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HOW CLIMATE AND VEGETATION INFLUENCE THE FIRE REGIME OF THE ALASKAN BOREAL BIOME: THE HOLOCENE PERSPECTIVE

FENG SHENG HU[1,*], LINDA B. BRUBAKER[2], DANIEL G. GAVIN[1,4],
PHILIP E. HIGUERA[2], JASON A. LYNCH[1,4], T. SCOTT RUPP[3]
and WILLY TINNER[1,4]
[1]*Departments of Plant Biology and Geology, and Program in Ecology and Evolutionary Biology, University of Illinois, Urbana, IL 61801*
[2]*College of Forest Resources, University of Washington, Seattle, WA 98915*
[3]*Department of Forest Sciences, University of Alaska, Fairbanks, AK 99775*
[4]*Present addresses: D.G. Gavin, Department of Botany and Agricultural Biochemistry, University of Vermont, Burlington VT 05405; J.A. Lynch, Department of Biology, North Central College, Naperville, IL 60540; W. Tinner, Institut für Pflanzenwissenschaften, Universität Bern, Altenbergrain 21, CH 3013 Bern*
*(*Author for correspondence: Tel: 217-244-2982; Fax: 217-244-7246, E-mail: fshu@life.uiuc.edu)*

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Abstract. We synthesize recent results from lake-sediment studies of Holocene fire-climate-vegetation interactions in Alaskan boreal ecosystems. At the millennial time scale, the most robust feature of these records is an increase in fire occurrence with the establishment of boreal forests dominated by *Picea mariana*: estimated mean fire-return intervals decreased from ≥300 yrs to as low as ~80 yrs. This fire-vegetation relationship occurred at all sites in interior Alaska with charcoal[†]-based fire reconstructions, regardless of the specific time of *P. mariana* arrival during the Holocene. The establishment of *P. mariana* forests was associated with a regional climatic trend toward cooler/wetter conditions. Because such climatic change should not directly enhance fire occurrence, the increase in fire frequency most likely reflects the influence of highly flammable *P. mariana* forests, which are more conducive to fire ignition and spread than the preceding vegetation types (tundra, and woodlands/forests dominated by *Populus* or *Picea glauca*). Increased lightning associated with altered atmospheric circulation may have also played a role in certain areas where fire frequency increased around 4000 calibrated[‡] years before present (BP) without an apparent increase in the abundance of *P. mariana*. When viewed together, the paleo-fire records reveal that fire histories differed among sites in the same modern fire regime and that the fire regime and plant community similar to those of today became established at different times. Thus the spatial array of regional fire regimes was non-static through the Holocene. However, the patterns and causes of the spatial variation remain largely unknown. Advancing our understanding of climate-fire-vegetation interactions in the Alaskan boreal biome will require a network of charcoal records across various ecoregions, quantitative paleoclimate reconstructions, and improved knowledge of how sedimentary charcoal records fire events.

Keywords: Alaska, boreal forests, charcoal records, climate change, fire regime, Holocene

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[†] In this paper, charcoal refers to macroscopic (≥180 μm) as opposed to microscopic (<180 μm) particles unless indicated otherwise.

[‡] Radiocarbon ages were converted to calibrated years before AD 1950 using the atmospheric calibration data set (Stuiver et al. 1998).

1. Introduction

Historic observations, computer simulations, and paleoecological analyses provided compelling evidence for strong climate-fire relationships in the boreal-forest biome of North America (Larsen and MacDonald 1998a; Hess et al. 2001; Kasischke et al. 2002; Stocks et al. 2002; Lynch et al. 2004b; Duffy et al. 2005). Most of the area burned in Alaska over the past 50 years resulted from fire activity in a limited number of years with particularly warm/dry growing seasons (Kasischke et al. 2002), and large-scale climatic forcings (e.g., ENSO and PDO) explained a significant portion of the variance in fire occurrence in that region (Hess et al. 2001; Duffy et al. 2005). Modeling suggests that future warming will lead to increases in the frequency, severity, and extent of boreal-forest fires in western North America (Flannigan and Van Wagner 1991; Starfield and Chapin 1996; Weber and Flannigan 1997). The sensitivity of the boreal-fire regime to climatic change is also evident in the paleorecord, which has revealed major fire-frequency shifts in response to centennial- and millennial-scale climatic variation (e.g., Larsen and MacDonald 1998a; Carcaillet et al. 2001; Lynch et al. 2003; Lynch et al. 2004a).

