burning of plant material at 350 °C appears to provide the greatest amount of charcoal. The created charcoal should be processed using the same steps employed for the fossil charcoal (see procedures described below). Even so, experimentally produced particles will not have undergone the same taphonomic processes as the sedimentary material and will have slightly different shape characteristics (Umbanhower & McGrath, 1998).

One issue in fire-history studies has been the lack of a standardized methodology. Several methods have been proposed for processing charcoal samples and quantifying the results (Table I). Methods concerned with fire occurrence in a general way have focused on the analysis of microscopic charcoal (with size fractions <100 μm size) on pollen slides (e.g., Swain, 1973; Cwynar, 1978; R. L. Clark, 1982). In this approach, the number or area of charcoal particles is calculated along a series of traverses or on a grid, and the data are expressed as charcoal accumulation rates, a percentage of the pollen sum, or as a ratio of the pollen sum. Because small particles can travel great distances, the source area is poorly defined but probably regional in extent. Another method, which has gained widespread favor, has been the analysis of macroscopic charcoal ($>100\,\mu$m size) to reconstruct local fires (e.g., Millspaugh & Whitlock, 1995; Long et al., 1998; Mohr et al., 2000; Hallett & Walker, 2000). Again, the data are presented as accumulation rates of area or particle number, and when contiguous samples are analyzed, they have been used to calculate fire frequency. A third method has been a chemical digestion to calculate charcoal abundance by weight (Winkler, 1985; Laird & Campbell, 2000). This approach avoids assessment of particle sizes, because in principle all charcoal in a subsample is analyzed. The procedure, although simple, seems to produce unreliable results, probably because of inaccuracies in measuring small charcoal quantities and weight-losses associated with the decomposition of clay minerals upon ignition (e.g., MacDonald et al., 1991). The method will not be discussed further.

Microscopic charcoal

Iversen (1941) was the first to recognize that pollen-slide charcoal could be used as a fire proxy, and today most sedimentary charcoal studies are based on an analysis of particles contained in pollen preparations. The method has intrinsic limitations: (1) samples in most Holocene studies are spaced centimeters apart in a core, and gaps of decades to centuries exist in the record; (2) charcoal particles are broken during pollen preparation, thus creating an artificially high abundance of microscopic particles (<100 um); and (3) the exact source area of microscopic charcoal is generally vague—somewhere in the region, but often not the immediate watershed (Table I). Fire frequency *per se* cannot be calculated from pollen-slide charcoal, because the source area is ambiguous and the records are discontinuous. Despite these caveats, the data are useful in that they disclose periods of burning in the past, and often the paleoclimatic inferences are consistent with those based on the pollen record (perhaps because the source areas of pollen and microscopic charcoal are similar). For example, a common conclusion from studies that combine pollen and microscopic charcoal analysis is that many fires occurred during periods when disturbance-adapted species were more prevalent; thus both charcoal and pollen suggest climate conditions suitable for fires (e.g., Cwynar, 1987; MacDonald, 1989; Horn, 1993; Sarmaja-Korjonen, 1998).

Samples for microscopic charcoal analysis are prepared as part of routine pollen analysis (see Bennett & Willis, this volume). Because charcoal area on pollen slides decreases with increased numbers of steps in pollen processing (R. L. Clark, 1984), samples should receive similar treatments. The data are presented as abundance of charcoal particles or charcoal area. Both measurements are often converted to accumulation rates by dividing charcoal concentration, typically assessed by the use of an exotic tracer (e.g., Stockmarr, 1971), by the deposition rate (yr cm^{-1}). Charcoal area is calculated from size-classes, point-counts, or computerized imaging techniques (described below). The size-class method (Waddington, 1969) involves measuring the area of each particle by use of a gridded eyepiece in the microscope. The size of each piece is recorded or placed into a size class. Geometric size classes are usually used because more small particles are present than large. Particles <50–$90\,\mu\mathrm{m}^2$ in size are usually not measured because of their great abundance and minimal

Table I. Methods of charcoal analysis from lake sediments.

