WEAK CLIMATIC CONTROL OF STAND-SCALE FIRE HISTORY DURING THE LATE HOLOCENE

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Abstract. Forest fire occurrence is affected by multiple controls that operate at local to regional scales. At the spatial scale of forest stands, regional climatic controls may be obscured by local controls (e.g., stochastic ignitions, topography, and fuel loads), but the long-term role of such local controls is poorly understood. We report here stand-scale (<100 ha) fire histories of the past 5000 years based on the analysis of sediment charcoal at two lakes 11 km apart in southeastern British Columbia. The two lakes are today located in similar subalpine forests, and they likely have experienced the same late-Holocene climatic changes because of their close proximity. We evaluated two independent properties of fire history: (1) fire-interval distribution, a measure of the overall incidence of fire, and (2) fire synchroneity, a measure of the co-occurrence of fire (here, assessed at centennial to millennial time scales due to the resolution of sediment records). Fire-interval distributions differed between the sites prior to, but not after, 2500 yr before present. When the entire 5000-yr period is considered, no statistical synchrony between fire-episode dates existed between the two sites at any temporal scale, but for the last 2500 yr marginal levels of synchrony occurred at centennial scales. Each individual fire record exhibited little coherency with regional climate changes. In contrast, variations in the composite record (average of both sites) matched variations in climate evidenced by late-Holocene glacial advances. This was probably due to the increased sample size and spatial extent represented by the composite record (up to 200 ha) plus increased regional climatic variability over the last several millennia, which may have partially overridden local, non-climatic controls. We conclude that (1) over past millennia, neighboring stands with similar modern conditions may have experienced different fire intervals and asynchronous patterns in fire episodes, likely because local controls outweighed the synchronizing effect of climate; (2) the influence of climate on fire occurrence is more strongly expressed when climatic variability is relatively great; and (3) multiple records from a region are essential if climate–fire relations are to be reliably described.

Key words: bivariate Ripley K function; British Columbia; charcoal; climatic change; fire history; fire regime; landscape connectivity; late Holocene; synchrony.

INTRODUCTION

Climatic changes have affected forest fire occurrence over broad areas in the past and will do so in the future (Flannigan et al. 2001). At regional-to-subcontinental scales, synoptic weather patterns over the past century greatly affected the annual burned area in the Canadian Rocky Mountains (Johnson and Wowchuk 1993, Skinner et al. 1999). These weather patterns change the susceptibility of forest stands to fire at a regional scale, which can synchronize fires over a broad area (10s of kilometers) during particular years (Nash and Johnson 1996). At smaller spatial scales, however, more variation in fire occurrence may be explained by

locations of ignitions, specific weather following ignition, topography, and other local controls on fuel load and flammability (Lertzman and Fall 1998, Rollins et al. 2002). This scale-dependent pattern in the observational record of fire is supported by multi-century tree-ring fire histories: although records from individual stands have only limited similarity, instances of synchrony of fire among stands over periods lasting from a year to centuries can be attributed to climatic change (Swetnam 1993, Weisberg and Swanson 2003).

Despite these insights from observational and tree-ring studies, the spatial and temporal scales at which climate synchronizes fire occurrence remain poorly understood, especially in forests with infrequent (>100-yr intervals) stand-replacing fires. For example, it is unclear at what spatial scale(s) fire occurrence is correlated with climatic variability, or what magnitude of climatic change should be evident in a long-term, stand-scale fire history. In western North America, this inadequate understanding reflects the fact that few

studies of long-term fire histories have been done until recently (e.g., Long et al. 1998, Hallett and Walker 2000, Brunelle and Whitlock 2003, Gavin et al. 2003, Hallett et al. 2003a). Information on the controls on fire regimes and their spatial hierarchy has now begun to emerge from lake-sediment records. For example, recent studies revealed the lack of centennial to millennial synchrony among fire records from the same areas during the middle to late Holocene. This has been attributed to spatial variability in climate (Brunelle and Whitlock 2003) or complex relationships among climate, vegetation, and fire (Lynch et al. 2004). However, no study has focused explicitly on assessing the relative importance of local, non-climatic controls vs. regional climatic controls on stand-scale fire occurrence over centennial to millennial time scales.

In this study, we investigate stand-scale fire histories at two British Columbia lakes in relation to climatic change over the past 5000 years. We reconstructed fire histories based on the analysis of charcoal in lake-sediment cores. To aid our interpretations of fire–climate relationships, we used pollen and/or plant-macrofossil data from the same sites to reconstruct past vegetation, and searched for evidence of past regional climatic change. We selected our two study sites for the following similarities and differences that permit an assessment of regional climatic vs. local controls on the fire regime. Because they are only 11 km apart, the two sites should have experienced the same regional climate throughout the past 5000 years. The sites are also very similar in terms of vegetation and late-Holocene vegetation history (dense subalpine forests), topography (moderate hillslopes), and microclimate (same elevation and similar aspects). However, a large river and several major topographic firebreaks separate the sites, and only one of the sites has landscape connectivity to low-elevation, south-facing slopes that are susceptible to fire.