However, climate-fire relationships are complex, and predicting responses of boreal fire regimes to future climate change is not straightforward. This complexity stems from the multiple biological and physical controls of fire occurrence whose relative importance may vary across a wide range of spatial and temporal scales (Figure 1). For example, weather conditions may override the importance of fuels as a regulator of fire occurrence at sub-annual time scales, but the direct impacts of climate on the fire regime may be dwarfed by the effects of vegetation composition at longer time scales, which can exert a key control through changing the abundance, structure, and combustibility of fuels (Rupp et al. 2002). Paleoecological research can help elucidate the patterns and controls of fire-regime change by providing records of fire occurrence at stand to regional scales and decadal to millennial scales. The long-term perspective of paleoecological analysis is particularly useful for ecosystems characterized by long fire return intervals, such as boreal forests. Furthermore, paleoecological studies offer insights into climate-fire-vegetation interactions unavailable from observational and modeling studies. Existing observational data do not capture the whole spectrum of climatic variability in the past and anticipated for the future, and simulation models are often constrained by knowledge from short-term observations.

In Alaska, several decades of paleoecological studies have resulted in a large pollen database for vegetational and climatic reconstructions (Anderson et al. 2003). Paleoecologists working in that region have generally acknowledged the role of fire disturbances in modulating Holocene vegetational response to climatic change (Hu et al. 1993; Anderson and Brubaker 1994; Hu et al. 1996). However, the study of fire history is in its infancy in this region. Quantitative fire-frequency reconstructions based on charcoal records did not begin until recently (Lynch et al. 2003; Lynch et al. 2004b). This paper reviews our current state of knowledge and discusses

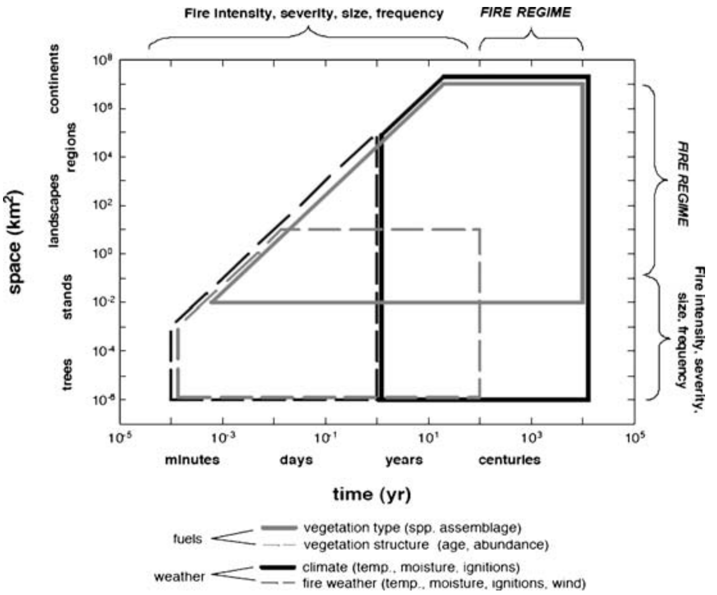

Figure 1. Fire occurrence at any one point in space and time is controlled by different aspects of vegetation (fuels) and weather, represented by the different polygons. Although topography is an important control of fire occurrence, its stability over centuries to millennia is assumed in paleoecological research. Scaling prevents events from happening simultaneously at short time scales and large spatial scales (i.e., the void in the upper left). In boreal ecosystems, the fire regime concept takes form only at larger spatial and temporal scales, while metrics specific to individual fires operate at smaller scales.

the challenges to advancing our understanding of Holocene climate-fire-vegetation relationships.

2. State of Knowledge: Fire-Regime Shifts at the Millennial Time Scale

2.1. FIRE-CLIMATE RELATIONSHIPS CAN BE COUNTER-INTUITIVE

Existing paleorecords from Alaska demonstrate that Holocene fire-climate relationships were greatly influenced by millennial-scale vegetational shifts. Charcoal data from Dune Lake (Lynch et al. 2003; Figure 2) provided the first estimates of Holocene variations in mean fire intervals (MFI[1]) in the region. This record shows that fires were infrequent 9000–5500 BP when the vegetation around the lake was dominated by *Picea glauca*, *Betula*, and *Alnus* (Figure 3). Fire frequencies increased dramatically at 5500 BP when *P. mariana* became a prominent component of the pollen spectra, marking the establishment of modern boreal forests in the area. This finding is consistent with results from two other lakes in interior Alaska

