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Climatic and land cover influences on the spatiotemporal dynamics of Holocene boreal fire regimes

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Abstract. Although recent climatic warming has markedly increased fire activity in many biomes, this trend is spatially heterogeneous. Understanding the patterns and controls of this heterogeneity is important for anticipating future fire regime shifts at regional scales and for developing land management policies. To assess climatic and land cover controls on boreal forest fire regimes, we conducted macroscopic-charcoal analysis of sediment cores and GIS analysis of landscape variation in south-central Alaska, USA. Results reveal that fire occurrence was highly variable both spatially and temporally over the past seven millennia. At two of four sites, the lack of distinct charcoal peaks throughout much of this period suggests the absence of large local fires, attributed to abundant water bodies in the surrounding landscape that have likely functioned as firebreaks to limit fire spread. In contrast, distinct charcoal peaks suggest numerous local fires at the other two sites where water bodies are less abundant. In periods of the records where robust charcoal peaks allow identification of local-fire events over the past 7000 years, mean fire return intervals varied widely with a range of 138–453 years. Furthermore, the temporal trajectories of local-fire frequency differed greatly among sites and were statistically independent. Inferred biomass burning and mean summer temperature in the region were not significantly correlated prior to 3000 years ago but became positively related subsequently with varying correlation strengths. Climatic variability associated with the Medieval Climate Anomaly and the Little Ice Age, along with the expansion of flammable *Picea mariana* forests, probably have heightened the sensitivity of forest burning to summer temperature variations over the past three millennia. These results elucidate the patterns and controls of boreal fire regime dynamics over a broad range of spatiotemporal scales, and they imply that anthropogenic climatic warming and associated land cover changes, in particular lake drying, will interact to affect boreal forest burning over the coming decades.

Key words: boreal forest; charcoal analysis; climate change; Copper River Basin, Alaska, USA; fire history; land cover; spatial analysis.

Introduction

In the boreal forests of North America, area burned has more than doubled since the 1960s (Kasischke and Turetsky 2006), and this increase is attributed primarily to anthropogenic climatic warming (IPCC 2007). Model simulations suggest that future warming will continue to increase the frequency, severity, and extent of boreal forest fires (Flannigan and Van Wagner 1991, Starfield and Chapin 1996, Weber and Flannigan 1997, Balshi et al. 2009, Flannigan et al. 2009, Wolken et al. 2011). Increased forest burning has major implications for climate change feedbacks and resource management, such as ecosystem carbon storage (Kasischke et al. 1995, O'Neill et al. 2003), land–atmosphere energy fluxes (Randerson et al. 2002), and habitat availability for caribou, a major subsistence resource for northern peoples (Rupp et al. 2006). However, fire regime changes can be spatially heterogeneous because top-down (e.g., climate) and bottom-up (e.g., land cover) controls on burning operate at multiple spatiotemporal scales (Heyerdahl et al. 2001, Gavin et al. 2003*a*). Although summer temperature and precipitation play a key role in determining annual burned area in many forest biomes (Duffy et al. 2005, Westerling et al. 2006, Balshi et al. 2009), bottom-up controls, such as landscape configuration and topography also exert strong influences on fire ignition and spread by changing microclimate, fuel connectivity, vegetation composition, and biomass abundance (Turner and Romme 1994, Miller and Urban 2000, McKenzie et al. 2011). Understanding how fire regimes vary across space and time is important for anticipating their responses to future climate change and for assessing socioeconomic impacts at regional scales.

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The relative importance of climate and landscape features on forest burning may shift through time and across space. The paleoecological approach is key to elucidating these shifts (Heyerdahl et al. 2001, Gavin et al. 2003*a*), especially in biomes such as the boreal forests where fire return intervals are long relative to the length of observational fire records. Recent paleoecological studies have revealed major variations in fire frequency in response to climatic change at centennial–millennial timescales (Carcaillet et al. 2001, Lynch et al. 2002, 2004, Higuera et al. 2009). Several studies also highlight spatial variability of fire regime change in relation to landscape features such as slope (Cyr et al. 2007), topography (Stambaugh and Guyette 2008), aspect (Clark 1990), and distance to and density of water bodies (Dansereau and Bergeron 1993, Larsen 1997, Hellberg et al. 2004). However, few paleoecological studies have been designed explicitly to evaluate the role of both climate and landscape features in the spatio-temporal dynamics of fire regimes.

We investigated fire regime changes over the past seven millennia in the Copper River Basin (CRB) of south-central Alaska. The CRB is well suited for exploring the relative importance of climate and land cover in determining fire regimes because of (1) the highly variable distribution of water bodies at the landscape scale and (2) the documented summer temperature and effective-moisture variations at centennial to millennial timescales (Lynch et al. 2004, Clegg et al. 2010, 2011). We analyzed Holocene sediment cores from four lakes in the CRB for macroscopic charcoal to evaluate spatial and temporal variations in fire frequency and biomass burned. Spatial analysis of land form and land cover surrounding each lake was performed to examine potential bottom-up controls of fire occurrence. We also compared the charcoal records with existing paleoclimate data from the region (Lynch et al. 2004, Clegg et al. 2010, 2011) to evaluate the influence of potential top-down controls on biomass burning. In particular, summer temperature has been consistently identified as the dominant climatic control of arctic and boreal fire occurrence (Duffy et al. 2005, Balshi et al. 2009, Krawchuk et al. 2009*b*, Parisien and Moritz 2009, Hu et al. 2010, Wotton et al. 2010), and recent advances in summer temperature reconstruction (Clegg et al. 2010, 2011) allow for the first assessment of the sensitivity of boreal forest burning in this region to temperature fluctuations over centuries to millennia. Overall, this research enhances our understanding of how anthropogenic warming and associated land cover change may affect future boreal forest burning.

Methods

Study area

We conducted this study at four lakes in the Copper River Basin (CRB) ecoregion (Fig. 1a; Gallant et al. 1995), which is surrounded by the Alaska, Wrangell, Chugach, and Talkeetna mountain ranges. The regional climate is continental, characterized by mean annual temperature of −2.0°C, mean January temperature of −17.2°C, mean July temperature of 12.9°C, and mean total annual precipitation of 284 mm for the 1981–2010 period (Gulkana Airport, 62°09′19.00″ N, 145°27′49.37″ W; WRCC 2011). Since 1950, mean annual temperature has increased by ~3°C ($r = 0.40$, $P < 0.001$). This increase has occurred primarily in winter, with a statistically insignificant increase of ~0.4°C in mean summer temperature ($r = 0.14$, $P = 0.30$). The boreal forests of the CRB span an area of 19 000 km^2, and are dominated by *Picea mariana* and *Picea glauca*. Deciduous species such as *Populus tremuloides*, *Betula papyrifera*, and *Alnus viridis* are prominent constituents in disturbed areas.

We chose the lakes in this study, Hudson (HUD), Super Cub (CUB), Minnesota Plateau (MP), and Crater (CR), using two criteria. First, their lack of or small inflow and outflow streams, relatively small surface areas, and relatively great depths (Table 1) should preserve charcoal signals of past fire events (Larsen and MacDonald 1993). Second, topographic maps and aerial surveys provided qualitative evidence that the landscapes surrounding CR and MP had a greater number of lakes than those surrounding HUD and CUB, which allowed us to evaluate the potential effects of lakes as fire breaks on forest burning. Although paleolimnological studies suggest that lake levels have remained relatively stable in Alaska since the middle Holocene (Hu et al. 1998, Abbott et al. 2000), recent studies revealed hydrological variations within the past 7000 years (Lynch et al. 2004, Anderson et al. 2005, Tinner et al. 2008, Clegg et al. 2010). These variations may have affected the temporal trajectories of fire regime change at each of our sites. However, the relative land cover differences between the two pairs of sites in this study likely remained throughout the past 7000 years, and we therefore assume that land cover effects on the spatial patterns of fire regimes also remained relatively constant across our sites.

Anthropogenic effects on the fire regimes of our study area were likely minimal throughout the Holocene. The Ahtna Athabascan people have lived in the CRB for thousands of years (Pratt 1998) and set small fires to encourage new growth near settlements (Simeone 2006). However, no evidence exists that they significantly modified the natural fire regime (Gibson and Pinther 1976, Simeone 2006).