We evaluated two independent properties of fire history: (1) fire-interval distribution, a measure of the overall incidence of fire, and (2) fire synchroneity, a measure of the co-occurrence of fire between sites. (We do not expect to detect synchrony of fire at annual or decadal resolution because fire extents are very patchy, even in years with extensive fires, and chronological error in radiocarbon-dated sediment records may be as great as 200 years. However, longer term fluctuations in climate may result in periods of higher fire frequency that are synchronous across sites. Thus, we assess synchrony of fire at resolutions of centuries to millennia.) Comparison of these properties should yield different patterns, depending upon the relative importance of climate controls vs. local controls of fire occurrence. First, fire-interval distributions may be similar and fires synchronous between sites if regional climate predominates over local controls, which is our expectation in this study, given the similarity of the sites. Second, fire-interval distributions may differ but fires

may be synchronous if different levels of landscape connectivity (or other local factors) result in a higher long-term probability of fire occurrence at one site than at the other, but climatic fluctuations affect fire similarly at both sites. Third, fire-interval distributions may be similar but fires asynchronous if the long-term probability of fire is similar at both sites but the effect of climatic fluctuations on fire are overridden by local controls at one or both sites. Last, it is also conceivable that fire-interval distributions differ and fires are asynchronous if all types of local controls (connectivity, ignition, and fire weather) predominate over climatic controls. In addition, changing magnitude and/or periodicity of climatic fluctuations, and thus their importance relative to local factors may cause the similarity of two fire histories (measured by synchroneity and interval distributions) to change over time.

Study Sites

We conducted this study at Rockslide Lake (49°33.0′ N; 117°31.3′ W; 1539 m above sea level [a.s.l.]) and Cooley Lake (49°29.5′ N; 117°38.7′ W; 1515 m a.s.l.) in southeastern British Columbia (Fig. 1). These lakes were chosen for properties that aid in the preservation of a charcoal signal of local forest fires: small surface area (Rockslide, 3.2 ha; Cooley, 4.5 ha), relatively deep water (Rockslide, 14.1 m; Cooley, 11.0 m), and narrow littoral zones (Whitlock et al. 1997). The catchments of Rockslide Lake and Cooley Lake are 86 and 107 ha, respectively, and both lakes lack a perennial inflowing stream. Assuming the source area for charcoal particles >125 μm to be a distance of <500 m from the lake shore (Lynch et al. 2002), each study site records fires within an area of <100 ha. The forests surrounding both lakes are dominated by subalpine fir (Abies lasiocarpa) and Engelmann spruce (Picea engelmannii). The area around Cooley Lake supports minor amounts of several species that are absent or rare at Rockslide, including western hemlock (Tsuga heterophylla), western redcedar (Thuja plicata), lodgepole pine (Pinus contorta), western white pine (Pinus monticola), Douglas-fir (Pseudotsuga menziesii), and western larch (Larix occidentalis). The climate at the elevation of the sites is marked by mild summers and cold winters (July and January mean temperature is 15°C and −8°C, respectively), and annual precipitation is ~1000 mm, of which ~180 mm occurs July through September (Daly et al. 1994).

Insect outbreaks, windthrow, and fire are the major disturbances affecting forest ages and species composition in Engelmann spruce–subalpine fir forests of the region, with stand-replacing disturbance intervals of 150–350 years during the last several centuries (Wong et al. 2004). In these high-elevation forests, cool summers and persistent spring snowpack limit the fire season, and steep terrain or broken topography create complex fire perimeters and limit fire extent. Fire intervals prior to European settlement are poorly understood, partly because of extensive human-set fires during railroad
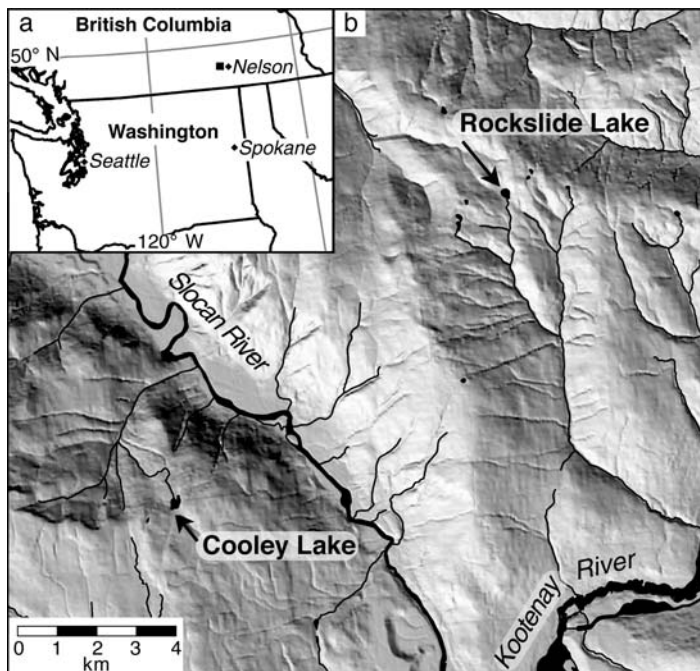
FIG. 1. (a) Location of the study area (square) near Nelson, British Columbia, Canada. (b) Topography of the study area surrounding Rockslide Lake and Cooley Lake. The shaded relief map is based on a SSW solar azimuth.

construction and mineral prospecting in the late 1800s that homogenized stand ages in many areas, especially at low elevations (Johnson et al. 1990, Owen 1994). At the study sites, the existence of late-successional stands today is consistent with long fire intervals (>200 yr) and intense stand-replacing fires in which fuels are rarely a limiting factor (Pollack et al. 1997, Wong et al. 2004).

METHODS

Field and laboratory methods

At each lake we obtained two sediment cores with overlapping 1-m drives from the deepest portion of the lake using a modified Livingstone piston corer (Wright et al. 1984). At both lakes coring ceased at a thick, impenetrable, volcanic tephra layer. Macroscopic sediment charcoal (125–250 μm) was tallied from subsamples (1–5 cm^3) taken at contiguous 0.5- or 1-cm intervals, following Long et al. (1998) and Gavin et al. (2003). Plant macrofossils were identified from each charcoal sample, and, at Cooley Lake, ≥350 pollen grains were identified from each of 76 subsamples following standard methods (Faegri et al. 2000).

