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Paleoecology and its application to fire and vegetation management in Kootenay National Park, British Columbia*

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Abstract

High-resolution analysis of macroscopic charcoal and pollen ratios were used to reconstruct a 10,000 yr history of fire and vegetation change around Dog Lake, now in the Montane Spruce biogeoclimatic zone of southeastern British Columbia. Lake sediment charcoal records suggest that fire was more frequent in the early Holocene from 10,000 to 8200 calendar yrs BP, when climate was warmer and drier than today and forest fuels were limited. Fire frequency increased and reached its maximum during the early to mid-Holocene from 8200 to 4000 calendar yrs BP, corresponding to the dry and warm Hypsithermal period in the Rocky Mountains. During the Hypsithermal period forests around Dog Lake were dominated by *Pseudotsuga/Larix*, *Pinus* and open meadows of Poaceae that were subject to frequent fire. From 4000 calendar yrs BP to present, fires became less frequent with the onset of cooler and wetter Neoglacial climate and an increase in wet-closed *Picea* and *Abies* forests in the valley. Changes in fire frequency are supported by dry-open/wet-closed pollen ratio data indicating that forest type and disturbance regimes vary with changing climate. The fire frequency and forest cover reconstructions from Dog Lake are a first attempt at defining a range of natural variability for Montane Spruce forests in southeastern British Columbia. Fire and vegetation management in Kootenay National Park can now use this century to millennial-scale range of variability to define the context of current forest conditions and potential changes under global warming scenarios.

Introduction

Fire history reconstructions in the Canadian Rockies are based largely on dendrochronological studies that extend our knowledge of forest disturbance back about 500 yrs. Three measures are commonly used to characterize a fire regime in dendrochronological studies and they can also be applied to paleoecological fire history reconstructions. These three measures are listed below according to Merrill & Alexander (1987):

1. Fire Cycle – The number of yrs required to burn over an area equal to the area of interest.
2. Fire Frequency – The average number of fires that occur per unit time at a given point.
3. Fire Interval – The average number of yrs between the occurrence of fires at a given point.

Master's (1990) fire history study of Kootenay National Park (KNP) indicated that the present stand-age structure and fire frequency in the Kootenay and Vermillion valleys can be best explained by long-term (decade to century level) climatic influences. Longer fire cycles after 1788 and 1928 (and less area burned) are believed to be due to cool Little Ice Age (LIA) climate and increased precipitation in the recent century. Other researchers found evidence for LIA climate changing the fire regime in the Canadian Rockies (Johnson &

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Larsen, 1991) and the Columbia Mountains of British Columbia (Johnson et al., 1990). Most of the area burned in the boreal forest and the subalpine forests of the Canadian Rockies can be attributed to large blocking high pressure systems that cause dry fuel conditions and wind (Johnson & Wowchuk, 1993; Bessie & Johnson 1995). If these high pressure systems have significant moisture or begin to breakdown, convective activity leading to numerous lightning strikes can occur and ignite forest fires (Nash & Johnson, 1996). Humans are also a potential source of ignition in the region; however, dry forest fuels and wind are still needed to cause large stand-destroying fires (e.g. Johnson et al., 1990; Masters 1990; Turner, 1991; Johnson, 1992).

In general, most fire history studies in the Canadian Rockies concluded that fire regimes have responded to decade to century level climate changes such as the LIA and current 20th century warming. This warming trend and an increase in forest fuels are a current concern of forest managers in the region. A broad scale policy of forest fire suppression has been in place in KNP since the early 1900s, but it has been only truly effective since the 1950s with the use of helicopter support (Masters, 1990). Fire suppression is believed to have changed montane forest structure significantly in the Canadian Rockies by creating more closed-continuous forests and a build up of fuels (Luckman, 1998).

A recent review of fire history studies in circumboreal forests, combined with the results of sensitive daily outputs from a General Circulation Model (GCM), indicate that widespread reduced fire frequency is linked to global warming trends and less frequent drought since 1850 (Flannigan et al., 1998). The GCM calculated the Canadian Fire Weather Index (FWI) which uses temperature, relative humidity, wind speed and precipitation to assess the intensity of a spreading fire. The FWI results show that climate warming will influence fire disturbance in a spatially dependent context. Large areas of western North America may have a reduced FWI under a warming scenario, while central North America and the states of Montana and Wyoming show significant increases in the FWI (Flannigan et al., 1998). KNP, in southeastern British Columbia, is where a small decrease in the FWI or no change is predicted with further CO_2 based atmospheric warming.

Management-altered disturbance regimes involving fire, insects and pathogens in forested ecosystems can confound estimates of natural variability (Sprugel, 1991); however, the current forest state remains an essential starting point for determining ecological objectives. In order to manage forests effectively, park managers need to have ecological data that span century to millennial time scales (Brubaker, 1988). Paleoecology is an important tool for determining the natural variability of ecosystems (Smol, 1992) and allows us to extend our knowledge of landscapes and climate change over millennial time scales. Ecosystem processes such as fire respond directly to climate change because fire behaviour is linked to fuel moisture and the effects of precipitation, relative humidity, air temperature and wind speed (Weber & Flannigan, 1997). Changing climate and new fire regimes can alter forest structure by changing age class distribution, species composition, ecotones and forest boundaries. Forest susceptibility to insect and pathogen outbreaks is also linked to climate change, fire regimes and current forest structure (Weber & Flannigan, 1997). All these climate driven ecological processes contribute to vegetation change and help define its range of natural variability. Nested within this range of natural variability is the context of human influence from Aboriginal to post-European times. The effects of past and present human-lit fire, fire suppression and the control of insect and pathogen outbreaks on vegetation may or may not lie within the range of natural variability.

Many paleoenvironmental studies in the Canadian Rockies focused on sensitive high elevation sites that were used to infer broad changes in climate throughout the Holocene (e.g. Kearney & Luckman, 1983; Beaudoin, 1986; Luckman & Kearney, 1986; Kearney & Luckman, 1987; Reasoner & Hickman, 1989; Beaudoin & King, 1990; Leonard & Reasoner, 1999; Reasoner & Huber, 1999). Pollen ratio analysis was used to infer tree-line shifts throughout the Holocene (Beaudoin, 1986; Luckman & Kearney, 1986), but it is also effective for inferring changes in forest cover at lower elevation sites (Whitlock & Bartlein, 1998). Only a few studies have investigated forest changes at lower elevations or valley bottoms in the Rockies (Hazell, 1979; Mack et al., 1983; Hebda, 1995). We were interested in using high-resolution pollen ratio analysis to reconstruct forest cover changes from a valley bottom lake in the Kootenay Valley.