Lake sediments

We obtained two sediment cores from the center of each lake using a modified Livingstone piston corer (Wright et al. 1984). The two cores were stratigraphically overlapping and were correlated on the basis of lithological patterns and magnetic-susceptibility measurements. An additional core with an intact sediment–water interface was taken from each lake using a polycarbonate tube fitted with a piston. We sliced the top 20–55 cm of

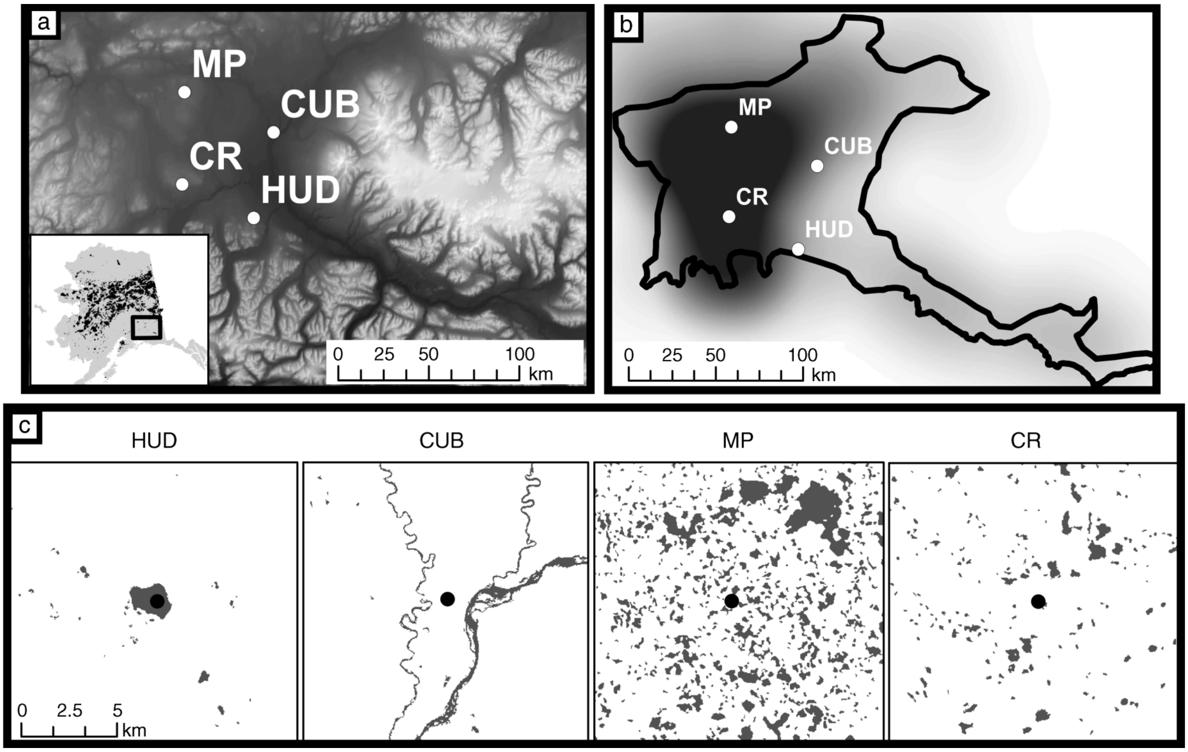

FIG. 1. Study region. (a) The four study sites (white dots) in the Copper River Basin (CRB), Alaska, USA: Hudson (HUD), Super Cub (CUB), Minnesota Plateau (MP), and Crater (CR). The inset is a map of Alaska highlighting the location of the CRB; black polygons are the fires in Alaska since 1942. (b) Smoothed lake density within a 50-km window, with darker shades indicating higher density. (c) Area around each of the study sites (black dots) showing the abundance of open water (gray).

TABLE 1. Characteristics of study lakes, surrounding landscapes, and charcoal records in the Copper River Basin ecoregion, Alaska, USA.

	Study site			
Characteristics	Hudson (HUD)	Super Cub (CUB)	Minnesota Plateau (MP)	Crater (CR)
Latitude (N)	61°53′51.76″	62°17′47.80″	62°32′30.46″	62°6′6.17″
Longitude (W)	145°40′14.60″	145°20′49.82″	146°14′ 18.35″	146°22′54.57″
Lake surface (ha)	270	3	5	1
Water depth (m)	14	4.7	6.4	4.2
Landscape within 5 km				
Mean (±SD) distance to fire break (m)	1253 ± 887	832 ± 655	132 ± 88	384 ± 257
Open-water cover (number of patches)	22	15	286	103
Open-water cover (%)	3.6	5.5	20.7	5.8
Evergreen forest cover (%)	88.2	57.7	61.2	70.7
Deciduous forest cover (%)	1.9	17.4	0.1	0.7
Woody wetland cover (%)	3.3	7.9	2.2	6.1
Shrub-scrub cover (%)	2.4	1.5	15.8	15.2
Mixed-forest cover (%)	0.6	7.3	0	0.1
Mean (±SD) elevation (m a.s.l)	681 ± 98	478 ± 41	808 ± 13	797 ± 71
Mean (±SD) slope (degrees)	5.8 ± 5.9	5.1 ± 4.6	6.4 ± 4.4	7.7 ± 5.5
Mean (±SD) aspect (degrees)	134 ± 117	179 ± 107	174 ± 110	183 ± 101
Sediment records				
Core length (cm)	512	156	362	145
Resolution of charcoal analysis (yr/sample, mean ± SD)	10 ± 5	13 ± 5	16 ± 3	16 ± 7
Sedimentation rate (cm/yr; mean ± SD)	0.071 ± 0.10	0.030 ± 0.026	0.039 ± 0.082	0.034 ± 0.028
Median signal-to-noise index	4.8	5.1	3.1	4.1

Note: Land cover classes are only reported if there is >5% cover within 5 km of the study sites; a.s.l. stands for above sea level.

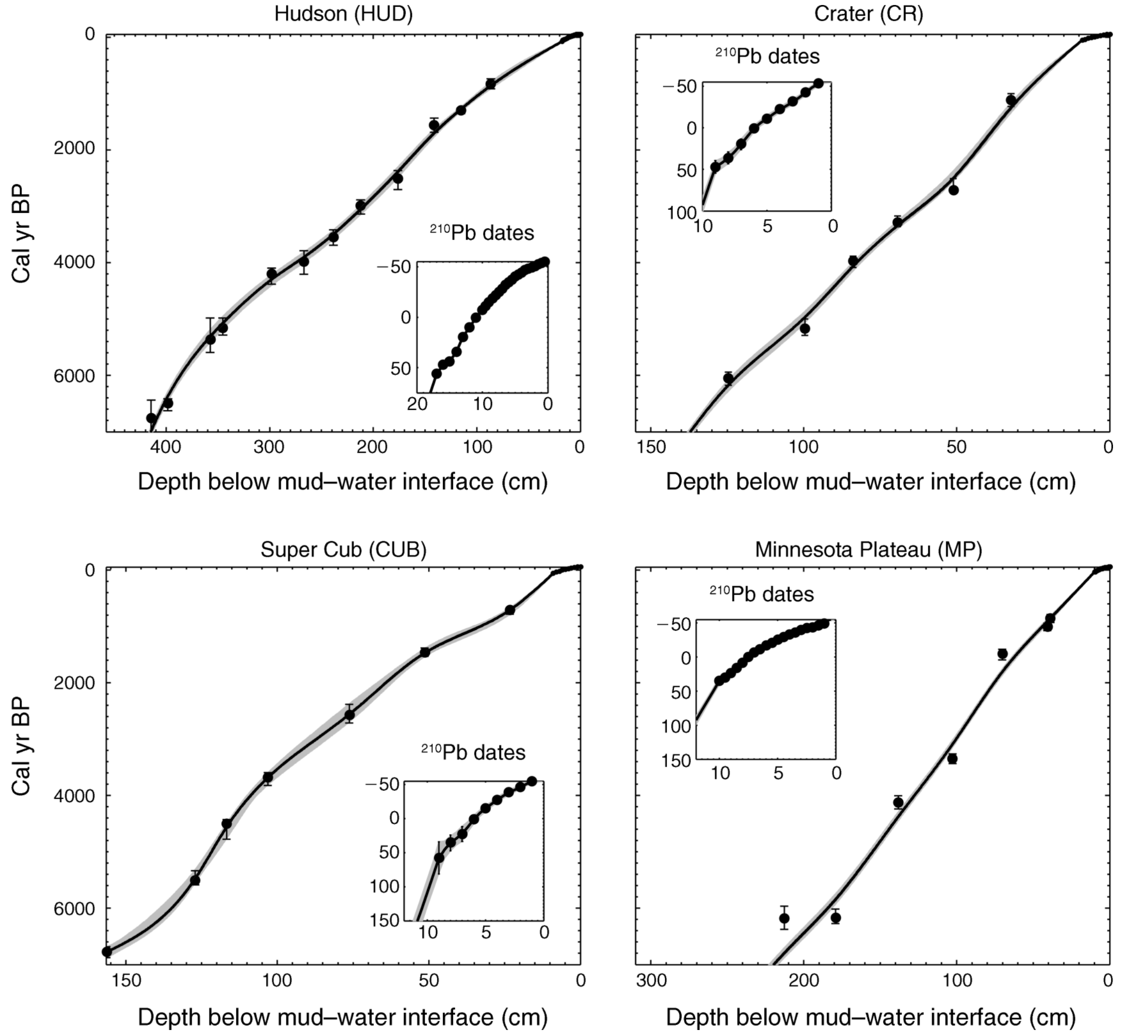

FIG. 2. Age–depth models for sediment cores from the four CRB sites calculated using a cubic spline. Black dots are ^{14}C or ^{210}Pb ages, and error bars represent estimated 95% confidence intervals based on 1000 bootstrap samples of the calibrated dates.

these cores into 0.5-cm intervals in the field, and the remainder was correlated with the other cores and sliced at 0.25–0.5-cm intervals in the laboratory. Sediments from all four sites were mostly composed of gyttja with occasional clay and silt laminations.