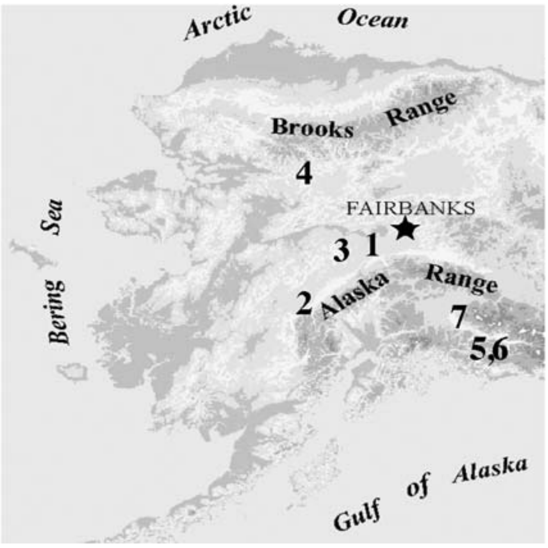

Figure 2. Map of Alaska showing locations of sites discussed in this paper. 1, Dune Lake; 2, Low Lake and Farewell Lake; 3, Wien Lake; 4, Ruppert Lake; 5, Moose Lake; 6, Chokasna Lake; 7, Grizzly Lake.

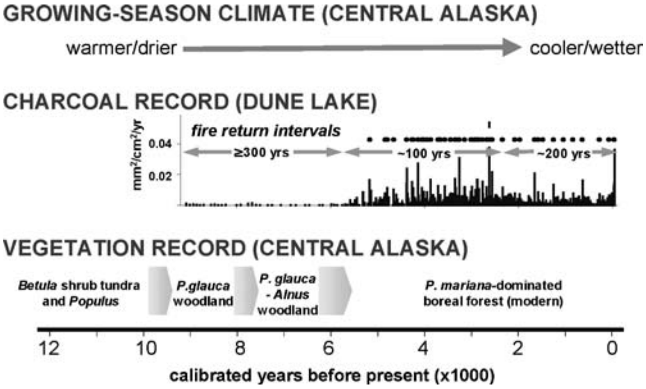

Figure 3. Schematic diagram showing Holocene changes in climate, vegetation, and fire regime in central Alaska. The MFI of ≥300 years before the establishment of *Picea mariana* forests, as discussed in the main text, is based on charcoal data from Dune Lake (Lynch et al. 2003) as well as Low (Lynch et al. 2004c) and Ruppert (Higuera et al. 2004) Lakes.

(Wien Lake, Hu et al. 1993; Farewell Lake, Hu et al. 1996; Figure 2), although only qualitative charcoal information (presence or absence) is available from these sites. Quantitative analyses of sediment charcoal records from Low Lake (Lynch et al. 2004c) and Ruppert Lake (Higuera et al. 2004), also located in the closed boreal forests of interior Alaska (Figure 2), confirm that MFI decreased markedly with the arrival/expansion of *P. mariana*. Together, the data from Dune, Low, and Ruppert Lakes indicate that MFI decreased from $\geq$300 years to as short as $\sim$80 years with the development of *P. mariana*-dominated forests. The time of *P. mariana* forest establishment differs greatly among these five sites, ranging from 5500 BP at Dune Lake (Lynch et al. 2003) to 7500 BP at Wien Lake (Hu et al. 1993). These differences probably reflect both non-climatic (e.g., edaphic) and climatic controls of Holocene forest development. For example, the arrival of *P. mariana* at Dune Lake occurred much later (by $\sim$2500 years) than at other central Alaska sites (Hu et al. 1993; Bigelow and Edwards 2001). This discrepancy probably resulted from the extensive sandy dry soils in the Dune Lake area that delayed soil paludification to trigger the establishment of *P. mariana*, rather than from a delayed climatic shift. Thus the fact that inferred fire occurrence increased with the arrival/expansion of *P. mariana* at all of the sites implies a robust vegetation-fire relationship.

Our current understanding of the Alaskan climate history suggests that the establishment of *P. mariana* forests was associated with a climatic trend toward cooler and wetter conditions (Figure 3; Hu et al. 1998; Abbott et al. 2000; Kaufman et al. 2004). The concurrent increase in fire is counter-intuitive in light of recent investigations indicating that a shift to cool, wet conditions should reduce fire occurrence (e.g., Flannigan et al. 2001; Kasischke et al. 2002). A plausible cause of this counter-intuitive association between fire and climate is related to the greater flammability of *P. mariana* compared to *P. glauca/Betula* forests (Hu et al. 1993, 1996; Lynch et al. 2003). This interpretation is consistent with observations and modeling results. *P. mariana* forests are highly susceptible to burning because of the low stature and persistent fine branches of trees, along with abundant mosses, lichens, and ericaceous shrubs in the understory (Rouse 1976). Although detailed data of fire periodicity are absent in interior Alaska, estimated fire cycles are significantly shorter in *P. mariana* forests than in *P. glauca* forests (Yarie 1981; Dyrness et al. 1986; Fastie and Lloyd 2003). In agreement, a recent modeling study (Rupp et al. 2002) found that the addition of *P. mariana* greatly increased the fire frequency and magnitude of large-scale burning events in interior Alaska.

