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Postglacial fire, vegetation, and climate history in the Clearwater Range, Northern Idaho, USA

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Abstract

The environmental history of the Northern Rocky Mountains was reconstructed using lake sediments from Burnt Knob Lake, Idaho, and comparing the results with those from other previously published sites in the region to understand how vegetation and fire regimes responded to large-scale climate changes during the Holocene. Vegetation reconstructions indicate parkland or alpine meadow at the end of the glacial period indicating cold-dry conditions. From 14,000 to 12,000 cal yr B.P., abundant *Pinus* pollen suggests warmer, moister conditions than the previous period. Most sites record the development of a forest with *Pseudotsuga* ca. 9500 cal yr B.P. indicating warm dry climate coincident with the summer insolation maximum. As the amplification of the seasonal cycle of insolation waned during the middle Holocene, *Pseudotsuga* was replaced by *Pinus* and *Abies* suggesting cool, moist conditions. The fire reconstructions show less synchroneity. In general, the sites west of the continental divide display a fire-frequency maximum around 12,000–8000 cal yr B.P., which coincides with the interval of high summer insolation and stronger-than-present subtropical high. The sites on the east side of the continental divide have the highest fire frequency ca. 6000–3500 cal yr B.P. and may be responding to a decrease in summer precipitation as monsoonal circulation weakened in the middle and late Holocene. This study demonstrated that the fire frequency of the last two decades does not exceed the historical range of variability in that periods of even higher-than-present fire frequency occurred in the past.

Keywords: Idaho; Clearwater Range; Selway–Bitterroot Wilderness Area; Fire history; Charcoal analyses; Pollen; Paleoecology

Introduction

The role of fire on the landscape has gained increasing attention in the popular and scientific literature ever since the Yellowstone fires of 1988. Three of the largest fires on record in the Northern Rocky Mountain (NRM) region of Idaho and Montana occurred between 1988 and 2000 (National Interagency Fire Center, 2000) and is appears that large, stand-replacing fires are becoming relatively more frequent. This increase in the occurrence of large fires has been attributed to fuel accumulation resulting from half a century of effective fire suppression (Arno, 1976). However, it is not clear if management practices are responsible for the increased occurrence of large fires or if these fires reflect climate changes over the last century. To determine whether these recent fires exceed the historical range of fire conditions, and to understand vegetation, fire, and climate linkages better, requires information on the occurrence of fire prior to extensive Euro-American activity (Swetnam and Betancourt, 1998).

Fire history can be reconstructed in three ways: (1) compilation of historical records, such as fire atlases (e.g., Rollins et al., 2001); (2) analysis of dendrochronological data, such as fire-scarred trees and stand-ages (e.g., Grissino-Mayer and Swetnam, 2000); and (3) analysis of charcoal particles in lake-sediment cores (e.g., Carcaillet et al., 2001; Tinner and Lotter, 2001; Whitlock and Larsen, 2002). Documentary sources of fire history are not always available and often cover less than the last 100 years. Fire scars on living trees provide high-resolution fire records that generally span the last 500 years, and are especially useful in areas with high fire frequency, such as dry low-elevation

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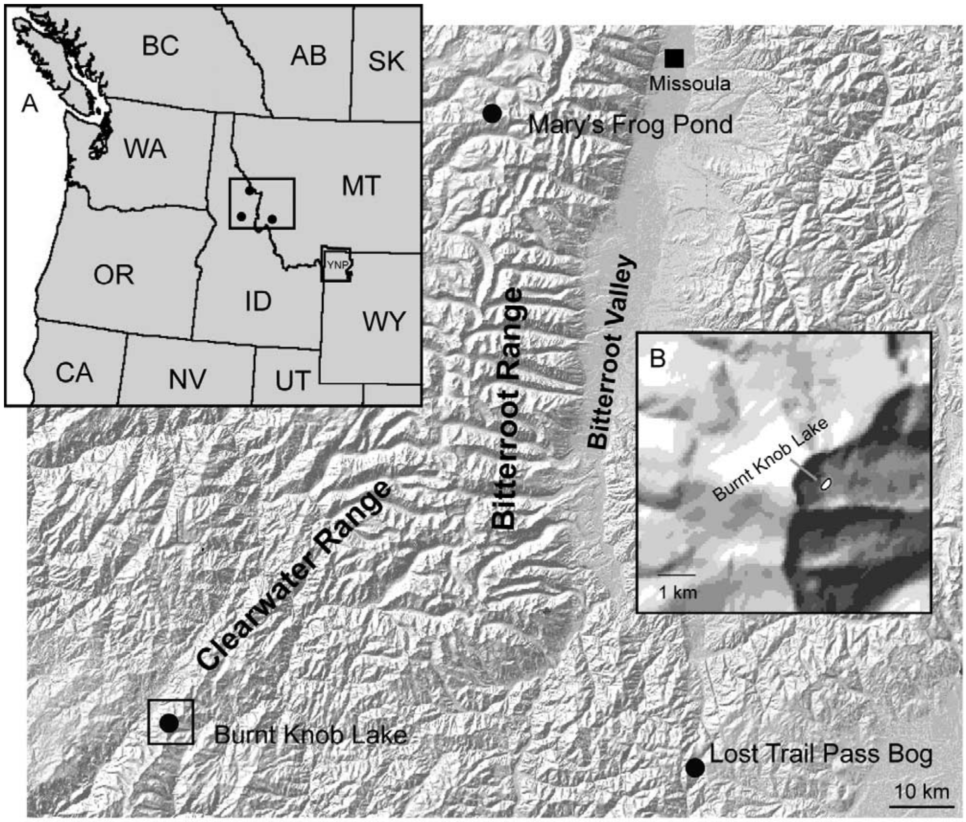

Fig. 1. Map of the Bitterroot region showing location of Burnt Knob Lake and other sites (overlain on a 30 m DEM). Inset A shows the area in a larger geographical context and includes Cygnet Lake in Yellowstone National Park (YNP). Inset B shows the watershed of Burnt Knob Lake in greater detail.

forests (Fule et al., 1997). However, tree-ring records may only register one or two fires in mesic high-elevation forests where fires are infrequent. Charcoal and pollen records from lake-sediment cores provide information on long-term variations in fire and forest composition and disclose changes in fire frequency during past shifts in climate and vegetation. Because of their length, charcoal records are well suited for fire history reconstructions in forests that typically experience stand-replacing fires (Barrett and Arno, 1991). In this study, we describe a 15,000-year-long vegetation and fire history from subalpine forests in the Clearwater Range of northern Idaho. The reconstruction is compared with other records from the NRM to better understand the relationships among fire, vegetation, and climate on Holocene time scales.

