Geographic and temporal variations in fire history in boreal ecosystems of Alaska

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[1] Charcoal and pollen analyses were used to determine geographic and temporal patterns of fire importance in boreal forests of the Kenai Peninsula and interior Alaska. Sieved, large charcoal particles were measured in continuously sampled cores of Rock, Portage, and Arrow Lakes (Kenai Peninsula) and Dune and Deuce Lakes (interior Alaska) to estimate regional fire importance and fire occurrence. Charcoal accumulation rates have been low for the past 1000 years in both regions with slightly higher values in interior Alaska than on the Kenai Peninsula. An exception to this general pattern was the period of post-European settlement on the Kenai Peninsula, where charcoal accumulation rates increased by 10-fold. This increase most likely reflected increased fire occurrence due to human ignition. The Holocene charcoal and pollen records from Dune Lake indicate low fire occurrence during the early (9000 to 5500 calibrated year before present (yr BP)) birch-white spruce-alder (*Betula-Picea glauca-Alnus*) communities and high fire occurrence as black spruce (*Picea mariana*) became established after 5500 yr BP. Increased fires probably resulted from a change to fire-prone black spruce forests. For the past 5500 yr BP, two distinct fire regimes occurred. Frequent fires, with an average fire return interval of 98 years, characterized the period from 5500-2400 yr BP. Fewer fires, with an average fire interval of 198 years, characterized the period after 2400 yr BP. Fuel accumulation, stand structure, and vegetation species contributed to the natural variability in fire regimes during past changes in climate. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1699 Global Change: General or miscellaneous; 1851 Hydrology: Plant ecology; *KEYWORDS:* Charcoal, pollen, fire, boreal

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1. Introduction

[2] Future responses of boreal ecosystems to climate warming will depend on how the fire regime and vegetation change with climate [*Goldammer and Furyacv*, 1996]. Fire frequency governs the rate of change of many community-level and ecosystem-level processes of high latitude forests [*Viereck and Schandelmeier*, 1980]. Climate data [*Chapman and Walsh*, 1993; *Overpeck et al.*, 1997] and fire statistics [*Stocks et al.*, 2000; *Nash and Johnson*, 1996; *Flannigan and Harrington*, 1988] indicate a strong link between present-day weather conditions (e.g., temperature and precipitation) and fire occurrence and severity. In fact, these climate and fire data confirm model predictions that fire severity and fire season length have increased with the recent temperature increase [*Stocks et al.*, 2000; *Fosberg et al.*, 1996]. These links among fire, weather conditions, and ecosystem-level processes suggest further climate warming may change boreal forest composition and carbon pools [*Alm et al.*, 1999]. The FROSTFIRE experiment attempted to assess the specific effects of fire and climate change on boreal ecosystems of Alaska. In order to understand the ecological effects of fire and climate change and to derive meaningful extrapolations from experimental burn results, a perspective on the natural variability of fire and its interaction with vegetation (fuel) is necessary.

[3] Despite the important role of fire in influencing ecosystem change, the long-term relationships between fire, climate, and vegetation are not well understood. Fire research in the boreal forest of Alaska has been mostly

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limited to short-term fire-return intervals based on tree age and fire-scar dates [*Dyrness et al.*, 1986; *Mann et al.*, 1995; *Yarie*, 1981]. These records do not reveal how forest composition is affected by changes in fire regimes or how fire regimes respond to climate changes. Charcoal particles in lake sediments can provide past records of fire regimes during vegetation and climate changes [*Clark*, 1990]. However, previously studied charcoal records used to reconstruct Alaskan fire histories lack the temporal resolution needed to identify individual fires and to determine the interaction between fire and vegetation. These studies only provide insight into the general fire importance in Alaska during the Holocene. *Earle et al.* [1996] showed high charcoal accumulation within early Holocene, *Betula*-dominated communities at Sithylemenkat Lake. *Hu et al.* [1993, 1996] found a higher occurrence of charcoal particles during the *Picea mariana* dominated period at Wien and Farewell Lakes. Although these results appear contradictory, they to suggest that changes in fire importance may be strongly linked to vegetation change. The significance of vegetation-fire interactions is evident at Devils' Bathtub in northern New York, where the fire regime shifted from frequent fires (every 80 years) during the early Holocene, when *Picea-Pinus* dominated, to near absence of fire, as temperate deciduous forest came to dominate [*Clark et al.*, 1996c]. Modern boreal forest studies indicate that stand type, species composition, and fuel accumulation affect fire behavior [*Hely et al.*, 2001; *Viereck and Schandelmeier*, 1980]. For example, black spruce is highly flammable and accumulates fuel, allowing for ignition and spread.

[4] While some previous research on boreal ecosystems supports the idea that vegetation change can impact fire regimes, other studies suggest that climate also affects fire regimes. There is a strong correlation between fire importance (severity and area burned) and present-day weather conditions (precipitation and temperature) in Canada, suggesting that weather is the most important factor affecting fire occurrence [*Nash and Johnson*, 1996; *Flannigan and Harrington*, 1988]. Furthermore, in northeastern Alberta, area burned is highly correlated with annual precipitation [*Larsen and MacDonald*, 1995; *Larsen*, 1996]. Weak relationships between fire importance and pollen-inferred vegetation types inferred from Alberta, eastern Canada, and western Oregon, support that climate is the overriding control on fire regimes [*Hallett and Walker*, 2000; *Carcaillet et al.*, 2001; *Long et al.*, 1998]. In order to fully understand the relationships among climate, fire, and vegetation and to determine if climate or vegetation has the strongest effect on the fire regime, more detailed records of fire and vegetation histories from charcoal and pollen records are needed.

[5] High-resolution charcoal and pollen records offer the best opportunity to determine fire and vegetation interactions [*Clark*, 1990; *Long et al.*, 1998]. Studies from experimental fires show that most charcoal particles >100 μm in diameter are deposited within 60 m of the fire edge [*Clark et al.*, 1996b; *Ohlson and Tryterud*, 2000]. It has also been shown that charcoal deposition in lake sediment occurs within a few years following a fire [*Earle et al.*, 1996; *Whitlock and Millspaugh*, 1996]. Therefore, local reconstruction of the fire history is possible by measuring the frequency of large charcoal particles in sediments. Individual fires can be distinguished from background charcoal when the number of years represented by each sample is less than the minimal fire-return interval (i.e., 20 years for boreal forest [*Niklasson and Granstrom*, 2000]) and when charcoal peaks can be clearly separated from background.

Table 1. Site Descriptions

Site name	Longitude, °W	Latitude, °N	Area, ha	Maximum Depth, m	Elevation, m
Kenai Peninsula					
Rock Lake	150°15′	60°25′	3.0	5.3	285
Portage Lake	150°32′	60°43′	11.6	15.6	75
Arrow Lake	150°31′	60°45′	10.5	10.1	90
Interior Alaska					
Dune Lake	149°54′	64°25′	12.0	9.0	134
Deuce Lake	147°31′	65°31′	3.0	5.0	170

[6] In this study high-resolution charcoal and pollen records from lake sediment cores were examined to determine how human activity, present-day regional climate differences, and Holocene climate and vegetation changes have influenced the fire regimes surrounding lakes from interior Alaska and the Kenai Peninsula. First, the effects of European settlement on the fire regime were assessed by comparing regional charcoal accumulation data for the periods 1) 800 AD to European settlement, and 2) European settlement to present. Second, regional climate differences were assessed by comparing average charcoal accumulation data for the past 1000 years from sites in the dry, fire-prone interior of Alaska to the wet, less fire-prone Kenai Peninsula sites (Table 1 and Figure 1). We hypothesize that the wetter conditions and low incidence of lightning strikes on the Kenai Peninsula [*Gabreil and Tande*, 1983] should produce lower charcoal accumulation than present in the interior. However, the dominance of fire-prone vegetation, such as black spruce, in both regions may neutralize climate differences. Third, we estimated fire-return intervals from the charcoal data for each vegetation and climate period to assess the importance of vegetation versus climate change on the fire regime at Dune Lake. The Holocene climate reconstruction was inferred from previously documented paleoclimate studies of the region (see section 2.2). Pollen data from *Bigelow* [1997] were used to define the timing of vegetation changes. Previous low-resolution charcoal records from Alaska suggest a stronger influence of vegetation composition and fuel load on fire regimes [*Earle et al.*, 1996; *Hu et al.*, 1993, 1996].

2. Study Area

2.1. Site Description

[7] Rock, Portage, and Arrow Lakes are located in the Kenai National Wildlife Refuge on the Kenai Peninsula, Alaska. Dune Lake is located 44 km southwest of Nenana, Alaska. Deuce Lake is located on the campus of The University of Alaska at Fairbanks (Table 1, Figure 1). All lakes have small surface areas ranging from 3.0 to 12.0 hectares and depths ranging from 5.0 to 15.6 m. The lakes on the Kenai Peninsula formed 10,000 years ago with the retreat of mountain glaciers [*Reger and Pinney*, 1997]. Dune Lake lies within a sand dune field that formed 10,000 ^{14}C yrs ago when dune activity ceased [*Bigelow*, 1997]. Deuce Lake is a

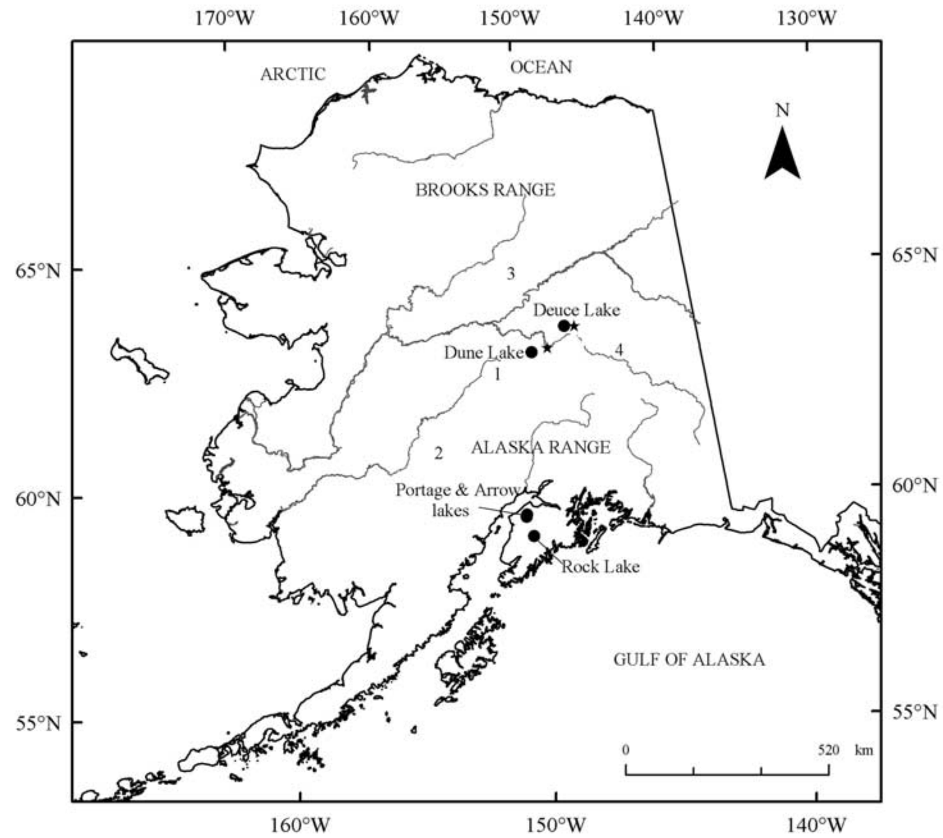

Figure 1. Location of lakes sampled in this study and other sites discussed in the paper. 1, Wien Lake; 2, Farewell Lake; 3, Sithylemenkat Lake; 4, Birch Lake. A star represents the location of Nenana and Fairbanks, Alaska.

thermokarst lake that formed 1300 years ago based on data collected during this study.

