Holocene development of Boreal forests and fire regimes on the Kenai Lowlands of Alaska

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Abstract: Several studies have noted a relationship between vegetation type and fire frequency, yet despite the importance of ecosystem processes such as fire the long-term relationships between disturbance, climate and vegetation type are incompletely understood. We analysed pollen, plant macrofossils and sedimentary charcoal from three lakes within the Kenai lowlands to determine postglacial relationships between disturbance, climate and vegetation for the Boreal forest of southwest Alaska. An herb tundra was established in the lowlands following deglaciation by 13,000 cal. BP. Salix, Alnus and probably Betula kenaica expanded in the area after 10,700 cal. BP, followed by Picea glauca by 8,500 cal. BP. Picea mariana became established by 4,600 cal. BP. The early Holocene was probably the driest time during the postglacial, as determined by aquatic plant macrofossils and climate models. Lake levels reached near-modern conditions by at least 8,000 cal. BP. Mean Fire Intervals (MFI) were longest during the shrub/C1 herb tundra phase (138 ± 65 yr), decreased after expansion of B. kenaica, Salix and Populus (77 ± 49 yr) and Picea glauca (81 ± 41 yr), and increased again with the arrival of P. mariana (130 ± 66 yr). Unlike previous studies, our data demonstrate the highest fire frequencies during the early to mid-Holocene and less frequent fire during the late Holocene when P. mariana forests dominated the lowlands. Early Holocene forests of P. glauca and B. kenaica existed in summers that were longer and drier than today, while the increasingly wetter and cooler climates of the late Holocene probably hindered forest fire around Paradox Lake, perhaps because of less frequent summer drought.

Key words: Boreal forest, charcoal analysis, climate change, fire history, vegetation history, Holocene, Alaska.

Introduction

Our understanding of vegetation development in Alaska has advanced rapidly during the last two decades (Anderson et al., 2004). Much debate has centred on determining the spatial and temporal history of modern boreal forest development and its relationship to Holocene climatic changes. Lateglacial and early Holocene forests were often dominated by Populus, then Alnus and Salix, either as woodlands or in riparian galleries (Ager, 1983; Brubaker et al., 1983; Hu et al., 1993; Anderson et al., 1994; Mann et al., 2002). The modern Boreal forest developed time transgressively, however. Picea glauca was probably the first Boreal conifer to spread from east to west across central Alaska, most likely between c. 9000 and 8000 cal. BP (Anderson and Brubaker, 1993, 1994; Brubaker et al., 2001), followed by Picea mariana at least 2000 years later (Anderson et al., 2004). However, our understanding of the role of ecosystem disturbance in vegetation development has lagged far behind.

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Even though climatic influences on wildfire behaviour in the Boreal forest have been well-documented (e.g., Johnson, 1992; Flannigan et al., 2003), the influences on fire occurrence and extent in Alaska are complex (Kasischke et al., 2002). Perhaps because of this the limited data on palaeo-fire occurrence in Alaska are contradictory. Some authors have suggested that higher fire event frequencies occurred in the early Holocene (Earle et al., 1996) when models suggest climate was warmer and drier than today (Kaufman et al., 2004a), while others have documented higher frequencies for the late Holocene (Hu et al., 1993, 1996; Lynch et al., 2003, 2004) when climate became wetter and cooler.

Discrepancies in fire histories may be related to climatic factors. Carcaillet et al. (2001) showed the importance of climate in determining fire, since changes in species with more combustible foliage did not accompany significant changes in fire occurrence during the Holocene. Alternatively, differences may be moderated by the timing of species immigration or by soil development or edaphic conditions. Differences in fire history corresponded with a change from conifer- (Picea–Pinus; greater fire occurrence) to hardwood-dominated (lesser fire occurrence) forests in an early Holocene sequence from northern New York (Clark et al., 1996). This suggests the relative importance of forest type over climate conditions for determining fire event frequencies.

In the present study we used high-resolution sedimentary charcoal, pollen and plant macrofossils from three sites in the lowlands of the Kenai Peninsula to answer the following questions: what was the timing of development of the Picea (boreal spruce) – Betula (birch) forest over the last c. 13 000 years in this maritime location? What is the history of fire disturbance, and how does it compare with other sites in Boreal forest in Alaska? What is the relative importance of climatic versus species composition factors in determining fire history? What can the fossil assemblages tell us about the climate history of the region? This study also contributes to our understanding of the characteristics of climate change in the subarctic, projected to be among the regions most vulnerable to global warming (Serrzeze et al., 2000; Moritz et al., 2002).