To verify that the most recent fires occurring near the lake were detectable in the sediment record, we determined the age of shade-intolerant canopy trees near each lake. At Cooley Lake, increment cores were taken close to ground level from the nearest 10 canopy-dominant shade-intolerant trees (pines, Douglas-fir, or larch) in each of six plots spaced evenly around the perimeter of the lake (60 total). Forty-two of these trees could be cored to within ~5 yr of the pith as estimated from the curvature of the inner rings. At Rockslide Lake, only six shade-intolerant individuals (western white pine and Douglas-fir) were present within 200 m of the lake, of which only three could be cored close to the pith. Exploratory tree coring elsewhere around Rockslide Lake indicated that these late-successional forest stands were uneven-aged. Increment cores were mounted, sanded, and cross-dated (Stokes and Smiley 1996). Tree ages were inferred to the nearest decade by extrapolating missing tree-rings to the pith and assuming ~15 cm/yr height growth to the coring height (Wong and Lertzman 2001).

At each lake, sediment ages were interpolated between four AMS radiocarbon dates of identifiable plant macrofossils and the ages of identifiable volcanic tephras using polynomial regression (Fig. 2). All radiocarbon ages were converted to calibrated years before AD 1950, hereafter referred to as yr BP, using the atmospheric calibration data set (Stuiver et al. 1998). The Rockslide Lake sediment core terminated at 5000 yr BP due to a thick redeposited Mazama tephra layer whereas the Cooley Lake core reached the airfall-deposited Mazama tephra (7627 yr BP; Zdanowicz et al. 1999); thus statistical comparisons were based on the 5000 yr in common between the records. Two other tephras occurred in both cores: St. Helens Wn (AD 1482) and St. Helens P (2620 yr BP; Foit et al. 2004). Details of radiocarbon dates, tephra identification, and

polynomial curve fitting are in Appendix A and Foit et al. (2004).

Identification of charcoal peaks

We calculated charcoal accumulation rate (CHAR; pieces per square centimeter per year) from charcoal concentration and sediment accumulation rate. Peaks in CHAR that were most likely caused by local fires were identified following the general framework outlined in Clark et al. (1996) and Long et al. (1998). This approach decomposes CHAR into two components. The background component represents centennial-scale variation in overall CHAR magnitude due to changes in vegetation, fire behavior, and mechanisms that deliver charcoal to the lake center. We estimated the background component using a locally weighted regression (Cleveland 1979) with a time window (500-yr) narrow enough to capture centennial-scale changes in CHAR but wide enough not to be affected by discrete peaks.

The peak component, calculated as the difference between CHAR and the background component, includes peaks in CHAR related to fires occurring near the lake. If a CHAR record is a clear recorder of fires, the peak component should be composed of a small population of high values related to local fires and a large population of low values (both positive and negative) due to distant fires, analytical noise, and charcoal redeposition within the watershed or within the lake (Clark et al. 1996). We used two methods to identify a threshold value that best separates these two populations. First, we determined the range of threshold values that show little sensitivity to the number of peaks detected (Clark et al. 1996). Second, we modeled the frequency distribution of the peak component as a mixture of overlapping Gaussian distributions using the program CLUSTER (Bouman 2001). This program uses an information-theory approach to determine the number of Gaussian distributions, and their means and variances, which in combination best fit the observed distribution. This method assumes that the distribution of peak-component values of samples not coincident with local-fire years is Gaussian with a mean near 0, and that such samples are common enough to be identified by CLUSTER. Although a more appropriate distribution cannot be completely ruled out, a few known processes should contribute to a Gaussian (or Poisson) distribution, including sediment mixing, sampling effects, and analytical noise. Prior to fitting the Gaussian mixture model, the peak component was resampled at 10-yr time intervals to make all parts of the record equally represented irrespective of the sedimentation rate. A final threshold at each lake was chosen at a level that had strong agreement between the two methods.

Each CHAR peak exceeding the threshold is hereafter assumed to be a fire episode, which represents one or more fires occurring within the charcoal source area and within the average sampling resolution of 20 yr. Fire
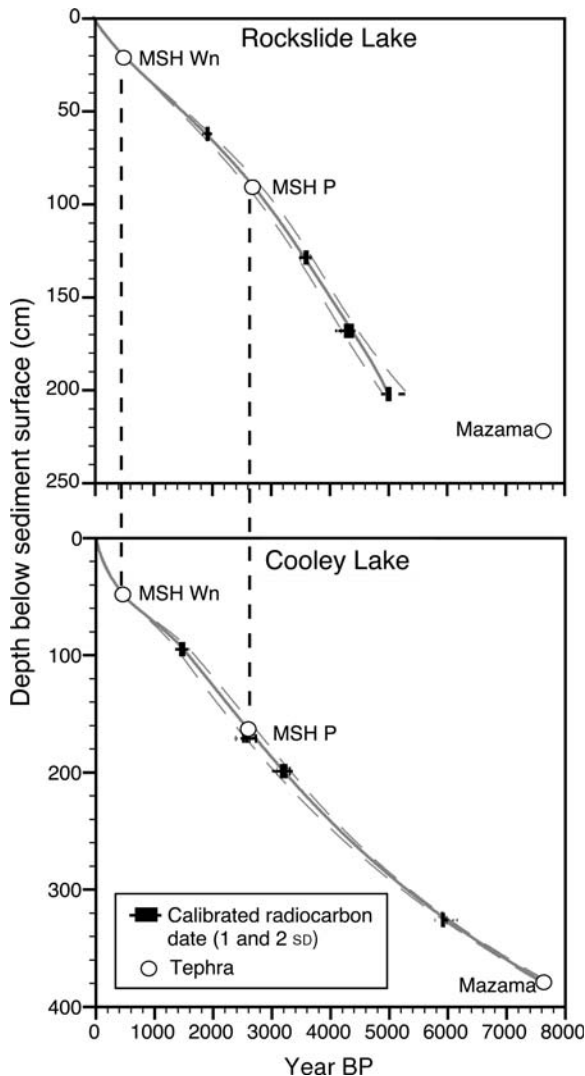