[8] Present-day vegetation surrounding each lake is characterized by a *Picea*/*Betula* (spruce/birch) dominated boreal forest with relative species abundances varying with soil types and disturbance history. Black spruce (*Picea mariana* (Mill) BSP) is the dominant tree species and the understory is dominated by feather mosses (*Pleurozium* spp., *Ptilium* spp., and *Hylocomium* spp.), lingonberry (*Viccinium vitis-idea* L.), and Labrador tea (*Ledum palustre* L.) on poorly drained sites. On better drained lowland sites, black spruce is present with paper birch (*Betula papyrifera* Marsh), quaking aspen (*Populus tremuloides* Michaux), balsam poplar (*Populus balsamifera* L.), white spruce (*Picea glauca* (Moench) Voss), and green alder (*Alnus crispa* (L.) Moench). On well drained upland soils is a mixed forest of white spruce, paper birch, and occasional black spruce. The understory shrubs include a mixture of green alder, willow (*Salix* spp.) and roses (*Rosa acicularis* L.), with a ground cover of lingonberry, bunchberry (*Cornus canadensis* L.), and mosses.

[9] Although the vegetation communities around each lake are similar, differences do exist. Black spruce and paper birch are more abundant on the Kenai National Wildlife Refuge than at other sites. White spruce, paper birch, quaking aspen, and balsam poplar are restricted mostly to the well-drained moraines. At Dune Lake open-canopy forest is located mostly on well drained south-facing dune slopes, where a mix of white spruce, paper birch, green alder, and occasional black spruce occurs. At the southern end of Dune Lake there is a mixed community of willow, quaking aspen, and paper birch establishing following the 1986 fire. At Deuce Lake a mixed community of white spruce, black spruce, and patches of hardwood species, such as paper birch and quaking aspen dominate.

[10] The climates of Kenai Peninsula and near Dune and Deuce Lakes are distinctly different. The moist Kenai Peninsula is characterized by 483 mm of annual precipitation, a mean winter temperature of $-15°C$, and a mean summer temperature of 16°C, as recorded at the Kenai climate station (available at http://www.Cdc.noaa.gov/USclimate). The continental climate near Dune and Deuce Lakes is characterized by 276 mm of annual precipitation, a mean winter temperature of $-28°C$, and a mean summer temperature of 22°C, as recorded at the Fairbanks climate station (available at http://www.Cdc.noaa.gov/USclimate).

[11] The fire season in both region lasts from April to September with the greatest activity from May through July, when high-pressure systems bring high temperatures and low humidity [*Viereck*, 1973]. In interior Alaska, lightning strikes associated with the break-up of high-pressure systems are the dominant ignition source [*Gabreil and Tande*, 1983]. On the Kenai Peninsula, people are the main ignition source; lightning strikes are rare [*Gabreil and Tande*, 1983]. The most recent fires to burn the area around the lakes include the 1947 fire that burned 109,836 hectares around Portage, Rock, and Arrow Lakes, the 1996 fire that burned

1500 hectares around Rock Lake, and the 1969 fire that burned 32,000 hectares in adjacent watersheds of Portage and Arrow Lakes [*Alaska Fire Service*, 1999]. Based on tree ring analysis, *De Volder* [1999] identified four additional fires around these lakes. He estimated that fires occurred in 1849 at Portage Lake, in 1888 at both Portage and Arrow Lakes, and in 1833 and 1834 at Rock Lake. These fires burned 36,692, 20,038, 4101, and 16,455 hectares, respectively. The most recent fire at Dune Lake occurred in 1986, while the last fire at Deuce Lake probably occurred during the settlement of Fairbanks between 1903 and 1908.

[12] Before the first Russian explorers arrived in the 1700s, Tlingit and Yupik, and Dena'ina (Athabascans tribe) people occupied south-central Alaska and interior Alaska and the Kenai Peninsula, respectively [*Gibson*, 1976]. Russians settled the Kenai Peninsula from 1743 to 1799, with permanent establishments at Georgievsk Fort, Nikolaeusk Redoubt, and Derevnia Knyk in 1787, 1791, and 1845, respectively [*Gibson*, 1976; *Naske and Soltnick*, 1987]. Settlement of the Fairbanks region by Americans did not occur until Felix Pedro's discovery of gold and the resulting gold rush of the early 1900s [*Cole*, 1999]. The population of Fairbanks grew rapidly from 800 inhabitants in 1902 to 5000 by 1908 [*Cole*, 1999].

2.2. Vegetation and Climate History

[13] Pollen, sediment geochemistry and lake-level data reported from a number of sites in interior Alaska suggest several distinct vegetation and climate changes during the past 10,000 years [*Abbott et al.*, 2000; *Ager*, 1971; *Anderson et al.*, 1994; *Bigelow*, 1997; *Edwards and Barker*, 1994; *Finney et al.*, 2000; *Hu et al.*, 1998]. Early-Holocene vegetation was dominated by deciduous taxa (e.g., birch, poplar, and willow). White spruce expanded its range approximately between 10,000–9000 yr BP. White spruce was followed by an expansion of alder between 7000 and 8000 yr BP and an increase in black spruce beginning at 6000 yr BP. After the expansion of black spruce, there were no major compositional changes in the interior boreal forest.

[14] Water levels of closed-basin lakes in interior Alaska were low in the early Holocene and began to rise about 10,000 yr BP, coincident with the first expansion of white spruce [*Finney et al.*, 2000]. *Hu et al.* [1998] used ostracode geochemical records from Farewell Lake to infer a cold, dry climate existed in the region during the earliest Holocene. Warm conditions prevailed between 9500–8800 yr BP (8500 to 8000 ^{14}C yr BP). An increase in moisture balance (i.e., the difference between precipitation and evapotranspiration) began during the middle Holocene. At Birch Lake, an increase in lake-levels after 6800 yr BP (6000 ^{14}C yr BP) was inferred from changes in sediment type [*Abbott et al.*, 2000] and from hydrological model predictions [*Barber and Finney*, 2000]. Moreover, a decrease in the Sr/Ca ratio of ostracode shells at Farewell Lake suggests an increase in the moisture balance after 7425 yr BP (6500 ^{14}C yr BP) [*Hu et al.*, 1998]. The record of moisture change in the late Holocene is not as clear because many lakes overflowed their outlets. However, a relatively stable Sr/Ca ratio at Farewell Lake suggests that available moisture had not changed much since the middle Holocene [*Hu et al.*, 1998]. Growing season temperatures may have fluctuated during the middle to late Holocene. According to Mg/Ca ratios of ostracode shells deposited in Farewell Lake, growing season temperatures increased from 6800–5100 yr BP (6000–4500 ^{14}C yr BP), decreased from 5100–1350 yr BP (4500–1500 ^{14}C yr BP), and increased with fluctuations there after. Moreover, the expansion of mountain glaciers and the renewal of ice-wedge growth between 2200 and 3800 yr BP [*Hamilton et al.*, 1984; *Wiles et al.*, 1999] suggest temperatures decreased sometime between 3800 to 2200 yr BP. A general change from warm/dry to warm/moist to cool/moist climates during the Holocene in interior Alaska can be inferred from these data [*Edwards et al.*, 2001].

3. Field and Laboratory Methods

3.1. Sampling and Core Chronology

[15] All sediment cores were collected during the summers of 1995 and 1996 from the deepest part of each lake using a piston corer [*Wright*, 1984]. The water-sediment interface and the top 80 cm of each core were retrieved using a freeze core or a clear polycarbonate piston corer, and were extruded at 1-cm intervals in the field. Stratigraphy was visually described for each core. Charcoal and loss-on-ignition (LOI) [*Dean*, 1974] were measured from sediment samples taken at continuous 1-cm intervals. Pollen was sampled at two to 10-cm intervals. Fossilized charcoal particles, terrestrial plant macrofossils (e.g., seeds), and pollen were removed from each core for AMS ^{14}C dating at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. AMS ^{14}C dates were converted to calendar years with the use of CALIB 4.3 program [*Stuiver et al.*, 1998] (Table 2).

[16] Chronologies for the past 140 to 180 years were determined from ^{210}Pb analyses at one to 2-cm intervals. Sediment ^{210}Pb activity was quantified by utilizing a modified *Eakins and Morrison* [1978] procedure. Ages and sedimentation rates were calculated according to a constant rate of supply model (c.r.s) with first-order error based on *Binford* [1990]. The chronology for each core was based on both ^{14}C and ^{210}Pb dates with the exception of the core from Arrow Lake, where the age model was based only on ^{210}Pb, because the ^{14}C date was contaminated. Sample ages were interpolated using a local regression (Loess) model.

3.2. Charcoal Analysis

[17] Charcoal was quantified using the methods of *Clark and Hussey* [1996]. Sediment samples of 1.0 cm^3 were removed at 1-cm intervals, deflocculated with 10% KOH, and sieved though a 180 μm screen. The remaining sieved contents were dispersed over a petrie dish in distilled water. Charcoal particles were identified by visual examination with a stereoscope at 20 power. Black particles that were angular and opaque were identified as charcoal [*Clark*, 1988]. Image analysis was used to quantity the surface area of charcoal, but was not used to identify charcoal pieces. Surface area (mm^2) was measured by optical density using an analog camera attached to the stereoscope and NIH image analysis software. Charcoal accumulation rates were expressed as $mm^2/cm^2/yr$.

3.3. Pollen Analysis

[18] Sediment samples of 0.5 cm^3 were prepared for pollen analysis using standard techniques [*Faegri and

Table 2. ^{14}C Dates for All Lake Cores

Lab Number	Depth, cm	^{14}C Age	Calibrated Age (2 Sigma) yr BP	Material Dated
Rock Lake				
Cams-46219	68–69	980 ± 120	925 (1046–741)	Birch seed
Portage Lake				
Cams-46220	65–66	1170 ± 50	1063 (1171–992)	Charcoal/ macrofossil[a]
Arrow Lake				
Cams-46218	63–64	>Modern	Contaminated	Macrofossil
Dune Lake				
Cams-56316	936–939	820 ± 50	739 (675–785)	Pollen
Cams-56368	961–965	1210 ± 50	967 (928–1059)	Mean pollen/macrofossil
Cams-56363		940 ± 60		
		1075 ± 78		
Cams-29561	987–993	1840 ± 60	1780 (1707–1865)	Pollen
Cams-29562	1088–1091	2880 ± 60	2980 (2851–3210)	Pollen
Cams-56309	1176–1178	4050 ± 40	4458 (4444–4570)	Pollen
Cams-56310	1267–1269	5150 ± 50	5668 (5602–5890)	Mean pollen/macro
Cams-56311		4810 ± 90		
		4980 ± 103		
Cams-56312	1293–1295	5740 ± 50	6435 (6292–6556)	Mean pollen/ macrofossil
Cams-56313		5520 ± 120		
		5630 ± 130		
		6000 ± 10	6825 (6759–7855)	Tephra
Cams-56314	1323–1325	6670 ± 50	7430 (7265–7608)	Mean pollen/ macrofossil
Cams-56315		6410 ± 200		
		6540 ± 206		
Cams-29559	1336–1339	7420 ± 60	8191 (8173–8333)	Pollen
Cams-22020	1362–1368	8670 ± 60	9576 (9547–9701)	Pollen
Cams-31082	1427–1429	9780 ± 90	11195 (11163–1131)	Bark
Deuce Lake				
Cams-22001	64	1300 ± 60	1261 (1091–1299)	Wood

[a]All macrofossils used for dating were from terrestrial plant sources.

Iversen, 1975]. *Lycopodium* spores were added to each sample prior to preparation [*Stockmarr*, 1972]. At least 300 pollen grains were counted in each sample using a light microscope at 400–1000 power. Black spruce and white spruce pollen grains (30–40 spruce grains) were differentiated based on saccus height, saccus width at the base, corpus breadth [*Brubaker et al.*, 1987], and other morphological characteristics [*Hansen and Engstrom*, 1985]. Pollen percentages were based on all tree, shrub, and herb pollen. Pollen was not counted in the core from Deuce Lake.

3.4. Data Analysis

[19] To compare presettlement charcoal accumulation between the two regions, we examined the distributions of charcoal accumulation rates from 1000 to 1850 AD using a non-parametric Kolmogorov-Smirnov (KS) two-sample test [*Sokal and Rohlf*, 1981; *Clark et al.*, 1996a]. Charcoal records contain information on regional fire importance, although charcoal accumulation rates may vary between sediment types [*Clark et al.*, 1996d]. This variation is likely related to sediment mixing at the water-surface interface and the deposition of charcoal from secondary sources [*Whitlock and Millspaugh*, 1996]. However, evidence from multiple studies suggests that regional signals in charcoal accumulation are not fully masked by sediment processes. *Clark* [1990] and *Millspaugh and Whitlock* [1995] found that charcoal accumulation was similar among different cores from the same lake and from nearby lakes within the same region. Charcoal accumulation was similar among lakes located in similar vegetation and climate settings [*Clark and Royall*, 1995]. Moreover, no correlation was found between charcoal accumulation rates and sediment accumulation rates in varved and non-varved sediments, indicating charcoal accumulation is not closely linked to processes controlling sediment deposition [*Clark et al.*, 1996c; *Lynch*, 2001].