Site description

Burnt Knob Lake (45°42′16″N, 114°59′12″W, elevation 2250 m) is located in a late-Pleistocene cirque basin in the Clearwater Range and lies within the Selway–Bitterroot Wilderness Area (Fig. 1). The lake has a surface area of approximately 3.5 ha, a small inflowing and outflowing stream, and a maximum water depth of about 5.5 m. The climate of the NRM is characterized by cold winters with high snow accumulation and short, relatively dry summers. Winter storm systems form in the Gulf of Alaska and northeast Pacific Ocean and release moisture ultimately derived from the subtropical central and western Pacific Ocean (Finklin, 1983; Mock, 1996). Large-scale subsidence in summer is associated with the eastern Pacific subtropical high-pressure system and the western North American ridge and suppresses precipitation. Elevationally adjusted interpolations of nearby weather-station data suggest that January temperatures for Burnt Knob Lake average −10.1°C, and July temperatures average 10.8°C (Bartlein, unpublished data, 2001). Average January and July precipitation are 182 mm and 35 mm, respectively, and annual precipitation for Burnt Knob Lake is 1266 mm (Bartlein, unpublished data, 2001).

Burnt Knob Lake is surrounded by a closed forest of *Abies bifolia* (subalpine fir) and *Pinus albicaulis* (whitebark pine). Botanical nomenclature follows Hitchcock and Cronquist (1973), except in the case of *A. bifolia*, which was recently distinguished from *Abies lasiocarpa* as a distinct species (Hunt, 1993). *Pinus contorta* (lodgepole pine) grows on southern dry slopes, and some *Picea engelmannii* (Engelmann spruce) is present in the watershed. *Alnus viridis* (green alder) and *Salix* (willow) grow in seeps and moist areas. Dominant understory species include *Vaccinium scoparium* (whortleberry), *Xerophyllum tenax* (beargrass), and

Phyllodoce empetriformis (mountain heather). Various members of Poaceae (grass family), Asteraceae (Sunflower family), and Rosaceae (rose family), including *Spiraea* spp. (spirea) and *Amelanchier alnifolia* (serviceberry), are also present in the watershed.

Methods

Sediment cores were collected from an anchored platform in the center and deepest part of the lake using a modified Livingstone corer. Cores were split longitudinally, and color and lithology were described. Samples of 1 cm^3 were taken every 5 cm from the short core and every 10 cm from the long core to determine the water, organic, and carbonate content of the sediment (Dean, 1974). Samples of 8 cm^3 were taken every 1 cm from the short and long cores for magnetic susceptibility. Samples were placed in plastic vials, and magnetic susceptibility was measured in emu (electromagnetic units) using a cup–coil instrument from Sapphire Instruments. In addition, 5-cm^3 samples were taken from contiguous 1-cm intervals from long and short cores for charcoal analysis to reconstruct the occurrence of fire episodes in the watershed. Samples were soaked in sodium hexametaphosphate for 24–36 hours and then washed through nested sieves (mesh size 250 and 125 μm). These size fractions were selected because modern studies have shown that particles of this size do not travel far from their source and therefore likely come from fires in the watershed (Clark, 1988; Gardner and Whitlock, 2001; Whitlock and Millspaugh, 1996). The residue from the sieves was placed in a gridded petri dish and counted.

Charcoal abundance was converted to charcoal concentration (particles/cm^3). Charcoal accumulation rates (CHAR) were calculated by multiplying charcoal concentration by sedimentation rate (cm/yr). This CHAR time series was then interpolated to pseudo-annual accumulation rates and binned in 30-yr time intervals. The 30-yr interval was selected because based on the age model for the full core, it generally represents the shortest deposition time in the Burnt Knob Lake record. This approach preserves the total number of particles accumulated over time and allows presentation of the data at equally spaced time intervals (Long et al., 1998; Mohr et al., 2000).

The CHAR time series was separated into two components (see Long et al., 1998). The background component represents trends in charcoal data that are probably related to processes of production and deposition. The peaks component is the CHAR above background that is assumed to register fire episodes (Long et al., 1998; Mohr et al., 2000). Charcoal production varies through time with changes in vegetation type and thus fuel biomass, and charcoal inputs can change if the amount of charcoal entering the lake from terrestrial or littoral sediment storage changes. Therefore, the background component reflects changes in vegetation (fuel loads), slopewash, and/or surficial delivery to the lake, as well as sediment deposition within the lake itself (Bradbury, 1996; Whitlock and Millspaugh, 1996). A fire episode is identified when CHAR exceeds background by a preset threshold ratio. The term “fire episode” is different from “fire event” used in dendrochronological studies. A fire event is defined as “a single fire or series of fires within an area at a particular time” (Agee, 1993), whereas a fire episode describes tree-ring fire dates that do not have annual resolution, are dated without cross-dating calibration, or reflect several years of fire events (Barrett et al., 1997). Because most sedimentary records of fire do not have annual resolution and charcoal peaks may represent more than one event, “fire episode” seems an appropriate term to describe the sedimentary charcoal record of fire occurrence. The threshold ratio is chosen specifically for each site and is determined through the correlation of the age of the recent charcoal peaks with the age of watershed fires identified from tree-ring or documentary records.

Pollen samples were taken every 10 cm in both cores (at ca. 100–400 yr intervals) and processed following the methods of Faegri et al. (1989) to reconstruct broad changes in vegetation composition through time. *Lycopodium* was added to each sample as an exotic tracer. Between 300–500 terrestrial grains were counted per sample, and the counts were converted to percentages of the total terrestrial grains. Pollen accumulation rates (PAR; grains/cm^2/yr) were used to identify changes in the absolute abundance of individual pollen taxa over the course of the record.

Diploxylon- and haploxylon-type *Pinus* grains were assigned to *Pinus contorta* and *Pinus albicaulis* types based on modern phytogeography and the identification of needle fragments in the core. Grains lacking distal membranes were identified as *Pinus* undifferentiated, and total pine included *Pinus* undifferentiated, *Pinus albicaulis*, and *Pinus contorta*. *Abies* pollen was referred to as *Abies bifolia*, and *Picea* pollen was identified as *Picea engelmannii*, based on their phytogeography and presence of macrofossils. Pollen that could not be identified with available reference material was classified as “Unknown”; hidden or degraded pollen was classified as “Indeterminate.” These two categories never exceeded 1%.

Needle and male cone remains were identified from the 5-cm^3 charcoal residues using the modern reference collection at the University of Oregon and reference material from the Oregon State University Herbarium. The presence of needle and male cone macrofossils at a particular time (depth) was plotted next to the corresponding pollen percentage curve on the percentage diagram.