Method	Procedure (P) and Quantification (Q)	Objective	Advantages (Adv) and Disadvantages (Dis)	References
Pollen Slide	P-Standard pollen-preparation methods. Q-A grid (in microscope eyepiece) is moved on traverses across pollen slide. Number or area of charcoal is expressed as an accumulation rate by division with ratio of counted to added marker grains or as a relative measure as a ratio of total pollen count. Q-A grid is moved step-by-step across a pollen slide and only charcoal particles that intersect a grid line are counted. Area of charcoal particles is estimated.	To determine the importance of fire in a region on centennial or millennial time scales.	Adv: charcoal is counted on pollen slides without additional preparation Dis: spatial and temporal resolution of fire reconstruction is poor; difficult to identify breakage; problems calculating concentration or accumulation rates	Swain, 1973; Cwynar, 1978; R. L. Clark, 1982
Thin-section	P-Varved sediments are dehydrated with acetone, impregnated with epoxy, cured, and then thin sectioned. Q-Measurements are based on size classes. A grid is moved on traverses across each varve. Number and area of macroscopic charcoal ($>50\,\mu$m) are recorded.	To reconstruct history of local and extralocal fires on annual to millennial time scales.	Adv: provides record with annual resolution Dis: expensive, varved-sediment lakes are rare	J. S. Clark, 1988b; Rhodes & Davis, 1995
Macroscopic Sieving	P-Contiguous 1 cm core intervals are gently washed through analytical sieves (mesh sizes >0.100 mm). Sieved samples put in gridded petri dish. Q-Macroscopic charcoal ($>100\,\mu$m) are counted under stereomicroscope. Recorded as charcoal per volume.	To reconstruct history of local & extralocal fires on decadal to millennial time scales.	Adv: easy, can be used for non-varved lake sediments, preserves macrofossils for AMS-dating Dis: nonarboreal, difficult to disaggregate	Millspaugh & Whitlock, 1995; Long, et al., 1998
Chemical Extraction	P-Sediment is digested in nitric acid, then weighed. Sample is ignited at 500 °C then weighed again. Q-To calculate % charcoal: weight after nitric digestion is subtracted from weight after ignition. Results are multiplied by 100, then divided by weight of sample.	To determine the importance of fire on millennial time scales	Adv: analyzes all particle size ranges Dis: method considered unreliable	Winkler, 1985
Image Analysis	P-A video camera is mounted on a microscope to scan preparation for charcoal particles. Q-Scanner recognizes charcoal based on optical density and records number, area, and size-class distributions of charcoal.	To quantify charcoal area for different size ranges	Adv: use of scanner is less time consuming than visual counting. Dis: scanner mis-identifies other types of dark particles, underrepresents counts	MacDonald et al., 1991; Horn et al., 1992; Earle et al., 1996; J. S. Clark & Hussey, 1996

contribution to total area; particles $>2000\,\mu\mathrm{m}^2$ are recorded individually because of their great contribution to total area (Patterson et al., 1987; Pitkänen & Huttunen, 1999). The number of particles in each size class is multiplied by its midpoint size and these are summed across the classes.

The point count method (R. L. Clark, 1982) involves selecting random points on the pollen slide and determining the percentage of points that overlie charcoal. This method tends to produce values of zero in cases where the surface-area method indicates low values, and it is not faster than the size class method when charcoal content is low (Patterson et al., 1987). Both methods typically add 5–10 minutes to the time required to count a pollen slide. The ratio of charcoal-to-pollen accumulation rates was introduced by Swain (1973) to better identify a fire event by integrating an increase in charcoal with a presumed decrease in pollen as a result of burned vegetation. The ratio, however, appears to broaden and dampen the charcoal peaks based on charcoal accumulation rates (e.g., Swain, 1973; Cwynar, 1978) and does not register some fires (e.g., MacDonald et al., 1991).

Comparison with historic fire records points to the regional nature of the fire reconstructions provided by pollen-slide charcoal. For example, peaks in charcoal accumulation rates were matched with fires occurring within a 120 km radius of a lake in the Canadian boreal forest (MacDonald et al., 1991). Similarly, charcoal peaks in a lake from the mixed deciduous forest of Switzerland corresponded with the dates of fires that occurred 20–50 km away (Tinner et al., 1998). Other studies have used peaks in microscopic charcoal to reconstruct local fire history (e.g., Swain, 1973; Tolonen, 1978; Cwynar, 1978; MacDonald et al., 1991; Larsen & MacDonald, 1998a). Microscopic charcoal abundance increases during local fires, but other proxy records, such as macroscopic charcoal or lithologic changes, are needed to confirm if the fire is local. Rhodes & Davis (1995) found that peaks in the charcoal-to-pollen ratio coincided with 8 of 9 fires inferred from pollen, sedimentological, and paleolimnological data. Larsen & MacDonald (1998b) observed that peaks in pollen-slide charcoal coincided with 10 of 16 fires inferred from pollen and macroscopic charcoal, but at least 15 other charcoal peaks did not match other proxy data.