Similarly, counter-intuitive climate-fire relationships are evident in sediment records from Moose and Chokasna Lakes (Figure 2), $\sim$20-km apart in the Copper River basin (Lynch et al. 2004b). Pollen profiles from these sites start after the arrival of *P. mariana*. The charcoal data from both sites show that MFI decreased from $>$500 years before ca. 4000 BP to $\leq$200 years afterward. This change coincided with an increase in effective moisture (precipitation – evaporation), as inferred from lithological and macrofossil evidence of elevated lake levels after 4000 BP. Though independent temperature reconstructions are unavailable at these sites, the onset of neoglaciation in Alaska suggests that the regional climate became cooler around this time (Calkin 1988; Calkin et al. 2001). Thus, like the longer millennial trend described above, fire frequencies in the Copper River basin appear to have increased with a climatic shift to cooler/wetter conditions. A key difference from the previous example is that the pollen spectra at Moose and Chokasna Lakes do not display changes around 4000 BP, implying that altered species composition (and associated flammability) did not cause the increase in fire occurrence. Lynch et al. (2004b) speculated that an increase in lightning strikes (ignition) plus greater variability in seasonal moisture (dry fuels during the fire season) might have resulted in more fires after 4000 BP. However, vegetation played a role in late-Holocene fire-regime variation near Chokasna Lake, as evidenced by decreased MFI after ~2000 BP with the expansion of *P. mariana*.

Little is known about how the regional fire regime changed in response to major biome shifts before the establishment of *P. mariana* forests. Of particular interest is the *Populus* interval (ca. 11,000–9500 BP), which presumably corresponded to the Holocene thermal maximum (Figure 3; Ritchie et al. 1983; Kaufman et al. 2004). Several charcoal records from interior Alaska spanning this interval show few fires (Lynch et al. 2004c; Higuera et al. 2004, 2005b), lending additional support for the importance of vegetational controls over fire regimes. Specifically the low flammability and/or fuel loads of the early-Holocene *Populus* forests/woodlands probably limited fire occurrence even though the regional climate was conducive to burning. Similarly, the fire regimes of the early-postgacial *Betula* tundra before and after *Populus* (Figure 3; Anderson and Brubaker 1994) remain poorly understood. Since 1950, tundra fires have accounted for ~5% of the area burned in Alaska (Alaska fire Service, cf. Kasischke et al. 2002). The early-postglacial *Betula* tundra is thought to have been more productive with greater shrub cover than the modern *Betula* shrub tundra (Anderson and Brubaker 1994). The possibility of greater fine-fuel loads, along with the presumably severe aridity over the region (Hu et al. 1998; Abbott et al. 2000), probably led to more frequent and intense fires than in the modern tundra. This speculation is supported by new charcoal records from interior Alaska suggesting that fire occurrence in those communities was frequent, and in some cases as frequent as in modern boreal forests (Higuera et al. 2005b; Tinner et al. In press).

Overall, Alaskan sediment records illustrate that paleorecords offer unique information about how climate and vegetation impact boreal-forest fires. In particular, the finding that fire frequency increased under the colder/wetter climate of the middle-late Holocene contradicts the current understanding of the climate-fire relationship based on historic observations and computer simulations (Flannigan et al. 2001; Kasischke et al. 2002). This finding underscores the important role of vegetational change in modulating boreal fire-regime responses to anthropogenic climatic warming. For example, the abundance of *P. mariana* in Alaskan boreal forests may decrease as a result of elevated temperature and diminished soil moisture (ACIA 2004). The associated increases in the abundance of *P. glauca* and *Populus* should reduce the overall flammability of the regional forest mosaics, countering the potential of increased fire occurrence due to climatic change and insect outbreaks (Berg and Henry 2003; Wittwer 2003). Although our results are inconsistent with paleoecological studies in several regions that show increased fire-frequencies with warmer and/drier conditions (Clark 1988; Larsen 1997; Larsen and MacDonald 1998b; Long et al. 1998; Bergeron et al. 2001), they agree with evidence of a fire-frequency increase when the regional climate of eastern Canada became cooler/wetter in the late Holocene (Carcaillet et al. 2001). In eastern Canada, no change in vegetation combustibility occurred that could account for the fire-frequency increase, and the authors attributed the increase to greater seasonality and drier fire seasons. Together these studies suggest that the relationships among climate, vegetation, and fire vary regionally in the boreal-forest biome. However, the causes of discrepancies among these paleorecords are not well understood partially because of our inability to reconstruct all aspects of climate controlling fire occurrence.