Results

Chronology and lithology

An age model for the Burnt Knob Lake record was developed from eight AMS-^{14}C age determinations, tephro-

Table 1
Age-depth relations[a] for Burnt Knob Lake, ID

Depth (cm below mud surface)	Lab number	Source/material	Age (^{14}C yr B.P.)	Age (cal yr B.P.)[b]
8		1883 fire		67
23		1709/1719/1729 fire		231
32		1580 fire		371
39		1527 fire		423
70.5	AA-27849	conifer needles	2220 ± 45	2340–2130
104.5	AA-31755	charcoal	3795 ± 80	4410–3980
135.5	AA-27847	twig/charcoal	4485 ± 50	5310–4970
181	AA-27848	male cone	5915 ± 55	6880–6630
207	AA-31756	charcoal	6830 ± 95	7860–7550
213		Mazama tephra		7627 ± 150[c]
240	AA-29546	conifer needles	8300 ± 100	9440–9060
314	AA-29547	conifer needles	10,270 ± 80	12,390–11,635
332		Glacier Peak tephra	11,200	13,430–12,997[d]
340	AA-32532	conifer needles	11,922 ± 83	14,140–13,580

[a] $y = -1\times10^{-6}x^3 + 0.023x^2 + 32.403x$; $R^2 = 0.9951$.
[b] Calendar ages determined using CALIB 4.1, 2σ (Stuiver et al., 1998).
[c] Age as reported in Zdanowicz et al. (1999).
[d] Age based on Carrara and Trimble (1992).

chronology, years of known fires, and a series of ^{210}Pb dates (Table 1). Correlation between long and short cores was facilitated by the presence of a distinctive charcoal peak in both. The long core contained two volcanic ashes of known age (Mazama ash, 7627 cal yr B.P.; Glacier Peak ash, 13,155 cal yr B.P.) (Carrara and Trimble, 1992; Zdanowicz et al., 1999). Radiocarbon dates were calibrated to "calendar" years before present (cal yr B.P.) using CALIB 4.1 (Stuiver et al., 1998). ^{210}Pb was reported as an average sedimentation rate (0.08 cm/yr) by Dave Edgington at the Center for Great Lakes Studies in Wisconsin. Because ages of charcoal peaks matched the age of fires in the tree-ring data set (Fig. 2, Table 2), recent fire dates were included in the age model to refine the recent chronology (Table 2). A single age model for the entire Burnt Knob Lake record was based on a third-order polynomial because this model best described the dates while representing a fluid change in sedimentation rates throughout the core (Table 1). Depth was adjusted in the model to not include the ashes because the deposition of each ash was considered a rapid event.

From 348 to 369 cm depth, the sediment was composed of inorganic clay (2% organic content) with high magnetic susceptibility (Fig. 3). It was probably deposited during deglaciation in an oligotrophic lake. The sediment from 256- to 348-cm depth consisted of organic silt gyttja and fine-detritus gyttja with low magnetic susceptibility. Increased organic content (to approximately 25%), suggests the development of a more productive lake. The uppermost 256 cm was composed of fine detritus gyttja. Magnetic susceptibility and organic content were similar to the previous zone, except for the period ca. 7627 cal yr B.P. (depth ca. 214 cm, Fig. 3) when 73 cm of Mazama ash was deposited. This ash was characterized by high magnetic susceptibility and low organic content (5% organics). At ca. 3200 cal yr B.P. (ca. 90–91 cm), magnetic susceptibility increased and organic content decreased, possibly related to the deposition of Mount St. Helens Y ash (3400–3800 cal yr

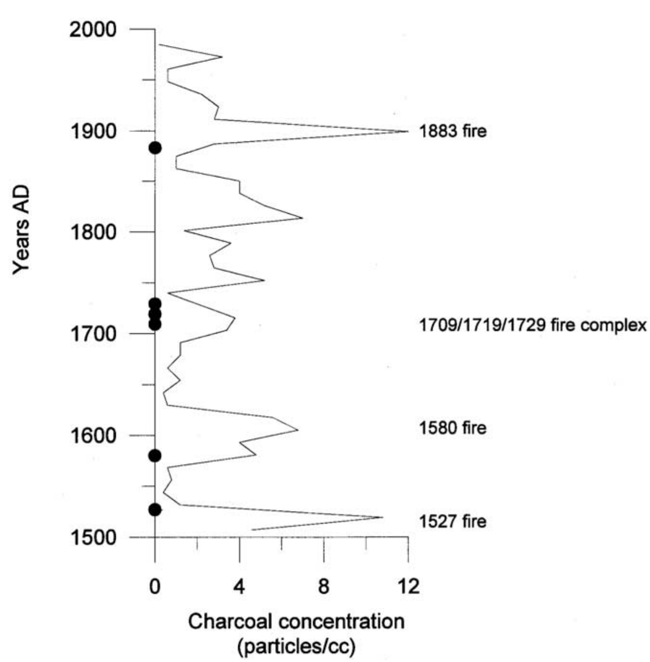

Fig. 2. Charcoal concentration values for Burnt Knob Lake plotted on a chronology based on the ^{210}Pb sedimentation rates. Black dots on the *y*-axis represent fires in the watershed identified from tree-rings. All tree-ring records of fire are temporally associated with a charcoal peak within 25 yr. which is less than the error associated with the ^{210}Pb dates. All fires identified through tree-ring analysis are represented by a peak in sedimentary charcoal; however, a sedimentary charcoal peak at ca. 1820 may represent a fire event in the watershed not detected through dendrochronology.

Table 2
Age (years AD) of sedimentary charcoal peaks in short core, Burnt Knob Lake

Depth (cm) of charcoal peak	Age (^{210}Pb)	Age of known watershed fires
8	1899	1883[a]
23	1716	1709, 1719, 1729 complex[a]
32	1606	1580[a]
39	1520	1527[b]

[a] Based on tree-ring data (≥ 3 fire scars) (Kipfmueller, 2003).
[b] Based on tree-ring data (two fire scars and three age structures)

B.P.) (Luckman et al., 1986); however, the ash layer was not evident by visual inspection.