**Location of sites**

The Kenai Peninsula includes the Kenai Mountains in the east and the Kenai lowlands in the west (Figure 1). The central core of the Kenai Mountains (over 1 900 m elevation) is dominated by the Harding Ice Field. Elevations of the lowlands rarely exceed 550 m and are mostly below 300 m (De Volder, 1999). Repeated glacial advances from the Kenai Mountains and the Aleutian Range to the west across Cook Inlet formed the lowland physiography during the late Pleistocene (Reger and Pinney, 1997).

Today, climate of the Kenai Peninsula is boreal maritime (De Volder, 1999), more continental in the central peninsula, and more oceanic along the coast. Annual precipitation at Kenai, Alaska (60° 34’ N, 151° 15’ W) is c. 484 mm (National Climate Data Center – United States Historical Climatology Network) (NCDC–USHCN, 1998). Mean July and January temperatures are 12.3°C and −10.9°C, respectively (Leslie, 1989).

Our longest record comes from Paradox Lake. c. 10 km north of Sterling in the Kenai lowlands (Figure 1). The lake occupies a glacially deepened trough that may have been a postglacial spillway. Maximum depth of the lake is c. 15.8 m (Figure 2), and the lake is meromictic. Sediment cores also come from Portage and Arrow Lakes, c. 16.6 and 19.5 km, respectively, from Paradox Lake (Figure 1). These cores come from < 3 m depth.

Typical vegetation of the lowlands and in the vicinity of all three lakes is *Picea glauca* and *Betula nana* on well-drained soils and slopes, and *P. mariana* on more poorly drained lowland flats. Additional upland trees and shrubs around Paradox Lake include *Populus tremuloides*, *Alnus crispa*, *Sambucus racemosa*, *Rosa acicularis*, *Viburnum edule*, *Linnacea borealis*, *Rubus* sp., *Echinopanax horridum*, *Ribes* sp. and * Ledum palustre*. Plants common in moist areas around the lake include *Salix* sp., *Myrica gale*, *Menziesia ferruginea*, *Spiraea Beauverdiana*, *Betula nana*, *Streptopus amplexifolius*, *Lycopodium sp.*, *Equisetum silvaticum* and *E. arvense*. Nomenclature follows Hultén (1968) and Flora of North American Editorial Committee (FNAEC, 1997).

**Methods**

At Paradox Lake we obtained a Livingstone core (885 cm long) and a short core (to 70 cm length) in June 1998. The two cores were matched based on a similar tephra layer in the upper c. 45 cm of each core. Short cores from Portage and Arrow Lakes were obtained in June 1995. Sediment stratigraphy (including tephra; de Fontaine, 2003) was determined by visual inspection and/or petrographic analysis. Magnetic susceptibility was determined by a Bartington MS2E meter at 5-mm intervals.

One cubic centimetre of sediment was processed for pollen (Faegri et al., 1989) including addition of *Lycopodium* tracers for pollen concentration calculation. Residues were stained, suspended in silicone oil, and examined at 400 ×, with comparison to the modern pollen reference collection at the Laboratory of Paleocology (LOP). Pollen of *Picea glauca* and *P. mariana* was differentiated as in Hansen and Engstrom (1985). Pollen data were clustered using CONISS (Grimm, 1987), and graphed using Tilia View.

Plant macrofossils were sieved from c. 100 cm³ of sediment at 10- to 20-cm intervals (Paradox) or from each successive centimetre of depth (Arrow and Portage). Needle fragments, seeds and other macrofossils were identified under a binocular microscope.

High resolution sedimentary charcoal analysis followed Millspaugh and Whitlock (1995), using 5 cm³ subsamples from each linear centimetre of the core length. We analysed charcoal accumulation rates (CHAR) as a time series and decomposed the record into background and peaks components using Charcoal Analysis Programs (CHAPS) (Long et al., 1998). The background component considers variations in overall charcoal production and sedimentation. The peaks component represents the charcoal input from a fire event within or near the watershed, where a fire event is defined as one or more fires occurring within the sampling interval.

The CHAR time series is created by dividing charcoal concentration values by deposition times (Long et al., 1998). When a CHAR value exceeds the background by a selected threshold ratio (e.g., 1.05, 1.1, 1.2) a charcoal peak (fire event) is recorded. We compared the fire interval statistics for three scenarios (many inferred fires using 300–1.05, moderate fires using 300–1.2, few fires using 500–1.2) from CHAPS to see how the fire intervals might vary. A 2000-yr smoothing function was used to plot the frequency of fire events per 1000 years (Long et al., 1998).