The analysis of macroscopic charcoal in lake sediments (e.g. Clark, 1988; Millspaugh & Whitlock, 1995; Clark & Royall, 1996; Clark et al., 1996; Long et al., 1998) is now widely used to reconstruct fire history records over millennial time scales. The challenge with macroscopic charcoal analysis is the separation of a slowly varying background component of charcoal from a rapidly varying peak component (Clark & Royall, 1996; Clark et al., 1996; Long et al., 1998). The peaks in the charcoal record are an indicator of a fire event occurring at or near a lake basin, although direct interpretation of a charcoal peak as a fire event should be done cautiously. Charcoal peaks may occur in the sediments of unburnt watersheds downwind from a fire (Whitlock & Millspaugh, 1996), or peaks may be a result of redeposition of charcoal from the littoral to the profundal zone (Whitlock et al., 1997), or possibly due to remobilization of soil charcoal in a watershed (Wainman & Mathewes, 1987). Despite these taphonomic concerns, macroscopic charcoal remains the best paleoecological tool for reconstructing fire regimes on millennial time scales. In order to better understand the temporal and spatial variability of fire regimes, we need to link high-resolution dendrochronological fire history data with long-term macroscopic charcoal records (Lertzman et al., 1998).

In this paper, our goal is to reconstruct the fire frequency and vegetation changes around Dog Lake for the last 10,000 yrs. Our techniques include high-resolution macroscopic charcoal and pollen ratio analysis. Our study represents the first analysis of its kind for the Montane Spruce (MS) biogeoclimatic zone (Meidinger & Pojar, 1991) in southeastern British Columbia. Kootenay National Park's (KNP) fire and vegetation management decisions are based currently on historical and dendrochronological fire history studies that document disturbance regimes and vegetation change over the last 500 yrs (Masters, 1990). KNP's mandate is to preserve the integrity of the park ecosystem as a representative example of the Rocky Mountain natural region. To follow this mandate, managers need to know more about the timing and extent of disturbances over millennial time scales.

Description of study site

The north-south trending Kootaney Valley sits just west of the Continental Divide in southeastern British Columbia. Dog Lake is a 15.1 ha rectangular lake with a maximum depth of 4.7 m and watershed area of 2080 ha. There is an inlet to the lake from a wetland system to the southwest, and a small outlet on the northwest end that drains into the Kootenay River. It is situated at the base of Mt. Harkin (Figure 1) and a small bedrock outcrop separates the lake from the Kootenay River. Vegetation around the lake is currently in the Montane Spruce biogeoclimatic zone (Meidinger & Pojar, 1991). Mixed stands of *Pinus contorta*, *Pseudotsuga menziesii* and *Picea glauca* grow on the slopes above the lake.

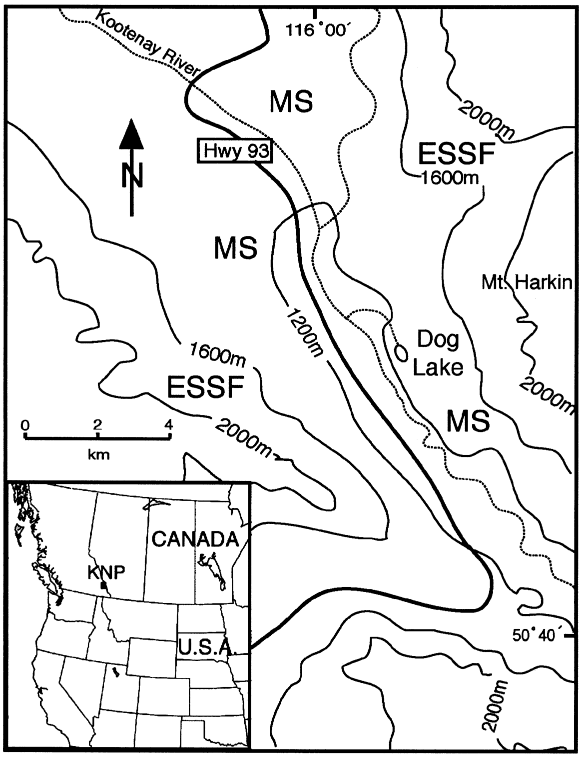

Figure 1. A map of the Kootenay Valley showing the Montane Spruce (MS) and Engelmann Spruce-Subalpine Fir (ESSF) biogeoclimatic zones relative to elevation (Meidinger & Pojar, 1991). Inset is a map of western North America showing the location of Kootenay National Park in British Columbia.

Around the perimeter of the lake stands of mixed *Pinus contorta* and *Pseudotsuga menziesii* occur on xeric sites, and *Picea glauca*, *Populus tremuloides*, and *Betula papyrifera* are found on mesic sites.

At subalpine elevations upslope from the lake, the Engelmann Spruce-Subalpine Fir zone (ESSF) dominates as closed stands of *Picea engelmannii* and *Abies lasiocarpa*. The area around Dog Lake represents the most northern extent of *Larix occidentalis* in the Rocky mountains, with larger isolated stands existing just 10 km south in the valley (Achuff et al., 1984). The drier Columbia Valley lies just west of KNP and is classified as Interior Douglas-fir zone (IDF) forest (Meidinger & Pojar, 1991). Xerophytic taxa from the IDF enter the Kootenay Valley from lower elevations (~1000 m) in the south near Canal Flats, where the drier Columbia and the Kootenay valleys converge. Disturbances such as fire, or drier climate may create conditions that would allow IDF forest to increase its area by migrating both upvalley and upslope in the Kootenay Valley.

Methods

Core retrieval and chronology

We used a percussion corer (Reasoner, 1993) to extract a 254 cm sediment core from the deepest part (4.7 m) of Dog Lake. The sediment stratigraphy consisted of well laminated calcareous gyttja throughout the core with a distinct Mazama tephra layer from 200–177 cm. Age-vs.-depth relations for Dog Lake were based on two accelerator mass-spectrometry (AMS) ^{14}C dates and the age of the Mazama tephra layer (Hallett et al., 1997). The ^{14}C dates were converted to calendar ages using the calibration program CALIB 3.01 described in Stuiver & Reimer (1993). A third-order polynomial regression was used to describe the deposition time of sediments and smooth any sharp changes in sedimentation (Figure 2). A tephra layer was located at 54 cm, but it could not be identified successfully by microprobe analysis at the University of Calgary (Len Hills, personal communication) or Washington State University (Nick Foit, personal communication) because of its highly eroded state. We suspect the eroded tephra layer is St. Helen's Y_n (ca. 3400 C^{14} yrs

Table 1. AMS ^{14}C dates for the Dog Lake core

Depth (cm)	Material dated	^{14}C age ($\pm 1\sigma$)	Calendar yrs BP[c] (2σ range)	Lab no. or reference
54	St. Helen's Y_n ash	ca. 3400	~ 3400–3800	(Luckman et al., 1986)
84	Twig fragment	4140 ± 70[a]	4510–4840	TO-5193
200–177	Mazama ash	6730 ± 40	7470–7620	(Hallett et al., 1997)
252	Multiple charcoal fragments	9010 ± 60[b]	9900–10040	B-93859

[a]Corrected for isotopic fractionation to a base of $\delta^{13}C = -25.0‰$; [b]Corrected for isotopic fractionation to a base of $\delta^{13}C = -26.9‰$; [c]Calibrated 2σ age ranges were determined using CALIB version 3.03 (Stuiver& Reimer, 1993).