FIG. 2. Depth–age relationship from the Rockslide Lake and Cooley Lake sediment cores. Vertical dashed lines indicate Mount St. Helens (MSH) volcanic tephras identified in both sediment cores. Radiocarbon dates are shown as mean ± 1 SD (wide bar) and 2 SD (narrow line) age ranges. Radiocarbon dates and tephra identifications are reported in Appendix A and Foit et al. (2004).

frequency and fire intervals refer to fire episodes per 1000 yr and years between episodes, respectively. Note that this is not the point-based estimate of fire incidence but is rather an area-based estimate reflecting the catchment from which charcoal is drawn for the record. The fire intervals, as we use the term here, may diverge from point-specific fire intervals if (1) fires did not encompass the entire source area, and/or (2) fires occurred at shorter intervals than can be detected by the sediment record (e.g., reburns), both of which are unlikely given that the fire regime of the region is characterized by large, intense, and infrequent fires (Wong et al. 2004).

Comparing fire records

We tested whether the statistical properties of the fire-interval distributions differed between the sites. We divided each record into two periods at 2500 yr BP; this is the midpoint of the record, and it generally corresponds to a regional climatic change to cooler and moister conditions (Luckman et al. 1993, Rosenberg et al. 2004). We compared the median fire interval between sites by fitting each period with a parametric Weibull distribution that uses a maximum-likelihood method to estimate the Weibull median fire interval and its variance (Grissino-Mayer 1999). We also examined the overall difference in fire-interval distributions between sites using the nonparametric two-sample Kolmogorov-Smirnov (KS) test (Clark 1989).

We assessed the synchroneity of fire occurrence between the sites using two methods. First, at the millennial scale, we tested whether the fire-interval distributions changed in the same direction from before to after 2500 yr BP between the two sites, using both the Weibull median fire interval and the KS test. Second, at the centennial to millennial scale, we used a modification of the bivariate Ripley's K function (Ripley 1977). The bivariate K function tests for attraction or repulsion between two classes of points (e.g., whether two tree species occur closer together than would be expected by chance) in two-dimensional space by summarizing distances between all point pairs of different classes (Lotwick and Silverman 1982). Here, we use the bivariate K function modified for one dimension (i.e., time; Doss 1989) where each class is a site. The K function was transformed to the L function, $\hat{L}_{AB}(t)$, where values >0 suggest synchrony, values near 0 suggest independence, and values <0 suggest asynchrony of fire episodes within a window of t yr. We also constructed 95% confidence envelopes for $\hat{L}_{AB}(t)$ from 1000 randomizations of shifting one record a random number of years and wrapping fire episodes from the end to the start of the record (see Appendix B for detailed methods and a demonstration with simulated data). Because the K function analyzes the entire record at once, it cannot detect changes in synchrony over time. Therefore, in addition to analyzing the entire record, we computed K functions separately for the two periods separated at 2500 yr BP.

Last, to visualize trends in fire frequency at different temporal scales, we plotted the number of fire episodes in 200-, 500-, and 800-yr moving windows over the entire record. These window sizes were chosen based on the duration of the Little Ice Age, a period typically dated AD 1300–1850 and well documented in the region (Luckman 2000) when cooler/wetter climatic conditions may reduce fire occurrence; the 200-yr and 800-yr intervals test the potential for shorter and longer climatic fluctuations to affect fire occurrence. For each of the moving windows, we also calculated a composite fire-frequency record for the two sites by rescaling the range of fire frequencies at each site from 0 to 1 and averaging the two scaled frequency series. In this way each site contributes equally to the composite record regardless of the range of frequency at each site.

RESULTS

Reconstructing fire episodes

Overall charcoal concentrations were greater at Cooley Lake (median, 63; range, 3–1836 pieces/cm^3) than at Rockslide Lake (median, 12; range, 0–227 pieces/cm^3). Charcoal accumulation rates (CHAR) were also an order of magnitude greater at Cooley Lake (median, 3.37; range, 0.63–89.24 pieces·cm^{-2}·yr^{-1}) than at Rockslide Lake (median, 0.49; range, 0–6.80 pieces·cm^{-2}·yr^{-1}; Fig. 3).

Our identification of fire episodes was robust at both lakes, as determined by three lines of evidence. First, the age of the last fire based on tree-ring evidence is consistent with the age of distinct charcoal peaks. At Cooley Lake, the ages of 42 shade-intolerant trees clustered between AD 1640 and AD 1660, suggesting that the last fire occurred ca. AD 1640 and that this fire encompassed >80% of the area around the lake. This fire is seen as a distinct CHAR peak at ca. AD 1650 in the Cooley Lake CHAR record (Fig. 3b). This record also showed a CHAR peak within the last 20 yr, excluded in subsequent analyses, from slash burning in clearcuts occupying ~30% of the charcoal source area and within 50 m of the lake shore. At Rockslide Lake, tree ages indicated that the most recent fire was before AD 1680, but this result is inconclusive because of rotten tree centers and too few corable trees. The most recent large charcoal peak shortly postdates the AD 1482 Wn tephra and thus does not contradict the limited tree-age evidence.