AMS and whole sediment radiocarbon ages were calibrated to calendar ages (Table 1) using CALIB version 4.4 (Stuiver
et al., 1998). 210Pb and 137Cs ages were measured by gamma spectrometry (R. Ku, personal communication, 2004).

Results and discussion

Stratigraphy and chronology

The Paradox Lake sediments are bedded throughout, have high organic content, and are generally alternating grey to black and brown and dark-brown gyttja and clayey-silt layers (Figure 3). Magnetic susceptibility is generally highest below c. 780 cm depth.

The Paradox Lake chronology is based upon a composite of the 210Pb profile for the upper portion, and the AMS 14C ages for the remainder of the core (Table 1). We excluded Beta-125980, believing this to be anomalously old, since Picea needles dated separately from the same interval were over 2000 years younger (Table 1). Chronology for the short core was based on measurements of 210Pb from the upper 25 cm, and identification of the 137Cs peak (AD 1963). Our identification of this peak in the core gives us the linear sedimentation rate averaged over the past ~ 40 years. For determining the average sedimentation rate over the past ~ 100 years, we used the slope of a semi-log plot of excess 210Pb versus depth in the core. The resulting sediment accumulation rate of $2.5 \pm 0.5$ mm/yr determined in the upper 10 cm was applied down to 37 cm depth, and verified by comparison with the known fire history of the area (see below).

The sediment accumulation curve (Figure 4) consists of the linear interpretation of sediment accumulation above 37 cm matched to a sixth-order polynomial (using the median probability values (Telford et al., 2004) of the 11 calibrated age dates) below 37 cm. We chose a sixth-order polynomial because other polynomials poorly approximated ages between 550 and 800 cm depth.

The upper c. 34 cm of Portage Lake sediments consist of gyttja with interspersed sands, while below this to 59 cm is mostly pure gyttja (Figure 5). The record is c. 9400 cal. yr long (Table 1). The Arrow Lake sediments are primarily gyttja, but...
include sandy layers and layers with coarse organic fragments (Figure 5). This record is c. 9500 cal. yr BP long (Table 1). Paradox Lake

Zone 1 (prior to c. 10700 cal. BP) pollen spectra are dominated by *Betula* (to 69%), while Poaceae (to 13%), Cyperaceae (to 11%), and *Artemisia* (to 6%) are at their postglacial maxima (Figure 6a). We consider it likely that most *Betula* are shrub birch, such as *B. nana* or *B. glandulosa*, rather than tree birch, *B. kenaica* (see Clegg et al., 2005). *Salix* (to 12%) pollen occurs throughout the zone, while *Populus* (to 3.5%) is found in the middle. We interpret the local environment as shrub tundra.

In Zone 2 (c. 10700 to 8500 cal. BP) herbaceous and sub-shrub species (*ie*, *Betula*, *Eriaceae*, *Cyperaceae*, *Poaceae* (Figure 6a) decline. *Salix* (to 24%) increases, followed by *Populus* (to 26%), then *Alnus* (to 37%). By the zone's end, *Betula* increases again. These changes are consistent with successive immigrations of large shrubs and common deciduous trees into the Paradox Lake area. *Botryococcus* and *Chara* increase (Figure 6b), along with *Najas* and *Nuphar* (Figure 7a), indicating lowered lake levels during the early Holocene.

By Zone 3 time (c. 8500 to 4600 cal. BP) *Betula* and *Picea* pollen percentages are consistent with *Picea glauca* – *Betula* woodland (Anderson and Brubaker, 1986) on the uplands around the lake. *Sphagnum* spores (Figure 6b) increase, and suggest establishment of boggy conditions on the lake perimeter.

Zone 4 (c. 4600 cal. BP to present) pollen and spore assemblages suggest that the *Picea glauca* – *Betula kenaica* forests persisted in uplands around the lake throughout the remainder of the Holocene. However, by c. 4600 cal. BP *Picea mariana* pollen percentages increase, suggesting the establishment of *P. mariana* in lowlands around the lake. This coincides with a second increase in the *Sphagnum* spores. While the former may be related to a late migration to the region, the latter suggests further development of boggy conditions locally.