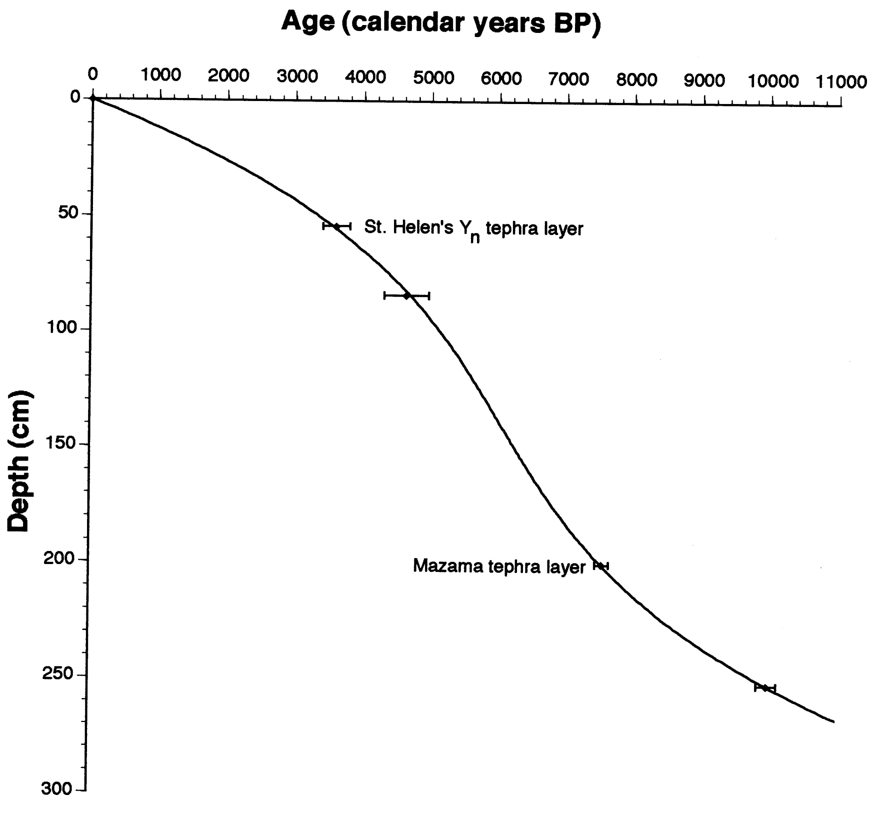

Figure 2. Age-vs.-depth relationship for the Dog Lake core based on the age model information listed in Table 1.

BP; Luckman et al., 1986; Mullineaux, 1986) based on our age-vs.-depth relationship so we included its approximate calibrated age range in Figure 2.

Macroscopic charcoal analysis

Macroscopic charcoal was contiguously sampled in 1 cm^3 volumes using a knife and a syringe. The 1cm^3 samples of calcareous gyttja were first treated with cold 10% HCL for 1 h to deflocculate the sediment and remove all carbonates. After treatment, the residue was gently washed through a 150 μm sieve. The remaining material was transferred from the sieve to a petri dish where charcoal was identified, measured and counted using an ocular grid on a binocular dissecting microscope at 250 × magnification. Charcoal fragments > 50 μm represent evidence of local fire events in lake sediments (Clark, 1988; Clark & Royall, 1995). We used the > 150 μm sieve fraction of macroscopic charcoal because it is more practical to count and we wished to be consistent with other studies in western North America (e.g. Millspaugh & Whitlock, 1995; Long et al., 1998). Charcoal fragments were measured on two axes and assigned to one of the following five size classes: < 10,000, 10,000–20,000, 20,000–30,000, 30,000–40,000, > 40,000 μm^2. The sum of the charcoal area for each sample was used to calculate a total charcoal area accumulation rate ($\mu m^2 \bullet cm^{-2} \bullet yr^{-1}$) (e.g. Clark & Royall, 1995). The simpler particle counts were used to calculate a total charcoal particle accumulation rate (particles $\bullet cm^{-2} \bullet yr^{-1}$) or CHAR (e.g. Millspaugh & Whitlock, 1995; Long et al., 1998).

Pollen ratio analysis

We collected 125 pollen (1 cm^3) plugs taken in 1–2 cm intervals at visually distinct lamination boundaries. This high-resolution pollen analysis was intended to track closely any vegetation changes around the lake. Based on Sugita's (1994) model for pollen loading in a lake this size (radius ~ 250 m), we calculated that the relevant source area for 30–45% of the pollen was from within 600–800 m of the lake. Pollen preparation followed the standard acetolysis technique outlined in Faegri & Iversen (1989). We used exotic *Lycopodium* marker tablets to calculate pollen accumulation rates. Pollen and spores were identified at 400 × magnification and difficult identifications were made at 1000 × under oil immersion. Pollen sums ranged from a minimum of 500 to over 700 terrestrial grains per sample and pollen percentages were calculated using TILIA software (Grimm, 1993). A complete presentation of the pollen data for Dog Lake is included in Hallett (1996).

Pinus contorta pollen is the dominant pollen type in the Rocky Mountains (Mack et al., 1978; Hazell, 1979; Kearney, 1983; Fall, 1992) and this important tree species currently dominates large areas of the Kootenay Valley. We based our pollen ratio analysis on only locally distributed pollen types that would be used to infer local forest cover changes around Dog Lake (e.g. Whitlock & Bartlein, 1998). We needed to exclude *Pinus contorta* pollen from the analysis because of its long distance distribution, even though it is an important forest component in the valley throughout the Holocene (Hallett, 1996). In order to construct our dry-open/wet-closed pollen ratio, we selected local indicator pollen types from Hallett (1996) that would represent modern IDF dry-open forests. These pollen types included *Pseudotsuga*/*Larix* and Poaceae (Kearney, 1983; Mack et al., 1983; Fall, 1992; Hebda & Allen, 1993). These taxa are found in the IDF and in the drier parts of the MS zone (Meidinger & Pojar, 1991). *Pseudotsuga* and *Larix* were included together because they cannot be separated confidently by grain morphology (Owens & Simpson, 1986). *Larix occidentalis*, which requires fire for regeneration, reaches its northern limit in the Kootenay Valley at Dog Lake and small stands are visible 10km south (Achuff et al., 1984). Presently, *Pseudotsuga menziesii* covers a greater area around Dog Lake than *Larix occidentalis* and it is assumed that *Pseudotsuga menziesii* is the more abundant pollen contributor in the fossil record because it is not as limited ecologically as *Larix occidentalis* in the Kootenay Valley.