2.2. TEMPORAL TRAJECTORIES OF FIRE REGIMES VARY ACROSS SPACE

The spatial patterns of Holocene fire-frequency shifts are complex, and their causes are unclear. This complexity is evident in the plots of cumulative fire episodes during the past 5500 years (Figure 4) when *Picea*-dominated forests were present at all of the four sites in comparison. Over this period, twice as many fires occurred at the interior sites (Dune and Low Lakes) as at the Copper River basin sites (Moose and Chokasna Lakes) (Figure 4). This pattern agrees with observational data of the past 50 years, showing shorter fire cycles in the interior than in the Copper River basin (Alaska fire Service 2004, http://agcd.usgs.gov/data/blm/fire). However, this difference in fire regimes was not constant over time. It probably did not exist prior to 4500 BP, as evidenced by the nearly complete overlap of the four cumulative fire curves (Figure 4) and the similar numbers of fire episodes among the sites (Figure 5). The fire-frequency regimes began to diverge around 4500 BP, and subsequently the numbers of fire episodes were consistently greater in the interior than in the Copper River basin. This divergence cannot be attributed to differences in *P. mariana* abundance and associated flammability, as this species

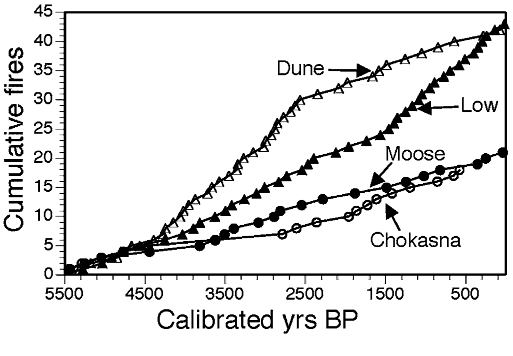

Figure 4. Cumulative fire episodes over the past 5500 years when *Picea*-dominated forests existed at all four sites. The Chokasna record does not cover the past 500 yrs because sediments of that interval were not obtained for charcoal analysis (Lynch et al. 2004b).

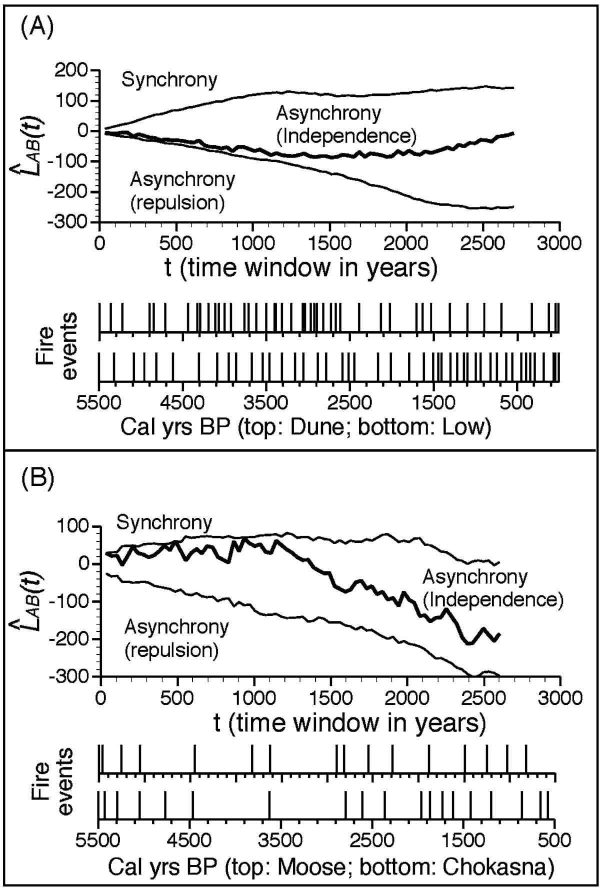

Figure 5. Synchrony analysis of fire histories over the past 5500 years: (A) Dune Lake *versus* Low Lake, and (B) Moose Lake *versus* Chokasna Lake. In each part, the lower figure shows the dates of fire episodes at each site and the upper figure is the bivariate L-function [$\hat{L}_{AB}(t)$]. The L-function is a transform of Ripley's bivariate K-function that is commonly used to show attraction or repulsion in spatial point patterns. As applied here, it tests for significantly synchronous or asynchronous occurrence of fire by summarizing the time difference between all pairs of events between records (Gavin et al. In press). The X-axis represents the time window in which synchrony test is done, and the thin lines define the 95% confidence envelope based on 2000 randomizations of shifting one record relative to each other. L-functions above and below the envelope indicate significant synchrony and repulsion, respectively, of fire occurrence for a particular time window. L-functions within the envelope indicate that fire histories are independent of each other between the two sites of comparison.