[20] The long-term charcoal record at Dune Lake was analyzed to determine the distribution of time intervals between charcoal peaks that likely correspond to individual fires. Charcoal records contain information on 1) regional fire importance, which can vary at low frequency; 2) nearby fires, which tend to produce charcoal peaks; and 3) residual variance, which can result from transport, deposition, and sampling [*Clark and Royall*, 1996]. Identification of individual local fires from sediment charcoal records requires separating the different sources of charcoal particles (Figure 2) [*Clark and Royall*, 1996]. Background charcoal was estimated from the raw charcoal series by a kernel smoother (local average function that calculates a weighted average from a range of points (bandwidth)) [*Silverman*, 1986]. A bandwidth of 100 years was used (Figure 2a), which best represented the data. Background values ranged from 0.0004 to 0.048 $mm^2/cm^2/yr$. This estimate of background charcoal was subtracted from raw charcoal accumulation data to emphasize residual peaks (Figure 2b).

[21] To extract local events, two methods were used that yielded comparable results. First, we examined the distri-

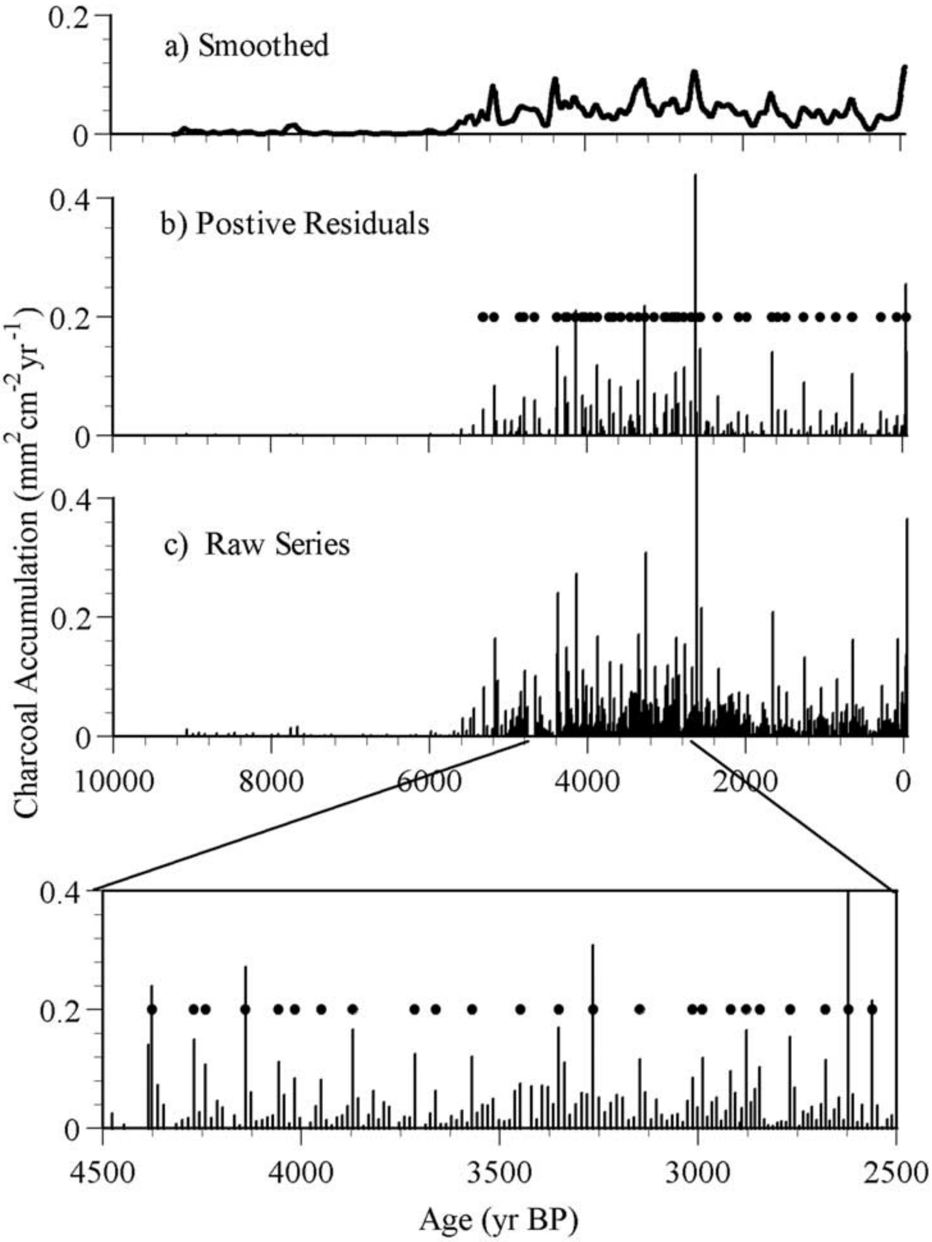

Figure 2. Example of the method used to distinguish fire events from the charcoal record at Dune Lake. (a) Smoothed charcoal accumulation rates using a 100-year window that shows low frequency changes in regional burning, (b) positive residuals between 100-year smoothed and raw charcoal series, and (c) raw charcoal series with a selected section from 4500 to 2400 yr BP showing estimated fire events. Dots on both Figure 2b and selected section in Figure 2c mark charcoal peaks >0.07 $mm^2/cm^2/yr$ that represent fire events (see methods).

bution of residuals to estimate the proportion of peak accumulation values above a threshold value P. A sensitivity analysis was used to identity how the proportion of peak accumulation rates changes with P. This analysis was used to identify an intermediate range of charcoal accumulation rates between background and the largest peak values [*Clark et al.*, 1996c]. Local fire events were assumed to be represented by the range of charcoal accumulation rates where the mean intervals (in years) between peak values were relatively insensitive to changes in P. Residual peak variance was normally distributed (Figure 3a). The range where mean interval between peaks is insensitive to change in P occurs from 0.84–0.91, those within the upper 9–22% tail of the distribution. For this study, the upper 12% of residual distribution was used as an estimate of local fires. This corresponds to charcoal accumulation values above 0.072–0.220 $mm^2/cm^2/yr$, which is well above estimated background values (Figure 2c).

[22] Second, we used results from charcoal transport studies from two modern controlled boreal fires to define

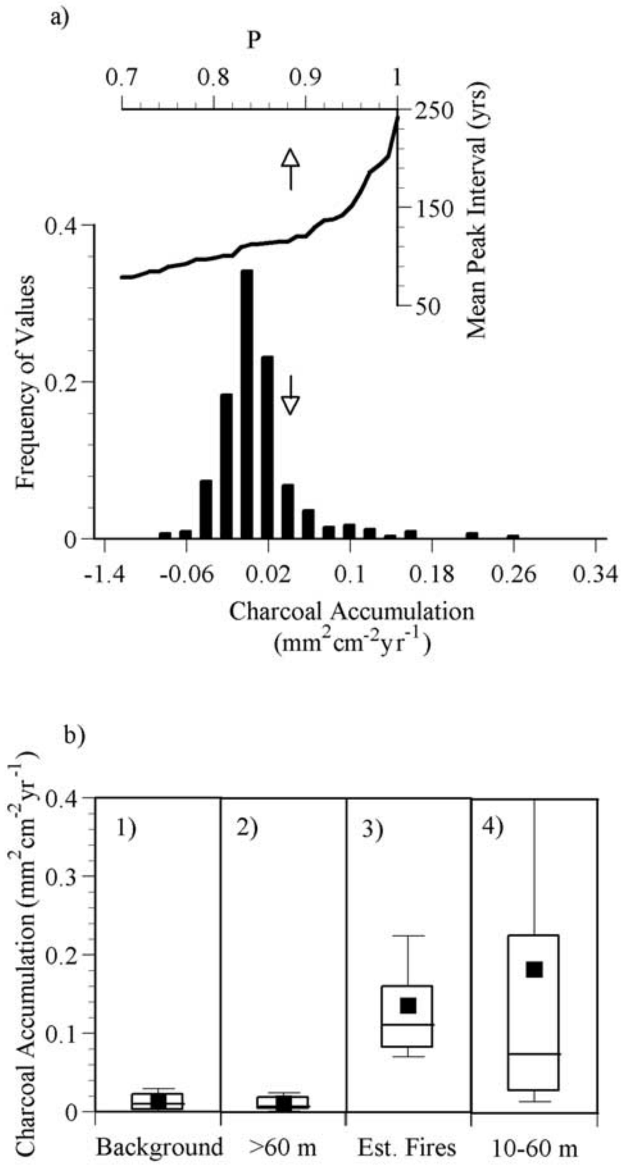

Figure 3. (a) Distribution of residual peaks (lower graph) and sensitivity index (upper graph, right-hand axis) for Dune Lake. Arrows indicate the point (0.88) where P is less sensitive to mean fire return interval (years). Fires were estimate to be upper 12% of the residual distribution, charcoal peaks >0.07 $mm^2/cm^2/yr$; (b) distribution of charcoal accumulation rates from (1) estimated background charcoal at Dune Lake (Background), (2) modern control burn values greater than 60 m (>60 m) from the fire, (3) estimated fires at Dune Lake (Est. Fires), and (4) modern control burn values from 1 to 60 m from the fire (1–60 m). Modern charcoal accumulation estimates are based on two boreal control burns at Bor, Siberia, Russian Federation [*Clark et al.*, 1996b] and Fort Providence, N.W.T., Canada [*Lynch*, 2001]. Both studies measured charcoal deposition in traps at various distances (0 to 200 m) from a typical boreal crown fire. Charcoal accumulation rates from the control fires were quantified using the same method used in this paper and represent rates in mm^2/cm^2/fire.

a clear distinction between charcoal deposition of 0.01–0.522 mm^2/cm^2/fire (not including values within the burn itself) within 60 m of the burn edge and deposition of 0.003–0.023 mm^2/cm^2/fire at distances greater than 60 m (Figure 3b) [*Clark et al.*, 1996b; *Lynch*, 2001]. Peak values interpreted from our first method (those within the upper 12% tail of the residual distribution) were well above the background charcoal level recorded from the burn experiments (Figures 3b and 4). Consecutive peak values were assumed to have occurred from the same fire. An average age was assigned for the two cases of consecutive peak values. Fire return intervals were calculated as the time (yr) between peaks.

[23] Fire intervals were summarized with a Weibull model fitted by maximum likelihood [*Clark*, 1989]. The hypothesis that fire probability increases with time since last fire was tested using a likelihood ratio test against an exponential model ($c = 1$). Ninety-five percent confidence intervals on all parameters were constructed using a non-parametric bootstrap analysis.

4. Results

4.1. Core Chronology and Sedimentation Pattern

[24] Sedimentation rates are similar among cores from Kenai Peninsula Lakes and from lakes in interior Alaska. Unsupported surface sediment activity ranges from 6.5 to 30.0 dpm/g and declines to background levels at core depths between 15–30 cm. Plots of ^{210}Pb concentrations versus sediment depth (Figure 5a) are generally monotonic. Age versus depth relationships for the upper 80-cm are shown in Figure 5b for all lakes. Sedimentation rates (cm/yr) at all sites are highest during the past 100 years, intermediate between 100 to 200 years ago, and lowest between 200 to 1000 years ago. At Rock, Portage, and Arrow Lakes, sedimentation rates for the past 100 years are 0.415, 0.370, and 0.350 cm/yr, respectively. For the same period at Dune and Deuce Lakes, sedimentation rates are 0.17 to 0.260 cm/yr, respectively. At all sites, sedimentation rates decline to 0.07 to 0.09 cm/yr from 100–200 years ago, and to 0.01 to 0.05 cm/yr from 200 to 1000 years ago. Trends in sediment accumulation of dry mass ($gram/cm^2/yr$) are similar to trends in sedimentation rates. At all sites, but Dune Lake, dry mass accumulation rates are 0.02 to 0.03 $gram/cm^2/yr$ for the past 200 years and 0.005–0.01 gram/cm^2/yr for the period between 200 to 1000 years ago. At Dune Lake dry mass accumulation rates differ only slightly between the past 200 years (0.007 $gram/cm^2/yr$) and prior to 200 years (0.005 $gram/cm^2/yr$). An increase in sediment input to the lakes on the Kenai Peninsula after European settlement is supported by the increase in sedimentation rates and dry mass accumulation rates following settlement.