Our wet-closed forest indicator pollen types were used to represent a MS or ESSF forest that included *Picea* and *Abies* (Mack et al., 1978; Kearney, 1983; Hebda & Allen, 1993; Pellatt et al., 1997). These taxa are important components in the transition zone between MS and ESSF forests located upslope from the lake. *Picea* pollen is derived from *Picea glauca*, *Picea engelmannii* and their hybrids in the MS/ESSF transition. *Abies* pollen represents *Abies lasiocarpa* which is an important component of subalpine forests in the region (Meidinger & Pojar, 1991).

With these taxa we created a forest pollen ratio that roughly corresponded to dry-open forest divided by a wet-closed forest. Our goal was to determine if pollen-inferred vegetation changes also tracked variations in the macroscopic charcoal record and the fire frequency reconstruction. Percentage data from the dry-open pollen indicators were summed together and divided

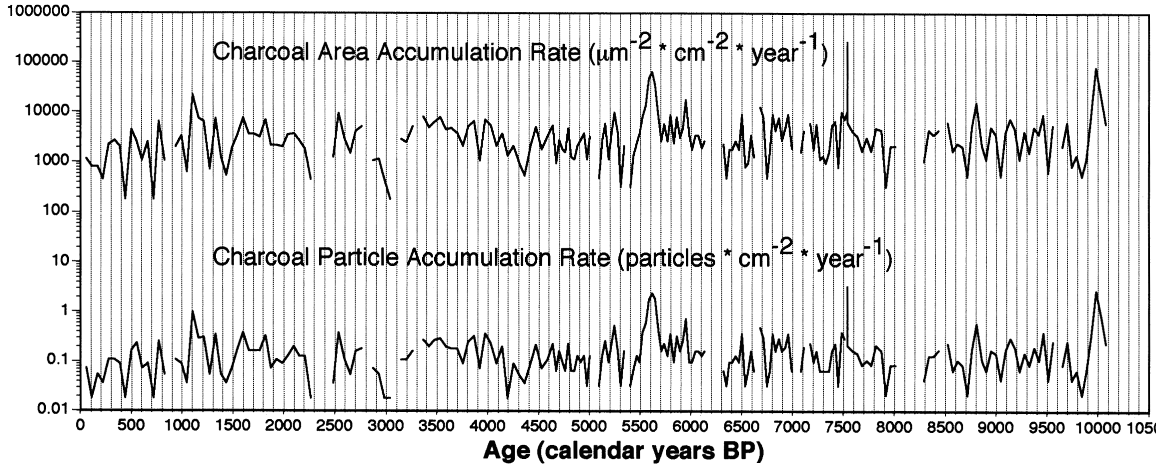

Figure 3. Log plots of both charcoal area (upper line) and particle (lower line) accumulation rates are shown for Dog Lake. Blanks in the CHAR records indicate no charcoal. Note the similarity of the peaks and troughs throughout each time series.

by the sum of the wet-closed pollen indictors to create the dry-open/wet-closed forest ratio for the Holocene. Our 1–2 cm sampling strategy gave us 125 continuous pollen ratio data points that resolve at decade to century (~ 30–100 yr) time scales. Pollen percentage data is approximately log normally distributed, therefore the data were log (base 10) transformed before being plotted (Whitlock & Bartlein, 1998).

Results

Macroscopic charcoal analysis

We plotted charcoal accumulation rates (CHAR) on a log scale for both charcoal area calculations (e.g. Clark & Royall, 1995, 1996) and the simpler charcoal particle counts using a sieve fraction > 150 µm (e.g., Millspaugh & Whitlock, 1995) (see Figure 3). For the 1 cm^3 sediment volumes we used, the time series characteristics of the two measurements are almost identical. Samples with no charcoal appear as blanks in the two CHAR series and some blanks can be as long as ~250 yrs of sediment deposition time. Samples with rare but large (> 1 mm) charcoal pieces tended to introduce small peaks in the charcoal area series but not in the particle count series. We chose to further analyse the particle count data because it gave us an almost identical series of peaks and troughs for the Holocene record. More importantly, we wanted to compare the Dog Lake record to other CHAR (particles • cm^{-2} • yr^{-1}) records in western North America (e.g. Millspaugh & Whitlock, 1995; Long et al., 1998). In order to reconstruct fire frequency from CHAR data, we needed to separate the low-frequency or slowly varying background component and the high-frequency or rapidly varying peaks component. We decided to follow the method of decomposition by locally weighted averaging which is outlined in detail by Long et al. (1998).

We used the same Charcoal Analysis Programs (CHAPS) used by Long et al. (1998) to decompose the CHAR record for Dog Lake. The CHAR record was first mathematically resampled at evenly spaced ten year intervals. The data was then log transformed before an appropriate smoothing window was used to define a background level in the CHAR series. In order to choose an appropriate window, we needed to calibrate known peaks in the CHAR record with a dendrochronological fire history reconstruction that spanned the last 500 yrs (Masters, 1990). Matching the peaks in the CHAR record with known fires around Dog Lake allows us to calibrate our Holocene record to a modern ecological study. This fire-peak matching calibration method was demonstrated by Millspaugh & Whitlock (1995) using short Pb^{210} dated cores and dendrochrononlogic data from Yellowstone National Park. Similarily, Long et al. (1998) matched regional fire history data from the Oregon Coast range to their CHAR peaks in a short Pb^{210} dated core and a long 9,000 yr core.