was more abundant near the interior sites both before and after 4500 BP (Lynch et al. 2003, 2004b). Rather, changing spatial patterns of the regional climate were probably responsible. Today the Copper River basin receives substantially higher precipitation than the interior (http://www.wrcc.dri.edu), but the opposite was possibly the case throughout the early and middle Holocene. Existing paleorecords of moisture balance are insufficient to verify this speculation. Nonetheless, one line of supportive evidence is the young ^{14}C ages (6000–9000 BP) of basal core samples from all of the lakes in the Copper River basin where sediment coring has been conducted (Lynch et al. 2004b; Hu and Tinner, unpublished data). These ages suggest that lakes did not exist before 9000 BP, probably reflecting extremely severe aridity. In contrast, most of the lakes found in the interior today existed during the early-middle Holocene, albeit with much shallower water levels (Abbott et al. 2000).

The spatial complexity of fire regimes is also evident after 4500 BP (Figure 4). In particular, the two interior sites appear to have had different temporal patterns of fire-frequency changes, even though their total numbers of fire episodes are nearly identical over the past 5500 years. The MFI was lower at Dune Lake than at Low Lake between 4500 and 2500 BP, but higher after 1500 BP. Lynch et al. (2003) estimated that at Dune Lake, MFI was 97 (±68) years prior to 2400 BP and 198 (±90) years since 2400 BP. The latter MFI value is similar to the 178-year fire cycle in the observational records of regional fires (Kasischke et al. 2002), suggesting that the modern fire regime became established ~2400 BP (Lynch et al. 2003). As this fire-regime shift was not induced by a vegetational change detectable in the pollen record, the authors postulated that it was caused by a regional temperature decrease or moisture increase. The fact that an increase in fire frequency occurred around 1500 BP at Low Lake argues against a climate explanation. Alternatively, the spatial heterogeneity in climate might have been sufficient to cause differences in the late-Holocene fire histories at the two interior sites.

Another dimension to understanding the spatial complexity of Holocene fire histories is highlighted by the statistical independence of our fire records (Figure 5). We compared two pairs of sites (Low *versus* Dune Lakes, and Moose *versus* Chokasna Lakes) using the bivariate K-function, a method commonly used for spatial point patterns and recently modified for temporal data (Gavin et al. In press). Statistical synchrony (see Figure 5 legend and Gavin et al. In press) is expected if climate exerted the dominant control over fire occurrence (e.g., by uniformly modifying fuels or ignition rates). Conversely, the lack of synchrony implies that fire occurrence was controlled by site-specific and/or stochastic factors, such as topography, local vegetation, ignition rates, and fire spread, at the spatial scales (~100 ha) represented by an individual charcoal record from a lake. The fire records of each pair are statistically independent regardless of the time window of comparison (Figure 5). The lack of synchrony between Dune and Low Lakes could be attributed to spatial heterogeneity in climate, as discussed above. However, it is inconceivable that Moose and Chokasna Lakes have experienced different climatic changes because these sites are only 20 km apart. Gavin et al. (In press) report a similar finding from southern British Columbia, where the fire histories of two lakes only 11-km apart have been largely independent for the last 5000 years. These results do not necessarily indicate the absence of climatic controls on the late-Holocene fire regimes in these two regions. Rather, they point to the importance of accounting for the variability inherent to local fire occurrence before invoking climatic explanations for fire-regime shifts through time. Understanding this variability requires combining fire records from multiple sites within a given region.

Overall, these spatial patterns reveal two important points regarding fire in evolving ecosystems over the Holocene. First, sites with the same fire regime today do not necessarily have the same fire histories, as illustrated by the fire-record comparisons among our sites. Thus the spatial array of the regional fire regimes was non-static through time. We should not expect that the boreal fire regimes in different regions will respond to future climate warming in parallel because temperature increases and associated changes in other climatic variables (e.g., precipitation, lightning) and vegetation will not occur uniformly across the regions. Second, major constituents of the same ecosystem may have evolved independently of one another. For example, though vegetation communities similar to those of today established by 5500 and 6500 BP at Dune and Low Lakes, respectively, fire regimes similar to those of today did not develop until 2400 at Dune Lake and 1500 BP at Low Lake. These differences likely reflect the different sets of climatic and non-climatic variables controlling vegetation and fire developments. Alternatively, they may reflect inaccuracy in vegetational and fire reconstructions. For example, the existing pollen records may be too coarse in spatial, temporal, and taxonomic resolutions to capture the sensitivity of species-assemblage variations within *P. marina* dominated communities.

3. Challenges: Limitations and Opportunities of Paleoecological Records

Despite the infancy of fire-climate-vegetation research in Alaska, intriguing patterns have emerged at the millennial time scale, which require verification with additional paleoecological analyses. In addition a number of conceptual and technical issues must be resolved in order to advance our knowledge of how climate and vegetation influence fire-regime dynamics. We discuss below several key aspects of future paleo-fire studies, some of which are applicable to such efforts in other regions.