Charcoal

The tree-ring record of fires near Burnt Knob Lake dates back to 1580 A.D. and includes fires in 1527, 1580, the 1709, 1719, 1729 complex, and 1883 A.D. (Table 2) (Kipfmueller, 2003). These fires were identified from the cores of at least three trees with the exception of the 1527 fire, which was identified from two fire-scarred trees and age structure evidence at three sites. Selecting background and peak-threshold ratios that produced a sequence of peaks that correctly matched the age of known fires provided the basis for reconstructing the long-term fire history. Background windows of 750, 900, 1200, and 1500 years were combined with several peak-threshold ratios (1.0, 1.1, 1.15, and 1.2) to reconstruct a fire history that identified the known watershed fires (Brunelle-Daines, 2002). Several different combinations of these parameters identified charcoal peaks that matched in age the three known fires in the watershed. The similarity of the results suggests that the fire frequency reconstructions are reasonably robust. Two criteria were used to select final parameters: (1) whether background curves identified a large decrease in CHAR following the deposition of the Mazama ash, and (2) whether the late-glacial fire frequency was low, given pollen evidence of a sparse *Picea* parkland. Larger window widths (900, 1200,

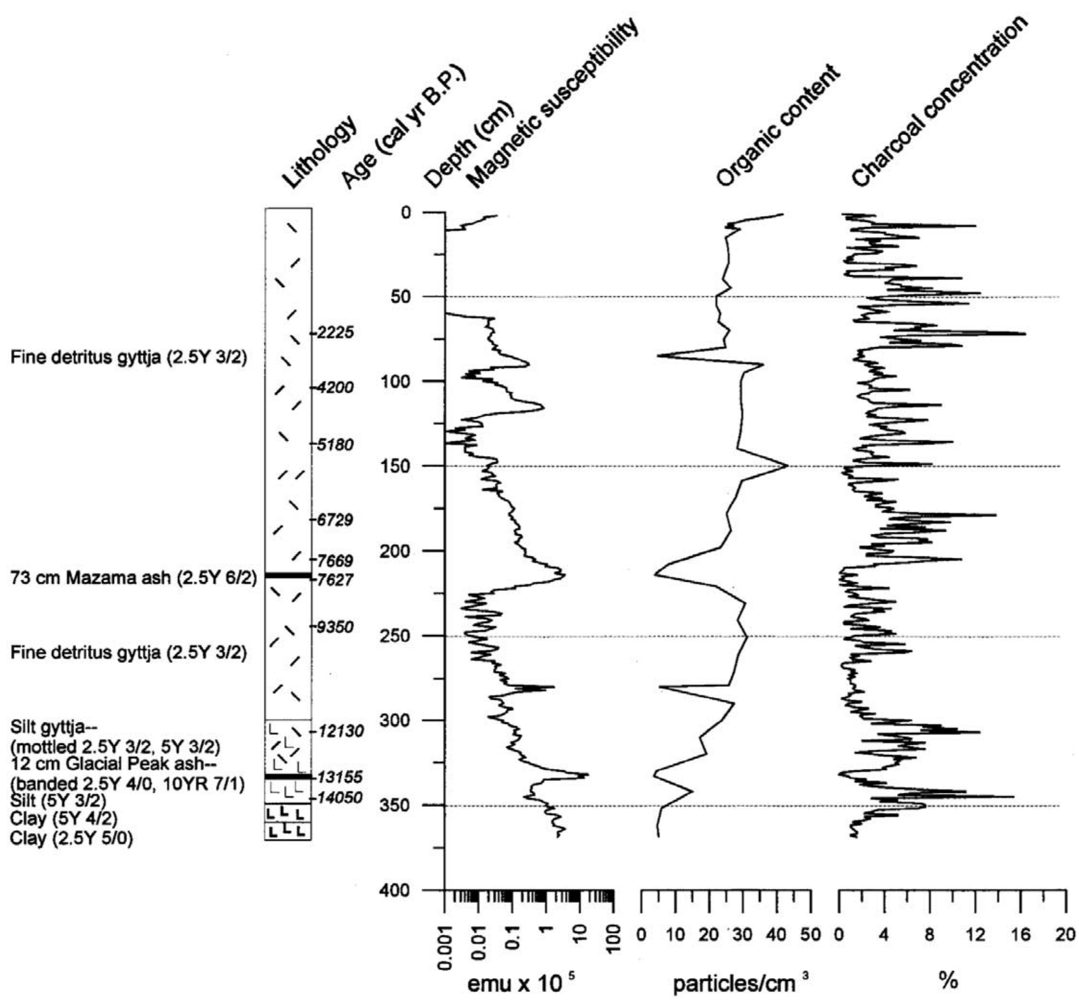

Fig. 3. Lithology, magnetic susceptibility, charcoal concentration, and organic content plotted against depth and age. Lithologic symbols after Troels-Smith (1955).

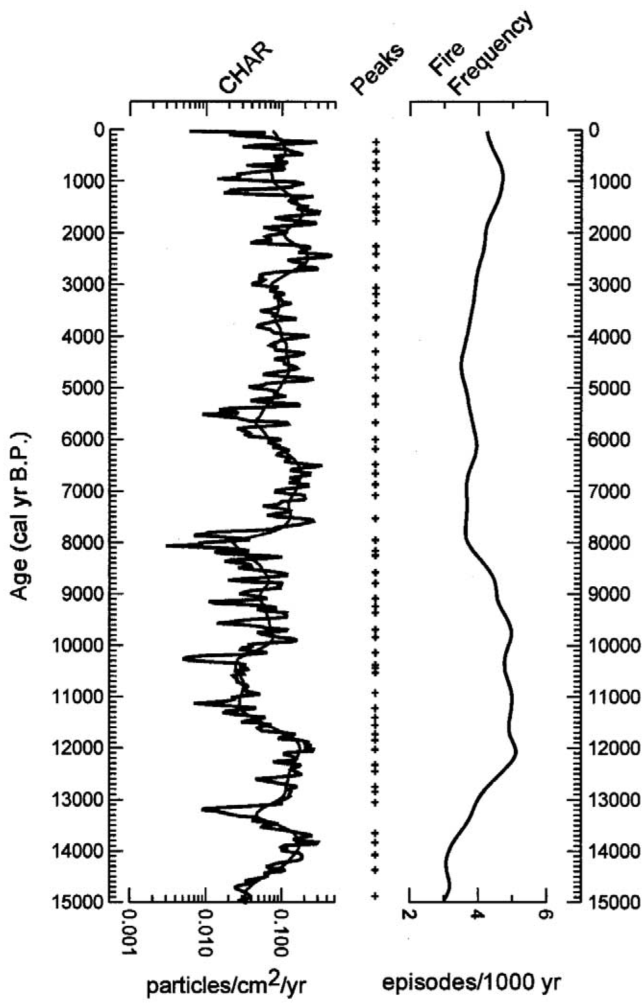

Fig. 4. Results of the charcoal analysis from Burnt Knob Lake. Charcoal accumulation rates (CHAR-particles/cm^2/yr) were smoothed using a window width of 750 yr (background). Peaks (fire episodes) are indicated by a "+" symbol when CHAR exceeds background by a threshold ratio of 1.15. Fire episodes are smoothed using a 3000-yr window to illustrate the change frequency of fire episodes through time.

1500 yr) produced background components that did not meet these criteria, whereas a window width of 750 yr satisfied both.

The choice of a threshold ratio also affected the fire frequency results. Threshold ratios of 1.0 and 1.1, and a 750-yr window width led to unrealistically high fire frequency in the late-glacial period (>4 and 6 episodes/1000 years respectively). In comparison, a threshold of 1.15 and a background window width of 750 yr yielded a late-glacial fire frequency of ca. 3 episodes/1000 yr. This estimate compares well with modern fire regime estimates for subalpine parkland (Agee, 1993; Arno, 1980; Bergeron, 1998) and was selected for the final analysis (Fig. 4).