Macroscopic charcoal

A convincing demonstration that large particles provide a record of local fires comes from comparing macroscopic charcoal from varved lake sediments with known watershed fires (e.g., J. S. Clark, 1990). Similarly, peaks in macroscopic charcoal in nonlaminated sediments match times of local fires, although with less temporal precision (Millspaugh & Whitlock, 1995; Long et al., 1998; Mohr et al., 2000) (Fig. 4). J. S. Clark & Hussey (1996) compared macroscopic charcoal measurements based on area, volume and mass, and concentration in several lakes in northeastern North America. Although different methods produced different peak magnitudes, the records all showed a similar time-series of peaks.

Macroscopic charcoal is generally quantified from petrographic thin sections or in sieved sediment fractions. The thin-section method is desirable for varved-sediment records, because it permits fire history reconstructions with annual precision (J. S. Clark, 1988b). Anderson & Smith (1997) also used the thin-section method to analyze eight wet-meadow cores from widely separated sites in the Sierra Nevada, California. The use of petrographic thin sections enabled them to tally charcoal particles at 1- mm intervals, thus increasing the temporal resolution.

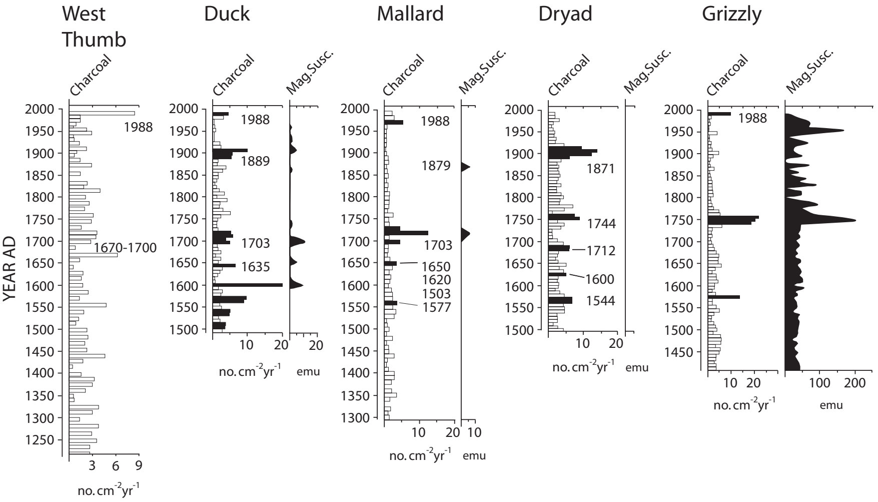

Figure 4. Charcoal accumulation rates (CHAR) and magnetic susceptibility (emu) from sediment cores from a large lake (>4250 ha) and four smaller (14–47 ha) lakes in Yellowstone National Park (after Millspaugh & Whitlock, 1995). Chronology is based on an age model extrapolated from a series of lead-210 dates. Black bars indicate charcoal peaks inferred to represent a local fire event. Dates of known local fires, based on tree-ring studies, are shown next to appropriate peaks. The stratigraphic record extends the fire history beyond the tree-ring record.

The sieving method is used to reconstruct local fire frequency in lakes with nonlaminated sediments. Compared with the thin-section method, sieving is inexpensive and relatively fast. Enumeration is based on simple counts of particles of different size (Millspaugh & Whitlock, 1995; Mehringer et al., 1977) or area measures (MacDonald et al., 1991; Horn et al., 1992; Earle et al., 1996) (Table I). Charcoal is generally analyzed in contiguous samples, usually 1-cm-thick. In most lakes from temperate North America, a single centimeter represents about 5–20 years, depending on the sedimentation rate. Where fires are infrequent, this time span is short enough to discriminate particular fire events, but in regions of frequent burning, a single sample may represent one or more fires occurring years apart. For that reason, the term “fire event” (*sensu* Agee, 1993), rather than “fire”, is more appropriate for the information provided by the sieving method. Although sub-samples at 0.25-cm intervals have provided distinct peaks in boreal lakes (Larsen & MacDonald 1998b), sampling at intervals of <1cm did not improve the temporal resolution in temperate lakes probably because bioturbation blurs the charcoal signal at a finer scale.

The sieving method uses between 1 and 5 cm^3 of wet sediment from each 1-cm interval, depending on the charcoal concentration. Each sample is soaked in a deflocculant (e.g., solution of 5% sodium hexametaphosphate) for a few days and then gently washed through a series of nested sieves (we use mesh sizes of 250, 125, and 63 μm). As a first step, charcoal in the different size fractions is tallied for several samples to assure that the three fractions show similar trends. Most studies use the 125–250 μm fraction or the $>100\,\mu$m fraction as the most practical size range for analysis. In our experience, a fire event is typically represented by >50 particles cm^{-3} and a nonfire event by substantially fewer or no particles. The resulting data set is converted to charcoal concentration (number of charcoal particles cm^{-3}) and then to charcoal accumulation rates by dividing by the deposition time (yr cm^{-1}).