[25] Age versus depth relationship for the past 9500 yr BP is shown in Figure 6a for Dune Lake. Sediments deposited between 9000 and 3000 yr BP are laminated. Sedimentation rates vary sevenfold over the past 9500 years at Dune Lake (Figure 6b). Sedimentation rates for the period from 9500 to 7000 yr BP average 0.020–0.025 cm/yr (deposition rates 40–50 yr/cm). During the past 6000 years, sedimentation rates average 0.065 ± 0.017 cm/yr (15.4 ± 12 yr/cm), with lower rates of 0.05 ± 0.01 cm/yr (20 ± 16 yr/cm) after 2000 yr BP. Despite changes in sedimentation

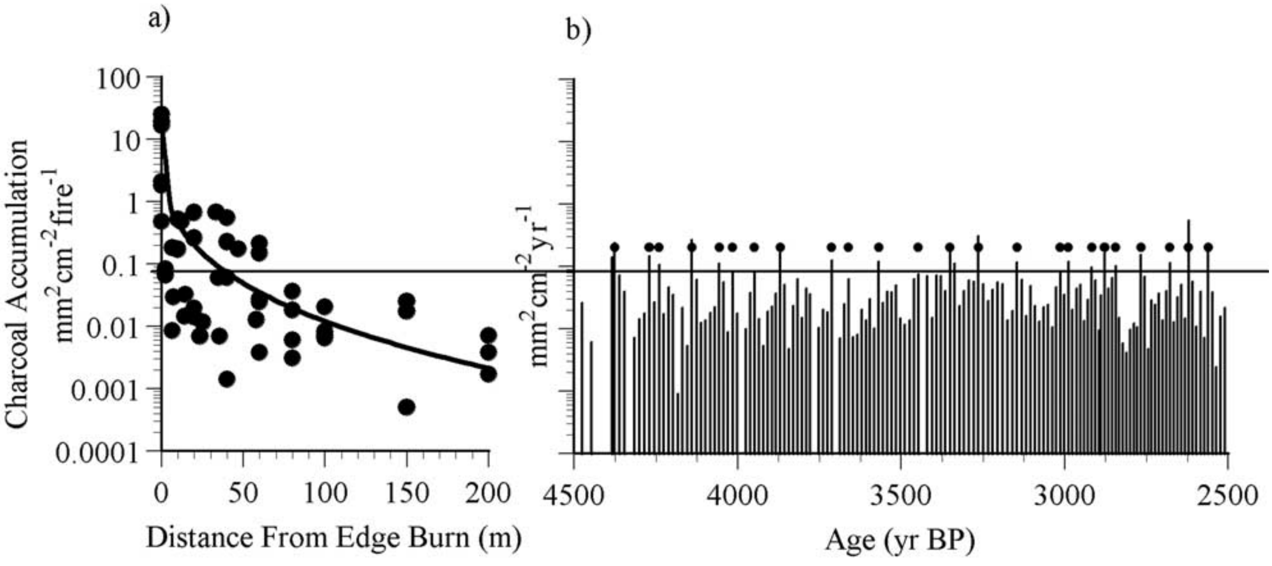

Figure 4. (a) Particle-accumulation rates from both Bor and Fort Providence controlled fires. Model fits are given for the combination of transects on log scale. (b) Charcoal accumulation from Dune Lake on log scale. Dots represent estimated fires. The line showing estimated fire events corresponds to similar charcoal accumulation <60 m from the control fire.

rates, the organic content of 30% is relatively constant from 9000 to 3000 yr BP (Figure 6b).

4.2. Charcoal and Pollen During the Past 1000 Years

[26] During the past 1000 years, charcoal series from sampled lakes display similarities. Rock and Deuce Lakes have the lowest charcoal accumulation, Arrow and Portage Lakes have intermediate levels, and Dune Lake has the highest values (Table 3, Figure 7). At all lakes, the highest average charcoal accumulation occurs after 1850 AD (Table 3).

[27] In lakes on the Kenai Peninsula, charcoal series records distinct peaks of charcoal accumulation at 1950 ± 2 AD, 1953 ± 3 AD, and 1951 ± 3 AD for Rock, Portage, and Arrow Lakes, respectively (Figure 8). These large charcoal peaks (0.24–0.66 $mm^2/cm^2/yr$) in the early 1950's are associated with the 109,839 hectares stand-replacing fire in 1947 AD, which burned the watersheds of these lakes. Dendrological studies on the Kenai Peninsula identified fires that burned within the watershed of the various lakes [*De Volder*, 1999]. These fires are represented by charcoal peaks in this study. At Portage Lake charcoal peaks in 1888 ± 8 AD (0.18 $mm^2/cm^2/yr$) and 1850 ± 15 AD (0.18 $mm^2/cm^2/yr$) correspond to the dendrological fire estimates of 1888 AD (20,000 hectares) and 1849 AD (36,000 hectares). At Arrow Lake a charcoal peak at 1885 ± 11 AD (0.22 $mm^2/cm^2/yr$) is the same as the 1888 AD fire at Portage Lake. At Rock Lake a charcoal peak at 1846 ± 10 AD (0.11 $mm^2/cm^2/yr$) may correspond to the 1834–1835 AD (20,000 hectares) fire. Charcoal peaks dated 1975 ± 3, 1968 ± 3, and 1989 ± 3 AD at Portage, Arrow, and Rock Lakes, respectively, may correspond to the 1969 AD fire that burned 32,000 hectares of the watershed adjacent to Portage and Arrow Lakes and the 1996 AD fire that burned 1,500 hectares around Rock Lake. Three other charcoal peaks (1670 ± 21, 1486 ± 50, and 1264 ± 99 AD) are present at Rock Lake; however, charcoal accumulation rates are much lower (0.04–0.07 $mm^2/cm^2/yr$) than other peaks (Figure 8).

[28] At Dune Lake a distinct charcoal peak at 1986 ± 2 AD coincides with the large stand replacing fire of 1986 AD (Figure 8). Other charcoal peaks occur at 1880 ± 4, 1675 ± 20, 1312 ± 44, and 1110 ± 50 AD. At Deuce Lake distinct charcoal peaks occur at 1990 ± 2, 1909 ± 8, 1885 ± 20, 1773 ± 20, and 1055 ± 35 AD. The 1909 AD peak coincides with the American settlement of Fairbanks during the gold rush of the early 20th Century [*Cole*, 1999].

[29] During the past 1000 years, pollen percentages (Figure 9) are relatively constant at all sites where pollen was completed. Black spruce, birch, alder, and, to a lesser extent, poplar are the dominant taxa at Dune, Portage, and Arrow Lakes. Only a few changes in pollen percentages are recorded in response to the large change in accumulation of charcoal (i.e., fire regime) after European settlement at sites on the Kenai Peninsula. At Rock Lake white spruce and alder pollen percentages increase following the 1947 AD fire, while birch pollen percentages decrease. At Portage Lake alder pollen percentages also increase along with black spruce pollen percentages.

4.3. Holocene Charcoal and Pollen Records at Dune Lake

[30] Low charcoal accumulation rates and lack of charcoal peak values occur before 5500 yr BP (Figure 2a). This period of low charcoal accumulation is dominated first by birch and white spruce pollen from 9000 to 8000 yr BP and later by alder, birch, and white spruce pollen from 8000 to 5500 yr BP (Figure 10).

[31] High background charcoal accumulation and frequent large charcoal peaks occur after 5500 yr BP. The distribution of intervals between peaks after 5500 yr BP has a mean value of 127 years (range of 24 to 301 years). The

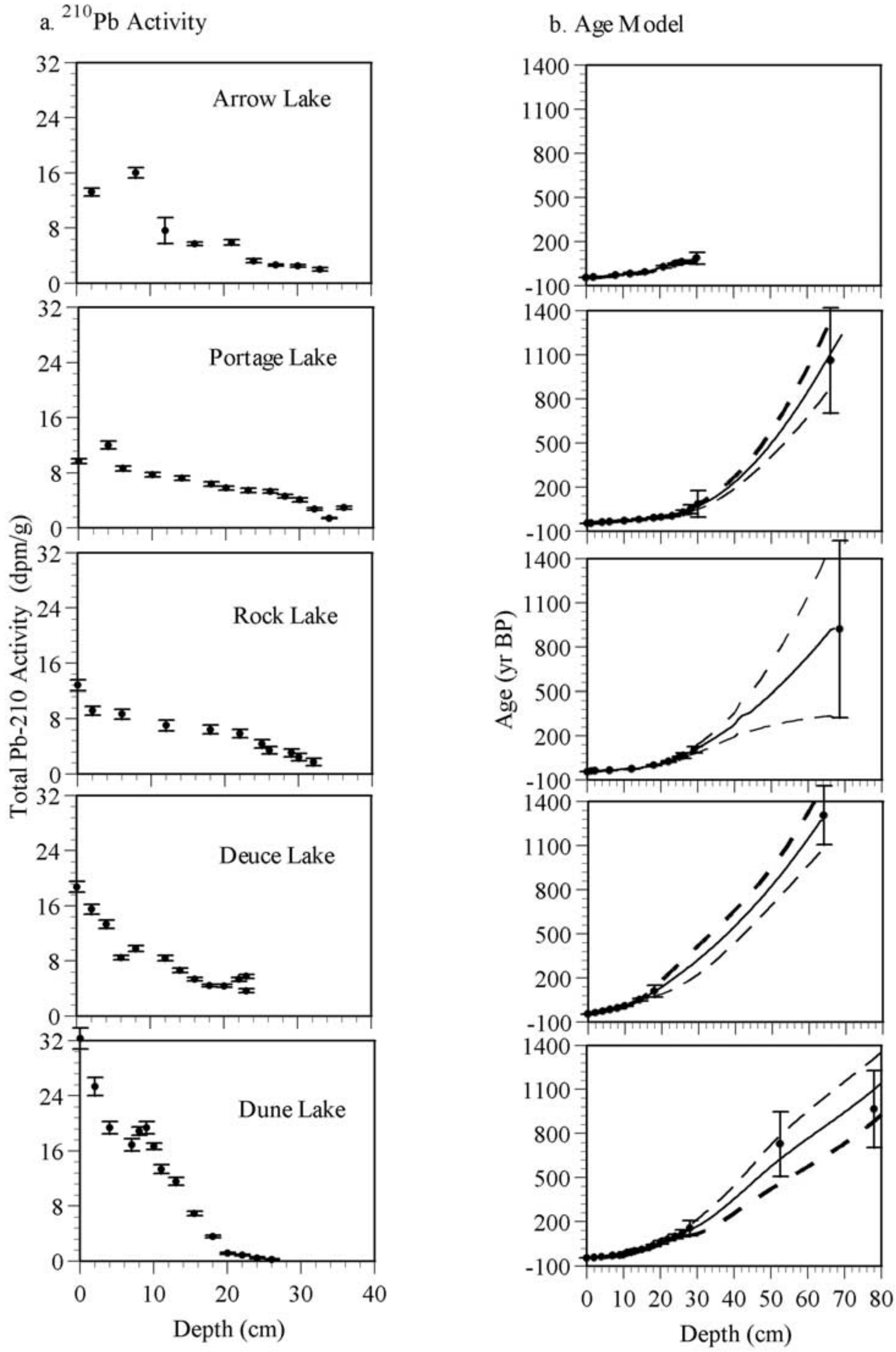

Figure 5. (a) Plots of total supported ^{210}Pb versus sediment depth with counting errors, (b) Age chronology versus depth of ^{210}Pb and calibrated ^{14}C dates. ^{14}C dates are listed in Table 2. Error bars represent 2 s.d. propagated from counting uncertainty for ^{210}Pb and ^{14}C dates. Dashed lines represent 95% confidence intervals.

magnitude of these large, individual peaks is consistent with stand replacing fires documented from the Kenai Peninsula cores (Figure 8). This increase in charcoal accumulation and charcoal peaks at 5500 yr BP occurs slightly after a sharp increase in black spruce pollen at 5770 yr BP (Figure 10).