3.1. THE SPATIAL AND TEMPORAL PATTERNS OF HOLOCENE FIRE REGIMES REMAIN POORLY KNOWN IN ALASKA

Given the paucity of high-resolution charcoal records in Alaska, the existing array of sediment records is inadequate to assess the range of fire-regime responses to Holocene climate change. For example, although the relationship between *P. mariana* and fire appears robust at our paleo-fire sites, whether it occurred in other regions of Alaska remains uncertain. Today, fire cycles differ greatly across Alaskan ecoregions, and these differences are linked to patterns of growing-season temperature and precipitation (Kasischke et al. 2002). To uncover temporal trajectories of fire regimes in different regions and assess the controls (e.g., climate, vegetation, and topography) of spatial variations in fire regimes, future charcoal analyses should include systematic sampling of lake cores across various modern ecoregions. Such spatially detailed data sets are essential for testing model simulations of fire responses to climatic change at the regional scale.

A conspicuous gap in our current understanding of the Alaskan fire history is fire response to decadal-to-centennial climatic change. Data from the past millennium, which spans the Little Ice Age (LIA, ca. AD 1400–1800) and warmer times before and after, are particularly relevant to addressing this issue for two reasons. First the magnitude of the LIA-related climatic fluctuations is similar to those projected for future changes. Second the vegetational composition of that period was similar to today and the near future (unlike the millennial-scale changes discussed above). On the basis of microscopic-charcoal analysis at Grizzly Lake (Figure 2), Tinner and Hu (2001) found greater charcoal abundance within the LIA than during the adjacent warmer periods. Because microscopic charcoal originates from both short and long distances, it integrates fires from multiple spatial scales and does not allow us to estimate fire frequencies. Qualitatively, the higher charcoal abundance suggests that fires were larger and/or more frequent during the LIA, probably reflecting the effects of drier climatic conditions and an increased abundance of dry fuels resulting from vegetation dieback. This inference concurs with a 300-year fire history from southern Quebec where tree-ring analysis showed that drier conditions elevated the frequency of boreal-forest fires during the LIA compared to the 20th century (Bergeron and Archambault 1993).

The LIA results from Grizzly Lake have not been verified at other sites in Alaska. Given the small spatial scale of macroscopic charcoal records (Clark et al. 1998; Gavin et al. 2003b; Lynch et al. 2004a) and the relatively long fire cycles of boreal ecosystems, estimates of MFI can vary widely by chance alone for periods of the length of the LIA. Thus, although a preliminary analysis of the fire data from Lynch et al. (2003, 2004b) reveals statistically insignificant differences between pre-LIA (AD 1000–1400) and LIA fire-frequency regimes (two sample Kolmogorov-Smirnov test on the fire return interval distributions), little statistical power exists with this test (ca. 50%; P. Higuera, unpublished data). A larger sample of fires is necessary to overcome the lack of power related to the inherent variability in fire-occurrence data. The only way to sample an adequate number of fires for detecting statistically significant changes in fire regimes between two periods lasting several centuries is to pool fire records from multiple sites of similar vegetation and climate. Future work documenting the effects of decadal- to centennial-scale climate change on boreal fire regimes thus requires a substantial increase in the number of paleo-fire records and an acute attention to sampling design. This challenge is accentuated for detecting fire-frequency response to climatic fluctuations of shorter durations (e.g., PDO) using lake-sediment charcoal records.

3.2. IMPROVING TECHNIQUES FOR CLIMATE AND FIRE RECONSTRUCTIONS IS KEY TO ADVANCING KNOWLEDGE ON FIRE-VEGETATION-CLIMATE RELATIONSHIPS

As in many other regions, our current understanding of fire-climate-vegetation interactions in Alaska suffers greatly from the scarcity of paleoclimate information. Unequivocal temperature reconstructions are generally lacking at any temporal resolution, and little is known about precipitation changes at decadal to centennial resolutions. However, new quantitative paleoclimate techniques (e.g., oxygen isotopes of carbonate and silica, compound-specific hydrogen isotopes, and chironomid assemblages) are emerging, and several recent studies in Alaska have applied some of these techniques to reconstruct growing-season temperature and moisture balance (Hu et al. 2001; Hu et al. 2003; Hu and Shemesh 2003; Barley 2004). Additional quantitative information on past climate is imperative for advancing our understanding of climate-fire relationships. Such information promises to open a new avenue for other opportunities as well. For example, quantitative paleoclimate records can be used to drive simulation models designed to examine climate-vegetation-fire relationships (e.g., ALFRESCO; Starfield and Chapin 1996; Rupp et al. 2000), which have the capacity to elucidate ecological processes (e.g., successional trajectories and transition rates) involved in fire response to transient climate change – information that is generally unavailable from paleo-studies.