Second, the frequency distribution of the CHAR peak component at both lakes suggests a distinct separation between populations of high and low values. Specifically, the best-fit Gaussian mixture model required only two distributions: one with a mean near 0 and a low variance, and the other with a high mean and a very high variance (Fig. 3c, d). The upper end of the lower distribution may be considered the upper limit of noise-related values, falling at values of ~0.6 at Rockslide Lake and 4 at Cooley Lake.

Third, the low sensitivity of the number of detected peaks to varying the threshold suggests a distinct separation of large peaks. The number of detected peaks does not vary substantially between threshold values of 0.8–0.9 at Rockslide Lake and 4.5–5.5 at Cooley Lake. Thresholds of 0.8 and 5 result in 33 and 32 (23 after 5000 yr BP) charcoal peaks at Rockslide Lake and Cooley Lake, respectively.

Comparing fire records

The fire-interval distribution showed inconsistent temporal trends between the sites. Before 2500 yr BP, the median fire interval was less than half as long at Rockslide Lake (118 yr) as at Cooley Lake (273 yr; Fig.
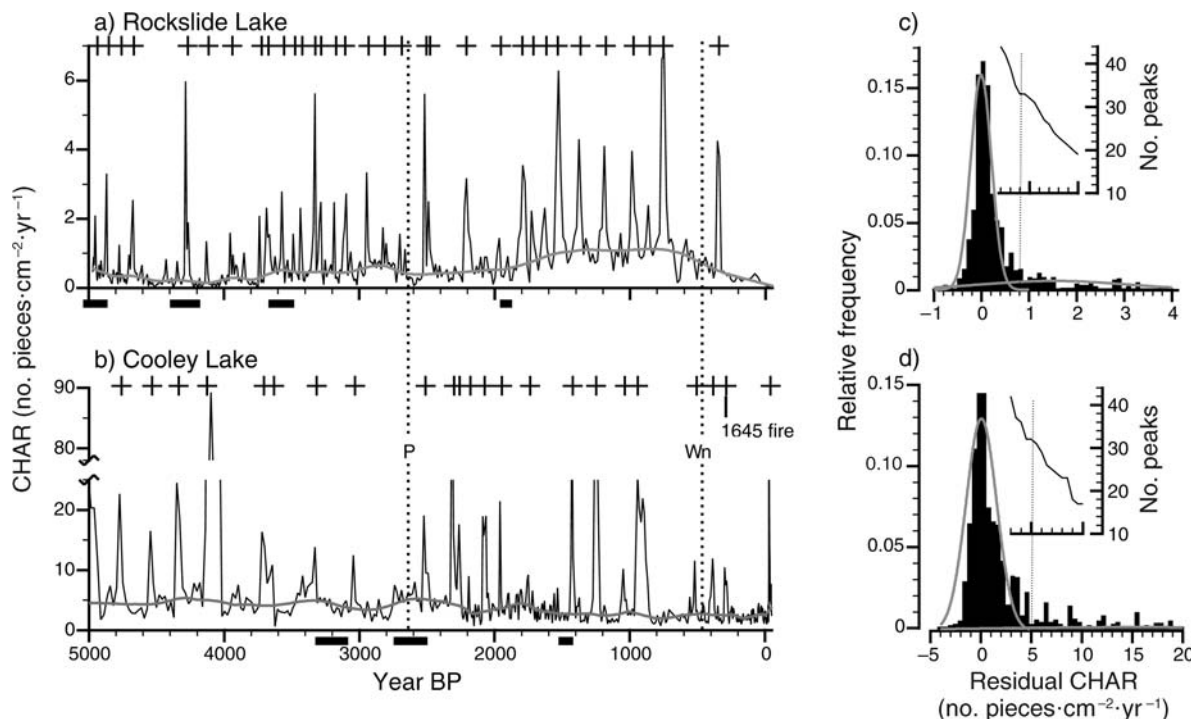
FIG. 3. Charcoal accumulation rate (CHAR) with background (gray line) from (a) Rockslide Lake and (b) Cooley Lake sediment cores. Dashed vertical lines indicate the Mt. St. Helens Wn and P tephras that were identified in both sediment cores. Horizontal black bars below the x-axes indicate 1 SD ranges of radiocarbon dates on plant macrofossils. The "+" symbols represent identified charcoal peaks. (c, d) Frequency distribution of the CHAR residuals with fitted curves from a Gaussian mixture model. Insets show the sensitivity of the number of CHAR peaks detected using a range of threshold values. The vertical dotted line shows the threshold chosen to identify charcoal peaks most likely due to local fire episodes.

4), and the fire-interval distribution differed greatly between the two sites (KS test; $P = 0.009$). After 2500 yr BP, the median fire intervals were very similar at Rockslide Lake and Cooley Lake (186 and 168 yr, respectively), and the fire-interval distributions were indistinguishable (KS test, $P = 0.998$). Thus fire occurrence shows different millennial-scale trends at the two sites. The fire-interval distribution changed relatively little at Rockslide Lake (KS test, $P = 0.348$) but decreased nearly significantly ($P = 0.061$; Fig. 4) at Cooley Lake from before to after 2500 yr BP. Varying the CHAR threshold that defines fire episodes upward or downward to include ±4 fire episodes at each site did not change the interpretation of the Weibull or KS tests.