[32] Two distinct fire regime periods occur after 5500 yr BP. The first period occurs from 5500 to 2400 yr BP, where the mean time between charcoal peaks is 97 ± 68 years and the Weibull parameter c = 1.6 (CI 1.30 to 2.70) (Table 4, Figure 11). The second period occurs from 2400 yr BP to the present, where the mean time between charcoal peaks is 198 ± 86 years and c = 2.3 (CI 1.03 to 3.90). The likelihood ratio test rejects the hypothesis that the Weibull parameter c = 1 for both intervals, which indicates an

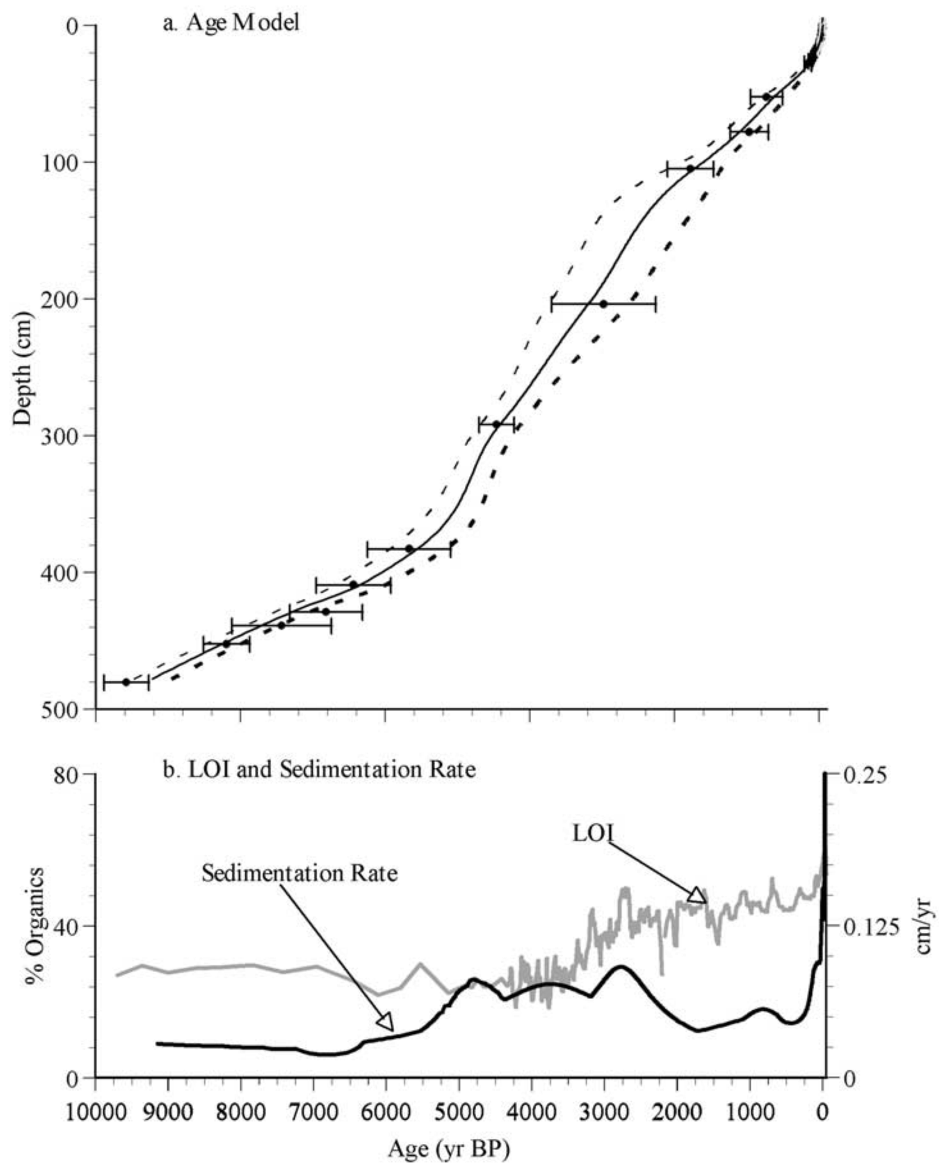

Figure 6. (a) Age chronology versus depth from calibrated ^{14}C and ^{210}Pb dates for Dune Lake. ^{14}C dates are listed in Table 2. Error bars represent 2 s.d., dashed lines represent 95% confidence interval. (b) Percent organic content (LOI) of core (light line) and sedimentation rates (cm/yr) (dark line).

increased probability of burning with time since the last fire (Table 4, Figure 11).

5. Discussion

5.1. Recent Charcoal Accumulation Trends

[33] The overall higher charcoal accumulation at lakes in interior Alaska compared to lakes on the Kenai Peninsula is consistent with the record of area-burned and high occurrence of lightning-caused fires [*Alaska Fire Service*, 1999; *Gabreil and Tande*, 1983]. In interior Alaska, both the number of fires and the area burned (fires >400 hectares) recorded between 1954 and 1990 are higher than on the Kenai Peninsula [*Alaska Fire Service*, 1999]. However, the fire occurrence in interior Alaska for the last 1000 years was still relatively low when compared to the charcoal record at Dune Lake for the period from 5500 to 1000 yr BP.

[34] Before European settlement, the fire regime on the Kenai Peninsula most likely consisted of few small fires or ones that burned at greater distance from the study lakes. This interpretation is supported by the absence of charcoal peaks before European settlement of the same magnitude as charcoal peaks deposited by the 1947 fire or deposited by the fires estimated by *De Volder* [1999] (Table 3, Figure 8) over the length of record. The small charcoal peaks present before settlement, such as the charcoal peaks of 1670 and 1264 AD at Rock Lake, may represent fires that burned less then 20,000 hectares because the known fires (i.e., 1947 fire) that deposited clear charcoal peaks burned 20,000 to 110,000 hectares in area. However, it is difficult to interpret

Table 3. Mean Charcoal Accumulation Rates[a]

Site Name	1850–1000 yr AD	Present–1850 yr AD	Dune (1850–1000)	Deuce (1850–1000)
Kenai Peninsula				
Rock Lake	0.013 ± 0.02	0.053 ± 0.07	P < 0.001	P < 0.22
Portage Lake	0.020 ± 0.03	0.110 ± 0.10	P = 0.089	P < 0.001
Arrow Lake	n/a	0.118 ± 0.14		
Interior Alaska				
Dune Lake	0.028 ± 0.03	0.073 ± 0.09		
Deuce Lake	0.016 ± 0.03	0.027 ± 0.06		

[a]Comparisons of distributions of charcoal accumulation rates using a two-way Kolmogorov-Smirnov Test.

low charcoal accumulation rates because these rates are based on only a few pieces of charcoal which can be strongly influenced by sediment redeposition and focusing [*Whitlock and Millspaugh*, 1996].

[35] The four large fires recorded in the charcoal records and the significant increase in charcoal accumulation from the three lakes indicate a fire regime shift around sites on the Kenai Peninsula after European settlement (Table 3, Figure 8). This fire regime shift was likely caused by increased fire ignition by people, because today, people are the main ignition source; lightning strikes are rare on the Kenai Peninsula [*Gabreil and Tande*, 1983]. Human ignition has accounted for four other fires since 1940 and the 1947 fire in the northern Kenai Peninsula [*Alaska Fire Service*, 1999]. However, recent temperature increases in boreal regions may also have contributed to the fire regime shift [*Chapman and Walsh*, 1993; *Overpeck et al.*, 1997].

[36] A fire regime shift after European settlement is less clear at Deuce and Dune Lakes. The slight increase in charcoal accumulation, without an increase in large charcoal peaks, after European settlement indicate that logging and land clearing during the early 1900s gold rush had limited affect on the fire regime around Deuce Lake. Furthermore, a shift in the fire regime at Dune Lake is uncertain, because the increase in charcoal accumulation is dominated by charcoal deposited from the 1986 fire.

5.2. Role of Fire in the Early Boreal Forest (10,000 to 5500 yr BP)

[37] Fire was not an important ecological process during the period when the birch-white spruce community dominated the early boreal forest and later during the expansion of alder at 8000 yr BP. It is unclear whether shrub (*Betula glanulosa* or *nana*) or tree (*Betula papyrifera*, paper birch) birch was present during this period [*Edwards et al.*, 1991]. This early community likely represented a paper birch-white spruce forest, because macrofossils of paper birch occurred near Fairbanks [*Hopkins et al.*, 1981] and at Wien Lake [*Hu et al.*, 1993] during the arrival of white spruce. Thus, fire appears not to have played an important ecological role in

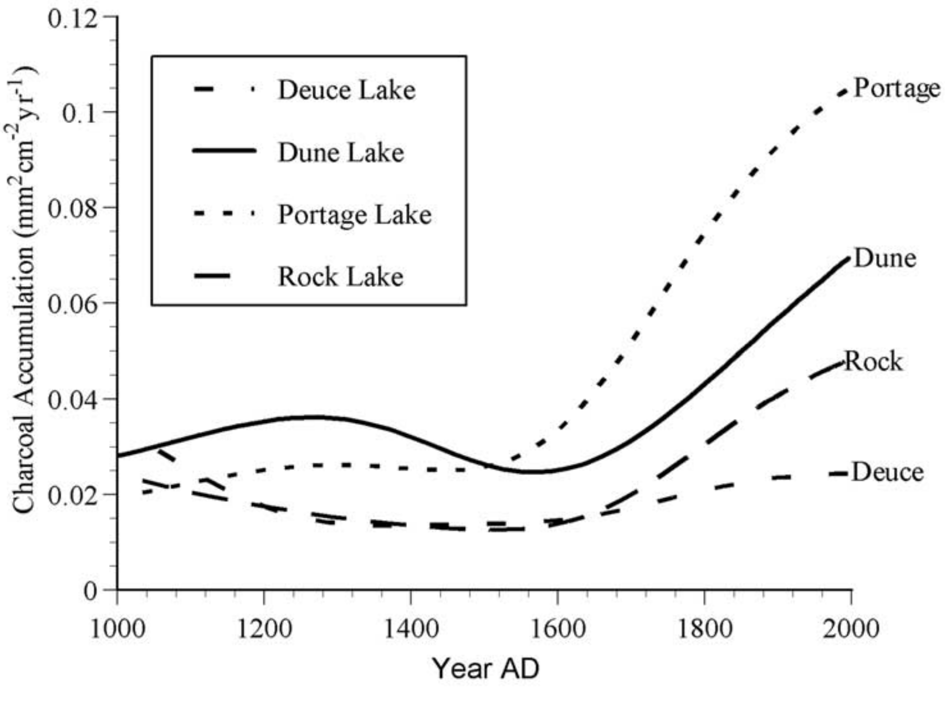

Figure 7. Smoothed charcoal accumulation rates for the past 1,000 years for Portage (narrow dark dashed), Dune (dark), Deuce (wide dark dashed), and Rock (wide light dashed) Lakes. Differences in curves indicate regional differences in charcoal accumulation rates. Smoothed data was not used in statistical comparisons between sites.