### Table 1 Radiocarbon dates and calendar age ranges for Paradox, Portage and Arrow Lakes, Alaska

<table>
<thead>
<tr>
<th>Lake</th>
<th>Lab no.</th>
<th>Depth (cm)</th>
<th>$^{14}C/^{12}C$</th>
<th>$^{14}C$ yr BP</th>
<th>Max and min of 2 sigma cal. age range</th>
<th>Median probability used in Age Model</th>
<th>Date type</th>
<th>Materials dated</th>
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<tr>
<td></td>
<td>AA-45099</td>
<td>97.5</td>
<td>–28.0</td>
<td>1225 ±45</td>
<td>1012–1265</td>
<td>1147</td>
<td>AMS</td>
<td>Wood, charcoal, <em>Betula</em> fruit, <em>Picea</em> needles</td>
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<td></td>
<td>AA-45101</td>
<td>193.0</td>
<td>–28.4</td>
<td>2969 ±51</td>
<td>2969–3321</td>
<td>3140</td>
<td>AMS</td>
<td>Wood</td>
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<td></td>
<td>AA-45102</td>
<td>289.0</td>
<td>–26.2</td>
<td>4054 ±43</td>
<td>4418–4806</td>
<td>4529</td>
<td>AMS</td>
<td><em>Picea</em> needles, wood, <em>Betula</em> fruit</td>
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<td>AA-45103</td>
<td>311.0</td>
<td>–25.8</td>
<td>4565 ±45</td>
<td>5047–5447</td>
<td>5183</td>
<td>AMS</td>
<td>Charcoal, wood, <em>Betula</em> fruit</td>
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<td>AA-38445</td>
<td>344.5</td>
<td>–27.8</td>
<td>4917 ±88</td>
<td>5471–5893</td>
<td>5663</td>
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<td><em>Picea</em> needles</td>
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<td>–27.4</td>
<td>5598 ±76</td>
<td>6204–6616</td>
<td>6381</td>
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<td><em>Picea</em> needles</td>
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<tr>
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<td>AA-38447</td>
<td>552.5</td>
<td>–28.5</td>
<td>7100 ±59</td>
<td>7761–8104</td>
<td>7901</td>
<td>AMS</td>
<td><em>Picea</em> needles</td>
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<td></td>
<td>AA-45104</td>
<td>799.0</td>
<td>–30.4</td>
<td>9974 ±65</td>
<td>11203–11907</td>
<td>11416</td>
<td>AMS</td>
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<td>Beta-177159</td>
<td>873.0</td>
<td>–28.8</td>
<td>10970 ±70</td>
<td>12664–13160</td>
<td>12994</td>
<td>AMS</td>
<td>Wood</td>
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<td>Beta-125980</td>
<td>864.0–874.0</td>
<td>–30.3</td>
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<td>15016–16465</td>
<td>15892</td>
<td>AMS</td>
<td>Bulk sediment</td>
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<td>–27.7</td>
<td>2227 ±37</td>
<td>2149–2335</td>
<td>2253</td>
<td>AMS</td>
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<tr>
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<td>–28.0</td>
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<td>4203</td>
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<td>AMS</td>
<td><em>Nuphar</em> seeds</td>
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<td>8355 ±55</td>
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<td>9372</td>
<td>AMS</td>
<td><em>Nuphar</em> seeds</td>
</tr>
<tr>
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<td>–25.0</td>
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<td>9707–11061</td>
<td>10343</td>
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<td>Bulk sediment</td>
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<tr>
<td>Arrow</td>
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<td>15.0–16.0</td>
<td>–28.3</td>
<td>4675 ±48</td>
<td>5308–5578</td>
<td>5406</td>
<td>AMS</td>
<td><em>Picea</em> needles</td>
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<tr>
<td></td>
<td>AA 58543</td>
<td>28.0–29.0</td>
<td>–26.8</td>
<td>8050 ±48</td>
<td>8719–9232</td>
<td>8937</td>
<td>AMS</td>
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<td>45.0–50.0</td>
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<td>9433–9551</td>
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<td>AMS</td>
<td><em>Nuphar</em> seeds</td>
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*Median probability values from CALIB 4.4 were chosen for construction of the age–depth curve using Stuiver et al. (1998).

*Excluded from age model.*
fruits and *Picea* needle fragments are found at Portage and Arrow Lakes, respectively. We interpret the earliest portion of the record as recording lowered lake levels prior to and into the establishment of the *Picea glauca* – *Betula kenaiaca* forests there.