Equally important, many technical issues must be resolved in using sediment charcoal records for fire reconstruction. Within the paleo-fire community, no general consensus exists regarding the specific techniques for charcoal measurement and data processing. For example, both macroscopic and microscopic techniques are applied, and some researchers infer fires from the charcoal number whereas others from the charcoal area. Tinner and Hu (2003) recently demonstrated a strong linear relationship between charcoal area and number for microscopic charcoal and concluded that area and number data are comparable, but such analysis has not yet been made for macroscopic charcoal.

Estimating fire frequencies from distinct peaks in macroscopic charcoal records has become a widely accepted approach for fire reconstruction (e.g., Clark et al. 1996; Long et al. 1998; Millspaugh et al. 2000; Mohr et al. 2000; Lynch et al. 2003; Gavin et al. 2003a; Gavin et al. In review). This approach is attractive because researchers can interpret fire frequencies and fire return intervals, metrics widely used by ecologists and land managers to describe fire regimes. Support for the use of fire identification from charcoal peaks comes from an increasing body of literature on charcoal production, deposition, and preservation in sediment records (e.g., Clark 1988; Whitlock and Millspaugh 1996; Clark et al. 1998; Blackford 2000; Ohlson and Tryterud 2000; Gardner and Whitlock 2001; Lynch et al. 2004a; Higuera et al. 2005a). However, questions remain about the merits of specific analytical techniques used in this approach. For instance, no standard method exists for choosing the background and threshold values, which ultimately determine which charcoal peaks are interpreted as local fires. To some extent the lack of standard procedure for identifying fire episodes from charcoal data is compensated for by the fact that many macroscopic charcoal records exhibit very distinct peaks, which greatly simplifies the fire-history reconstruction.

Many of these questions could be addressed by translating conceptual models of charcoal production, transport, and depositional processes into numerical modeling frameworks. The need for the paleo-fire community to move in this direction has been acknowledged (Whitlock and Anderson 2003). Numerical models of charcoal production, dispersal and incorporation into sediment offer a powerful tool for assessing the sensitivity of fire-history interpretations to a variety of natural and analytical variables, and they provide an avenue for objectively testing the effects of different methodologies. Preliminary work in this direction has been fruitful (Higuera et al. 2004), but it has also highlighted the need for continued empirical research to quantify the processes leading to sediment-charcoal records. The combination of empirical process studies and numerical modeling promises to greatly improve the techniques of charcoal-data analyses and enhance the accuracy of fire-history interpretations from charcoal records.

3.3. SOUND KNOWLEDGE OF FIRE HISTORY IS IMPORTANT FOR CONTEMPORARY FIRE MANAGEMENT

Information on the natural variability of fire regimes is critical for developing management guidelines (Cissel et al. 1999; Bergeron et al. 2004). However, this variability is poorly understood for Alaskan boreal ecosystems. Systematic record keeping and reporting of fires in interior Alaska were initiated in the 1940s, but more complete, aerial monitoring of fires in the entire region did not begin until the late 1970s. Beyond this brief observational period, managers in Alaska have been forced to rely on fire-history data. However, only four dendrochronological studies have been published that infer fire regime over decadal to century intervals (Yarie 1981; Mann et al. 1995; De Volder 1999; Mann and Plug 1999). Paleo-fire records from lake sediments have the potential to greatly enhance management's knowledge base through expanding both the temporal and spatial perspectives of the existing sparse fire-history data set. To that end, the paleo-fire community must address the challenges discussed above in order to acquire accurate fire reconstructions with spatial and temporal resolutions that are appropriate for specific management targets.

Paleo-fire information is also critical for developing and validating ecosystem models that incorporate the behavior and effects of forest fires. Such models are increasingly being employed in an operational management setting. However, the modeling approach is severely constrained because models are generally developed and tested with knowledge from the modern landscape and short-term observations (Neilson 1993). Consequently, it is impossible to rigorously assess an ecosystem model's ability to simulate boreal fire regimes of the future when climatic warming is expected to far exceed the scope of instrumental weather records. In contrast, the paleorecord often encompasses a wide range of climatic and ecological conditions, some of which may be analogous to future changes and can be used to verify model simulations of those changes. Thus the coupling of modeling and paleo-records provides an opportunity to improve our ability to project system behavior in a changing environment and offer management insights.

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Note

1. MFI is the mean of years between adjacent fire episodes, where a "fire episode" is defined as one or more fire events within the time window represented by a sediment sample with a distinct charcoal peak (Whitlock et al. 2003).

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