One centimeter contiguous samples throughout the core had deposition times ranging from 31–55 yrs/cm. This relatively coarse sampling interval effectively pre-smooths the CHAR data. We found it necessary to use a small background window width and a low peak-threshold ratio to detect our two most recent CHAR peaks. Two stand destroying fires occurred around Dog

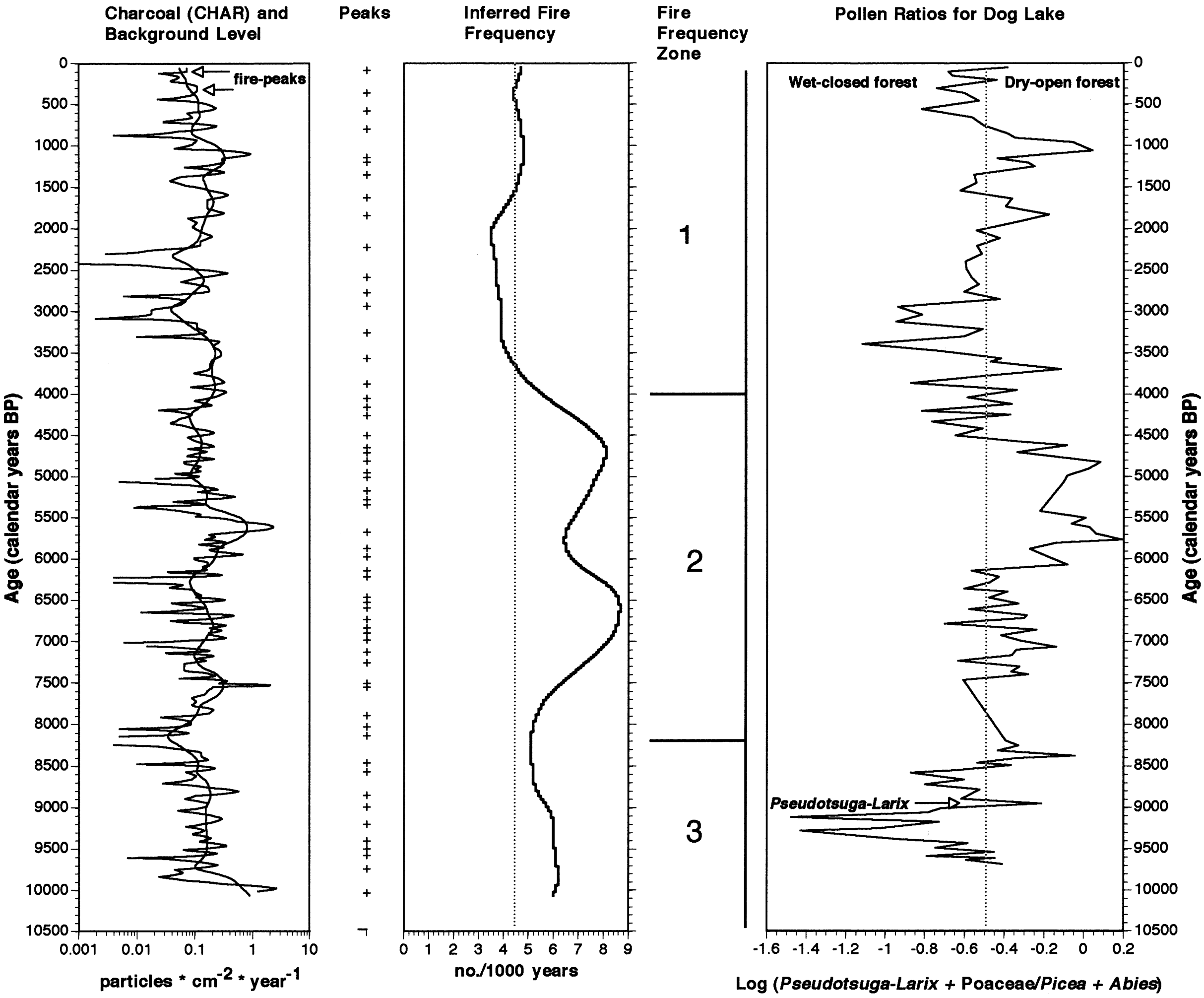

Figure 4. Log-transformed CHAR, background level, peaks, and the inferred fire frequency are shown for the Dog Lake sediment core. This fire history reconstruction uses a background window width of 500 yrs and a peak-threshold ratio value of 1.0 to denote CHAR peaks. The two calibration 'fire-peaks', which are matched with Masters' (1990) study, are indicated by arrows on the upper part of the CHAR series. Zone boundaries for the fire frequency reconstruction are marked by horizontal lines separating the Holocene into zone 3 (10,000–8200 calendar yrs), zone 2 (8200–4000 calendar yrs), and zone 1 (4000 calendar yrs to present). Log (base 10) pollen ratios of *Pseudotsuga-Larix* + Poaceae divided by *Picea* + *Abies* are used to infer periods of dry-open and wet-closed forest vegetation around Dog Lake. The first arrival of *Pseudotsuga-Larix* pollen in the core is noted at approximately 9000 yrs BP. Vertical dotted lines in the fire frequency and the pollen ratio diagrams represent relative modern values or conditions.

Lake in the last 500 yrs. The 50 yr age class stand-age maps from Masters (1990) place these fires in two periods of 1801–1850 yrs A.D. (~150–200 yrs BP) and 1751–1800 (~250–200 yrs BP). We needed a relatively small background window width of 500 yrs and a peak threshold-ratio value of 1.0 to detect the two most recent charcoal peaks or 'fires' around Dog Lake (Figure 4). The 500 yr background window width, used in calculating the locally weighted moving average or background level, tended to track the CHAR data very closely. A peak-threshold ratio value of 1.0 was used to denote a peak event. This ratio was calculated by dividing a CHAR data point by its respective background level. Only the first CHAR data point of a peak event that exceeded the threshold-ratio of 1.0 was plotted in the peaks column (see Figure 4). Once the two most recent CHAR peaks were recorded as fire events in the Holocene time series, we felt confident that the CHAR series was calibrated to the modern fire history record. This allowed us to examine the fire-peak record throughout the Holocene and infer any fire frequency changes.

The CHAR and background level, peaks and inferred fire frequency were plotted together to allow a better comparison with the dry-open/wet-closed forest pollen ratios (Figure 4). Background CHAR levels were stationary and consistently centred around 0.1 particles • cm^{-2} • yr^{-1} for the entire core. Peaks ranged between 0.1–1 particles • cm^{-2} • yr^{-1} and a few peaks reached as high as 3 particles • cm^{-2} • yr^{-1}. These values are an order of magnitude lower than CHAR values in the Oregon Coast Range (Long et al., 1998), but comparable to values recorded for Yellowstone National Park (Millspaugh & Whitlock, 1995). Some intervals in the Dog Lake core had little or no CHAR and caused the background level to drop suddenly (Figure 4).

The CHAR record can be divided visually into three fire frequency zones: an early Holocene zone 3 (ca. 10,000–8200 calendar yrs BP) of intermediate peak frequency, an early to mid-Holocene zone 2 (ca. 8200–4000 calendar yrs BP) of high peak frequency, and a mid to late Holocene zone of relatively low peak frequency (Figure 4). The inferred fire frequency appears to vary continously throughout the Holocene. The mean fire interval (MFI) based on the sediment CHAR peaks for Dog Lake averaged 190 ± 25 yrs (mean ± S.E.) for zone 3 (ca. 10,000–8200 calendar yrs BP). The MFI decreased to 140 ± 15 yrs in zone 2 (ca. 8200–4000 calendar yrs BP). Fire frequency reached its maximum level of 9 events/1000 yrs in this zone. The MFI increased to 240 ± 25 yrs in zone 1 (ca. 4000 calendar yrs BP to present). Fire frequency reached a minimum of 3 events/1000 yrs in this zone.