Chronological control

We developed an age–depth model for the sediment sequence from each lake using a series of ^{210}Pb and ^{14}C ages. Bulk sediments were analyzed for ^{210}Pb on an OctêtePlus alpha spectrometer (Ortec, Oak Ridge, Tennessee, USA) following Eakins and Morrison (1978). A ^{210}Pb chronology of the past 100 years was developed using a constant rate of supply model with old-age correction adapted from Binford (1990). For ^{14}C dating, sediment samples were soaked in 9 mL of 5% sodium metaphosphate and sieved through a 180-μm mesh to search for terrestrial macrofossils, including spruce needles, charcoal, and other wood particles. Macrofossils were treated with an acid–base–acid procedure (Oswald et al. 2005) prior to accelerator mass spectrometry radiocarbon analysis. Radiocarbon ages (Appendix A) were converted to calibrated years before 1950 (cal yr BP) using CALIB 6.1.1 (Stuiver and Reimer 2011) with the IntCal09 data set (Reimer et al. 2009). Age–depth models were created with a weighted cubic smoothing spline derived from 1000 bootstrapped samples from the calibrated age distributions using the program MCAgeDepth 0.1 in MATLAB (Fig. 2; Higuera et al. 2009).

Charcoal analysis and fire reconstruction

Contiguous samples (0.25–0.50 cm intervals; 3 cm^3 each) were obtained from each sediment core for charcoal analysis. To increase the visibility of charcoal particles, we treated the samples with 9 mL of 5% bleach (CUB and CR) or 10% KOH (MP and HUD) and then sieved them through 180-μm mesh. Macroscopic charcoal pieces were identified and counted at 40× magnification. Charcoal accumulation rates (CHAR; number of pieces$\cdot$cm$^{-2}\cdot$yr^{-1}) were determined by multiplying concentrations (number of pieces/cm^3) by sedimentation rates (cm/yr) estimated from our age–depth models.

To identify fire events, we performed peak analysis on each charcoal record using CharAnalysis version 1.1 (Higuera et al. 2009; *available online*).[5] Each record was interpolated to a temporal resolution of 15 years/sample, approximately the median sampling resolution of the four records (Table 1). Sediment-charcoal records contain "background" charcoal deposited by biomass burning within the region, as well as by sediment mixing and secondary charcoal transport (Clark et al. 1996). We estimated background charcoal with a 1000-year moving median applied to the raw charcoal series. This background was subtracted from the interpolated record to obtain a residual CHAR series, which itself is composed of two populations: one with a mean near zero, interpreted to reflect random variability (noise), and the other with a mean much greater than zero, interpreted as local (i.e., within ~1 km of the lake; Higuera et al. 2007) fire events (signal). The signal and noise distributions were estimated in a 1000-year moving window using a Gaussian mixture model, and at the center of each window a threshold was defined as the 99th percentile of the modeled noise distribution. Any residual CHAR value greater than the threshold was considered a "peak" and a potential local-fire event.

We further screened each charcoal peak exceeding the local threshold using two criteria before accepting it as representative of a local-fire event. First, to guard against overinterpreting small differences in charcoal particle counts, we compared the maximum charcoal count associated with each peak to the minimum charcoal count of all "nonpeak" samples from the previous 150 years. If the two counts were found to have >10% probability of being drawn from the same Poisson distribution, the peak was deemed nonsignificant and excluded from further analysis (Higuera et al. 2010). Second, to assess the suitability of each record for peak detections, we calculated a signal-to-noise index (SNI) based on the statistical separation of signal and noise distributions (Kelly et al. 2011). We calculated SNI with a 1000-year bandwidth to account for potentially long fire return intervals (FRIs) in the CRB, which were suggested by the historical fire data from the Alaska Fire Service and by previous paleo-fire studies (Lynch et al. 2004, Tinner et al. 2006*b*). Portions of the record with SNI <3.0, the theoretical cutoff described by Kelly et al. (2011), were considered unsuitable for peak detection and omitted from further peak analysis (Higuera et al. 2009).

The charcoal records were used to infer several aspects of fire history. FRIs were calculated as the number of years between two consecutive fire events. When summarizing a sample of FRIs (e.g., within a particular record or time period), we fit them to a Weibull distribution (Johnson and Gutsell 1994) and estimated the 95% confidence interval for the mean of the distribution through parametric bootstrapping (Appendix B). Finally, to test whether inferred fires occurred synchronously between our records at various timescales, we used the L function, a modified version of Ripley's K-function in the program K1D (Gavin et al. 2006; *available online*).[6]

Recent theoretical (Higuera et al. 2007) and empirical studies (Higuera et al. 2010) indicate that in contrast to the local nature of fires inferred from CHAR peaks, background CHAR reflects area burned or the amount of biomass burned at the regional scale (within 10–20 km). To develop a regional estimate of biomass burning through time, we created a composite CHAR record from all four of our sites following the methods of Marlon et al. (2008). Briefly, we first normalized each CHAR record using a Box-Cox transformation (with lambda selected by maximum likelihood), rescaled to the range [0, 1], and *z*-score-transformed to a mean of 0 and standard deviation of 1. A composite record was then created by applying a lowess smooth to the standardized CHAR samples from all four lakes (Marlon et al. 2008). The composite thus includes periods of records with low SNI, which indicates a poor separation of signal and noise distributions used in the local peak analysis. However, our compositing method does not depend on any metric of charcoal peaks, and thus low SNI values should not influence the integrity of the CHAR record as an index of regional-scale biomass burning.

To elucidate the fire–temperature relationship through time, we created a composite July temperature curve smoothed to highlight millennial-scale changes (1000-year moving windows) from midge-based temperature reconstructions at Hudson and Moose lakes in the CRB (Clegg et al. 2010, 2011). This temperature record was compared with our composite CHAR (also with a 1000-year smooth window) using Pearson's correlation coefficient. To assess the climate–fire relationship at centennial timescales, we compared the higher-resolution Moose Lake temperature record and our CHAR composite record smoothed with a 200-year window. For this analysis, only the Moose Lake temperature record was used because (1) this record has a higher resolution than that from Hudson Lake, and (2) Moose Lake is substantially shallower (maximum depth: 4.5 m) and thus midge assemblages at this site should be more sensitive to small temperature shifts than Hudson Lake (maximum depth: 14 m) (Clegg et al. 2010, 2011). We assessed statistical significance using nonparametric bootstraps, with block resampling (25 samples per

[5] http://sites.google.com/site/charanalysis/

[6] http://geography.uoregon.edu/envchange/pbl/software.html

block) to account for autocorrelation (Gavin et al. 2011).

Landscape analysis

We conducted landscape analysis at spatial scales larger than those of local fires inferred from charcoal peaks (~1 km around a lake) in order to evaluate the potential importance of the surrounding landscape on fire spread and thus local-fire occurrence. We characterized topography and land cover types within a 5 km radius around each study site using ESRI's ArcMap version 9.3 (*available online*).[7] Topographic indices (elevation, slope, and aspect) were calculated for each site using a 30-m resolution digital elevation model (Statewide Digital Mapping Initiative 2012). Land cover classes in the 30-m resolution National Land Cover Database (Homer et al. 2004) were reclassified into two categories: open water and potential fuel, the latter of which pooled all non-water classes and contained no perennial snow/ice area near our lakes. For each of the four sites, the percentage of each land cover class and the number of open-water patches were calculated using the program FRAGSTATS (McGarigal et al. 2002), with a patch defined as a group of contiguous pixels of the same land cover class using an eight-neighbor rule. To assess water bodies as potential firebreaks, we calculated the mean and standard deviation of the nearest-neighbor distance of each potential fuel pixel to the nearest open-water pixel within a 5 km radius around each study site using Hawth's Analysis Tools for ArcGIS (Beyer 2004). This calculation took into consideration both the density and the spatial arrangement of lakes and rivers around each of our study sites. To help visualize landscape variation at a larger scale that is more consistent with regional burning inferred from the background-charcoal composite record, we also performed a kernel analysis in ArcMap using a 50-km bandwidth to determine the spatial density of water bodies on the landscape.

Results

Chronological control

We obtained a total of 42 ^{14}C ages and 70 ^{210}Pb ages for the chronological control of the charcoal records from the four sites (Fig. 2; Appendix A). The ^{14}C ages of two wood samples, at 88.0 cm from HUD and at 99.5 cm from CR, are ~7000 and 1000 years older, respectively, than predicted from adjacent ages. These wood fragments likely had resided in the watershed soils for long time periods before deposition in the lake sediments, a common problem for ^{14}C dating of lake sediments from high-latitude regions (Oswald et al. 2005). We excluded these two samples and created age models using the remaining ages (Fig. 2). On the basis of these age models, the sedimentation rates at our four sites ranged from 0.01 to 0.41 cm/yr with a median of 0.04 cm/yr, and the individual charcoal samples thus spanned <1 to ~40 yr/sample, with a median of ~15 yr/sample (Table 1).