Several studies have quantified charcoal using computerized image analysis (e.g., MacDonald et al., 1991, Szeicz & MacDonald 1991; Horn et al., 1992; Earle et al., 1996; J. S. Clark & Hussey, 1996). Image analysis estimates are often lower than those determined by eye (MacDonald et al., 1991; Horn et al., 1992), because the particle edge has a lower optical density than the center, resulting in small particles not being observed and large particles appearing smaller than they are. If the software is set to characterize the low-density edges as charcoal, then it also falsely characterizes many non-charred objects as charcoal. In more recent procedures (J. S. Clark & Hussey, 1996), charcoal particles are first identified using optical microscopy, and then measured using image analysis. The image is captured by video camera and analyzed while the sample is still on the microscope so particles can be compared with those on the enhanced image. A threshold density is set on the image for optimal differentiation of charcoal from optically dense organic and mineral matter. Other dark objects “misidentified” by this density slice are dismissed prior to analysis. The criteria are similar to those used without image analysis, but the approach allows particle dimensions and area to be calculated.

Interpretation of charcoal records

Interpretation of the charcoal time series rests on the ability to calibrate charcoal peaks with known fire events. Dendrochronology and historical documents provide information on historic fires. If the charcoal peaks in the upper sediments match poorly with known fires, the ability of that site to accurately depict older fires is suspect, and another lake should be considered (see site selection section).

Dendrochronological reconstructions of past fires are based on an analysis of fire-scarred tree rings and stand ages (see Arno & Sneck, 1977; Agee, 1993; Johnson & Gutsell, 1994 for a discussion of these methods). Fire scars on trees disclose the exact year of a fire, and fire-history reconstructions based on this method are spatially specific. However, since scars typically form during low-severity ground fires, they reflect incomplete stand destruction and thus may be from fires that did not produce much charcoal (Mohr et al., 2000). Stand-age analysis is used in regions of severe fires, where the forest structure provides an age on past disturbance events. The accuracy of the fire reconstruction fades with time (the so-called telescoping effect) as younger fires destroy the evidence of older events (Agee, 1993; Larsen, 1996; Kipfmueller & Baker, 1998).

Dendrochronological data have been used in a number of studies to calibrate charcoal data with fire age, size, and proximity (Swain, 1973, 1978; Cwynar, 1978; J. S. Clark, 1990; MacDonald et al., 1991, Millspaugh & Whitlock, 1995, Larsen & MacDonald, 1998a,b). In principle, a threshold value based on modern calibration should provide a tool for identifying significant charcoal peaks down core. However, local fires located downwind of lakes are often not recorded as charcoal peaks, and, conversely, some charcoal peaks may correspond with extralocal events (Fig. 4; Millspaugh & Whitlock, 1995).

Decomposition of the charcoal record

J. S. Clark & Royall (1996) and Long et al. (1998) outline methods for decomposing charcoal records into separate time series that describe different aspects of the fire history.

Their motivation is based on the fact that most time series of charcoal accumulation rates (CHAR) display a low-frequency or slowly varying component, called the *background component*, and a higher frequency or rapidly varying component, called the *peaks component*. Several sources may contribute to the background component or general trends in the data, but they are often difficult to separate. For example, a general time-varying level of background CHAR may be the result of changes in fuel accumulation and its influence on charcoal production. Millspaugh et al. (2000) argue that an increase in background CHAR in a Yellowstone lake ca. 11,000 years ago occurred as a result of changes in fuel during the transition from open meadow to forest vegetation. Background CHAR has also been attributed to secondary charcoal, i.e., material stored in the watershed that is delivered to the lake over a long period. In this case, the background component is not directly related to the fire regime. An increase in charcoal in late-Holocene lake sediments in the Oregon Coast Range was attributed to increased mass movements brought about by the onset of a wetter climate (Long et al., 1998). This hypothesis was supported by the high magnetic susceptibility of late-Holocene sediments. A third contributor of background charcoal may be extra-local or regional fires. This possibility has been proposed by J. S. Clark & Royall (1996), although we know of no studies that compare the background component of the macroscopic charcoal record with peaks of a pollen-slide charcoal record to see if they both record the same regional events. If the background component reflects variations in charcoal production and secondary charcoal delivery, these, in turn, are affected by changes in vegetation, climate, and fire weather, and possibly also by changes in hydrology, fluvial geomorphology, and lake characteristics.

A charcoal peak represents the contribution of charcoal from a fire event. As discussed above, this component probably has its source area within the watershed if small basins are chosen, but sometimes fires from adjacent upwind basins can also be recorded. In addition to a particular fire event, peaks may also represent "noise" from analytical error (Whitlock & Millspaugh, 1996) and natural random variations in CHAR. In practice, the largest variations in the peaks component are attributed to fire events, and the minor "noise" component is disregarded.