Vegetation and climate history of the Kenai Peninsula

Few well-dated pollen sites such as Paradox Lake have been analysed from the Kenai Peninsula. A herbaceous tundra was present until c. 16,000 cal. BP at Hidden Lake, persisting to c. 14,750 cal. BP at Circle Lake and Point Woronzof (Rymer and Sims, 1982; Ager, 1983, 2000). Subsequently, a shrub *Betula*–herb tundra existed at the northern sites (Point Woronzof and Hidden Lake) to c. 11,250 cal. BP, and in the Kachemak Bay area to c. 10,600 cal. BP (Ager, 2000). After immigration of *Populus* and *Salix* at the more northerly sites, *Alnus* arrived throughout the Peninsula by c. 10,600 cal. BP, mixing with *Betula* and ericaceous shrubs or grass at the Kachemak Bay sites (Ager, 2000), or *Salix* and other shrubs at the Kenai Mountain and upper Cook Inlet sites (Ager, 2000, 2001).

Boreal *Picea* – probably *P. glauca* – immigrated into the northern Kenai Peninsula perhaps as early as c. 8,750 cal. BP at Point Woronzof and Hidden Lake (Ager, 2000). *Picea* (again, probably *P. glauca*) and *Betula* invaded the Tern Lake area from the Kenai Lowlands to the west by c. 6,300 cal. BP. Immigration of *Picea* was delayed at the Kachemak Bay sites until c. 4,000 cal. BP.

The vegetation histories recorded at Paradox, Arrow and Portage Lakes are transitional between those previously inferred from northern and southern sites. At Paradox Lake, a shrub *Betula*–herb tundra gave way to *Populus* and *Salix* by 10,600 cal. BP. Successive immigrations occurred in the early Holocene, first by *Alnus* (c. 9,600 cal. BP) then *Betula* (cf. *kenaiaca*; c. 8,500 cal. BP). *P. glauca* also arrived by c. 8,500 cal. BP, creating a mixed boreal *Picea*–hardwood forest. By c. 4,500
cal. BP, however, *P. mariana* became established around Paradox Lake, and remained important in the lowland flora up to the present.

The spread of Boreal forest into the Kenai Peninsula and surrounding areas was fostered by climates that were warmer and drier than present (Heusser et al., 1985). Models suggest maximum Northern Hemisphere summer solar insolation occurred c. 12,000 to 10,000 years ago (Kutzbach et al., 1998), with empirical data suggesting the Holocene thermal maximum occurred c. 11,000 to 9000 cal. BP (Kaufman et al., 2004a). Lowered lake levels also suggest drier early Holocene climates in Interior Alaska (Abbott et al., 2000; Barber and Finney, 2000; Edwards et al., 2000, 2001). Remains of wetland and rooted aquatic plants dominate the macrofossil assemblage until c. 8000 years ago in our shallow-water Arrow and Portage Lake cores, suggesting lower lake levels here as well.

By the late Holocene, expansion of *Picea mariana* in the lowlands was contemporaneous with cooler and wetter climate (Heusser et al., 1985; Ager, 2000), as summer insolation decreased (Berger and Loutre, 1991) and Neoglacial advances occurred (Kaufman et al., 2004b). Locally, increasing soil moisture is indicated by expansion of *Sphagnum* on the valley floor around Paradox Lake.

**Fire history record**

*Previous fire history research on the Kenai Peninsula*

De Volder (1999) used a combination of stand-age mapping, fire-scars on living trees and ageing of burn poles to reconstruct fire history since AD 1708 in lowland black spruce forests. The AD 1947 Sterling fire burned the watersheds of Portage and Arrow Lakes but not Paradox Lake. An AD 1849 fire occurred at Paradox and Portage Lakes, while an AD 1888 fire burned at both Arrow and Portage Lakes. The AD 1969 Kenai fire (c. 32,000 ha) burned to within several kilometres of Paradox Lake (Alaska Fire Service, 1999). Fire return intervals in black spruce forests of the Lowlands have ranged from 25 to 185 years, with a mean of 89 ± 43 years (De Volder 1999).

Berg and Anderson (2006) analyzed the ages of charcoal layers from soil pits and throw mounds throughout the western Kenai lowlands. Clusters of the 17 charcoal radiocarbon dates suggest fires burned around Paradox Lake c. AD 1835, 1640, 1455, 1265, 670 and 120. The most recent charcoal age of AD 1835 probably represents the most recent fire in AD 1849. Calculated fire return interval for the whole lowland data set approximates 325 years for the entire series, but only 190 years since the thirteenth-century fire. Lynch et al.’s (2004) Rock Lake record, also in the Lowlands, is very similar to the Paradox Lake soil charcoal data, giving a pre-twentieth century fire return interval of 194 years.