Signal-to-noise index

The SNI values of the charcoal records are high for CUB and HUD (entire record median = 5.1 and 4.8, respectively), with the exception of the period from 7000 to 5400 cal yr BP at HUD (median = 2.6; Fig. 3). These high values indicate that these two records are mostly suitable for fire history reconstruction using peak analysis (Kelly et al. 2011). In contrast, much of the MP record lacks a distinct signal, with a median SNI of only 3.1 (Fig. 3). Although portions of the record are above the SNI cutoff of 3.0, we exclude the MP record from peak analysis because of its overall low SNI. The CR record has a median SNI value of 4.1, with periods of high SNI (7000–4500 cal yr BP and 2400 cal yr BP–present; median SNI = 5.1 and 5.5, respectively) suitable for charcoal peak analysis and a long period of low SNI (e.g., 4500–2400 cal yr BP; median SNI = 2.6) unreliable for peak analysis (Fig. 3).

Fire history reconstruction

Consistent with the historical record of the past 68 years indicating that no fires occurred within 15 km of the study lakes (AICC 2011), no charcoal peaks were identified during this period at any of our study lakes (Fig. 3). The CUB charcoal record has the highest number of fires ($n = 33$) with a mean FRI of 199 years (95% CI = 157–251). The HUD record has 25 fires with a mean FRI of 206 years (95% CI = 154–264) from 5400 cal yr BP through present (Fig. 3). At CR, fires occurred relatively frequently from 7000 to 4500 cal yr BP with a mean FRI of 138 years (95% CI = 94–187) and infrequently from 2400 cal yr BP to present with a mean FRI of 453 years (95% CI = 332–572; Fig. 3). Although HUD has a larger surface area and likely a larger source area of charcoal, the mean FRI at HUD is statistically indistinct from those of CUB and the period of 7000–4500 cal yr BP at CR.

Comparisons of these fire records using the bivariate L function allow for a quantitative assessment of whether local fires occurred synchronously across sites (Gavin et al. 2006). For the periods with sufficiently high SNI values, fire occurrence was not statistically synchronous across any timescales among our sites (Fig. 4).

The composite background-CHAR record from the four sites shows pronounced fluctuations (Fig. 5a). Background-CHAR values are near the mean of the entire record between 7000 and 5000 cal yr BP, reaching a peak around 4700 cal yr BP and displaying a multimillennial decreasing trend until 150 cal yr BP. Superimposed on these general patterns are centennial-scale fluctuations, including a broad peak centered around 950 cal yr BP, a trough between 600 and 150 cal yr BP, and peak values in most recent sediments. The

[7] http://www.esri.com/

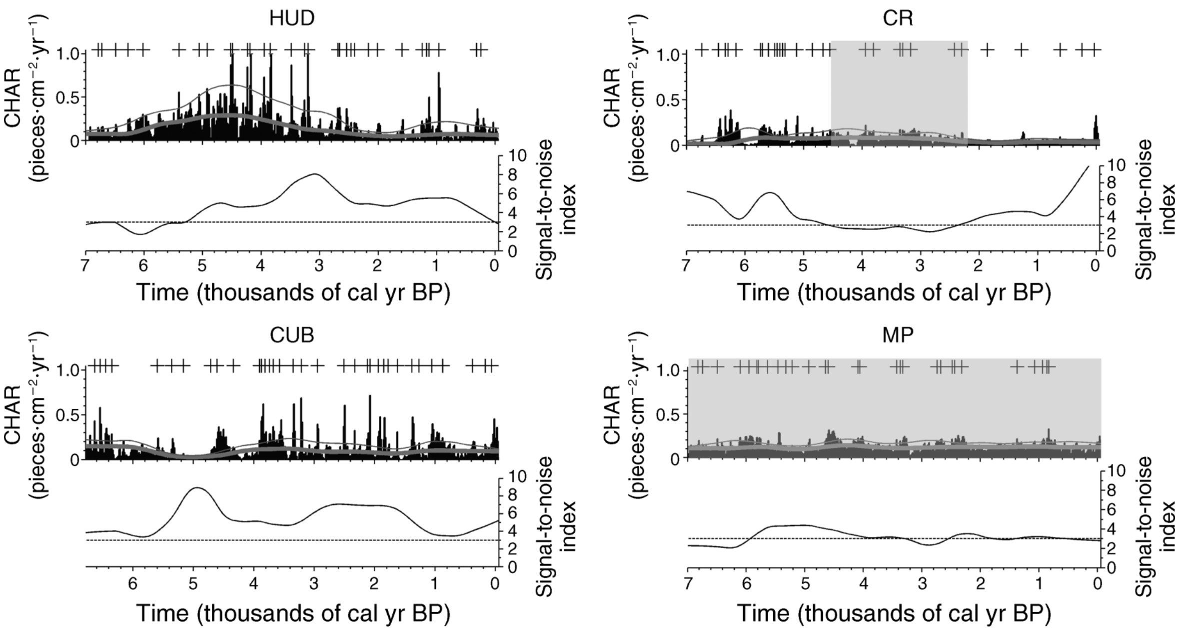

FIG. 3. Sediment-charcoal records over time. In the upper graph in each panel, vertical lines are the interpolated charcoal accumulation rates, the thick gray curve represents background charcoal, the thin gray curve indicates the threshold used to identify potential fires, and + symbols denote fire events; for CR and MP, the translucent gray sections indicate portions of the records with signal-to-noise index (SNI) values <3.0 when smoothed to 1000 years. In the lower graph in each panel, the solid curve shows SNI, and the dotted line indicates the 3.0 cutoff for robust peak detection, following Kelly et al. (2011). For site abbreviations see Fig. 2.

95% CI ranges of the record are particularly wide between 7000 and 5000 cal yr BP, and are generally greater prior to 3000 cal yr BP than after.

Landscape analysis

The spatial distribution and density of land cover types surrounding the four sites are highly variable (Fig. 1). Within a 5 km radius, open-water patches are more abundant at MP and CR ($n = 268$ and 103, respectively) than at CUB and HUD ($n = 15$ and 22, respectively). The percentage of open-water area is highest at MP (20.0%), followed by CR (5.9%), CUB (5.5%), and HUD (3.6%; Fig. 1c). Kernel analysis using a 50-km window reveals that lake density is higher around MP and CR (5.4–7.2%) than around CUB and HUD (0.9–2.7%; Fig. 1b). The distance to firebreaks (i.e., water bodies) within a 5 km radius is shortest for MP (130 ± 90 m, mean ± SD), followed by CR (380 ± 260 m), CUB (830 ± 660 m), and HUD (1250 ± 890 m).

Dominant vegetation within a 5 km radius of each site is evergreen forest (58–88%; Table 1). No significant differences in slope and aspect exist among the four sites. However, elevations are higher at MP and CR (820 ± 9.6 and 836 ± 58 m a.s.l., respectively, mean ± SD) than at CUB or HUD (492 ± 28 and 661 ± 81 m a.s.l., respectively). These elevational differences do not result in a consistent offset of climatic conditions between these two pairs of sites. On the basis of the PRISM downscaling of weather station data from 1971 to 2000 (Daly et al. 1994, PRISM 2004), CUB is significantly warmer than the other three sites and drier than MP and CR (Fig. 6). However, summer temperature does not differ between HUD and MP or CR, and the amount of precipitation is similar between CR and HUD.

DISCUSSION

Northern high latitudes are highly sensitive to anthropogenic and natural climatic forcings, and the magnitude of climate change over the next century is anticipated to be among the greatest in these regions (ACIA 2005). Recent climatic warming has resulted in pronounced changes in land surface processes, including permafrost melting, lake and wetland drying, and increased burning of boreal forests and tundra (Chapin et al. 2005, Klein et al. 2005, Kasischke and Turetsky 2006, Hu et al. 2010). Our fire history records help elucidate boreal fire regime dynamics over a broad range of spatiotemporal scales, with implications for how anthropogenic changes in climate and land cover may affect future boreal forest burning.