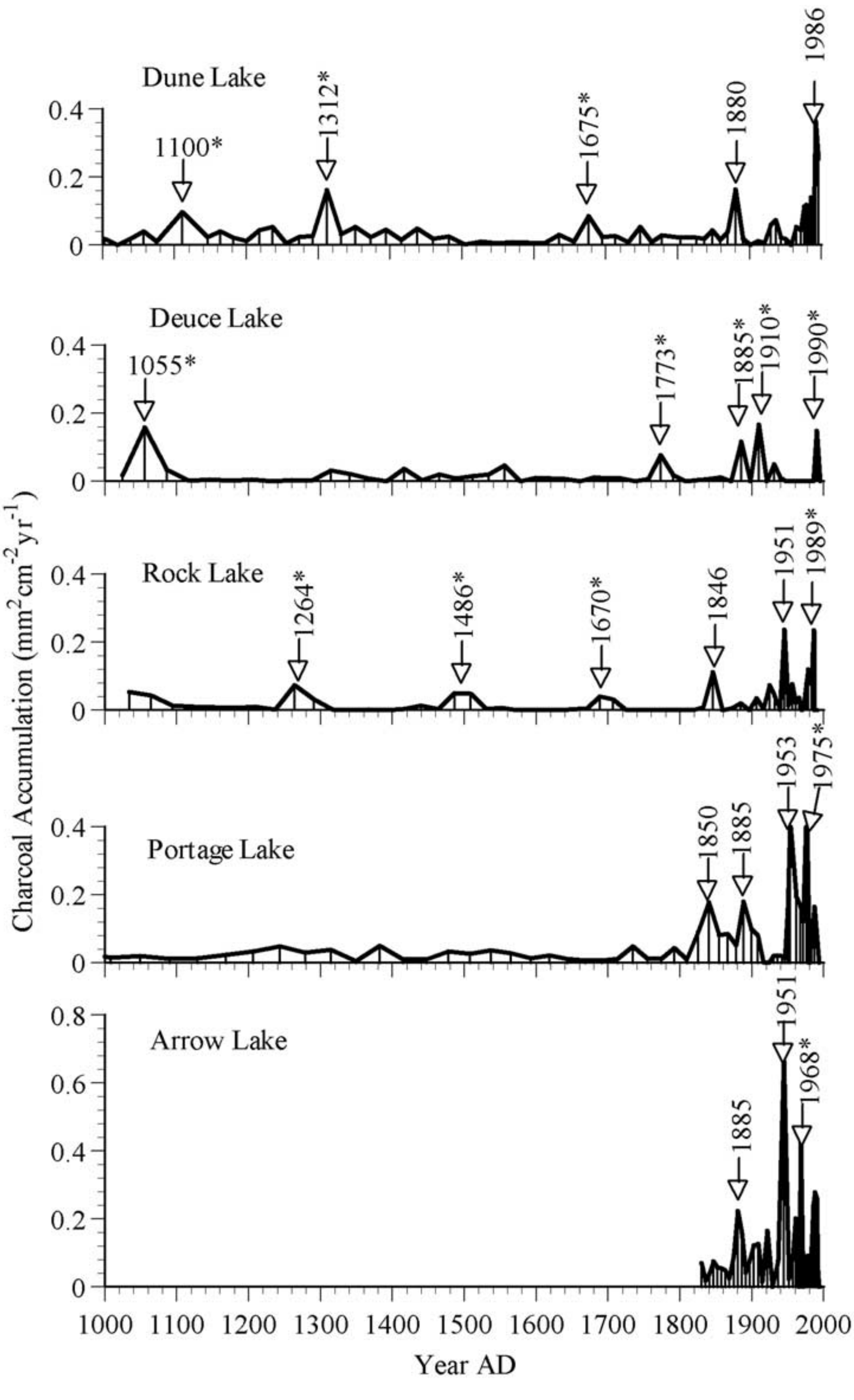

Figure 8. Charcoal accumulation rates from the past 1000 years in years AD. Arrows and dates indicate years of known fires in the watershed and dates with the asterisk indicate estimated fires. Past fire dates are based on tree ring records [*De Volder*, 1999] and area burn data.

these paper birch-white spruce and, later, alder forests. Complete absence of fires is unlikely, because medium to large (0.5 mm diameter) charcoal particles that characterize local fires (those deposited within 60 m of the edge of the lake) [*Clark et al.*, 1996b; *Lynch*, 2001] are evident at three depths. Small, low intensity, and infrequent fires are possible.

[38] Sedimentation changes, climate shifts, and vegetation composition changes can cause changes to the amount

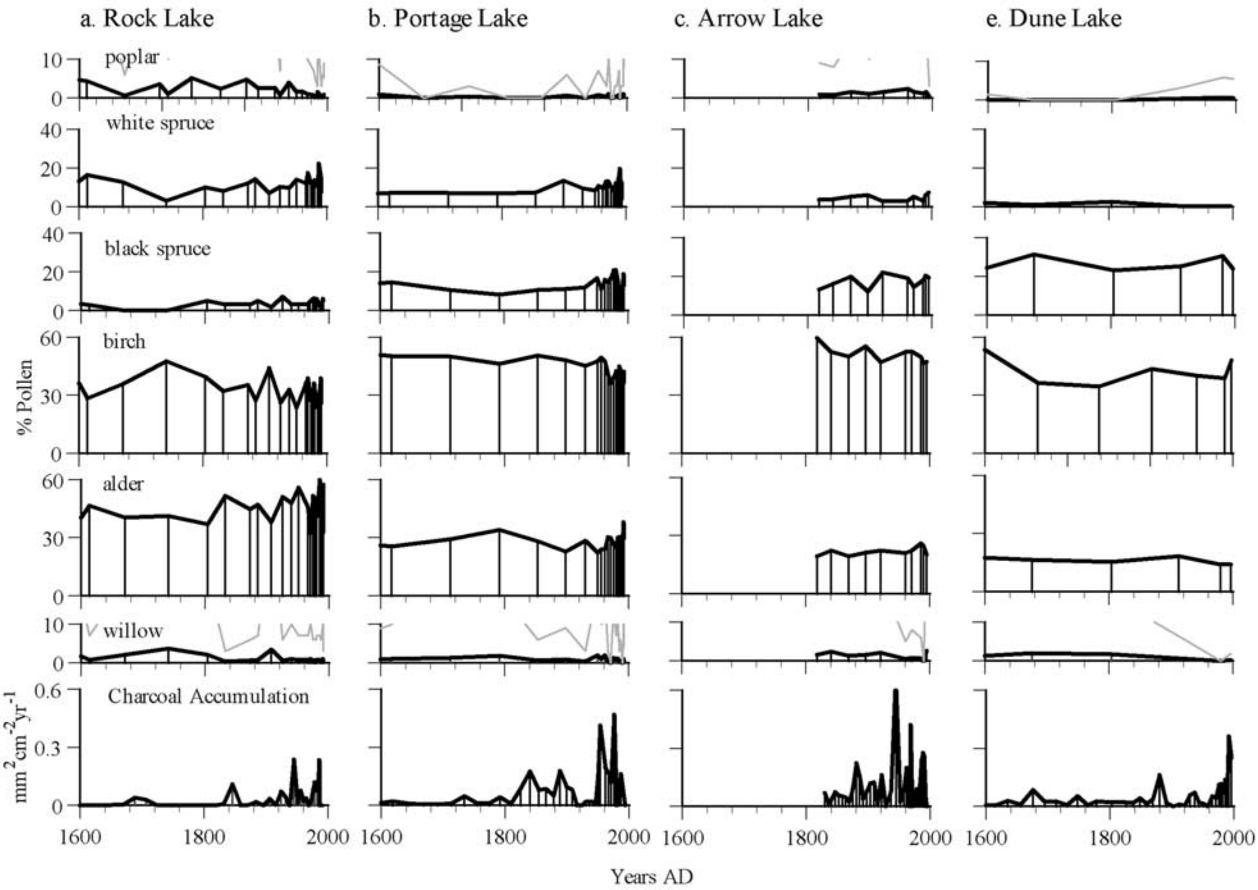

Figure 9. Charcoal accumulation rates and selected regional pollen types. Only the past 180 years are graphed for Arrow Lake because of uncertainty in the age model below ^{210}Pb dates. Upper curves are exaggerated 10 times.

of charcoal deposited in a lake. The low sediment deposition during this period could have influenced the low charcoal deposition. However, sediment characteristics did not change during this time. The percent organic and magnetic susceptibility (B. P. Finney, unpublished data, 1999) were relatively constant since 9000 yr BP (Figure 6b) with increases after 4000 yr BP.

[39] Climate conditions also cannot explain the low importance of fire during this period. Warmer/drier-than-present conditions have been inferred from geochemistry and stratigraphy records at Farewell and Birch Lakes [*Abbott et al.*, 2000; *Hu et al.*, 1998], respectively. In the present-day boreal forest in Canada, warm/dry periods have been correlated with periods of increased fire occurrence and area burned, because these conditions dry fuels, increase ignitions, and increase fire spread [*Nash and Johnson*, 1996; *Flannigan and Harrington*, 1988]. Therefore, warmer/drier-than-present conditions during this period would seem to favor fire importance, not inhibit it.

[40] Phenology and low flammability of deciduous species might contribute to low fire importance. Deciduous species are less flammable and they intercept more sunlight than conifers [*Brown and Davis*, 1973], creating cool, moist conditions in the understory [*Van Wager*, 1983], which reduce the likelihood of fire ignition and spread. Area burned from 1950 to 1995 in Canada indicates less frequent and smaller fires in vegetation dominated by deciduous species, such as paper birch, and in mixed conifer and hardwood stands [*Amiro et al.*, 2001]. Our data also are consistent with both *Hely et al.* [2001] and *Amiro et al.* [2001] results support the hypothesis that phenological differences of deciduous species exert a stronger influence of fire occurrence than the warm/dry conditions during this period.

[41] The low fire occurrence at Dune Lake is consistent with qualitative (present-absent data) sediment charcoal records at Farewell Lake [*Hu et al.*, 1996], although the change occurs earlier here, and Wien Lake [*Hu et al.*, 1993], which has more white spruce pollen (5–10% higher than Dune Lake) for the interval. However, the charcoal data from Farewell and Wien Lakes lack concentration data, making it impossible to describe the absolute fire regimes.

[42] The low charcoal accumulation findings at Dune Lake contradict the low-resolution quantitative charcoal record reported for the birch-white spruce period and later alder expansion at Sithylemenkat Lake [*Earle et al.*, 1996]. *Earle et al.* [1996] interpreted high charcoal accumulation to be a consequence of fuel accumulation and warm/dry conditions associated with the birch-white spruce forest. Since climate reconstructions for both Dune and Sithylemenkat Lakes were similar during the period from 9000 to 5500 yr BP (i.e., warmer-than-present temperature) we

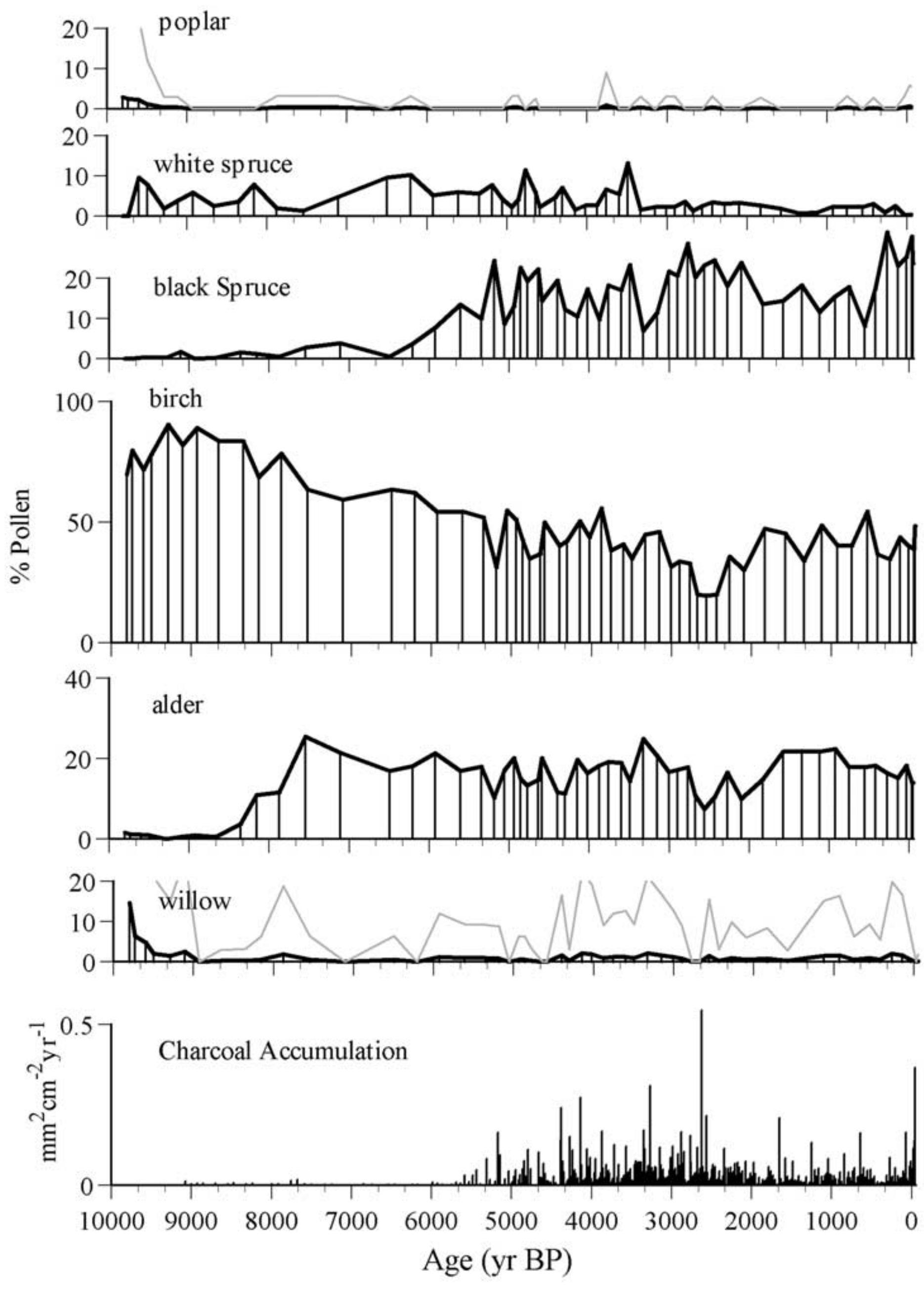

Figure 10. Charcoal accumulation rates and important boreal pollen types for Dune Lake. Upper curves are exaggerated 10 times.