**Calibration of the sedimentary record**

For the upper sediments, maximum values for CHAR peaks occur at 3 cm (AD 1878), 7 cm (AD 1969), 10 cm (AD 1958), 18 cm (AD 1926), and 35 cm (AD 1858) (Figure 8). The peak at 7 cm may be associated with the 32,000-ha ad 1969 fire that burned to within 2.4 km of Paradox Lake (De Volder, 1999). We did not use this peak to calibrate our reconstruction scenarios because the fire was too far from the lake site. The peak at 10 cm may be the AD 1947 fire, while the 35-cm peak undoubtedly corresponds to the AD 1849 fire that burned around the lake and represents the best calibration peak for reconstructing fire event frequency. The later two ages suggest that our chronology may be in error by several years. We know of no fire that burned around the lake corresponding to the 3 and 18 cm depth peaks. Our ability to match most of the peaks in the short core with known fire events within the watershed provides confidence in our interpretation of the longer record. Even so, some charcoal peaks may be derived from fires that burned close to, but not directly around, the lake (Whitlock and Millsbaugh, 1996). To decrease the potential for identifying charcoal peaks in our record created by distant (non-local) fires, we used soil charcoal evidence from the AD 1849 fire, and other fires listed above, to select appropriate threshold ratios for our analysis. Our goal was to identify parameters that verify CHAR peaks derived mainly from local watershed fire episodes at the top of the core where fire evidence overlaps. Parameters used for the fire frequency reconstruction verified all local fires and minimized the identification of non-local peaks in the top 2000 years of CHAR (Gavin et al., 2003; Hallett et al. 2003).
Calculation of mean fire intervals and fire event frequencies

The three CHAPS scenarios resulted in similar fire interval estimates for each pollen zone (Table 2). We selected the middle scenario because it conveyed the common trends in the Holocene fire interval data and corresponded well with known fire evidence in the watershed. In all the CHAPS scenarios, MFI (mean fire interval) was longest for Zone 1, a period of tundra. Mean values ranged from 124 to 172 yr between fire events. MFI for Zone 4 (mixed Boreal Picea zone) was also long, varying from 122 to 134 yr. MFIs for Zone 2 (mixed shrub and hardwoods), and Zone 3 (Picea glauca–Betula forest), were nearly identical, 77–82 and 77–85 yr, respectively (Table 2). The similarity between fire interval statistics based on three CHAPS scenarios suggests that the CHAPS estimates of Paradox Lake fire intervals are robust.

We used the Kolomogorov-Smirnov two-sample test to test whether fire interval distributions differed between pollen zones (Table 3). Zones 1 and 4 were significantly different from Zones 2 and 3. Zones 1 and 4 were not significantly different from each other, even though they occurred during the late Pleistocene and late Holocene when climates and vegetation types were very different. Fire intervals in Zones 2 and 3 from the early and mid-Holocene were also not significantly different (Table 3).

Based on our comparison of fire peaks in the sediment record with known fires on the Peninsula we believe that the sedimentary charcoal method somewhat overestimates local fires because it represents a complex spatial aggregation of fire events around the site, and thus provides a maximum fire event frequency. On the other hand, processes that limit preservation of charcoal in soil profiles tend to cause an underestimation.
Figure 7 (a) Plant macrofossils from Paradox Lake core. (b) Plant macrofossils from Portage Lake short core. (c) Plant macrofossils from Arrow Lake short core.
of local fires (Gavin, 2001, 2003; Lertzman et al., 2002; Gavin et al., 2003; Hallett et al., 2003), thus providing minimum local fire event frequencies.

**Fire history**

The high-resolution charcoal data allowed for complete identification of most fires considering the century-scale fire intervals that characterize the current forest type around Paradox Lake (Yarie, 1981; Larsen, 1997). A fire event frequency (FEF) of six to ten fires/1000 yr characterizes Zone 1 (Figure 9), when pollen evidence suggests that herb tundra vegetation surrounded the lake. Tundra fires are mostly rare events (Wein, 1976; Payette et al., 1989). Low FEF during the early postglacial may have been due to sparse vegetation leading to relatively light fuels necessary to carry fire and deposit charcoal in the lake.