The bivariate K function indicated that, for the 5000-yr record as a whole, the times of fire episodes at the two lakes were independent of each other across all temporal scales (0–2500 yr; Fig. 5), corroborating the fire-interval distribution analyses. However, analyzing the two 2500-yr periods separately revealed that the degree of synchrony differed between the two periods. Before 2500 yr BP, fire episodes occurred independently in all temporal windows, whereas after 2500 yr BP, significant synchrony occurred in two narrow ranges of window widths at 600 and 800 yr. Such limited significance in a small portion of many tests over a range of window sizes

should be interpreted conservatively (Diggle 2003). However, a sensitivity test indicates that this significance is robust to changes in the CHAR threshold resulting in ±4 fire episodes at each site.

Fire occurrence at the centennial scale also shows few common trends at the two sites (Fig. 6). Using a 200-yr smoothing window, fire frequency before 2500 yr BP at Rockslide Lake reached a minimum of 0 fire episodes per 1000 yr around 4500 yr BP, and maxima of 14.5 fire episodes per 1000 yr around 5000 and 3500 yr BP (Fig. 6a). In contrast at Cooley Lake fire frequency fluctuated around five fire episodes per 1000 yr before 2500 yr BP. Between 2500 and 1000 yr BP, fire frequency trended in opposite directions, exhibiting coeval maxima and minima around 2200, 1600, and 800 yr BP. Smoothing fire frequency with a 500-yr window resulted in patterns similar to those within the 200-yr window, though large changes in fire frequency over the last 2500 yr were more muted (Fig. 6b). Using an 800-yr window, both records displayed downward trends over the last 1500 yr (Fig. 6c).

DISCUSSION

Our data demonstrate that fire histories over the past 5000 yr were largely dissimilar between the two study sites, not supporting our expectation that climatic
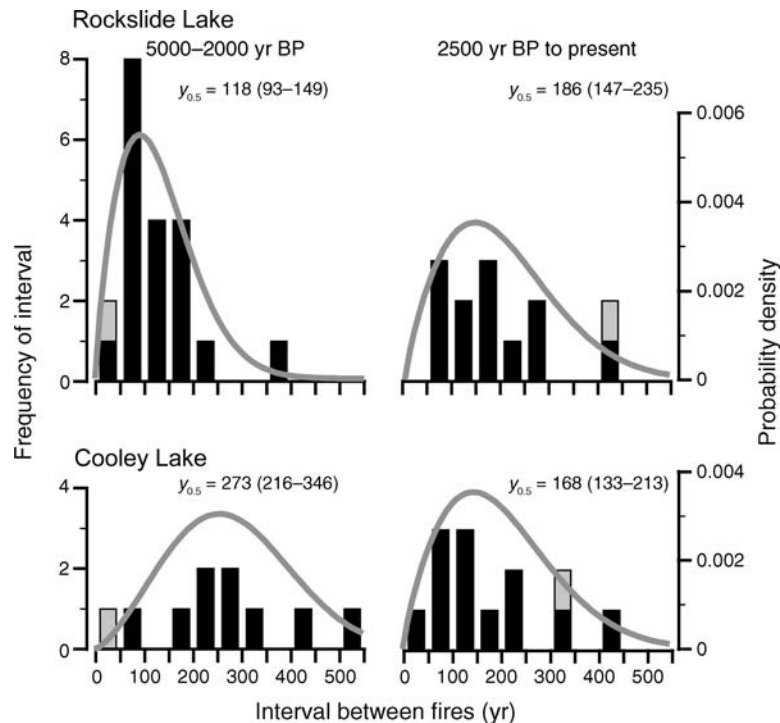
FIG. 4. Fire-interval distributions from the two lake sediment records and the fitted Weibull probability density function. The Weibull median fire intervals ($y_{0.5}$) are given, with 95% confidence intervals in parentheses. Gray bars indicate right-censored intervals (incomplete intervals following the most recent fire). Frequency is the number of times a particular interval of years between fires occurs.

changes resulted in similar fire intervals and a fair degree of fire synchroneity. Thus centennial-to-millennial scale climatic variability played a minor role in stand-scale fire occurrence relative to local controls, such as ignitions, local weather during the fire, and topography. Although the role of local non-climatic controls is widely appreciated in tree-ring-based fire history studies (Swetnam 1993), our data demonstrate its pervasive influence on stand-scale fire occurrence over millennia (see also Hu et al. 2006).

Local controls on fire occurrence were particularly important prior to 2500 yr BP, especially with respect to fire frequency. We attribute the higher fire frequency at Rockslide Lake compared with Cooley Lake during this period to their differences in landscape position. Rockslide Lake is located in steeper terrain with S and SW aspects that are contiguous with more extensive S aspects at lower elevations from which fires may spread upslope. In contrast, Cooley Lake is surrounded by more subdued topography farther from any extensive S
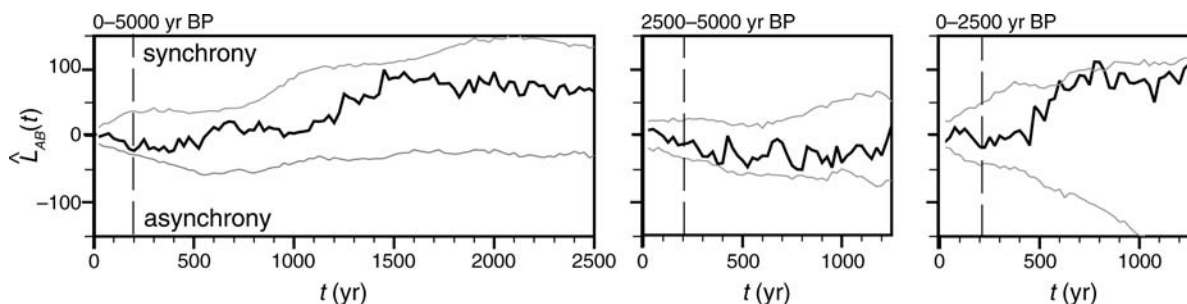