expected similar patterns. This similarity in climate suggests that geological site characteristics (e.g., topography) differed or fuels differed between these sites or that the different methods used for charcoal analysis affect the results. The overall trends in vegetation change during the early Holocene at Dune and Sithylemenkat Lakes were generally similar with an initial period from 10,000 to 8000 yr BP (9000 to 7500 ^{14}C yr BP) of high birch and white spruce pollen percentage, followed by a decline in white spruce and an increase in alder pollen from 8000 to 7000 yr BP (7500 to 6500 ^{14}C yr BP). An exception to this general trend was the 5 to 10% higher white spruce pollen at Sithylemenkat Lake. The high white spruce abundance could have caused more burning around Sithylemenkat Lake, because conifer species are generally more flammability than deciduous species [*Brown and Davis*, 1973].

[43] Methodological differences in charcoal analysis could also explain the differences between the lakes. At Sithylemenkat Lake there were fewer samples (15 samples for last 10,000 years) than Dune Lake (continuous) and image analysis was used to identify charcoal.

5.3. The Interpretation of Fire During Black Spruce Period (5500 yr BP to Present)

[44] Fire was an important ecological process around Dune Lake after the arrival of black spruce. Fire-interval

Table 4. Mean ± 2 s.d. and Fitted Weibull Parameters for Intervals Between Charcoal Peaks

	Fire Intervals		Weibull Parameters[b]	
Age Interval (yr BP)	N	yr (p = 0.9) (Range yr)[a]	b (yr) 95% CI	C 95% CI
−46–5,500	41	127 ± 86 (24–346)	142 (100–156)	1.5 (1.2–1.8)
−46–2,400	13	198 ± 90 (98–346)	224 (137–263)	2.8 (1.03–3.9)
2,400–5,500	28	97 ± 68 (24–327)	109 (85–137)	1.6 (1.3–27)

[a]Range of fire return intervals from the shortest to the longest.
[b]Parameters for the Weibull distribution: $f(x) = c(x^{c-1}/b^{c})\exp[-(x/b)^{c}]$.

distributions for the black spruce period indicate large fires burned regularly, with a more active fire period from 5500 to 2400 yr BP and less afterward. Three possible explanations for the change in charcoal accumulation and charcoal peaks after 5500 yr BP are shifts in sedimentation, climate, and vegetation composition.

[45] Sedimentation did not change from 9000 to 3000 yr BP, indicating a similar depositional environment in the lake before and after the transition at 5500 yr BP. Moreover, a slight increase in sedimentation rate occurred from 6000 to 3000 yr BP. However, the increase in charcoal accumulation far exceeds the increase in sediment accumulation. Change in depositional environment seems unlikely the cause for the increase in charcoal accumulation.

[46] The sharp change in the fire regime at 5500 yrs BP at Dune Lake also cannot be explained by our current understanding of changes in the climate regime. Recent climate reconstructions from Dune [*Bigelow*, 1997], Farewell [*Hu et al.*, 1998], and Birch [*Abbott et al.*, 2000] Lakes based on pollen, sediment geochemistry, and lake-level studies indicate cooler and wetter conditions after 6800, 7400, and 6800 yr BP, respectively (see section 2.2 for more climate details). The cooler and wetter conditions would favor wetter fuels, reducing fire ignition and spread.

[47] Similar timing of the increase in charcoal accumulation and black spruce pollen at Dune Lake indicates a strong connection between the fire regime change and the expansion of black spruce (Figure 10). Generally, black spruce form dense, closed canopy stands with abundant fine fuels that favor crown fires [*Viereck*, 1973]. A transition to a more fire prone vegetation (i.e., black spruce) coinciding with an increase in the frequency of peaks suggest the fire regime change was due to an alteration in fuel loads, as postulated by *Hu et al.* [1996]. The probability of fire

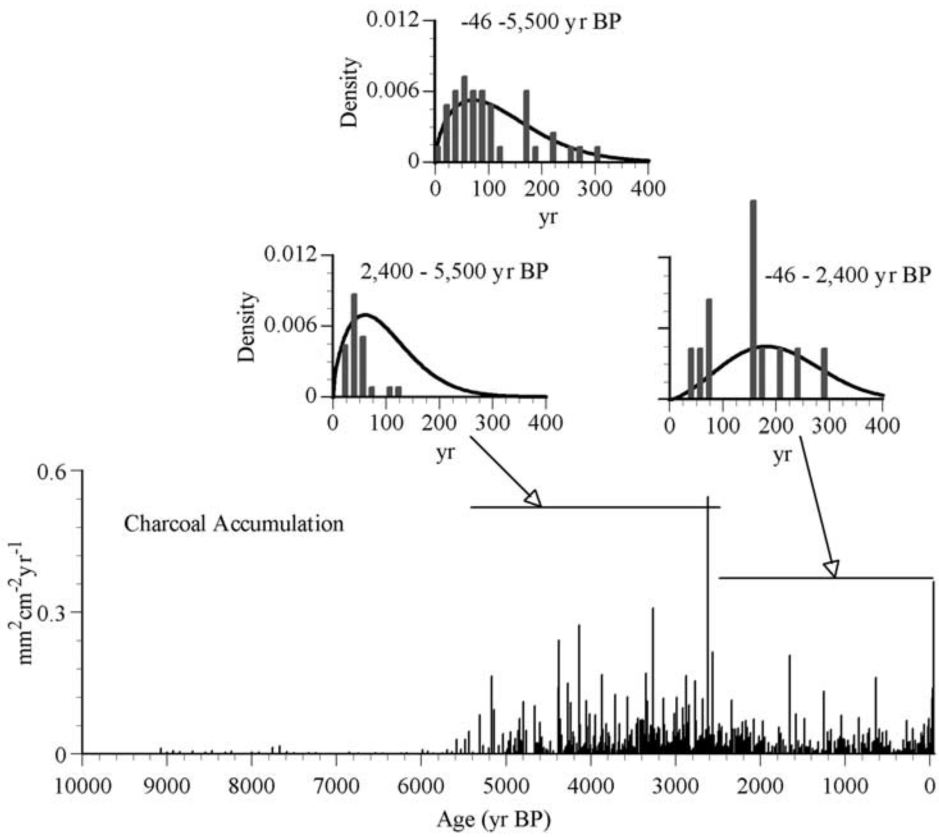

Figure 11. Fitted Weibull distribution between charcoal peaks for each period of charcoal accumulation for the past 5500 years. The overall distribution as well as separate distributions for 5500–2400 and 2400–present BP are shown. Both distributions imply increasing probability with time since last fire with means of 98 years (5500–2400 yr BP) and 198 years (2400–present yr BP).

increased with time since the last burn, (Table 4 and Figure 11), indicating an increase in fuel accumulation or changes in stand age structure attended the expansion of black spruce.

[48] The qualitative charcoal records from Farewell and Wien Lakes [*Hu et al.*, 1993, 1996] are similar to that of Dune Lake, with more charcoal associated with black spruce pollen. Although these records are difficult to compare to the charcoal record from Dune Lake, they support the proposition that the fuel change associated with an increase in black spruce controlled the fire regime at a larger scale than just around Dune Lake.

[49] This shift in fire occurrence after 2400 yr BP marked the onset of the modern fire regime in interior Alaska. The probability of fire occurrence still increased with time since last burn, indicating continued importance of fuel accumulation or stand age structure to the fire regime. This shift could have been due to a vegetation shift or cooler and moister conditions in the late Holocene as suggested by climate studies in Alaska from pollen [*Anderson et al.*, 1994], ice wedge formation, and alpine glaciers, [*Hamilton et al.*, 1984; *Wiles et al.*, 1999]. The decrease in birch pollen around 2400 yr BP could not explain the fire regime change, because, even after birch pollen again increased at 1800 yr BP, fire occurrence and charcoal accumulation remained low (Figure 10). A direct change in climate to colder summer temperatures likely reduced ignitions because stable arctic air with little lightning extended longer into the summer when storms with lightning were more frequent. Cold conditions likely also reduced fuel accumulation by shortening the growing season and decreasing fire spread by increasing fuel moisture through reduced evaporation.

6. Conclusion

[50] During the last 1000 years and before European settlement, overall charcoal accumulation was low in lakes from both interior Alaska and the Kenai Peninsula with slightly greater importance of fire in the former. The different climate regimes between the interior of Alaska (i.e., cold/dry) and the Kenai Peninsula (i.e., cool/wet) seem to have had minimal affects on the fire regimes, since only slight differences in charcoal accumulation occurred. The fire regime inferred for the Kenai Peninsula was characterized by small fires (<20,000 hectares in size) and rare large fire before European settlement. After European settlement, sites on the Kenai Peninsula recorded an increase in fire importance linked to greater fire ignition by people.

[51] The first high-resolution charcoal record from Dune Lake provides insight into understanding the fire dynamics during the transition from the birch/white spruce community to the present-day boreal forest and suggests that fuel mediates fire. Our results show that in the early-Holocene birch-white spruce and later alder forests in interior Alaska fires were rare. As black spruce expanded in interior Alaska, fires became much more frequent. In the absence of a coincidental change in climate that favored increased fire occurrence at this time, these data indicate that a shift in vegetation (fuel) may have caused the change in the fire regime, perhaps promoted by the low flammability of birch and the higher flammability of black spruce. A subsequent shift to fewer large fires was likely promoted by cool, moist conditions during the late Holocene. Community and ecosystem processes, such as fuel accumulation and stand structure were also found to be important in influencing boreal fire regimes. Additional studies are needed to determine regional spatial and temporal patterns at broad geographic scales.

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References

Abbott, M. B., B. P. Finney, M. E. Edwards, and K. R. Kelts, Lake-level reconstructions and paleohydrology of Birch Lake, central Alaska, based on seismic reflection profiles and core transects, *Quat. Res.*, *53*, 154–166, 2000.

Ager, T. A., Late Quaternary environmental history of Tanana Valley, Alaska, 54 pp., Ohio State Univ., Columbus, 1971.

Alaska Fire Service, *Historical Fire Perimeters*, 2nd ed., Ft. Wainwright, Alaska, 1999.

Alm, J., L. Schulman, J. Walden, H. Nykannen, P. J. Martikainen, and J. Silvola, Carbon balance of a boreal bog during a year with an exceptionally dry summer, *Ecology*, *80*, 161–174, 1999.

Amiro, B. D., J. B. Todd, B. M. Wotton, K. A. Logan, M. D. Flannigan, B. J. Stocks, J. A. Mason, D. L. Martell, and K. G. Hirsch, Direct carbon emissions from Canadian forest fires, 1959–1999, *Can. J. For. Res.*, *31*, 512–525, 2001.

Anderson, P. M., P. J. Bartlein, and L. B. Brubaker, Late Quaternary history of tundra vegetation in Northwestern Alaska, *Quat. Res. (Orlando)*, *41*, 306–315, 1994.

Barber, V. A., and B. P. Finney, Late Quaternary paleoclimatic reconstructions for interior Alaska based on paleolake-level data and hydrologic models, *J. Paleolimnology*, *24*, 29–41, 2000.

Bigelow, N. H., Late-Quaternary Vegetation and Climate in Central Alaska, Ph.D Dissertation, Univ. of Alaska, Fairbanks, 1997.