When large shrubs and trees were established around Paradox Lake during Zone 2, FEF increased substantially. Higher FEF (10–13 fires/1000 yr; maximum of 14 fires/1000 yr) occurs with the expansion of *Betula* at the end of the zone. Palaeoclimate reconstructions (Kutzbach et al., 1998; Edwards et al., 2001) suggest that this was the warmest and driest period of the Holocene.

With the expansion of *Picea glauca* and *Betula* around 8500 cal. BP, FEF reaches the highest values of the record (11–14 fires/1000 yr) and remains high until c. 4600 cal. BP. We believe that relatively high FEF resulted from a combination of increased flammable coniferous biomass in the uplands and continuation of relatively warm summers as shown from modelled data.

Coincident with the arrival of *Picea mariana*, FEF drops to 5–8 fires/1000 yr. Today *P. mariana* grows in a relatively narrow zone in boggy areas around the lake. Development of a peripheral wetland may have reduced the overall flammability around the lake during the last 4600 years, even while the uplands remained dominated by *P. glauca* and *Betula*. Alternatively, the expanded wetland may have hampered the movement of charcoal via traction from uplands to the lake.

The Paradox Lake record shows some similarities with other Alaskan studies, but also considerable differences. These differences may be a function of several factors, including the effect of vegetation type or climate change on frequencies and

![Figure 8](image-url) Charcoal accumulation rates from the Paradox Lake short core with a chronology in cal. yr BP and years AD from $^{210}$Pb data. Local fires of known ages (i.e., 1849 fire) are located with respect to the inferred $^{210}$Pb chronology. Charcoal peaks without a documented local fire (i.e., 1926?) are also shown.

<table>
<thead>
<tr>
<th>Age interval (yr BP)</th>
<th>Pollen Zone</th>
<th>Mean ± s.d. for CHAPS parameters (window width-threshold ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>300–1.05</strong></td>
</tr>
<tr>
<td>$-48$–$4600$</td>
<td>4</td>
<td>122 ± 56</td>
</tr>
<tr>
<td>4600–$8500$</td>
<td>3</td>
<td>77 ± 44</td>
</tr>
<tr>
<td>8500–$10700$</td>
<td>2</td>
<td>79 ± 43</td>
</tr>
<tr>
<td>10700–$13500$</td>
<td>1</td>
<td>124 ± 55</td>
</tr>
<tr>
<td>All fires $-48$–$13500$</td>
<td>1</td>
<td>97 ± 54</td>
</tr>
</tbody>
</table>

Table 2: Comparison of fire interval data for three scenarios of parameters used in CHAPS
patterns of burning, potential differences in charcoal delivery to the lake, or different methodologies in each study. For instance, Lynch et al. (2003) suggested that vegetation history was important in determining fire history. At Dune Lake, early Holocene *Picea glauca*–*Betula papyrifera* forests burned less frequently than late Holocene *P. mariana* forests. Further, calculated fire event frequencies were high in late Holocene forests around Moose and Chokasna Lakes, also dominated by *P. mariana* forests (Lynch et al., 2004). High fire frequencies under wetter climates suggested that stand type, species composition or fuel accumulation were more important than climate in determining fire occurrence there.

Our data suggest that climatic factors may have been of greater importance at Paradox Lake. Palaeoclimate simulations using a GCM suggest a weaker Aleutian Low in winter and a strengthened Subtropical High in summer during the early Holocene (Bartlein et al., 1998), leading to more ‘continental’ conditions then (increased lightning strikes; Reap, 1991). Conversely, a stronger Aleutian Low and weaker Subtropical High in the later Holocene would have led to wetter conditions with fewer convective storms and lightning ignitions. Thus, when climatic conditions were warmer and driest during the early Holocene, fire event frequencies are also highest. When climatic conditions were cooler and wetter during the late Holocene, fires were less frequent. While fuel loads may be different between *Populus*–*Salix* and *Picea glauca*–*Betula* associations (Johnson, 1992), FEF were statistically indistinguishable between these two vegetation types in the fossil record (Table 2), also favouring a climatic explanation.