Peaks of significance are identified by assigning a threshold value, such that CHAR higher than that value is assumed to signal a fire event. Depending on the deposition time, an event may represent one or more fires occurring during the time span represented by the peak. In sites with fast deposition times, a peak is generally less than 20 years (one or two centimeters thick) (Millspaugh, 1997; Long et al., 1998), whereas in sites with slow sedimentation, a comparable size peak may span several decades (Mohr et al., 2000; Anderson & Smith, 1997).

Values for the window width to infer background levels and the threshold-ratio are selected by (1) examining the CHAR from the short core relative to the record of recent fires near the site, and (2) using a variety of values of the two parameters to decompose the long record. The results of the decomposition are compared with information on present-day fire regimes in the region. This iterative approach helps assess the robustness of the method and the sensitivity of the outcomes to the choice of parameter values (Fig. 5).

To detect individual fires or calculate the mean fire interval (MFI; Romme, 1980), the sample interval must be significantly shorter than the average time between fires. Suppose for a given period that the MFI is described by a negative exponential distribution of fire-intervals, i.e., short intervals are more frequent than long ones. The cumulative proportion

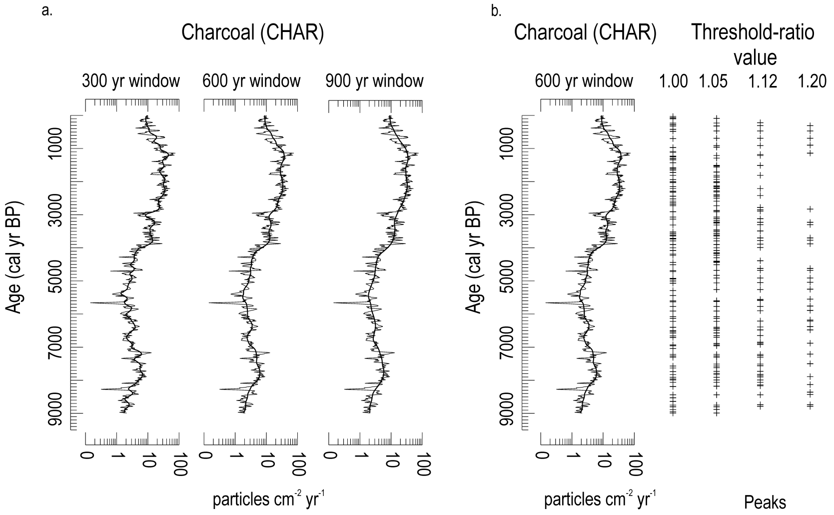

Figure 5. Comparison of (a) different window widths and (b) threshold-ratio values for the decomposition of CHAR at Little Lake in the Oregon Coast Range (after Long et al., 1998). CHAR values were log-transformed and interpolated to a constant time step. Different window-widths were considered to define background levels. The comparison of threshold ratios was based on a background window width of 600 years. The study used a threshold ratio of 1.12 for the fire history reconstruction because it correctly identified eight fire events in the last 1500 years and no additional events.

of all intervals up to a given length x can be calculated as:

$$\sum f(x) = 1 - e^{-px}, \tag{1}$$

where

$f(x) =$ frequency of a fire
$e =$ base of natural logarithms
$p =$ probability of fire in any year (inverse of the MFI).

(Van Wagner, 1978; Agee, 1993). This equation can be used to examine the influence of different sampling resolutions and the relation between actual MFI and the lowest possible MFI that can be estimated. The shortest interval that can be detected between fires is twice the sampling interval. The equation is used to first calculate the expected fire-interval distribution for a given MFI. Then, the portion of the distribution that was twice a particular sampling resolution is used to estimate the shortest possible MFI that this resolution can detect. The estimated shortest-possible MFI in all cases is longer than the actual MFI, an observation also made by Green (1983) for pollen data. The ratio between the actual and shortest-possible estimated MFI increases as the ratio between the estimated MFI and the sample resolution approaches two (i.e., every other sample is inferred to be a significant charcoal peak). When the actual MFI is 4× the sample resolution, the estimated shortest possible MFI is ca. 1.7× the actual MFI; when the actual MFI is 8× the sample resolution, the estimated shortest-possible MFI is ca. 1.3× the actual MFI. Although these results are based on a simple calculation that does not characterize the changing nature of fire regimes on long time scales, it does point to the importance of sample interval in estimating MFI from nonlaminated sediment records.