FIG. 5. Bivariate L functions for the Rockslide Lake and Cooley Lake fire history records, showing the temporal windows (t) in which fire episodes are independent or synchronous between the two sites. See *Methods: Comparing fire records* and Appendix B for detailed descriptions of the L function. Functions were calculated separately for three time periods. Thin lines are 95% confidence envelopes based on 1000 randomizations of shifting records relative to each other. Due to unavoidable error in the sediment chronology (radiocarbon dates and variable sedimentation rates), synchrony in time windows <200 yr (vertical dashed line) is not expected.

aspects (Fig. 1). It is unlikely that differences in vegetation and fuels contributed to differences in fire intervals. Plant macrofossils, though not abundant at Rockslide Lake, suggest that both sites supported dense Engelmann spruce–subalpine fir forests throughout the past 5000 years (Appendix C). In addition, the Cooley Lake pollen record, which reflects vegetation at distances much greater than the charcoal source area, shows no correlation between vegetation and fire history (Appendix C).

The relative importance of regional-climatic vs. local controls probably shifted around 2500 yr BP. After this date, climatic variability expressed at a decadal-centennial scale increased. Evidence of climatic variability comes mainly from glacial records from the Rocky Mountains 240 km north of our sites. The earliest widely recorded neoglacial activity in the area was the Peyto advance, which peaked at 2500 yr BP (Luckman et al. 1993, Osborn et al. 2001). Two other neoglacial advances were related to the Little Ice Age (750–600 and 250–100 yr BP; Luckman 2000). Summer temperatures inferred from fossil midge assemblages (Rosenberg et al. 2004) and water balance inferred from diatom assemblages (Cumming et al. 2002) also show the onset of cool/wet conditions with relatively brief warm/dry periods. We propose that this increased variability led to the convergence of fire-interval distributions and the marginally significant centennial-scale synchrony in fire history at the two sites (Fig. 5). During this period, climatic extremes of greater amplitude probably exerted dominant controls on fire-regime dynamics, and the impacts of local factors became less important. A similar pattern was detected in Yellowstone National Park (750 km southeast of our sites) where two lake-sediment fire histories show greater fire synchrony during the late Holocene than before, which was attributed to the onset of widespread droughts at both sites (Millspaugh et al. 2004).

The effects of these climatic fluctuations are not evident in the fire record from each individual site, but are clearer in the composite fire-frequency record (the average of both sites; Fig. 6). In particular, the periods of low fire frequency in the composite record coincided with the three neoglacial advances described above (Fig. 6a). Periods of low fire frequency at each site that did not occur during glacial advances were averaged out when the two sites were combined to form the composite record (i.e., during 2500–1000 yr BP). One exception is the interval of low fire frequency from 4400 to 3800 yr BP, which does not correspond to a known glacier advance but does coincide with the earliest detected neoglacial cooling (Rosenberg et al. 2004).

The combination of the fire frequency–climate correlation (Fig. 6) and the synchrony analysis (Fig. 5) provides some information on the spatial scale of fire controls during the past 2500 yr. At the spatial scale of individual sites (~100 ha based on the charcoal source area assumption), it is likely that climatic changes only weakly affected fire frequency. This weak control
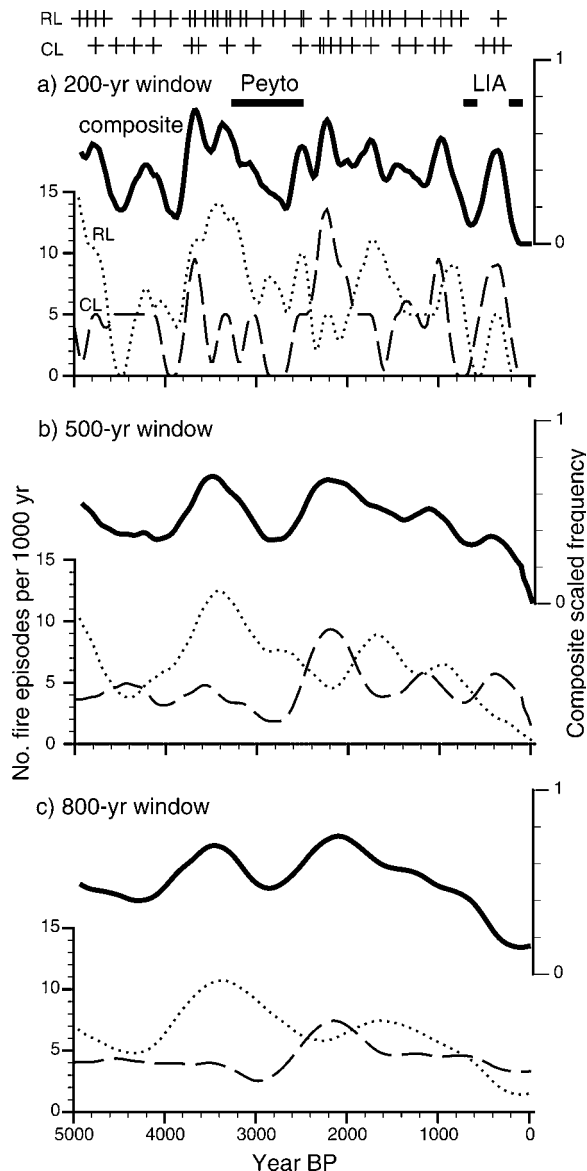