Different methodologies may also contribute to contrasting fire histories. We used the Paradox Lake charcoal data set to compare our calculations of FEF using CHAPS (threshold ratios) with the methodology of Lynch et al. (2003, 2004), which examines the distribution of residual peaks (Clark and Royall, 1996; Clark et al., 1996). We calculated residuals from the charcoal data, using Lowess smoothing filters of 300 and 500 years to match the 300- and 500-yr window widths from CHAPS (Gavin et al., 2003). A sensitivity analysis of residual threshold values and MFI estimates suggests that $\frac{1}{21}$ or 22% of the residual CHAR values (D. Hallett, unpublished data, 2005) identify charcoal peaks as local fires using our known fires and soil charcoal ages. The residual method

### Table 3

Comparisons of (300–1.2) fire interval summary statistics from different time periods and by Kolomogorov–Smirnov 2-sample tests

<table>
<thead>
<tr>
<th>Age interval (yr BP)</th>
<th>Fire intervals</th>
<th>Kolomogorov–Smirnov 2-sample tests (yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>mean ± s.d. (Range yr)</td>
</tr>
<tr>
<td>– 48–4600</td>
<td>35</td>
<td>130 ± 66 (40–270)</td>
</tr>
<tr>
<td>4600–8500</td>
<td>49</td>
<td>81 ± 41 (30–190)</td>
</tr>
<tr>
<td>8500–10700</td>
<td>27</td>
<td>77 ± 49 (30–220)</td>
</tr>
<tr>
<td>10700–13500</td>
<td>20</td>
<td>138 ± 65 (50–290)</td>
</tr>
<tr>
<td>all – 48–13500</td>
<td>131</td>
<td>102 ± 60 (30–290)</td>
</tr>
</tbody>
</table>

$^a$Table entries are KS 2-sample tests with no difference being NS where $p > 0.05$. Significant differences in fire interval data are shown at the $p < 0.05$ or 0.01 level.

Figure 9  Charcoal accumulation rates (CHAR, particles/cm² per yr), peak events, and inferred fire event frequency (no fires/1000 years) for the Paradox Lake, using methodology of Long et al. (1998). Arrows show where soil charcoal ages represent maximum ages for locally calibrated CHAR peaks. Pollen zones are shown for reference to vegetation reconstructions.

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produces similar results to our selected CHAPS scenario, by showing more frequent fire in Zones 2 and 3, and less frequent fire in Zones 1 and 4 and similar MFI estimates for the Holocene (Table 4). We conclude that methodological differences do not alter the general results of FEF reconstructions for the Paradox Lake CHAR series.

Conclusions

Despite the importance of ecosystem processes such as fire, the long-term relationships between disturbance, climate and vegetation type are incompletely understood (Lynch et al., 2003). Palaeoecology can assist in establishing relationships between these variables in the Boreal forest (ie, Clark and Royall, 1996; Clark et al., 1996; Carcaillet and Richard, 2000; Carcaillet et al., 2001). The record from Paradox Lake, the longest and most detailed record of fire and vegetation in Alaska, is an important demonstration of the inextricable linkage between climate, vegetation and fire. FEFs are lowest when shrub and herb tundra grew around the lake. FEFs increased with the immigration of Salix, Populus, Betula and Picea glauca. FEFs declined with the immigration of Alnus and Picea mariana.

Today, fire frequencies within P. mariana forests are typically greater than for uplands of P. glauca (eg, Yarie, 1981; Larsen, 1997). Yet our reconstructions suggest that fire burned more often in P. glauca-dominated forests than when P. mariana was more common around the lake. We believe this is due to two factors. First, the early Holocene forests of P. glauca and Betula existed during summers that were longer and drier than today. The combination of increased flammable coniferous biomass in the uplands and continuation of relatively warm summers must have allowed for periodically drier forest fuels. Lightning ignitions may have been more common during the early Holocene because of drier continental climate. Today, lightning storms are rare on the Kenai Peninsula, and ignition sources are dominated by human activity (Gabriel and Tande, 1983; De Volder 1999). Second, the increasingly wetter and cooler climate of the late Holocene was probably important. Even though P. mariana grows widely within the Kenai lowlands, its distribution within the Paradox Lake drainage basin is limited to a narrow boggy band immediately around the lake. Thus, P. mariana’s impact on the spatially aggregated fire event frequency of the drainage basin must be small.

Determination of fire event frequencies during the late Holocene using multiple proxies produced remarkably consistent results. For example, De Volder’s (1999) stand-age and burn pole analysis documented recent fire return intervals up to 185 years in black spruce; Berg and Anderson’s (2006) late Holocene soil charcoal fire return intervals for Paradox Lake average 190 years; Lynch et al.’s (2003) analysis of sedimentary charcoal in Rock Lake suggests a fire return interval of 194 years; and Lynch et al. (2004) suggests return intervals of <230 years. These figures compare with our fire return intervals of up to 195 years (Table 2).

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