Use of other data for verification

Evidence of fire-related erosion has been used to help constrain the charcoal source area, inasmuch as the co-occurrence of a charcoal peak and evidence of erosion provides confirmation that the fire event occurred within the watershed. Selecting a site suitable for lithologic analyses is not straightforward, because changes in lithology or geochemistry may be unrelated to fire. To maximize the input of the allochthonous component following fire, Birks (1997) and Rhodes & Davis (1995) suggest selecting a site with a large watershed relative to the lake.

The magnetic properties of lake sediments have been used to trace the input of allochthonous clastic material (Thompson & Oldfield, 1986; Gedye et al., 2000). The usefulness of such measurements depends on fire location, fire type and intensity, and soils and substrate type. In Millspaugh & Whitlock (1995), lakes that recorded the highest sediment magnetism were located in steep-sided watersheds, where the potential for post-fire erosion was greatest. Low-gradient watersheds, in comparison, showed no signal. Long et al. (1998) found that magnetic susceptibility increased dramatically in the late Holocene but peaks of magnetic susceptibility did not match charcoal peaks. Fire-induced erosion has also been inferred from increases in the content of aluminum, vanadium, and silt in sediments associated with charcoal peaks (Cwynar, 1978) and from an increase in varve thickness (Tolonen, 1978; Larsen & MacDonald, 1998a).

The decomposition approach described above for charcoal has also been applied to magnetic susceptibility data. Background levels of magnetic minerals provide information on pedologic and geomorphic processes that operate within the basin over the long term. Peaks in magnetic susceptibility measurements indicate individual geomorphic events, such as landslides, similar to the CHAR peaks. In Yellowstone, such peaks corresponded well with charcoal peaks, suggesting that they were from fire-related erosion events (Millspaugh & Whitlock, 1995). In other studies in the western United States, no direct relation between CHAR peaks and magnetic susceptibility peaks was noted, even when the possibility of a time lag was considered (Millspaugh, 1997; Long et al., 1998; Mohr et al., 2000; Brunelle & Anderson, in press).

The pollen record often complements the reconstruction provided by charcoal data by suggesting the proximity and size of the fire through changes in the composition of the vegetation. A number of studies have noted the correspondence between charcoal peaks and changes in key pollen taxa (Swain, 1973; Tolonen, 1978; Patterson & Backman, 1988; Pitkänen & Huttunen, 1999) or assemblages of pollen taxa that represent different stages of forest succession (Swain, 1978, 1980; Patterson & Backman, 1988; Rhodes & Davis, 1995; Larsen & MacDonald, 1998a,b; Tinner et al., 1999) (Fig. 6). Cross-correlations between pollen records and either charcoal or a fire-sensitive pollen taxon have been used to identify pollen taxa with repeated sequences of peaks and troughs relative to a fire record

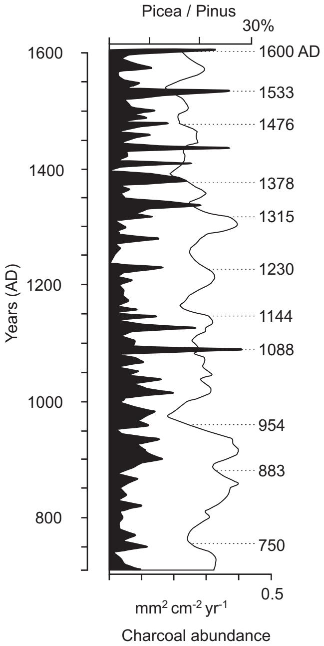

Figure 6. Comparison of *Picea/Pinus* ratio and CHAR (black) for a Lake Pönttölampi in eastern Finland from 700–1600 AD (after Pitkänen & Huttunen, 1999). Eleven local fires are identified by the peak in CHAR and associated decline in the *Picea/Pinus* ratio.

(e.g., Green, 1981; J. S. Clark et al., 1989; Larsen & MacDonald, 1998a,b; Tinner et al., 1999). For example, cross-correlation results for four pollen types from a site in northern Alberta that show peaks at different lengths of time after a peak in pollen-slide charcoal. These relations were used to identify fires in an 840-year record (Larsen & MacDonald, 1998a) (Fig. 7).