With a background window width of 750 yr and a peak threshold of 1.15, the background level of CHAR fluctuated through time, varying between ca. 0.003 and 0.11 particles/cm^2/yr (Fig. 4) with no obvious trend. Charcoal peaks superimposed on background were interpreted as fire episodes. In the late-glacial period (>14,000 cal yr B.P.), the number of fire episodes was relatively low, with three episodes/1000 years (Fig. 4). Fire activity increased after ca. 14,000 cal yr B.P. and reached its highest levels at ca. 12,000 cal yr B.P. (five to six episodes/1000 years). Fire frequency was ca. five episodes/1000 yr from ca. 12,000 to 8500 cal yr B.P. and decreased to four episodes/1000 yr from ca. 8500 cal yr B.P. to 1000 cal yr B.P. At ca. 1000 cal yr B.P., fire activity increased to five episodes/1000 yr then decreased to four episodes/1000 yr in the last 750 yr.

Pollen

Four pollen zones were identified in the record from Burnt Knob Lake based on distinctive changes in the pollen stratigraphy: Zone BK-1, a *Picea–Artemisia* assemblage; Zone BK-2 a *Pinus–Abies* assemblage; Zone BK-3 a *Pinus–Abies–Pseudotsuga/Larix* assemblage; and Zone BK-4 a *Pinus–Abies* assemblage (Fig. 5).

Zone BK-1 (depth 348–369 cm, 14,000–15,000 cal yr B.P.): Percentages of *Picea* (≤9%), *Artemisia* (sagebrush) (≤41%), and Poaceae (≤7%) were high and Other Asteraceae (≤3%), *Salix* (≤1%) and Liliaceae (lily family) (≤1%) were present in small amounts (Fig. 5). Average PAR for Zone BK-1 was ~2400 grains/cm^2/yr, which lies within the range of modern PAR values from subalpine forests in the western United States (ca. 1600–13,250 grains/cm^2/yr) (Fall, 1992). *Picea engelmannii* macrofossils were identified in this zone.

The abundance of *Picea*, *Artemisia*, and Poaceae pollen in zone BK-1 suggests a period of *Picea* parkland (Lynch, 1998). These vegetation types are consistent with cold conditions near upper treeline in the Rocky Mountains. *Picea* parkland was also present at other NRM sites during the late Pleistocene, which suggests a regional depression of treeline during cooler-than-present conditions (Baker, 1983; Barnosky et al., 1987; Thompson et al., 1993).

Zone BK-2 (256–348 cm depth, 9750–14,000 cal yr B.P.): Low values of *Picea*, *Artemisia* (≤3%), Poaceae (≤0.4%), and Asteraceae pollen (≤0.2%) and moderate amounts of *Abies* (≤5%), *Pinus albicaulis*-type (≤7%), *Pinus contorta*-type (≤2%), and *Alnus* (≤5%) were recorded in this zone. Average PAR for Zone BK-2 was ~9300 grains/cm^2/yr, which matched modern subalpine forest values (Fall, 1992). PAR of *Pseudotsuga/Larix* (Douglas-fir-larch) type pollen increased at ca. 13,500 cal yr B.P., even though percentages showed little change (Fig. 5). We assume that *Pseudotsuga/Larix* pollen was from *Pseudotsuga menziesii* (Douglas fir), because it currently grows about 300 m in elevation below the lake, whereas *Larix* is not currently in or near the watershed. Needles of *Picea engelmannii*, *Abies bifolia*, and *Pinus contorta* were present in Zone BK-2 (Fig. 5).

High percentages of *Abies*, *Pinus albicaulis*, *Pinus contorta*, and *Alnus* in Zone BK-2 match modern pollen data