FIG. 6. (a) Fire episodes per 1000 yr, calculated as the number of events within a 200-yr moving window resulting in a time series that was then smoothed using a loess filter with a 200-yr window. The composite record is the average of the two sites after rescaling frequencies at each site from 0 to 1 so that each site contributes equally to the composite record. Dates of fire episodes from Rockslide Lake (RL) and Cooley Lake (CL) are from Fig. 3, and the dates of glacier advances (Peyto and LIA; Luckman 2000, Osborn et al. 2001) are shown as horizontal bars. (b, c) Fire-episode frequency summarized within 500- and 800-yr windows.

resulted in synchrony between sites only occurring at long (>600-yr) time scales (Fig. 5), apparently due to a synchronous decrease in long-term fire frequency after 1500 yr BP associated with the Little Ice Age glacial advances (Fig. 6b). At the spatial scale of both sites combined (~200 ha), climatic variations are correlated with fire frequency smoothed in a 200-yr window (Fig.

6a). Thus, combining the two records increased the agreement of fire frequency with centennial-scale climatic events. These results illustrate that, as shown with tree-ring studies (e.g., Swetnam 1993), adding more sites to our comparison should enhance the probability of detecting synchrony at shorter time scales.

Qualitative comparisons of our composite data with the few long-term fire records available from the region support the notion that climatic fluctuations synchronized fire occurrences across large spatial scales, especially after 2500 yr BP. Two small subalpine lakes 280 km west of our sites show increased synchrony of fire between 2400 and 1200 yr BP, with a strikingly similar pattern of fire occurrence to our composite record (Hallett et al. 2003a). Another site, 200 km northeast of our sites, exhibits strong resemblance to our data for the past 1000 yr but less so before 1000 yr BP (Hallett and Walker 2000, Hallett et al. 2003b), consistent with increasing regional fire synchrony over the last several millennia.

Fire-history studies using tree-ring data have also revealed the changing importance of climatic controls over time, though at shorter temporal scales than shown in this study. In areas with low-severity fire regimes, annually or seasonally resolved fire scars show greater regional synchrony of fire during years with more severe drought as well as a strong correlation between climatic variation (e.g., El Niño) and area burned (Swetnam and Betancourt 1998, Heyerdahl et al. 2002, Beckage et al. 2003, Hessl et al. 2004). In these areas, climatic variability contributes to fire synchrony by enhancing continuous fuel accumulation during wet periods and increasing the chance of fires spreading during severe drought (Swetnam and Betancourt 1998). Conversely, the fire–climate relationship weakens during periods of low decadal-scale climatic variability (Grissino-Mayer and Swetnam 2000), and regional synchrony of fire diminishes during warm periods when frequent fires create fuel discontinuity (e.g., in California sequoia groves; Swetnam 1993).

Compared to low-severity fire regimes, tree-ring studies in high-severity fire regimes determine fire dates from tree ages and are usually limited to reconstructing one fire per site. Although a few such studies show a link between decadal-scale climatic variability and fire synchrony, the relatively short temporal span of these records does not capture the range of variability in the fire regime (Larsen 1996, Weisberg and Swanson 2003). Our study shows the potential for lake-sediment records to capture enough variation in high-severity fire regimes such that they may be examined in a similar manner to fire-scar records from low-severity fire regimes.

While chronological error is theoretically a possible cause of lack of synchrony in stand-scale fire occurrence, it is unlikely in this study. For example, if consistently biased radiocarbon dates shifted one record by 200 yr, fire episodes that were actually synchronous would appear as asynchronous at a 200-yr resolution. We can demonstrate that this is not the case, at least for the

interval between the St. Helens P and Wn tephras, because the dates on the tephras anchor the chronology (Fig. 2). Furthermore, the age–depth relationship is also fairly linear at both lakes, suggesting little error in interpolation beyond that of the error of the calibrated radiocarbon date (approximately ±80 yr; Appendix A). A more likely scenario is that actual dates of fires randomly vary approximately ±80 yr from the reconstructed dates, but this would have no effect on the synchrony tests in windows >200 yr. We also minimized errors in detecting fire episodes by choosing lakes with a bathymetry that yields little secondary (within-lake) charcoal deposition and results in distinct charcoal peaks (Whitlock et al. 1997). As detailed in the Results, multiple lines of evidence attest to the reliability of our fire reconstructions.

Our findings of significant differences in fire return intervals and lack of fire synchrony between two sites in close proximity have important implications for interpreting fire history in regions with infrequent stand-replacing fires. First, sites that are similar in modern vegetation, climate, and fire regime may have experienced different fire histories if local, non-climatic, controls were more important than climatic controls on stand-scale fire occurrence. Because of the small source areas of macroscopic charcoal in lake sediments, identifying climatic controls of fire occurrence, when they are dominant, still requires multiple fire records. Thus paleoecologists must guard against attributing the fire history of a single site to climatic controls when such histories may result from local controls. Second, the relative importance of climatic and local controls over fire occurrence may shift over time. In this study, it appears to be the degree of climatic variability that controls the level of between-stand similarity in fire history. Use of multiple sites and quantitative inter-site comparisons should help to reveal the spatial hierarchy of controls on long-term fire regimes.

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APPENDIX A

Radiocarbon dates and volcanic tephras with known ages from the Cooley Lake and Rockslide Lake sediment cores (*Ecological Archives* E087-100-A1).

APPENDIX B

A description and example using simulated data of the bivariate *K*-function test for dependence between two temporal point processes (*Ecological Archives* E087-100-A2).

APPENDIX C

Pollen and plant macrofossil records from Cooley Lake, British Columbia (*Ecological Archives* E087-100-A3).