An interesting approach in fire reconstructions is the use of computer models to simulate the pollen source area (Sugita et al., 1997) and then estimate fire size and proximity based on pollen changes within that area. The method assumes that local fires lead to a decrease in pollen abundance. Model results for a site in the boreal forest of Canada suggest that a small lake (3 ha surface area) would register a 10% decline in local pollen from a 4-ha fire at the lake shore, a 100- ha fire on one side of the lake, or a 2500- ha fire within 100 m from one side of the lake. A large lake (314 ha surface area) exposed to fires of the same size and proximity would record decreases in local pollen of approximately 0, 1 and 2%. Decreases in the local pollen of 30% would be observed in the 100- m-radius lake if a 100 ha fire burned around the lake shore, and in the 1000- m-radius lake if a 2500 ha fire burned around the lake shore. The patchiness of the forest and the pollen productivity of the locally dominant species (Sugita, 1994) also affected the simulated relationships. If the modeled relations are correct, it is not surprising that the pollen record does not respond to every fire detected by the charcoal record. However, the pollen record may be sensitive enough to detect the large fire events that result in major changes in vegetation composition.

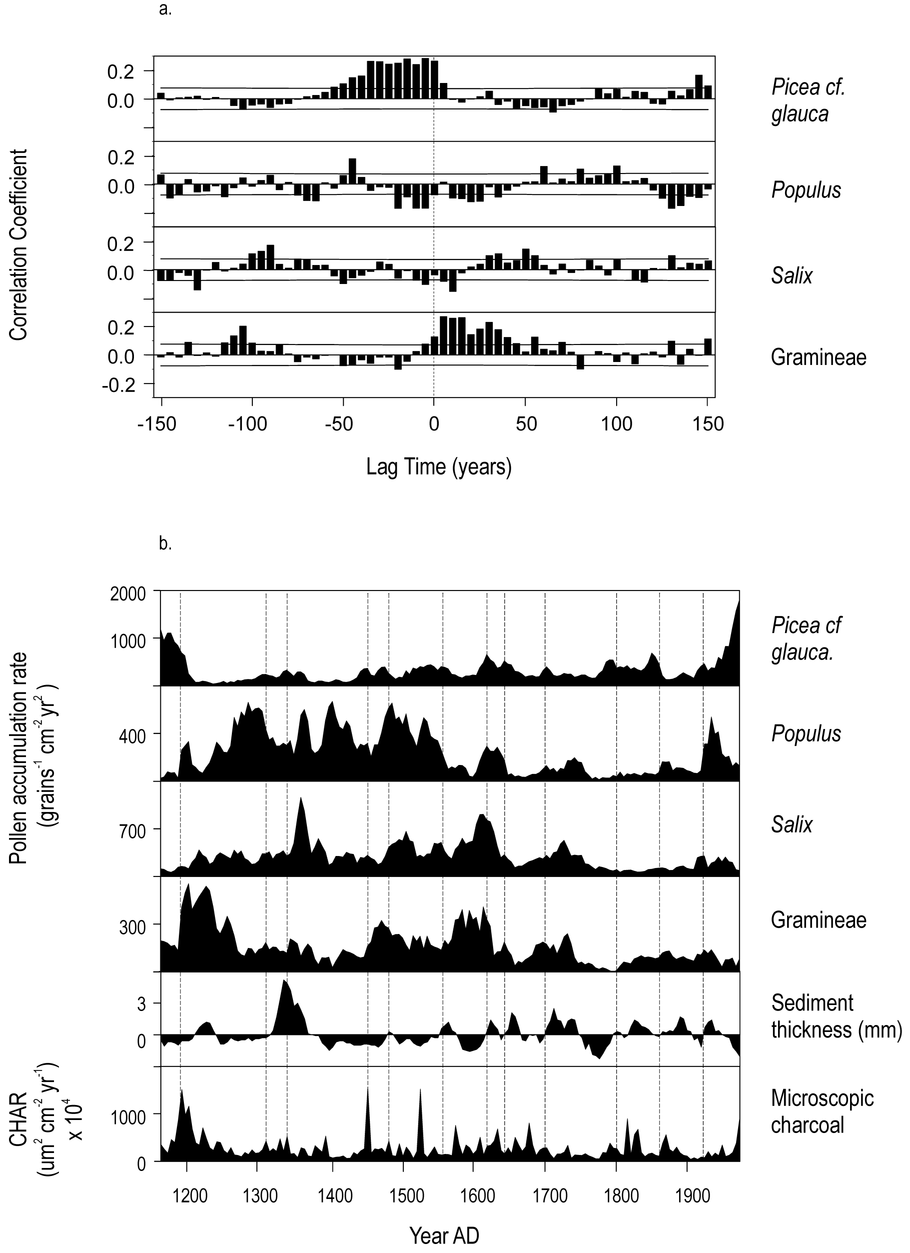

Figure 7. Analysis of pollen assemblages as a fire proxy at Rainbow Lake (59°51'N, 112°15'W) in the Canadian boreal forest (after Larsen & MacDonald, 1998a). (a) Cross-correlograms developed through cross-correlation analysis between the 840-year record of particular pollen taxa and pollen-slide charcoal accumulation rate. The solid bars indicate the cross-correlations at each time lag, and the horizontal lines indicate the 95% confidence limits. Positive cross-correlations after the peak in charcoal at year zero indicate a record whose peak values follow that of charcoal. (b) The 840-year records of *Picea* cf. *glauca, Populus, Salix*, Gramineae, pollen slide charcoal, and the detrended sediment thickness in each 5-year sample. Vertical dashed lines indicated inferred local fire events. All but the charcoal record was smoothed using a 3-sample mathematical average.