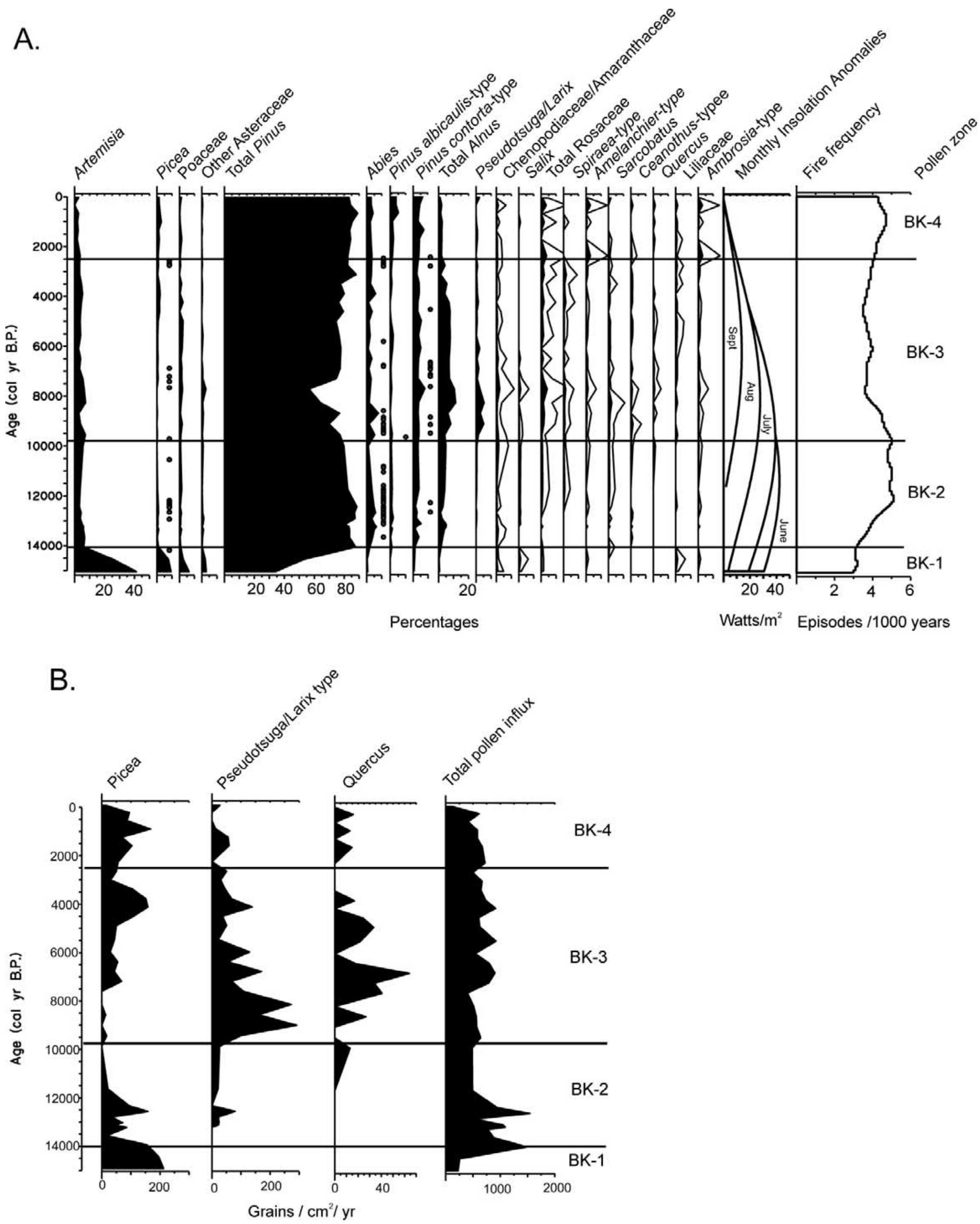

Fig. 5. (A) Percentages of selected pollen taxa, fire frequency in episodes/1000 yr, and monthly insolation anomalies for 45°N latitude. Circles indicate the presence of the associated macrofossils at that level in the core. Open curves represent a 10X exaggeration of solid curve. (B) Pollen accumulation rates (PAR; grains/cm^2/yr) for selected taxa.

from the Yellowstone region and indicate a period of *Pinus–Abies* forest (Whitlock, 1993). This shift from subalpine parkland to a mixed conifer forest implies warmer, moister conditions than before. Abundant needles confirm the local presence of *Picea engelmannii*, *Abies bifolia*, and *Pinus contorta*.

Zone BK-3 (73–256 cm depth, 2500–9750 cal yr B.P.): *Alnus* percentages were high (≤11%), *Pseudotsuga/Larix* and *Ceanothus*-type were present in moderate amounts (≤5%), and *Quercus* (oak) pollen percentages reach 1%. Several herb and shrub taxa were present in low percentages, including Chenopodiaceae/Amaranthaceae (goosefoot/amaranth families) (≤2%), *Salix* (≤1%), Rosaceae (≤4%), *Sarcobatus* (greasewood) (≤2%), *Quercus* (≤1%), Liliaceae (≤1%), and *Ambrosia* (ragweed) (≤1%). Total *Pinus* percentages decreased in Zone BK-3 (2500–9750 cal yr B.P.) (≤56%). Average PAR in Zone BK-3 was ~7100 grains/cm^2/yr and typical of modern subalpine forest (Fall 1992). Needles of *Picea engelmannii, Abies bifolia, Pinus albicaulis,* and *Pinus contorta* were recovered in Zone BK-3 (Fig. 5).

The pollen data for Zone BK-3 suggest the development of a forest with *Alnus* and *Pseudotsuga. Pseudotsuga* is more common at present in low-elevation montane forests in the Rocky Mountains (Fall, 1992; Whitlock, 1993), and its presence at Burnt Knob Lake suggests an upslope expansion of *Pseudotsuga* and warmer conditions than before. *Alnus* pollen most likely comes from *Alnus viridis*, a shrub that indicates moist conditions (Kershaw et al., 1998). The increase in *Alnus* pollen may reflect greater winter snowpack than present and persistence of soil moisture in spring. *Alnus viridis* is sometimes considered a "successional" species (Thilenius, 1990), but its presence is not strongly associated with fire. *Quercus* pollen increased in this zone, but percentages were not high enough to indicate a local presence. A marked decrease in percentages of *Pinus* and increase in those of herbaceous and shrubby taxa at ca. 7750 cal yr B.P. are probably related to the deposition of Mazama ash. It is possible that the nutrient-poor, well-drained pumiceous soils briefly favored herbaceous taxa, or that the ashfall weakened and killed conifers, or prevented their establishment (Segura et al., 1995; Zobel and Antos, 1997).

Zone BK-4 (depth 0–73 cm, 0–2500 cal yr B.P.): high percentages of Total *Pinus* pollen (up to 89%) and significant values of *Ambrosia* (≤3%) and *Pinus albicaulis*-type (≤4%) characterize the zone. *Alnus* decreased to 1%, and *Pseudotsuga/Larix* and *Spiraea*-type were absent. Liliaceae pollen was present at approximately 5%, similar to its abundance in Zone BK-1. Average PAR for Zone BK-4 was ~5275 grains/cm^2/yr, consistent with modern subalpine forest (Fall 1992). *Abies bifolia* and *Pinus contorta* needles were present in Zone BK-4 (Fig. 5).

The loss of *Pseudotsuga/Larix* during Zone BK-4 (ca. 2500 cal yr B.P. to present) suggests that *Pseudotsuga* moved to lower elevations and climate cooled from the previous period (Fall, 1992; Mehringer et al., 1977; Whitlock, 1993). Decreased *Alnus* percentages indicate drier soils than before. The pollen types and percentages found in Zone BK-4 are representative of the modern forest community at the site.

Holocene climate, vegetation, and fire history

In addition to those from Burnt Knob Lake, pollen and charcoal records have been described for Lost Trail Pass Bog, MT (Mehringer et al., 1977), and Mary's Frog Pond, MT (Karsian, 1995) in the Bitterroot region (Fig. 1), and Cygnet Lake in Yellowstone National Park (Millspaugh, 1997; Millspaugh and Whitlock, in press). Lost Trail Pass Bog (45°41′42″N, 113°56′54″ W, elevation 2147 m) is located in a forest at the southern end of the Bitterroot Range dominated by *Picea engelmannii, Abies bifolia,* and *Pinus contorta*. The record from Lost Trail Pass Bog covers the last ca. 15,000 cal yr B.P. Mary's Frog Pond (46°38′12″ N, 114°34′45″ W′ 2152 m) lies in an *Abies bifolia* and *Pinus contorta* forest located west of the Bitterroot crest. The record from Mary's Frog Pond covers the last ca. 7700 cal yr B.P.. Cygnet Lake (44°39′46″ N, 110°36′58″ W, elevation 2530 m) in Yellowstone National Park is surrounded by *Pinus contorta* forest and covers the last ca. 17,000 cal yr B.P.

It is difficult to compare the fire history from Burnt Knob Lake with the Bitterroot sites because different charcoal analysis methods were used. At Lost Trail Pass Bog and Mary's Frog Pond, charcoal particles in the size ranges of 25–50, 50–100, and >100 μm were tallied from discontinuous samples as part of routine pollen analysis (Karsian, 1995; Mehringer et al., 1977). The small size fractions may include charcoal from distant fires (Clark, 1988). In addition, the analysis of discontinuous samples makes it impossible to reconstruct fire frequency. In contrast, at Burnt Knob Lake and Cygnet Lake, large size fractions were examined in contiguous samples to identify fires within the watershed and estimate changes in the frequency of local fire episodes.