Spatial heterogeneity of fire history and the role of land cover

Spatial and temporal variability of fire regimes in the CRB over the past 7000 years reflects both land cover and climatic controls. Numerous local fires occurred around HUD and CUB over this period, as indicated by distinct charcoal peaks and high SNI values. In contrast,

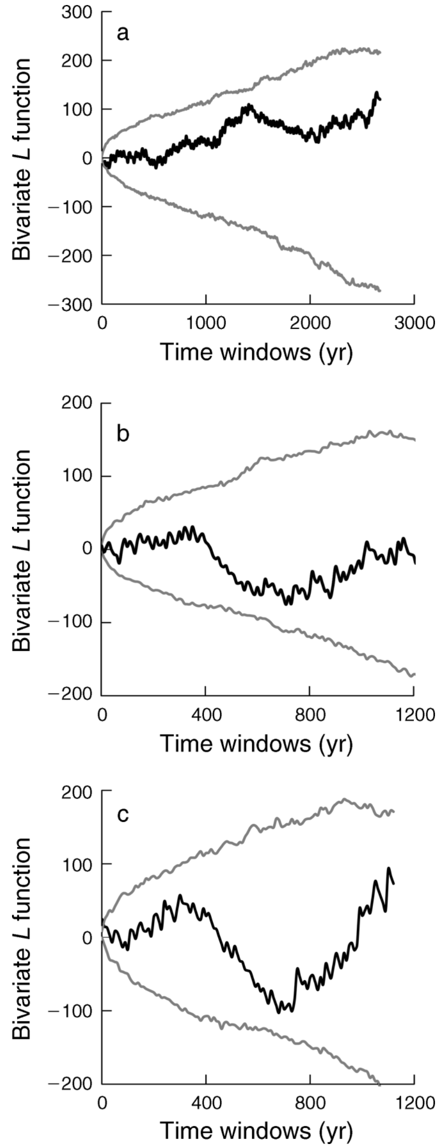

FIG. 4. Synchrony analysis of fire occurrence (a) between CUB and HUD records from 5400 cal yr BP to present, (b) among CR, HUD, and CUB from 2400 cal yr BP to present, and (c) between CR and CUB from 6750 to 4500 cal yr BP. In each plot, fire event synchrony is assessed by comparing the bivariate *L* function (black line) to a bootstrapped 95% confidence envelope (gray lines). Fire occurrence within a specified window width (*x*-axis) is considered significantly synchronous (or asynchronous) if the *L* function exceeds the upper (lower) confidence limit. Analysis was performed with the software program K1D version 1.2 (http://geography.uoregon.edu/envchange/pbl/software.html). See Gavin et al. (2006) for methodological details. For site abbreviations see Fig. 2.

low SNI values (<3.0) throughout much of the MP record and a large portion of the CR record suggest the absence of large fires around these lakes. Although sediment mixing could have also caused the low SNI values at MP and CR by obscuring charcoal peaks typically produced by large local fires (Larsen and MacDonald 1993, Kelly et al. 2011), this explanation is inconsistent with distinct peaks in the magnetic-susceptibility and bulk-density profiles of these cores (F. S. Hu and C. M. Barrett, *data not shown*). A more plausible interpretation is that a high density of firebreaks in the landscape around MP and CR, as inferred from the shorter mean distances to water bodies, impeded fire spread and decreased the probability of local-fire occurrence.

Superimposed on the overall contrasting pattern between our two pairs of sites are striking exceptions suggesting that other factors have also contributed to the spatial and temporal heterogeneity of fire regimes within our study region. For example, fires were relatively frequent around CR prior to 4500 cal yr BP

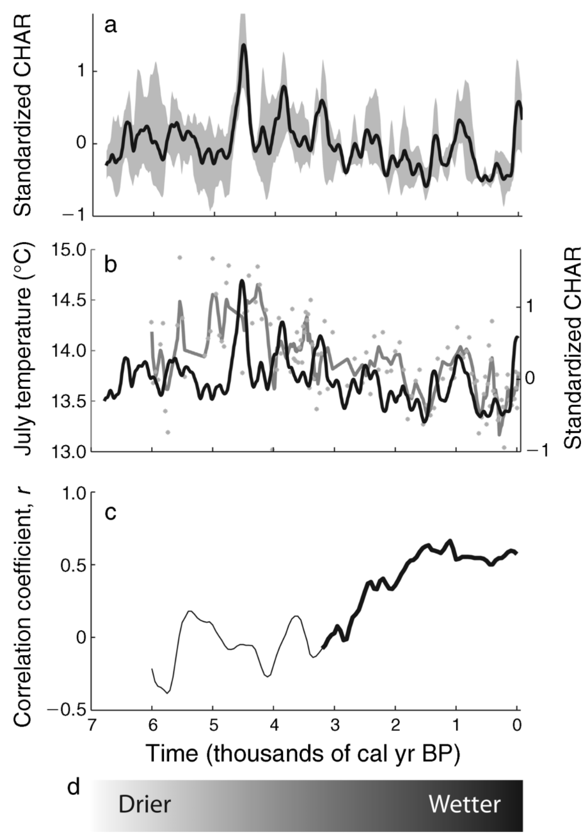

FIG. 5. Relationship between standardized CHAR and climatic variables. (a) The *z* scores of transformed charcoal accumulation (CHAR) from the four study lakes. Data were smoothed using a 200-yr moving window, and gray shading indicates the 95% confidence interval. (b) Comparison of CHAR (black) with midge-inferred July temperature (gray) from Moose Lake in the CRB (Clegg et al. 2010) smoothed with 200-yr window; gray dots represent raw data, and the gray line represents smoothed data. (c) Correlation between the CHAR and July temperature curves from panel (b); the darker line indicates the portions of the data set contributing to a significant correlation ($P \leq 0.05$); the correlation analysis was done with a 2000-yr moving window. (d) Qualitative moisture inferences at Moose and Chokasna lakes in the CRB (Lynch et al. 2004).

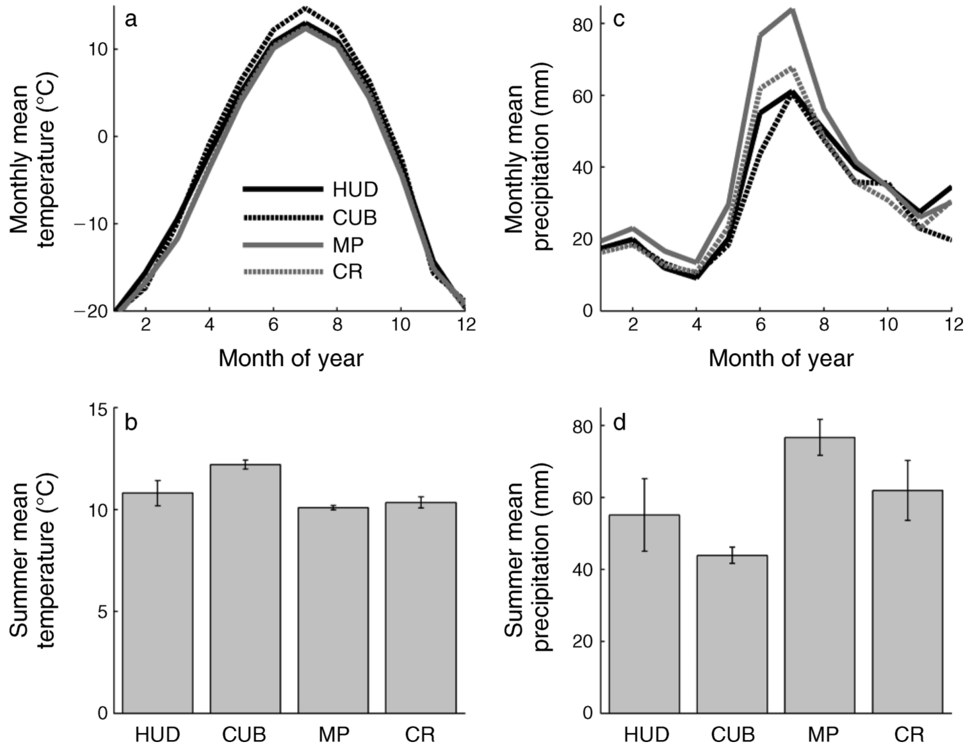

FIG. 6. Modern climatology around each study lake: (a, b) temperature and (c, d) precipitation within a 10-km radius around each study site using the 2-km PRISM data set summarizing weather station data from 1971 to 2000. In panels (b) and (d), "summer" is defined as the mean of June, July, and August values. Error bars represent the standard deviation. For site abbreviations see Fig. 2.

even though this site has a short mean distance to firebreaks today, and conversely, no local fires occurred around HUD prior to 5400 cal yr BP despite its great mean distance to firebreaks at present. The spatial and temporal complexity of fire occurrence is further illustrated by comparing our fire records using the bivariate *L* function (Gavin et al. 2006). Fire occurrence at HUD and CUB was statistically independent over the past 5400 years regardless of the time windows of comparison, and likewise fire occurrence was independent at all timescales among CUB, CR, and HUD (for overlapping periods with SNI >3.0; Fig. 4). We cannot pinpoint the specific factors leading to these spatial variations of fire history among our records. However, because of the close proximity of our sites, it is unlikely that the independent trajectories and the lack of synchrony in fire occurrence resulted from varying climate conditions among the sites (Fig. 6). Instead these variations suggest that fire occurrence was influenced by site-specific and/or stochastic factors related to variability in landforms, ignitions, and/or fire spread.