These MFI values are best considered in relation to each other rather than for their absolute value, because MFI calculations using dendrochronological data are largely dependent on area (Agee, 1993). The CHAR record for Dog Lake represents a spatially aggregated fire frequency (or fire interval) reconstruction at a given point. The 2080 ha watershed area of Dog Lake is the primary source area for charcoal, but aeolian charcoal from fires burning outside the watershed may still contribute to the CHAR record. It should be noted that variations in fire size, intensity and proximity influence the amount of aeolian charcoal received by a basin (Whitlock et al., 1997). Fires burning close to the lake are more likely to create a CHAR peak through direct aeolian input. Erosion of charcoal from a burnt landscape or resuspension of charcoal from littoral waters to the profundal zone may also occur for several yrs after a local fire event. This secondary charcoal input is usually related to background levels and may also create broad peak events that occur over decades (Whitlock et al., 1997).

Pollen ratio analysis

The dry-open/wet-closed pollen ratio data can be described using the three fire frequency zones in Figure 4. The early Holocene zone 3 (ca. 10,000–8200 calendar yrs BP) dry-open/wet-closed pollen ratio is not meaningful until *Pseudotsuga-Larix* pollen enters the core at around 9000 calendar yrs BP. From 10,000–9000 calendar yrs BP the pollen ratio is influenced only by Poaceae pollen, but near the end of zone 3 the pollen ratio increases and indicates dry-open forest cover. In zone 2 (ca. 8200–4000 calendar yrs BP), the pollen ratio consistently indicates dry-open forest cover around the lake. This zone records the highest pollen ratio values (0.2) from ca. 6100–4500 calendar yrs BP. By 4500 calendar yrs BP, the pollen ratio begins to decrease and indicate wet-closed forest conditions around the lake.

In zone 1 (4000 calendar yrs BP to present), the pollen ratio continues to decrease indicating more wet-closed forest cover. The lowest pollen ratio values (–1.0) occur from ca. 3500–2800 calendar yrs BP and these values represent a prolonged period of wet-closed forest cover around Dog Lake. After 2800 calendar yrs BP, pollen ratios increase and reach two high values centred around 1900 and 1000 calendar yrs BP. These two pollen ratio high points indicate dry-open forest cover around the lake. The pollen ratio values at these high points are similar to the early to mid-Holocene. Pollen ratios decrease rapidly after 700 calendar yrs BP and indicate a return to wet-closed forest cover around the lake.

Discussion

Holocene fire history, vegetation and climate changes in the Kootenay Valley

The Dog Lake CHAR record is a first attempt at defining a range of natural variability for fire frequency and vegetation change in the Kootenay Valley. The pollen ratio and CHAR records for Dog Lake can also be compared to the broad network of paleoenvironmental records in the Rockies and paleoclimatic model simulations for the Holocene derived from GCMs (COHMAP Members, 1988; Thompson et al., 1993). In general, our data suggest that forest cover and fire frequency around Dog Lake have changed in response to regional climate. Large scale controls on regional climate include the seasonal cycle of insolation due to changes in the timing of the perihelion and axis tilt (Kutzbach et al., 1993). Changes in climate appear to be responsible for the nonstationary fire frequency around Dog Lake; however, the timing of fire frequency change differs from the Little Lake CHAR record in the Oregon Coast Range (Long et al., 1998). This is not surprising considering the regional differences in vegetation change that are clearly evident in Holocene pollen records (Thompson et al., 1993; Hebda, 1995; Vance et al., 1995). Therefore, we must base our discussion of the Dog Lake CHAR and pollen ratio record on a comparison with other paleoecological studies in the Rockies region.

In zone 3 (Figure 4), high percentages and accumulation rates of Poaceae, *Juniperus* and *Pinus* pollen were apparent from 10,000–9000 yrs BP at Dog Lake (Hallett, 1996). These pollen assemblages indicate the early Holocene *Pinus-Juniperus* parkland vegetation also described for the Columbia (Hazell, 1979) and lower Kootenay valleys (Hebda, 1995). These dry-open forests probably had limited fuels available for fire. The low pollen ratios in this zone are not fully indicative of dry-open forest cover because *Pseudotsuga/Larix* pollen does not enter the core until 9000 calendar ys BP. Before 9000 yrs BP, the dry-open ratio value is influenced only by Poaceae pollen suggesting persistent grasslands. However, by the end of zone 3, *Pseudotsuga/Larix* pollen begins to influence the ratio and indicate dry-open forest conditions. This zone corresponds to paleoclimatic models of the early Holocene that indicate an 8% increase in summer insolation and an 8% decrease in winter insolation (Kutzbach et al., 1993) because of greater axial tilt (Berger & Loutre, 1991). Greater summer drought due to a strengthened eastern Pacific subtropical high led to widespread grasslands with limited forest fuel in the Kootenay Valley. The probability of lightning strikes may have been greater during these times of high pressure and low fuel moisture (Nash & Johnson, 1996). As summer insolation decreased into the middle Holocene, climate became cooler and wetter leading to increased forest cover, fuels and a shift in the fire regime.

An abrupt global cooling event at 8200 yrs BP (Alley et al., 1997; Stager & Mayewski, 1997; Bianchi & McCave, 1999) appears to be visible in the Dog Lake CHAR record as a ~200 yr absence of charcoal and less frequent fire at the end of zone 3. There is a decrease in CHAR and fire frequency during the 9000–8000 interval at Little Lake, Oregon (Long et al., 1998). The CHAR-inferred fire frequency in the North Cascade mountains of British Columbia also decreases after 9000 calendar yrs BP. In the North Cascades, the most dramatic change in the frequency of CHAR peaks occurs after 8200 calendar yrs BP (Hallett, unpublished data). Pollen ratios from high-elevation bog sites in Jasper National Park indicated a short interval of lowered treeline during this short cool period of the Hypsithermal (Luckman & Kearney, 1986). The agreement between these independent data sets in western North America suggests that global and regional climate has a widespread effect on fire frequency and vegetation. More study sites are needed to better determine the timing and extent of this early Holocene cooling event and its impact on fire frequency and vegetation change in western North America.