Binford, M. W., Calculation and uncertainty of ^{210}Pb dates for PIRLA project lake sediment cores, *J. Paleolimnology*, *3*, 252–267, 1990.

Brown, A. A., and K. P. Davis, *Forest Fire: Control and Use*, 2nd ed., pp. 28–44, McGraw-Hill, New York, 1973.

Brubaker, L. B., L. J. Graumlich, and P. M. Anderson, An evaluation of statistical techniques for discriminating *Picea glauca* from *Picea mariana* pollen in northern Alaska, *Can. J. Botany*, *65*, 899–906, 1987.

Carcaillet, C., P. J. H. Richard, B. Frechette, Y. S. Bergeron, S. Gauthier, and Y. T. Prairie, Fire intervals changed c.2000 years ago in the eastern Canadian boreal forest. Does vegetation or climate trigger the fire regime?, *J. Ecol.*, *89*, 930–946, 2001.

Chapman, W. L., and J. E. Walsh, Recent variations of sea ice and air temperature in high latitudes, *Bull. Am. Meteorol. Soc.*, *74*, 33–47, 1993.

Clark, J. S., Charcoal-stratigraphic analysis on petrographic thin sections: Recent fire history in Northwest Minnesota, *Quat. Res.*, *30*, 67–80, 1988.

Clark, J. S., Ecological disturbance as a renewal process: Theory and application to fire history, *Oikos*, *56*, 17–30, 1989.

Clark, J. S., Fire and climate change during the last 750 yr in northwestern Minnesota, *Ecol. Monogr.*, *60*, 135–159, 1990.

Clark, J. S., and T. C. Hussey, Estimating the mass flux of charcoal from sediment records: The effect of particle size, morphology, and orientation., *The Holocene*, *6*, 129–144, 1996.

Clark, J. S., and P. D. Royall, Particle-size evidence for source areas of charcoal accumulation in late Holocene sediments of Eastern North American Lakes, *Quat. Res.*, *43*, 80–89, 1995.

Clark, J. S., and P. D. Royall, Local and regional sediment charcoal evidence for fire regimes in presettlement Northeastern North America, *J. Ecol.*, *84*, 365–382, 1996.

Clark, J. S., T. C. Hussey, and P. D. Royall, Presettlement analogs for Quaternary fire regimes in Eastern North America, *J. Paleolimnology*, *16*, 79–96, 1996a.

Clark, J. S., J. A. Lynch, B. J. Stocks, and J. G. Goldammer, Relationships between charcoal particles in air and sediments in west-central Siberia, *The Holocene*, *8*, 19–29, 1996b.

Clark, J. S., P. D. Royall, and C. Chumbley, The role of fire during climate changes in an eastern deciduous forest at Devil's Bathtub, New York, *Ecology*, *77*, 2148–2166, 1996c.

Clark, J. S., B. J. Stocks, and P. J. H. Richard, Climate implications of biomass burning since the 19th Century in Eastern North America, *Global Change*, *2*, 433–442, 1996d.

Cole, D., *A Gold Rush Town That Beat the Odds*, Epicenter Press, Fairbanks, Alaska, 1999.

De Volder, A., Fire and climate history of lowland black spruce forests, Kenai National Wildlife Refuge, Alaska, Univ. of Northern Ariz., Flagstaff, Ariz., 1999.

Dean, W. E. J., Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods, *J. Sedimentary Petrol.*, *44*, 242–248, 1974.

Dyrness, C. T., L. A. Viereck, and K. van Cleve, Fire in taiga communities of interior Alaska, in *Forest Ecosystems in the Alaskan Taiga: A Synthesis of Structure and Function*, edited by K. van Cleve, F. S. Chapine III, and P. W. Flanagan, pp. 74–86, Springer, New York, 1986.

Eakins, J. D., and R. T. Morrison, A new procedure for the determination of ^{210}Pb in lake and marine sediments, *Int. J. Appl. Radiation Isotopes*, *29*, 531–536, 1978.

Earle, C. J., L. B. Brubaker, and P. M. Anderson, Charcoal in north central Alaskan lake sediments: Relationships to fire and Late Quaternary vegetation change, *Rev. Palaeobotaby Palynology*, *92*, 83–95, 1996.

Edwards, M. E., and E. D. Barker, Climate and vegetation in northern Alaska 18,000 yr-present, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *109*, 127–135, 1994.

Edwards, M. E., J. C. Dawe, and W. S. Armbruster, Pollen size of Betula in northern Alaska and the interpretation of late Quaternary pollen records, *Can. J. Botany*, *66*, 1666–1672, 1991.

Edwards, M. E., C. J. Mock, B. P. Finney, V. A. Barber, and P. J. Bartlein, Potential analogues for paleoclimatic variations in eastern interior Alaska during the past 14,000 yr: Atmospheric-circulation controls of regional temperature and moisture responses, *Quat. Sci. Rev.*, *20*, 189–202, 2001.

Faegri, K., and J. Iversen, *Textbook of Pollen Analysis*, pp. 72–89, Hafner, New York, 1975.

Finney, B., M. Edwards, M. Abbott, V. Barber, L. Anderson, and M. Rohr, Holocene precipitation variability in interior Alaska, paper presented at the 30th Arctic Workshop, Inst. of Arctic and Alpine Res. (INSTAAR), Boulder, Colo., 2000.

Flannigan, M. D., and J. B. Harrington, A study of the relation of meteorological variables to monthly provincial area burned by wildfires in Canada (1953–80), *J. Appl. Meteorol.*, *27*, 441–452, 1988.

Fosberg, M. A., B. J. Stocks, and T. J. Lynham, Risk analysis in strategic planning: Fire and climate change in boreal forest, in *Fire in Ecosystems of Boreal Eurasia*, edited by J. G. Goldammer and V. V. Furyacv, pp. 495–504, Kluwer Acad., Norwell, Mass., 1996.

Gabreil, H. E., and G. F. Tande, A Regional Approach of Fire History in Alaska, BLM-Alaska, Anchorage, 1983.

Gibson, J. R., *Imperial Russia In Frontier America*, 257 pp., Oxford Univ. Press, New York, 1976.

Goldammer, J. G., and V. V. Furyacv, Fire in ecosystems of boreal Eurasia: Ecological Impacts and links to the global system, in *Fire in Ecosystems of Boreal Eurasia*, edited by J. G. Goldammer and V. V. Furyacv, pp. 1, Kluwer Acad., Norwell, Mass., 1996.

Hallett, D. J., and R. C. Walker, Paleoecology and its application to fire and vegetation management in Kootenay National Park, British Columbia, *J. Paleolimnology*, *24*, 401–414, 2000.

Hamilton, T. D., T. A. Ager, and S. W. Robinson, Late Holocene ice wedges near Fairbanks, Alaska, USA, *Arctic Alpine Res.*, *15*, 157–168, 1984.

Hansen, B. C. S., and D. R. Engstrom, A comparison of numerical and qualitative methods of separating pollen of black and white spruce, *Can. J. Botany*, *63*, 2159–2163, 1985.

Hely, C., P. W. Flanagan, Y. Bergeron, and D. McRae, Role of vegetation and weather on fire behavior in the Canadian mixedwood boreal forest using two behavior prediction systems, *Can. J. Forest Res.*, *31*, 430–441, 2001.

Hopkins, D. M., P. A. Smith, and J. V. J. Matthews, Dated wood from Alaska and the Yukon: Implications for forest refugia in Beringia, *Quat. Res.*, *15*, 217–249, 1981.

Hu, F. S., L. B. Brubaker, and P. M. Anderson, A 12,000 year records of vegetation and soil development from Wien Lake, central Alaska, *Can. J. Botany*, *71*, 1133–1142, 1993.

Hu, F. S., L. B. Brubaker, and P. M. Anderson, Boreal ecosystem development in the northwestern Alaska range since 11,000 yr BP, *Quat. Res.*, *45*, 188–201, 1996.

Hu, F. S., E. Ito, L. B. Brubaker, and P. M. Anderson, Ostracode geochemical records of Holocene climate change and implications for vegetation response in the northwestern Alaska range, *Quat. Res.*, *49*, 89–95, 1998.

Larsen, C. P. S., Fire and climate dynamics in the boreal forests of northern Alberta, Canada, from AD 1850 to 1989, *The Holocene*, *6*, 449–456, 1996.

Larsen, C. P. S., and G. M. MacDonald, Relations between tree-ring widths, climate, and annual area burned in boreal forest of Alberta, *Can. J. For. Res.*, *25*, 1746–1755, 1995.

Long, C. J., C. Whitlock, P. J. Bartlein, and S. H. Millspaugh, A 9000-year fire history from the Oregon coast range, based on a high-resolution charcoal study, *Can. J. For. Res.*, *28*, 774–787, 1998.

Lynch, J. A., Fire history of boreal forests: Implications for past climate change, Ph.D thesis, Duke Univ., Durham, N.C., 2001.

Mann, D. H., C. L. Fastie, E. L. Rowland, and N. H. Bigelow, Spruce succession, disturbance, and geomorphology on the Tanana River floodplain, Alaska, *Ecoscience*, *2*, 184–199, 1995.

Millspaugh, S. H., and C. Whitlock, A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA, *Holocene*, *5*, 283–292, 1995.

Nash, C. H., and E. A. Johnson, Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests, *Can. J. For. Res.*, *26*, 1859–1874, 1996.

Naske, C. M., and H. Soltnick, *Alaska: A History of the 49th State*, 349 pp., Univ. of Oklahoma Press, Norman, 1987.

Niklasson, M., and A. Granstrom, Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape, *Ecology*, *81*, 1484–1499, 2000.

Ohlson, M., and E. Tryterud, Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal, *The Holocene*, *10*, 519–525, 2000.

Overpeck, J. T., et al., Arctic environmental change of the last four centuries, *Science*, *278*, 1251–1256, 1997.

Reger, R. D., and D. S. Pinney, Last major glaciation of Kenai lowland, in *1997 Guide to Geology of the Kenai Peninsula, Alaska*, edited by S. M. Karl, N. R. Vaughn, and T. J. Ryherd, 4 pp., Alaska Geol. Soc., Anchorage, 1997.

Silverman, B. W., *Density Estimation for Statistics and Data Analysis*, Chapman and Hall, New York, 1986.

Sokal, R. R., and F. J. Rohlf, *Biometry*, pp. 440–445, W. H. Freeman, New York, 1981.

Stockmarr, J., Tablets with spores used in absolute pollen analysis, *Pollen Spores*, *13*, 615–621, 1972.

Stocks, B. J., M. A. Fosberg, M. B. Wotton, T. J. Lynham, and K. C. Ryan, Climate change and forest fire activity in North American boreal forests, in *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, edited by E. S. Kasischke and B. J. Stocks, pp. 368–376, Springer-Verlag, New York, 2000.

Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, G. S. Burr, K. A. Hughen, B. Kromer, F. G. McCormac, J. Plicht, and M. Spurk, Radiocarbon Calibration Program Rev. 4.2, *Radiocarbon*, *40*, 1041–1083, 1998.

Van Wager, C. E., Fire bebavior in northern conifer forests and shrublands, in *The Role of Fire in Northern Circumpolar Ecosystems*, edited by R. W. Wein and D. A. Maclean, *SCOPE,18*, 65–81, 1983.

Viereck, L. A., Wildfire in the Taiga of Alaska, *Quat. Res.*, *3*, 465–495, 1973.

Viereck, L. A., and L. A. Schandelmeier, Effects of fire in Alaska and adjacent Canada, pp. 46–60, U.S. Dep. of the Int. Bur. of Land Manage., Anchorage, Alaska, 1980.

Whitlock, C., and S. H. Millspaugh, Testing the assumptions of fire-history studies: An examination of modern charcoal accumulation in Yellowstone National Park, USA, *The Holocene*, *6*, 7–15, 1996.

Wiles, G. C., A. Post, E. H. Muller, and B. F. Molnia, Dendrochronology and Holocene history of Bering piedmont glacier, Alaska, *Quat. Res.*, *52*, 185–195, 1999.

Wright, H. E., Piston Cores for peat and lake sediment, *Ecology*, *65*, 657–659, 1984.

Yarie, J., Forest fire cycles and life tables: A case study from interior Alaska, *Can. J. For. Res.*, *11*, 554–562, 1981.

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