Paleoclimate model simulations provide independent information on the regional responses to large-scale changes in the climate system and in this study we used CCM1 experiment results described by Bartlein et al. (1998). The 14,000 cal yr B.P. simulation illustrates late-glacial conditions, the 11,000 cal yr B.P. simulation depicts early Holocene conditions, and the 6000 cal yr B.P. simulation represents the middle Holocene. The late Holocene was not part of the model experiments.

Late-Glacial (16,000–11,000 cal yr B.P.)

Picea parkland was present at Burnt Knob Lake prior to 14,000 cal yr B.P. indicating conditions colder than present. Low fire frequencies (ca. 3 episodes/1000 yr) during the late-glacial period are similar to the long fire-free intervals between fires in present-day subalpine parkland and suggest cooler-than-present conditions. Lost Trail Pass Bog also records *Picea* parkland during this period, and data from Cygnet Lake suggest a period of alpine meadow. Lost Trail Pass Bog suggests and Cygnet Lake indicates low fire frequencies in the late-glacial period (Fig. 6) (Mehringer et al., 1977; Millspaugh et al., 2000).

After ca. 14,000 cal yr B.P., an expansion of *Pinus* and *Abies* forest at Burnt Knob provides evidence of increasing summer temperatures. *Pinus* forests also developed at Lost Trail Pass Bog and Cygnet Lake at ca. 14,000 and 11,500 cal yr B.P. respectively. At Cygnet Lake these forests persisted with little variation to the present (Fig. 6) because of

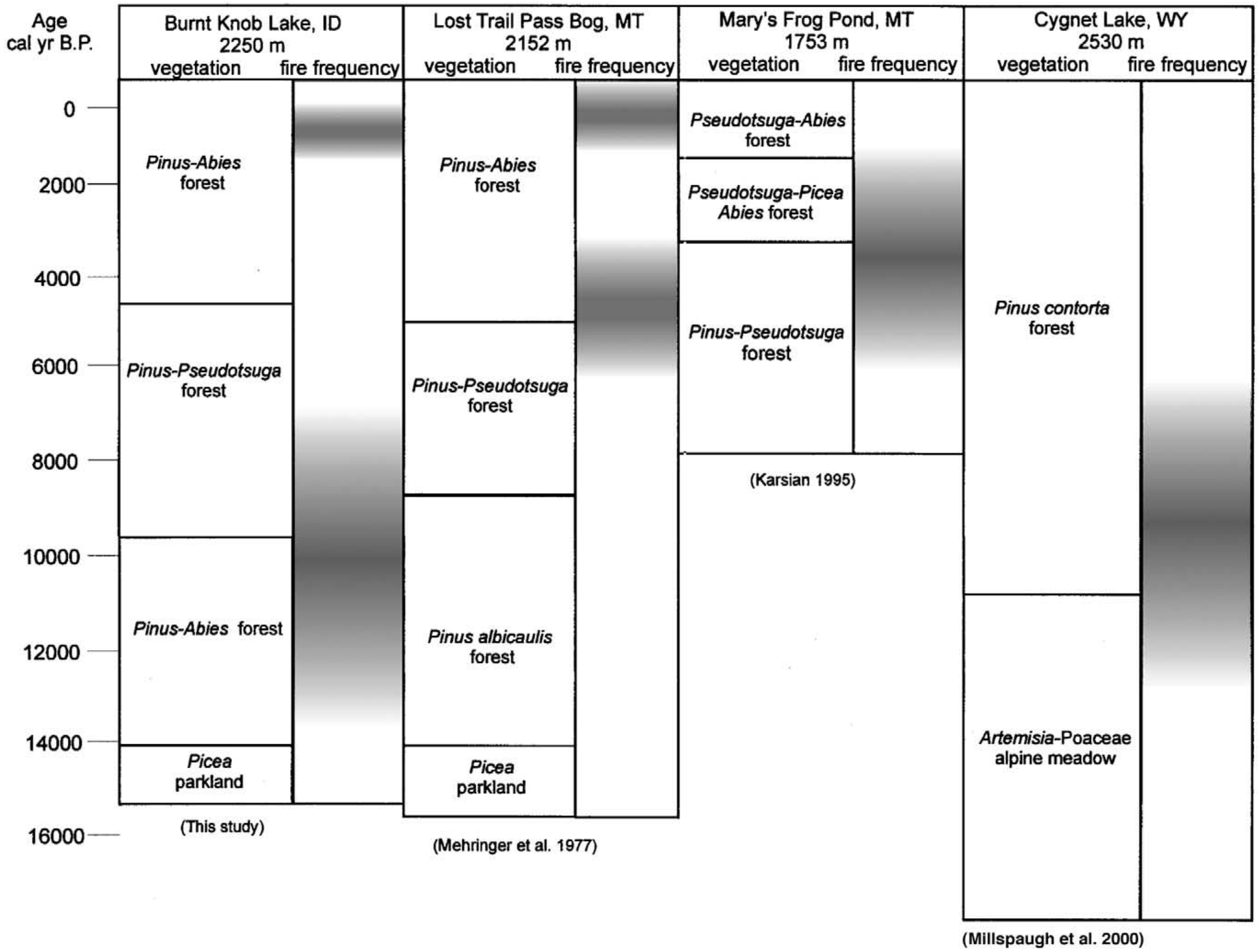

Fig. 6. Vegetation and fire reconstructions for the four Northern Rocky Mountain sites. Shading indicates periods of highest inferred fire frequency.

the strong edaphic effect exerted by the rhyolitic substrate (Whitlock, 1993). At Burnt Knob Lake, *Picea* became less important in the forest at ca. 14,500 cal yr B.P. and was replaced by *Pinus contorta* and *Abies bifolia*. Today *Abies bifolia* and *Pinus contorta* tolerate winter temperatures that are as much as 15°C lower than the limiting minimum temperature for *Picea engelmannii* (Thompson et al., 1999). The dominance of *Pinus* and *Abies* may have resulted from cold winter temperatures that restricted the growth of *Picea*.

Paleoclimate model simulations for the late-glacial suggest that average winter temperatures in the northern hemisphere were almost as low as during the glacial maximum (21,000 cal yr B.P.), but higher-than-present summer insolation resulted in summer temperatures as high as present (Kutzbach et al., 1998). Simulated summer climates for the western United States include a stronger-than-present northeast Pacific subtropical high, a deeper-than-present thermal low in the Southwest with all regions drier than present. Simulated winter conditions for the western United States includes conditions wetter than present (Bartlein et al., 1998).

Early Holocene (11,000–7000 cal yr B.P.)