Zone 2 (8200–4000 calendar yrs BP) is characterized by the highest fire frequencies (Figure 4) and suggests that fire was an important factor determining forest structure and composition during this time. An MFI of 140 ± 15 yrs and the highest dry-open pollen ratios indicate that dry-open *Pseudotsuga/Larix* and *Pinus contorta* forests dominated the Kootenay Valley during this period. The time of maximum warmth and aridity in much of western North America varies from 9000–6000 yrs BP (Thompson et al., 1993). The Hypsithermal period of dry-warm climate is identified at many high elevations sites in the Canadian Rockies and occurs from the early to mid-Holocene (Kearney & Luckman, 1983; Luckman & Kearney, 1986; Reasoner & Hickman, 1989; Beaudoin & King, 1990; Vance et al., 1995; Leonard & Reasoner, 1999; Reasoner & Huber, 1999). Hebda (1995) suggested that the Hypsithermal had both dry and wet stages across British Columbia. Most coastal sites experienced an increase in precipitation during the mid-Holocene (Hebda, 1995; Pellatt et al., 1998). Sites with drier mid-Holocene climate tend to be located closer to the Rockies where moist Pacific air masses have less influence (Thompson et al., 1993). Many of the radiocarbon based chronologies used at paleoecological sites in British Columbia and Alberta need to be calibrated to better interpret the timing and extent of ecological and climatological changes in the region (Bartlein et al., 1995). Including calibrated age scales provides an essential chronological link between modern ecological data sets and the paleoecological record.

Our pollen ratio and CHAR data show that the Kootenay Valley experienced dry and warm summer climate until 4700 calendar yrs BP, when a dramatic shift toward wet-closed forests occurred. This period of change is marked by a decrease in pollen ratios and the inferred fire frequency indicating that closed MS and ESSF forests increased in the valley (Figure 4). This change to wet-closed forests and less frequent fire after 4700 calendar yrs BP corresponds with the earliest Neoglacial advances in the Canadian Rockies (Osborn & Luckman, 1988; Luckman et al., 1993). Fire frequency approached modern day levels by 4000 calendar yrs BP and continued to decrease until 2000 calendar yrs BP. The lowest fire frequencies and pollen ratios around Dog Lake occur from 3500–2500 calendar yrs BP (Figure 4). This prolonged period of wet-closed MS and ESSF type forests in the Kootenay Valley is synchronous with glacial advances in the region. These glacial events are the Peyto Advance in the Canadian Rockies (Luckman et al., 1993; Luckman, 1995) and the Tiedemann Advance in western British Columbia (Ryder & Thompson, 1986).

Fire frequencies appear to increase slightly in the last 2000 yrs (Figure 4). These increases are also accompanied by higher pollen ratios that indicate a return to dry-open forest conditions around the lake. Hedba's (1995) pollen record from Bluebird Lake near Canal Flats, located farther south where the drier Columbia and Kootenay valleys converge, also indicates expanding *Pseudotsuga/Larix* forests beginning around 2000 yrs BP. More frequent fire and dry-open pollen ratios at 2000 calendar yrs BP may correspond to a period of increased aridity noted in pollen records in western North America (Thompson et al., 1993) and possibly the Roman Warm Period seen in North Atlantic records (e.g., Lamb, 1977; Bianchi & McCave, 1999). There is also frequent fire occurring around 2000 calendar yrs BP in the North Cascade mountains of British Columbia (Hallett, unpublished data). Recently, Reasoner & Huber (1999) found evidence of increased CHAR from ca. 2400–1200 calendar yrs BP in Crowfoot Lake, a subalpine lake in the upper Bow Valley of Banff National Park, Alberta. They attribute the increases in CHAR and pollen accumulation rates during this period to increases in fuel loads rather than more frequent fires. Higher resolution charcoal analysis is needed to determine if a change in peak frequency also occurred at Crowfoot Lake during this period.

The dry-open pollen ratios and forest conditions around 1000 calendar yrs BP (Figure 4) appear to be coeval with the Medieval Warm Period (MWP) (Lamb, 1977; Grove, 1988). Warmer and drier climate during this time led to a higher-than-present treeline in the Rockies and allowed *Larix lyallii* to extend its northern range in Jasper National Park (Luckman, 1993; Luckman, 1994). Aridity during the MWP lead to lower lake levels in the Great Plains region (Vance et al., 1992; Laird et al., 1996; Campbell et al., 1998) and may have increased fire frequencies across the Rockies. A solar activity maximum occurred during the MWP and contemporary solar activity has since returned to MWP levels. This increased solar activity is predicted to continue for the next 150 yrs (Jirikowic & Damon, 1994) and may have an affect on the strength and position of the eastern Pacific subtropical high (Christoforou & Hameed, 1997). Recently, Yu & Ito (1999) presented evidence for century-scale solar forcing of drought periods on the Great Plains. Interestingly, these drought periods and their link to century-scale solar-sunspot cycles also correspond with large area burned in the Pacific Northwest forests of the United States (Agee, 1993). Our Holocene CHAR record was sampled in 31–55 yr intervals and we feel that even higher resolution is needed to detect more accurately any decade to century-scale changes in fire frequency during the last millennium.

Millennial scale variations in climate may be also be responsible for changes in vegetation cover and fire frequency around Dog Lake over the Holocene. The cause of these variations may be linked to changes in solar flux, thermohaline ocean circulation or an internal oscillation in the climate system (Bond et al., 1997; Campbell et al., 1998; Bianchi & McCave, 1999). Campbell et al. (1998) modelled a ~1500 yr periodicity of dry and wet climate from proxy records in Alberta and predicted a dry and warm trend similar in magnitude to the MWP for the next 400 yrs. If these periodicity-based models prove to be correct then fire frequencies may increase and dry-open forests may again migrate and dominate the Kootenay Valley. GCM simulations of global warming and fire disturbance are based largely on temperature increases linked to increases in atmospheric CO_2 (Flannigan & Van Wagner, 1991; Wotton & Flannigan, 1993; Flannigan et al., 1998). Century to millennial scale climate variations also need to be addressed to accurately model global warming and fire frequency responses in western North America.

In the last 700 calendar yrs BP of zone 1, pollen ratios decrease abruptly to below modern conditions (Figure 4). This indicates a return to wet-closed MS and ESSF forests in the Kootenay Valley. Fire frequency also decreases slightly during this period down to modern levels. Both of these changes around Dog Lake may indicate a response to Little Ice Age (LIA) climate (Lamb, 1977; Grove, 1988). Luckman (1995) found evidence of early LIA glacier advances that date to this period at Robson Glacier, British Columbia. Again, higher resolution CHAR records are needed to confirm fire frequency changes during the LIA and any anthropogenic influences on the fire regime such as Aboriginal human-lit fire and modern fire suppression. Dendrochronologic fire history studies concluded that fire frequency has decreased in the Rockies due to LIA climate and increased precipitation linked to current 20th century warming (Johnson et al., 1990; Masters, 1990; Johnson & Larsen, 1991). The Dog Lake CHAR record suggests that these recent fire frequency decreases are possible and that even larger scale changes occurred during the Holocene. The pollen ratio data show that dry-open IDF forest types dominated the Kootenay Valley one thousand years ago and may return again if MWP climatic conditions occur in the future. The century to millennial-scale variability of fire frequency and vegetation change around Dog Lake may have serious implications for global warming and forest fire scenarios for southeastern British Columbia (Flannigan & Van Wagner, 1991; Wotton & Flannigan, 1993; Flannigan et al., 1998).