Recent observations and paleo-reconstructions provide compelling evidence that climatic warming increases fire occurrence across a wide range of biomes at regional to continental scales (Duffy et al. 2005, Power et al. 2008, Marlon et al. 2009, 2012). Our results from the CRB demonstrate that landscape factors also play a key role in fire regime dynamics at local to regional scales. Consistent with these results, a number of previous studies have emphasized the importance of local factors in the spatial patterns of fire regimes and their variations at decadal to millennial timescales (Grimm 1984, Dansereau and Bergeron 1993, Heyerdahl et al. 2001, Gavin et al. 2006, Ali et al. 2009). For example, sediment-charcoal records from the boreal forests of eastern Canada suggested that differences in watershed features and landscape connectivity resulted in asynchronous fire events and different fire frequencies among sites within the same region (Ali et al. 2009). In the temperate rain forests of Vancouver Island, Canada, soil-charcoal and tree-ring analyses revealed that time-since-fire was significantly shorter on hillslopes, terraces, and south-facing slopes than on north-facing slopes (Gavin et al. 2003*b*). Similarly, tree-ring analysis showed that in the Blue Mountains of Oregon and Washington, USA, variations in topographical features modified the effects of regional climate on fire frequency over the past ~400 years (Heyerdahl et al. 2001). Together with these previous studies, our data from the CRB underscore the importance of considering landscape factors in projecting the impacts of climatic change on fire regimes, especially at local to regional scales relevant to resource planning and land management policies.

Climatic control of boreal fire regimes at centennial–millennial timescales

The spatial complexity of local-fire occurrence does not preclude climate as a key control of fire regimes. Fire occurrence at the local scale has an inherent stochastic component, and the associated variability must be taken into consideration before invoking climatic explanations for fire regime shifts through time (Gavin et al. 2006, Hu et al. 2006). In contrast to the local nature of fires inferred from charcoal peaks, background CHAR reflects area burned or the amount of burned biomass at the regional scale, which should reflect climatic conditions better than local-fire occurrence (Whitlock and Anderson 2003, Marlon et al. 2009, Higuera et al. 2010). At millennial timescales, our composite CHAR record is moderately correlated ($r = 0.44$, $P = 0.08$) with a composite July temperature record from the same region based on midge analysis at Moose and Hudson lakes (Clegg et al. 2010, 2011). Both records show overall decreasing values from 4500 to 500 cal yr BP, suggesting that neoglacial climatic cooling (Kaufman et al. 2009, Clegg et al. 2010) reduced boreal forest burning at the regional scale. Summer temperatures were likely linked to burning through modifying fuel moisture, and possibly through correlations with storm tracks and associated lightning-caused ignitions (Price and Rind 1994, Krawchuk et al. 2009*a*).

Our composite CHAR record also suggests pronounced fluctuations in the amount of forest burning at centennial timescales. These fluctuations include peak CHAR values centered at ~950 cal yr BP, which correspond to the Medieval Climate Anomaly (MCA) when the region was probably as warm as at present, and low CHAR values at ca. 600–150 cal yr BP, which correspond to the Little Ice Age (LIA) when the region was ~1.5°C colder and drier than today (Hu et al. 2001, Tinner et al. 2008, Kaufman et al. 2009; Fig. 5b). However, the relationship between inferred biomass burning and summer temperature was nonstationary over the past 7000 years. Correlation analysis using a 2000-year moving window reveals that the composite CHAR and summer temperature are not significantly related before ca. 3000 cal yr BP, but that these metrics are positively related between 3000 cal yr BP and present (mean $r = 0.55$, and $P = 0.02$) with varying correlation strengths (r = 0.40–0.66; P = 0.001–0.040; Fig. 5c). These patterns remain the same when the entire temperature record is resampled to match the lower resolution prior to 3000 cal yr BP or shifted temporally to account for potential chronological errors. Thus the lack of correlation prior to 3000 cal yr BP is not a result of the lower resolution (and thus lower statistical power) or greater chronological uncertainties in the temperature reconstruction during that interval (Clegg et al. 2010).

Previous studies in other regions have also documented temporal variation in fire–climate linkages (Millspaugh et al. 2004, Gavin et al. 2006). Gavin et al. (2006) suggested that climatic fluctuations related to the MCA and LIA led to the dominance of climatic controls of fire occurrence over local and stochastic factors at two sites in southeastern British Columbia, Canada. A number of paleoclimate studies have documented pronounced climatic variations associated with the MCA and LIA across Alaska (Hu et al. 2001, Wiles et al. 2008, Clegg et al. 2010, 2011, Clegg and Hu 2010). These variations may have diminished the local and stochastic effects on forest burning at our sites, as evidenced by the reduced variability between records in our composite CHAR record (Fig. 5a), and therefore strengthened the climate–fire relationship over the past three millennia. Furthermore, a detailed pollen record from Grizzly Lake in the CRB shows that *Picea mariana* became consistently more abundant than *P. glauca* around 3000 cal yr BP (Tinner et al. 2006*a*), probably as a result of increased effective moisture (Fig. 5d; Lynch et al. 2004). Two additional pollen records with coarser temporal resolutions from the same region also suggest that the abundance of *P. mariana* increased relative to *P. glauca* between 3000 and 2000 cal yr BP (Lynch et al. 2004). Because *P. mariana* forests are highly flammable (Yarie 1981), this change may have heightened the sensitivity of forest burning to summer temperature fluctuations in the region. Thus regional fire regimes appear to have become less fuel-limited and more climate-limited (Flannigan et al. 2009) during the late Holocene, leading to an increase in the relative importance of top-down climatic control on forest burning.

In addition to the influence on fuel moisture, long-term temperature fluctuations can exert major controls on boreal forest burning by changing land cover types and, in turn, fuel connectivity. This potential is well illustrated by the fire history contrast between our two pairs of sites. Although our four study lakes are relatively deep with sediments indicating that they have never dried up over the past 7000 years, shallow lakes in the surrounding landscapes would have been more susceptible to climate-induced hydrological shifts. Changes in the amount of precipitation may have also accompanied temperature fluctuations to alter moisture balance and land cover. For example, decreased effective moisture could result in a greater abundance of dead, dry fuels that would in turn increase fire activity (Tinner et al. 2008). Elucidating linkages of forest burning to centennial-scale changes in moisture balance and land cover is difficult because of the lack of paleohydrological records with high temporal resolution from the region. However, at millennial timescales, the warmer/drier conditions prior to 3000 cal yr BP (Lynch et al. 2004, Clegg et al. 2010, 2011) did not result in more frequent local fires across all of our individual sites or more biomass burning across the study region. The greater abundance of *P. glauca* than *P. mariana* in the regional vegetation of that period (Tinner et al. 2006*b*) may have limited fire spread due to a lack of flammable fuel or fuel continuity.

Given that the magnitude of climatic fluctuations was relatively small over the late Holocene in our study region (~1.5°C; Hu et al. 2001, Clegg et al. 2010), the correspondence of biomass burning with midge-based temperature estimates during this period implies that at the regional scale, forest burning is sensitive to small variations in mean summer temperature. This inference is consistent with observational records of fire and climate in Arcto-boreal systems, indicating that summer temperature is the dominant driver of interannual variability in area burned (Duffy et al. 2005, Balshi et al. 2009, Krawchuk et al. 2009*a*, *b*, Hu et al. 2010). For example, Duffy et al. (2005) found that June temperature alone accounted for one-third of the interannual variation in area burned in the Alaskan boreal forests from 1950 to 2003. At continental and global scales, paleo-fire records also suggest temperature as a key predictor of biomass burning over centuries to millennia (Marlon et al. 2008, 2012).

Implications for ongoing and future fire regime shifts in boreal forests

Our results display complex spatial and temporal variability in fire regimes over the past seven millennia. These results highlight that climate change will interact with land cover patterns to affect the dynamics of future boreal fire regimes. Given that the magnitude of projected summer temperature increases over the next 100 years is significantly greater than those of the late Holocene in northern high latitudes (ACIA 2005), the significant links between temperature and fire over the past 3000 years in our study region imply the potential of marked increases in boreal forest burning in the coming century, with profound impacts on a number of biophysical and biogeochemical processes that will feedback to climate change (Flannigan et al. 2009). An important factor that has not yet been well recognized is that climate change can also exert important but indirect controls on boreal fire regimes by changing land cover and fuel abundance and connectivity (Berg et al. 2009, Higuera et al. 2009). Specifically, over the past several decades, ponds and wetlands have decreased in size and number in many northern high-latitude regions, including Alaska (Klein et al. 2005, Riordan et al. 2006). Areas that previously represented nonfuel land cover have been invaded by upland vegetation (Klein et al. 2005). These land cover changes may accelerate with continuing climatic warming, leading to increases in fuel connectivity and boreal forest burning. Thus anthropogenic climatic warming and associated land cover changes may have compounding effects on the boreal forest fire regime, with far-reaching implications for wildfire management and key ecosystem processes, such as soil carbon storage.