At Burnt Knob Lake, warmer and drier summers in the early Holocene presumably allowed *Pinus* and *Abies* to spread upslope. In addition, at both Burnt Knob Lake and Cygnet Lake fire occurrence reached its highest frequency of the Holocene (ca. 5.5 episodes/1000 yr) from ca. 12,000 to 8000 cal yr B.P. (Millspaugh et al., 2000). This time of highest fire frequency coincides with maximum June and July insolation (Fig. 5). Increased early-summer warming and dry, cold winters may have lengthened the fire season by drying fuels earlier in the year.

Paleoclimate model results for the western United States suggest that the subtropical high was stronger in the Pacific Northwest (PNW) and the thermal low in the Southwest was deeper in the early Holocene than in the late-glacial or at present (Bartlein et al., 1998). The strengthening of these circulation features resulted in dry conditions in the PNW and western Rocky Mountains west of the continental divide and wet conditions in the Southwest, Great Plains, and eastern Rocky Mountains (Bartlein et al., 1998). Overall, summers were drier than the late-glacial or present in the western United States and winters were drier than the late-glacial but similar to present (Bartlein et al., 1998; Kutzbach et al., 1998).

Middle Holocene (6800–2500 cal yr B.P.)

At Burnt Knob Lake, Lost Trail Pass Bog, and Mary's Frog Pond, thermophilous taxa including *Pseudotsuga/Larix*, *Alnus*, and *Quercus* became more abundant in the middle Holocene. Late summer and winter temperatures were higher than present and may have promoted the upslope expansion of *Pseudotsuga* from ca. 9700 to 2500 cal yr B.P. Thompson et al. (1999) suggest that *Pseudotsuga menziesii* does not tolerate extreme seasonality or dry winters, conditions that were better developed in the early Holocene than in the middle Holocene or at present.

Fire frequency at Burnt Knob Lake was relatively constant (ca. 4 episodes/1000 yr) from ca. 7000 to 5000 cal yr B.P. and did not appear to respond to changes in summer insolation. However, at Cygnet Lake, fire frequency decreased from approximately 10 fire episodes/1000 yr at ca. 7000 cal yr B.P. to only about 3 fire episodes/1000 yr at present (Millspaugh et al., 2000). High charcoal influx at Lost Trail Pass Bog during the middle Holocene may reflect a shift to drier summers east of the Bitterroot crest as the intensified monsoonal circulation associated with the early Holocene insolation maximum attenuated. The decrease in the amount of moisture available during the fire season likely resulted in more fires in this area.

Inferred climate based on paleoecological data are supported by simulated climate conditions. Model results for the western United States show a weakened subtropical high compared to the early Holocene, although still stronger than at present. A weakened subtropical high in the middle Holocene probably resulted in wetter summers than previously in the western NRM. Decreased summer insolation also reduced continental heating, which decreased onshore flow and led to drier summers in the American Southwest and less summer moisture in the Great Plains and eastern NRM (Kutzbach et al., 1998; Thompson et al., 1993). Middle Holocene winters in the western United States were likely wetter than the late-glacial or early Holocene and also wetter than present (Bartlein et al., 1998; Kutzbach et al., 1998). In the Burnt Knob Lake region summers would have been drier than at present but wetter than during the early Holocene. Winters would have been wetter than the early Holocene as a result of increased temperatures and effective moisture.

Late Holocene (2500 cal yr B.P.–present)

The modern forest developed after 2500 cal yr B.P. at Burnt Knob Lake, Lost Trail Pass Bog, and Mary's Frog Pond. A distinct increase in fire frequency at Burnt Knob Lake coincided with the beginning of the Medieval Warm Period (600–900 cal yr B.P., Gates, 1993). Charcoal accumulation rates also increased during this time at Lost Trail Pass Bog but not at Cygnet Lake or Mary's Frog Pond. Although the Medieval Warm Period is not registered everywhere (Hughes and Diaz, 1994), several records in the West suggest dry conditions during this period (e.g., Graumlich, 1993; Mohr et al., 2000; Stine, 1994).

The charcoal record from Burnt Knob Lake indicates a decrease in fire frequency from 5 to 4 episodes/1000 yr during the Little Ice Age (550–150 cal yr B.P., Gates, 1993). This decrease in fire frequency may be caused by greater effective moisture associated with colder conditions (Luckman, 1993). A concurrent change in fire activity is not registered at Lost Trail Pass Bog, Mary's Frog Pond or Cygnet Lake. Changes in the vegetation at Burnt Knob Lake, including increases in Rosaceae (rose family) and *Ambrosia* also occurred during the Little Ice Age. *Amelanchier alnifolia*, in particular, tolerates extremely cold winter temperatures, which may explain its abundance during this period (Thompson et al., 1999).

Conclusions

Fire and vegetation reconstructions at four sites in the NRM show several features in common. A subalpine parkland or alpine meadow indicating cold-dry conditions was present at the end of the glacial period. From 14,000 to 12,000 cal yr B.P., the appearance of *Pinus* forest suggests slightly warmer, moister conditions than the previous period. All sites except Cygnet Lake record the development of a forest with *Pseudotsuga* around 9500 cal yr B.P.. This vegetation type suggests a warmer drier climate in the early Holocene, coinciding with the timing of the summer insolation maximum. Cygnet Lake records *Pinus contorta* forest throughout the entire Holocene as a result of the rhyolitic soils of the central Yellowstone region. As the amplification of the seasonal cycle of insolation waned during the middle to late Holocene, *Pseudotsuga* was replaced by *Pinus* and *Abies* indicating a return to cool, moist conditions.

Whitlock and Bartlein (1993) suggest that sites that are west of the continental divide are under the influence of the subtropical high would have been even drier during the early Holocene as a result of the intensification of modern climate regimes. These regions would have been more prone to burning in the early Holocene than at present. In contrast, sites east of the continental divide would have been wetter than present during the early Holocene when monsoonal circulation was intensified, decreasing the probability of fire there. Burnt Knob and Cygnet lakes display a fire-frequency maximum around 12,000-8000 cal yr B.P., which coincides with the interval of high summer insolation and expansion of the subtropical high. Both Lost Trail Pass Bog and Mary's Frog Pond record low charcoal accumulation rates during this period of wetter summers, and higher accumulation rates around 6000–3500 cal yr B.P. as summer insolation declined and summers became dry in these regions. Examination of additional high-resolution charcoal records from the NRM region will clarify the relationship between the changing seasonal distribution of insolation and fire across a broader region.

Although fire activity in recent decades may exceed that observed in the 20th century, fire has been similar in the distant past. In the Holocene these periods are associated with intense, prolonged drought resulting from greater-than-present summer insolation. If drought conditions associated with the insolation maxima are an appropriate analog for future summer conditions resulting from the increase in atmospheric greenhouse gases, the shift towards more frequent crown fires may be persistent.

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