Modern ecological models help us to understand the effects of fire on stand dynamics in KNP. A successional process model developed by Keane et al. (1990) involving *Pinus ponderosa, Pseudotsuga* and *Larix occidentalis*, favours regeneration of *Larix occidentalis*, in a frequent fire regime (10–20 yr fire return intervals). Very frequent fires tend to prevent *Pseudotsuga* saplings from surviving and becoming part of the overstory. *Pinus ponderosa, Pinus contorta* and *Pseudotsuga* are favoured only when fire intervals are longer (Agee, 1993). *Larix occidentalis* tends to decrease when fires are more severe and at intervals greater than 50 yrs. According to the Keane et al. (1990) model, *Larix occidentalis* was probably a more important component of the Kootenay Valley vegetation in zone 2 when fire frequencies reached their maximum levels, and possibly, during the 1000 and 2000 calendar yr BP periods.

Barrett et al. (1991) studied *Larix occidentalis* and *Pinus contorta* stands west of the Continental Divide in Glacier National Park, Montana and identified two kinds of fire regimes. A mixed severity fire regime with fire intervals of 25–75 yrs was found in gentler topography with drier climate. A stand-replacing fire regime with fire intervals of 140–340 yrs was linked to wetter areas. The CHAR based MFI reconstruction for zone 1 (240 ± 25 yrs) suggests that a stand-replacing fire regime is the norm for the Kootenay Valley. These long fire-free intervals would allow forest structure to become closed and create continuous fuel conditions.

Implications for fire and vegetation management

Fire and vegetation management decisions are based ideally on an assessment of current vegetation, fire activity and their long-term range of natural variability. Dendrochronological fire history reconstructions in the Canadian Rockies provide data over the last 500 yrs (e.g., Masters, 1990). This study demonstrates that the range of variability over the last 500 yrs appears to be relatively narrow when contrasted with the millennial scale CHAR data.

Several management implications arise from this paleoecological data. First, there is no equilibrium or steady state for vegetation (Brubaker, 1988; Sprugel, 1991) and fire activity in the Kootenay Valley. Rather, there are several possible ecosystem states corresponding to fire frequency zones 1–3, and important periods of transition. Each of these possible ecosystem states includes fire as the principle process of vegetation change along with climate. While the frequency, and possibly the severity, of fires may vary, stand-replacing fire regimes are to be expected in the Kootenay Valley. Closed coniferous forests dominate the Kootenay Valley today and have for the past 4700 yrs. Periodic fuel loading and stand-replacing fires on century time scales should be viewed as a part of the natural dynamics of the Montane Spruce zone.

Second, our reconstruction of MFIs and forest cover around Dog Lake indicates that current global climate trends of increasing temperature may increase the frequency and possibly the severity of fire events in the park (Flannigan & Van Wagner, 1991; Wotton & Flannigan, 1993; Hebda, 1998). Global warming and less frequent drought from 1850 have caused a reduction in fire frequency across parts of western North America (Flannigan et al., 1998) and KNP (Masters, 1990). Our data suggest that the increased FWI model results from the GCM for central North America and the states of Montana and Wyoming may also apply to southeastern British Columbia if we consider past century-scale climate variations (Flannigan et al., 1998; Yu & Ito, 1999).

Third, fire-climate associations in the Canadian Rockies are strongly linked to mid-tropospheric surface-blocking events that lower fuel moisture conditions and promote lightning strikes (Johnson & Wowchuk, 1993). The probability of lightning strikes and fire occurrence may increase in the future if fuel moisture decreases in the region (Nash & Johnson, 1996). Decadal to century-scale solar variations, which affect the overall strength and position of the eastern Pacific subtropical high (Cristoforou &Hameed, 1997), are in need of further investigation. Teleconnections in fire-climate relationships in western North America can be best studied by linking modern ecological studies to long-term paleoecological records.

Fourth, ecological processes leading to vegetation change are not restricted to fire, but also include forest insects and other pathogenic organisms that may be limited by climate and forest structure (Price & Apps, 1996; Weber & Flannigan, 1997). We need to further refine our reconstruction of climate, vegetation change and fire frequency over the last millennium to anticipate future scenarios. The effects of past and present human-lit fire are not readily detectable in the Dog Lake CHAR and pollen ratio data for the Holocene. A higher resolution paleoecological reconstruction is needed to address the influence of Aboriginal and post-European land practices and other stand-replacing disturbances such as bark beetles (Coleoptera, Scolytidae). KNP has now initiated a paleoecological reconstruction of Coleopteran populations in the Kootenay Valley. Our goal is to determine if large-scale bark beetle infestations are a persistent part of the forest ecosystem in KNP and whether outbreaks are coupled with changes in climate.

Conclusions

The current vegetation cover and fire regime is within its range of natural variability according to changes in the paleoecological record and does not represent a divergence from natural conditions. Fire events were most frequent from 8200–4000 calendar yrs BP around Dog Lake. This corresponds well with the dry and warm Hypsithermal period in the Canadian Rockies. From 4000 calendar yrs BP to present, fire frequency around the lake decreased to modern values. This change can be attributed to cooler-moister Neoglacial climate in the region. A slight increase in fire frequency has occurred over the last 2000 yrs as *Pseudotsuga/Larix* forests increased in the Columbia and Kootenay valleys. A period of dry-open forest and more frequent fire occurred at 1000 calendar yrs BP and this may correspond to the MWP. A return to wet-closed forest cover occurred from approximately 700 calendar yrs BP to present and suggests a response to LIA climate. Current global warming trends and century-scale climate variability may again create the conditions necessary for dry-open IDF forest to expand in the Kootenay Valley.

Changes in climate are responsible for the non-stationary fire frequency around Dog Lake. The CHAR record has changed continuously with climate throughout the Holocene. The current fire regime around Dog Lake extends back about 1500 yrs with small changes noted in the last millennium. In general, the Dog Lake CHAR record is in agreement with modern dendrochronological fire history conclusions (Johnson et al., 1990; Masters, 1990; Johnson & Larsen, 1991; Swetnam, 1993; Swetnam & Betancourt, 1998), suggesting that fire regimes and forest cover have changed along with climate in the last millennium and will continue to change into the future. Higher resolution charcoal studies focusing on the last millennium are now needed to link modern ecological studies with the paleoecological record. With these long-term data sets we can start to understand the temporal variability in fire frequency reconstructions (Lertzman et al., 1998).

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