However, our results also highlight that boreal forest burning and climate warming do not have a straightforward relationship. These results are consistent with previous paleoecological studies demonstrating the important roles of species composition and stochastic factors (e.g., lightning, seasonal-moisture variability) in long-term shifts of forest fire regimes (Lynch et al. 2004, Tinner et al. 2008, Higuera et al. 2009). Furthermore, recent model simulations of boreal fire regime changes over the coming decades suggest possible negative feedback to increased fire occurrence resulting from the abundance of deciduous species under scenarios of frequent and high-severity burns (Johnstone et al. 2011). Reliable projections of future fire activity at regional scales are key to understanding the environmental consequences of burning and developing management policies. Such projections require the integration of the paleoecological perspective and a modeling framework (Brubaker et al. 2009), with the former providing insights into fire regime shifts at timescales beyond human observation, and the latter elucidating the direct and indirect impacts of climatic change on forest burning and the role of various feedback processes.

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Literature Cited

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

ACIA. 2005. Arctic Climate Impact Assessment—Scientific Report. Cambridge University Press, Cambridge, UK.

AICC. 2011. Alaska fire perimeters. Alaska Interagency Coordination Center. http://fire.ak.blm.gov/

Ali, A. A., C. Carcaillet, and Y. Bergeron. 2009. Long-term fire frequency variability in the eastern Canadian boreal forest: the influences of climate vs. local factors. Global Change Biology 15:1230–1241.

Anderson, L., M. B. Abbott, B. P. Finney, and S. J. Burns. 2005. Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada. Quaternary Research 64:21–35.

Balshi, M. S., A. D. McGuirez, P. Duffy, M. Flannigan, J. Walsh, and J. Melillo. 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Global Change Biology 15:578–600.

Berg, E. E., K. M. Hillman, R. Dial, and A. DeRuwe. 2009. Recent woody invasion of wetlands on the Kenai Peninsula Lowlands, south-central Alaska: a major regime shift after 18 000 years of wet *Sphagnum*–sedge peat recruitment. Canadian Journal of Forest Research 39:2033–2046.

Beyer, H. L. 2004. Hawth's analysis tools for ArcGIS. http://www.spatialecology.com/htools

Binford, M. W. 1990. Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores. Journal of Paleolimnology 3:253–267.

Brubaker, L. B., P. E. Higuera, T. S. Rupp, M. A. Olsen, P. M. Anderson, and F. S. Hu. 2009. Linking sediment-charcoal records and ecological modeling to understand causes of fire-regime change in boreal forest. Ecology 90:1788–1801.

Carcaillet, C., Y. Bergeron, J. P. H. Richard, B. Fréchette, S. Gauthier, and Y. T. Prairie. 2001. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? Journal of Ecology 89:930–946.

Chapin, F. S., et al. 2005. Role of land-surface changes in Arctic summer warming. Science 310:657–660.

Clark, J. S. 1990. Fire and climate change during the last 750 yr in northwestern Minnesota. Ecological Monographs 60:135–159.

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

Clegg, B. F., G. H. Clarke, M. L. Chipman, M. Chou, I. R. Walker, W. Tinner, and F. S. Hu. 2010. Six millennia of summer temperature variation based on midge analysis of lake sediments from Alaska. Quaternary Science Reviews 29:3308–3316.

Clegg, B. F., and F. S. Hu. 2010. An oxygen-isotope record of Holocene climate change in the south-central Brooks Range, Alaska. Quaternary Science Reviews 29:928–939.

Clegg, B. F., R. Kelly, G. H. Clarke, I. R. Walker, and F. S. Hu. 2011. Nonlinear response of summer temperature to Holocene insolation forcing in Alaska. Proceedings of the National Academy of Sciences USA 108:19299–19304.

Cyr, D., S. Gauthier, and Y. Bergeron. 2007. Scale-dependent determinants of heterogeneity in fire frequency in a coniferous boreal forest of eastern Canada. Landscape Ecology 22:1325–1339.

Daly, C., R. Neilson, and D. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33:140–158.

Dansereau, P. R., and Y. Bergeron. 1993. Fire history in the southern boreal forest of northwestern Quebec. Canadian Journal of Forest Research 23:25–32.

Duffy, P. A., J. E. Walsh, J. M. Graham, D. H. Mann, and T. S. Rupp. 2005. Impacts of large-scale atmospheric–ocean variability on Alaskan fire season severity. Ecological Applications 15:1317–1330.

Eakins, J. D., and R. T. Morrison. 1978. New procedure for determination of lead-210 in lake and marine-sediments. International Journal of Applied Radiation and Isotopes 29:531–536.

Flannigan, M. D., M. A. Krawchuk, W. J. D. Groot, B. M. Wotton, and L. M. Gowman. 2009. Implications of changing climate for global wildland fire. International Journal of Wildland Fire 18:483–507.

Flannigan, M. D., and C. E. Van Wagner. 1991. Climate change and wildfire in Canada. Canadian Journal of Forest Research 21:66–72.

Gallant, A. L., E. F. Binnian, J. M. Omernik, and M. B. Shasby. 1995. Ecoregions of Alaska. U.S. Geological Survey Professional Paper 1567.

Gavin, D. G., L. B. Brubaker, and K. P. Lertzman. 2003*a*. Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. Ecology 84:184–201.

Gavin, D. G., L. B. Brubaker, and K. P. Lertzman. 2003*b*. An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. Canadian Journal of Forest Research 33:573–587.

Gavin, D. G., A. C. G. Henderson, K. S. Westover, S. C. Fritz, I. R. Walker, M. J. Leng, and F. S. Hu. 2011. Abrupt Holocene climate change and potential response to solar forcing in western Canada. Quaternary Science Reviews 30:1243–1255.

Gavin, D. G., F. S. Hu, K. Lertzman, and P. Corbett. 2006. Weak climatic control of stand-scale fire history during the late Holocene. Ecology 87:1722–1732.

Gibson, J. R., and M. Pinther. 1976. Imperial Russia in frontier America: the changing geography of supply of Russian America, 1784–1867. Oxford University Press, Oxford, UK.

Grimm, E. C. 1984. Fire and other factors controlling the big woods vegetation of Minnesota in the mid-nineteenth century. Ecological Monographs 54:291–311.

Hellberg, E., M. Niklasson, and A. Granstrom. 2004. Influence of landscape structure on patterns of forest fires in boreal forest landscapes in Sweden. Canadian Journal of Forest Research 34:332–338.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. Ecology 82:660–678.

Higuera, P. E., L. B. Brubaker, P. M. Anderson, F. S. Hu, and T. A. Brown. 2009. Vegetation mediated the impacts of postglacial climate change on the fire regimes in the south-central Brooks Range, Alaska. Ecological Monographs 79:201–219.

Higuera, P. E., D. G. Gavin, P. J. Bartlein, and D. J. Hallett. 2010. Peak detection in sediment–charcoal records: impacts of alternative data analysis methods on fire-history interpretations. International Journal of Wildland Fire 19:996–1014.

Higuera, P. E., M. E. Peters, L. B. Brubaker, and D. G. Gavin. 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quaternary Science Reviews 26:1790–1809.

Homer, C., C. Huang, L. Yang, B. Wylie, and M. Coan. 2004. Development of a 2001 national landcover database for the United States. Photogrammetric Engineering and Remote Sensing 70:829–840.

Hu, F. S., L. B. Brubaker, D. G. Gavin, P. E. Higuera, J. A. Lynch, T. S. Rupp, and W. Tinner. 2006. How climate and vegetation influence the fire regime of the Alaskan boreal forest biome: the Holocene perspective. Mitigation and Adaptation Strategies for Global Change 11:829–846.

Hu, F. S., P. E. Higuera, J. E. Walsh, W. L. Chapman, P. A. Duffy, L. B. Brubaker, and M. L. Chipman. 2010. Tundra burning in Alaska: linkages to climatic change and sea ice retreat. Journal of Geophysical Research-Biogeosciences 115:G04002.

Hu, F. S., E. Ito, T. A. Brown, B. B. Curry, and D. R. Engstrom. 2001. Pronounced climatic variations in Alaska during the last two millennia. Proceedings of the National Academy of Sciences USA 98:10552–10556.

Hu, F. S., E. Ito, L. B. Brubaker, and P. M. Anderson. 1998. Ostracode geochemical record of Holocene climatic change and implications for vegetational response in the northwestern Alaska range. Quaternary Research 49:86–95.

IPCC. 2007. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. Cambridge University Press, Cambridge, UK.

Johnson, E. A., and S. L. Gutsell. 1994. Fire frequency models, methods, and interpretations. Advances in Ecological Research 25:239–287.

Johnstone, J. F., T. S. Rupp, M. Olson, and D. Verbyla. 2011. Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests. Landscape Ecology 26:487–500.

Kasischke, E. S., N. L. Christensen, and B. J. Stocks. 1995. Fire, global warming, and the carbon balance of boreal forests. Ecological Applications 5:437–451.