Conclusions

To realize the potential of charcoal data as a paleoenvironmental proxy requires standardization of both the techniques and assumptions used to interpret such data. Too many charcoal studies are based on imprecise or unsubstantiated assumptions and analytical approaches. Studies of modern charcoal transport and deposition are rare. Information on modern taphonomic processes is needed to calibrate charcoal data and refine the interpretation of the stratigraphic record. Similarly, additional modeling efforts that focus on the relationship between fire and charcoal production and transport are needed to verify the assumptions developed from empirical studies.

We offer some recommendations to improve fire-history reconstructions based on lake-sediment records:

1. Charcoal studies should routinely examine macroscopic charcoal in order to get a local fire reconstruction. The source area of macroscopic charcoal is better known than that of microscopic charcoal, and fire location is an essential part of any fire reconstruction.

2. Contiguous sampling at a fine interval is critical to calculate fire-event frequency; discontinous sampling misses charcoal peaks and often background trends are interpreted as fire events. The sample resolution ideally should be ca. 1/8th the estimated MFI to differentiate closely recurring fires.

3. An adequate chronology is essential, as is some method of calibration to identify a significant threshold level. Thus, charcoal studies require varved-sediments or a chronology based on a suite of calibrated AMS ^{14}C- and ^{210}Pb-dates.

4. The choice of a specific method of charcoal enumeration, whether charcoal counts through a sieving procedure, charcoal area measurements from image analysis, or charcoal abundance by sediment weight or volume, is less important than the decision to undertake high-resolution sampling and careful calibration. Most high-resolution methods seem to produce similar trends, although further comparison of the results derived from different methods is needed.

5. In analyzing the data, it is important to recognize that the time series consists of at least two components, a slowly varying background component, superimposed upon which is a peaks component. The information contained in these two components is different and should be interpreted separately. Periods with abundant charcoal may not necessarily represent times of more fires; they could be periods of high background charcoal as a result of a shift in fire severity or the introduction of secondary charcoal.

6. Each macroscopic charcoal record is a local reconstruction; to infer landscape, regional, or larger-scale patterns requires a network of sites, done to a similar high standard.

7. In addition to charcoal data, other fire proxy are worth considering, to supplement the fire reconstructions. The sensitivity of pollen and lithologic records to a particular fire event should to be carefully tested in each locality.

Summary

particles preserved in lake sediments provide a means of reconstructing fire history beyond documentary and dendrochrological records. Recent refinements in charcoal analysis and interpretation have greatly improved our ability to use charcoal records as proxy of past fire events and to calculate long-term variations in fire frequency. Standardization has also facilitated synthesis of different researchers' data. Interpretating charcoal records in terms of the fire location, size, and intensity requires an understanding of the processes that influence charcoal production, transport, and deposition. Studies of charcoal deposition following modern fires, as well as theoretical models of charcoal particle transport, suggest that macroscopic particles (>100 microns in size) are not transported far from source before settling. They become entrapped in lake sediments within a few years of the fire event through airborne fall-out and secondary reworking. Microscopic charcoal particles (<100 microns in size), in contrast, are able to be carried aloft during a fire and can travel long distances before settling. A record of these small particles provides a reconstruction of regional or extralocal fires. Macroscopic charcoal is tallied or measured in petrographic thin sections or in sieved residues and used to calculate charcoal accumulation rates. Microscopic charcoal is usually counted as a part of routine pollen analysis and its abundance is often presented as a ratio of the pollen sum. The choice of particle size dictates whether regional or local fire events are reconstructed, and whether calculation of fire frequency is possible. Interpretation of the charcoal record requires a well-constrained chronology, in order to analyze charcoal samples taken at a finer time interval than the mean fire return interval inferred from ecological data. In most cases, it is necessary to distinguish between background charcoal in the stratigraphic record, which may be introduced through secondary processes like erosion, and the primary charcoal signal of peaks that represents fire events. Calibration of the charcoal record in terms of background and peaks is also provided by comparing the uppermost stratigraphy with known fire events, inferred from documentary or dendrochronological evidence. Current efforts to be rigorous in methodology and explicit in assumption promise to produce a network of high-resolution charcoal records that can be more easily compared and interpreted.

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