Kasischke, E. S., and M. R. Turetsky. 2006. Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska. Geophysical Research Letters 33:L09703.

Kaufman, D. S., D. P. Schneider, N. P. McKay, C. M. Ammann, R. S. Bradley, K. R. Briffa, G. H. Miller, B. L. Otto-Bliesner, J. T. Overpeck, B. M. Vinther, and Arctic Lakes 2k Project Members. 2009. Recent warming reverses long-term Arctic cooling. Science 325:1236–1239.

Kelly, R. F., P. E. Higuera, C. M. Barrett, and F. S. Hu. 2011. A signal-to-noise index to quantify the potential for peak detection in sediment-charcoal records. Quaternary Research 75:11–17.

Klein, E., E. E. Berg, and R. Dial. 2005. Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska. Canadian Journal of Forest Research 35:1931–1941.

Krawchuk, M. A., S. G. Cumming, and M. D. Flannigan. 2009*a*. Predicted changes in fire weather suggest increases in lightning fire initiation and future area burned in the mixedwood boreal forest. Climatic Change 92:83–97.

Krawchuk, M. A., M. A. Moritz, M. A. Parisien, J. Van Dorn, and K. Hayhoe. 2009*b*. Global pyrogeography: the current and future distribution of wildfire. PLoS ONE 4:e5102.

Larsen, C. P. S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. Journal of Biogeography 24:663–673.

Larsen, C. P. S., and G. M. Macdonald. 1993. Lake morphometry, sediment mixing and the selection of sites for fine resolution paleoecological studies. Quaternary Science Reviews 12:781–792.

Lynch, J. A., J. S. Clark, N. H. Bigelow, M. E. Edwards, and B. P. Finney. 2002. Geographic and temporal variations in fire history in boreal ecosystems of Alaska. Journal of Geophysical Research 108:1–17.

Lynch, J. A., J. L. Hollis, and F. S. Hu. 2004. Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska. Journal of Ecology 92:477–489.

Marlon, J. R., P. J. Bartlein, C. Carcaillet, D. G. Gavin, S. P. Harrison, P. E. Higuera, F. Joos, M. J. Power, and I. C. Prentice. 2008. Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience 1:697–702.

Marlon, J. R., P. J. Bartlein, D. G. Gavin, C. J. Long, R. S. Anderson, C. E. Briles, K. J. Brown, D. Colombaroli, D. J. Hallett, M. J. Power, E. A. Scharf, and M. K. Walsh. 2012. Long-term perspective on wildfires in the western USA. Proceedings of the National Academy of Sciences USA 109:535–543.

Marlon, J. R., et al. 2009. Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences USA 106:2519–2524.

McGarigal, K., S. A. Cushman, M. C. Neel, and E. Ene. 2002. FRAGSTATS: spatial pattern analysis program for categorical maps. http://www.umass.edu/landeco/research/fragstats/fragstats.html

McKenzie, D., C. Miller, and D. A. Falk. 2011. Toward a theory of landscape fire. Pages 3–25 *in* D. McKenzie, C. Miller, and D. A. Falk, editors. The ecological studies: the landscape ecology of fire. Volume 213. Springer-Verlag, New York, New York, USA.

Miller, C., and D. L. Urban. 2000. Connectivity of forest fuels and surface fire regimes. Landscape Ecology 15:145–154.

Millspaugh, S. H., C. Whitlock, P. J. Bartlein, and L. L. Wallace. 2004. Postglacial fire, vegetation, and climate history of the Yellowstone-Lamar and Central Plateau Provinces, Yellowstone National Park. Pages 10–28 *in* L. L. Wallace, editor. After the fires: the ecology of change in Yellowstone National Park. Yale University Press, New Haven, Connecticut, USA.

O'Neill, K. P., E. S. Kasischke, and D. D. Richter. 2003. Seasonal and decadal patterns of soil carbon uptake and emission along an age sequence of burned black spruce stands in interior Alaska. Journal of Geophysical Research-Atmospheres 108:8155.

Oswald, W. W., P. M. Anderson, T. A. Brown, L. B. Brubaker, F. S. Hu, A. V. Lozhkin, W. Tinner, and P. Kaltenrieder. 2005. Effects of sample mass and macrofossil type on radiocarbon dating of arctic and boreal lake sediments. Holocene 15:758–767.

Parisien, M., and M. A. Moritz. 2009. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecological Monographs 79:127–154.

Power, M. J., et al. 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics 30:887–907.

Pratt, K. L. 1998. Copper, trade, and tradition among the Lower Ahtna of the Chitina River basin: the Nicolai era, 1884–1900. Arctic Anthropology 35:77–98.

Price, C., and D. Rind. 1994. Possible implications of global climate change on global lightning distributions and frequencies. Journal of Geophysical Research-Atmospheres 99:10823–10831.

PRISM. 2004. PRISM Climate Group, Oregon State University. http://prism.oregonstate.edu

Randerson, J. T., F. S. Chapin, J. W. Harden, J. C. Neff, and M. E. Harmon. 2002. Net ecosystem production: a comprehensive measure of net carbon accumulation by ecosystems. Ecological Applications 12:937–947.

Reimer, P. J., et al. 2009. Intcal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal bp. Radiocarbon 51:1111–1150.

Riordan, B., D. Verbyla, and A. D. McGuire. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. Journal of Geophysical Research-Biogeosciences 111:G04002.

Rupp, T. S., M. Olson, L. G. Adams, B. W. Dale, K. Joly, J. Henkelman, W. B. Collins, and A. M. Starfield. 2006. Simulating the influences of various fire regimes on caribou winter habitat. Ecological Applications 16:1730–1743.

Simeone, W. E. 2006. Some ethnographic and historical information on the use of large land mammals in the Copper River Basin. U.S. National Park Service, Alaska Region Technical Report Series, Cultural Resources Report NPS/AR/CRR-2006-56. Wrangell-St. Elias National Park and Preserve, Copper Center, Alaska, USA.

Stambaugh, M. C., and R. P. Guyette. 2008. Predicting spatio-temporal variability in fire return intervals using a topographic roughness index. Forest Ecology and Management 254:463–473.

Starfield, A. M., and F. S. Chapin. 1996. Model of transient changes in arctic and boreal vegetation in response to climate and land use change. Ecological Applications 6:842–864.

Statewide Digital Mapping Initiative. 2012. Alaska mapped. http://www.alaskamapped.org/

Stuiver, M., and R. W. Reimer. 2011. CALIB 6.1.1. http://calib.qub.ac.uk/calib/

Tinner, W., C. Bigler, S. Gedye, I. Gregory-Eaves, R. T. Jones, P. Kaltenrieder, U. Krahenbuhl, and F. S. Hu. 2008. A 700-year paleoecological record of boreal ecosystem responses to climatic variation from Alaska. Ecology 89:729–743.

Tinner, W., S. Hofstetter, F. Zeugin, M. Conedera, T. Wohlgemuth, L. Zimmermann, and R. Zweifel. 2006*a*. Long-distance transport of macroscopic charcoal by an intensive crown fire in the Swiss Alps—implications for fire history reconstruction. Holocene 16:287–292.

Tinner, W., F. S. Hu, R. Beer, P. Kaltenrieder, B. Scheurer, and U. Kraehenbuehl. 2006*b*. Postglacial vegetational and fire history: pollen, plant macrofossil and charcoal records from two Alaskan lakes. Vegetation History and Archaeobotany 15:279–293.

Turner, M. G., and W. H. Romme. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9:59–77.

Weber, M. G., and M. D. Flannigan. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environmental Reviews 5:145–166.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943.

Whitlock, C., and R. S. Anderson. 2003. Fire history reconstructions based on sediment records from lakes and wetlands. Pages 3–31 *in* T. T. Veblen, editor. Fire and climatic change in temperate ecosystems of the western Americas. Springer-Verlag, New York, New York, USA.

Wiles, G. C., D. J. Barclay, P. E. Calkin, and T. V. Lowell. 2008. Century to millennial-scale temperature variations for the last two thousand years indicated from glacial geologic records of southern Alaska. Global and Planetary Change 60:115–125.

Wolken, J. M., et al. 2011. Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. Ecosphere 2:124.

Wotton, B. M., C. A. Nock, and M. D. Flannigan. 2010. Forest fire occurrence and climate change in Canada. International Journal of Wildland Fire 19:253–271.

WRCC. 2011. Western regional climate center data set of historical climate data, Gulkana, Alaska. www.wrcc.dri.edu/

Wright, H. E., D. H. Mann, and P. H. Glaser. 1984. Piston corers for peat and lake sediments. Ecology 65:657–659.

Yarie, J. 1981. Forest fire cycles and life tables: a case study from interior Alaska. Canadian Journal of Forest Research 11:554–562.

Supplemental Material

Appendix A

Radiocarbon ages and associated metadata (*Ecological Archives* E094-033-A1).

Appendix B

Fire history statistics for the four study sites (*Ecological Archives* E094-033-A2).