PROJECT SUMMARY

Intellectual Merit: Recent observations attest to the profound ecological and societal consequences of climatic change in northern high latitudes. Evidence includes a doubling of area burned in the boreal forests of western North America over the past 30 yrs, attributed primarily to anthropogenic warming. Fire responses to climatic transients, however, are not straightforward. A major unknown in predicting earth-system behavior is how climatic change may alter boreal fire regimes, which has potential to overshadow the direct effects of anthropogenic warming on vegetation patterns, energy flux and biogeochemical cycling. The proposed project confronts this issue by integrating paleorecords and computer modeling to investigate fire responses to climatic change in Alaska. The centerpiece of the project is its innovative and rigorous approach to understand patterns and mechanisms of climate-fire-vegetation interactions from the recent geological past through the near future. The researchers will monitor charcoal processes (dispersal, transport, and deposition) of contemporary and recent burns to parameterize a newly developed numerical model of charcoal-fire relationships (CharSiM), a tool that greatly enhances the rigor of fire-history reconstruction. The resulting knowledge will be applied to interpret fire histories of the past 6000 years from lake-sediment charcoal data collected with statistical criteria in two study areas with contrasting fire regimes and recent climate anomalies, focusing on the neoglacial transition and oscillations associated with the Little Ice Age. These fire records will be compared with climatic and vegetational reconstructions using state-of-the-art paleoecological and geochemical techniques. An iterative paleodata-modeling approach will be applied to elucidate mechanistic processes of climate-vegetation-fire interactions (e.g., lead-lag relationship, fuel dynamics) using ALFRESCO, a model developed and well tested for studying Alaskan boreal ecosystems. Finally the improved ALFRESCO will be used to simulate regional fire regimes for the next 100 years based on a suite of forecast climate scenarios.

This project blends a wide array of research expertise and builds upon the PIs’ strong track records in paleoecological and modeling studies of Alaskan boreal ecosystems. Each of the proposed research elements represents the forefront of current research in the respective areas, and together they promise to substantially advance the understanding of fire-climate-vegetation relations of the boreal biome for the past, present, and future.

Broad Impacts: This project promises to bring new insights into the variability of boreal fire responses to climatic change and to improve the robustness of a key model for predicting future changes in boreal ecosystems. The prognostic simulations of the 21st century fire regimes will be directly relevant to fire management planning and policy. The project educates students and the general public. In particular, it provides the intellectual base, financial resource, and mentorship to help ensure the successful transition of an outstanding minority doctoral student to an independent arctic scientist. Students will receive interdisciplinary training and interact with a broad research community to gain an integrative perspective of global change study. In addition, the PIs will produce educational materials for outreach to the general public and for dissemination through visitor interpretive activities of the Alaska Fire Service, the US Fish and Wildlife Service, and the National Park Service.
1. RESULTS FROM PRIOR NSF SUPPORT

Rupp (OPP-0096-0328282, $1,347,857, 10/03-9/06, co-PI with F.S. Chapin et al.; Fire-Mediated Changes in the Arctic System: Interactions of Changing Climate and Human Activities). We are addressing the factors that determine the limits to resilience of regional systems that are changing directionally in biophysical and social drivers. This research is in the process of documenting and modeling the role of fire, particularly as affected by human activities, on the Arctic Climate System and its human residents. We will build on the research of McGuire and Rupp (NSF OPP-0095024) in this research by modifying and testing ALFRESCO so it has the capability to consider human effects on the fire regime and by using these models to assess climate feedbacks associated with plausible scenarios of future climate and fire regime that we will develop.

Hu (ATM-9619583, $246k, 6/97-5/01, co-PIs E. Ito and H.E. Wright; Climatic Oscillations during the Last Glacial-Interglacial Transition in Alaska). We analyzed lake sediments at multi-decadal resolution for a suite of proxy indicators, including oxygen and carbon isotopes, trace-element composition, pollen, and ostracode assemblages. Results unequivocally show abrupt climatic reversals coinciding with the Younger Dryas, the Intra-Allerod Cold Period, and the Preboreal Oscillation. These data provide compelling support for the hypothesis that the North-Pacific region experienced several of the abrupt events widely recognized in the North-Atlantic region. Thus large-scale climatic forcings, especially the strength of North-Atlantic thermohaline circulation, and their interactions with atmospheric processes resulted in the propagation of cooling from the North Atlantic to the North Pacific. However, the classic Bolling interstadial of the North Atlantic was absent in our sediment records, and postglacial warming occurred >1000 later in Alaska. As part of this project, we developed a database of lake-water δ¹⁸O and δD from ~150 sites throughout Alaska. This grant supported nine published articles (* in References), three manuscripts in internal review, and ~18 published abstracts. Research opportunities were made available for one postdoctoral associate, two graduate students, and four undergraduate students.

Brubaker (ARC-0112586, $730k, 6/01-6/05, co-PI P.M Anderson, collaborators T.S. Rupp and F.S. Hu; Understanding the Role of Climate-Vegetation-Fire Interactions in Early-Holocene Treeline Dynamics in Alaska). By coupling paleovegetation, climate and fire history records with the ecosystem model ALFRESCO, this ongoing project investigates the processes of the early-Holocene fluctuations in white spruce (Picea glauca) in central Alaska. Sediment records from >15 sites across the central Brooks Range are being analyzed for pollen, stomates, charcoal and/or paleoclimatic proxies. Results so far indicate that the rapid expansion of white spruce during the early Holocene was not accompanied by major shifts in fire regimes or climate. This finding contrasts sharply with evidence for fire-regime shifts with the expansion of black spruce (Picea mariana) during the mid Holocene. The integration of paleodata with ALFRESCO promises to reveal differences in ecological mechanisms linking white and black spruce expansions with fire regimes. The project supports one graduate student, and provides research experience for five undergraduate students. Results have been reported in five presentations at national and international meetings and one manuscript. Five or more publications are anticipated from the overall project.

2. INTRODUCTION

Concerns about the environmental and socio-economic consequences of anthropogenic warming have motivated numerous investigations of natural climatic variations and their effects on ecosystems (e.g., Clark 1988a; MacDonald et al. 1993; Foley et al. 1994; IPCC 2001; Kaufman et al. 2004; Smith et al. 2004). Boreal ecosystems are of particular interest because they are projected to be among the most sensitive to anthropogenic forcing and because biogeochemical and biophysical feedbacks to the global system can exacerbate climatic warming. Recent studies (e.g., Shugart et al. 1992; Rupp et al. 2000a; Flannigan et al. 2001; Chapin et al. 2003) suggest that the indirect effects of climate-induced change in fire regimes will over-shadow the direct effects of temperature and precipitation change on forest composition, energy fluxes, and biogeochemical processes in boreal and other ecosystems. Furthermore,
fire-regime responses to climate may lead to major losses of boreal soil-carbon accumulations, contributing to atmospheric CO$_2$ and amplifying climatic warming (e.g., Kasischke et al. 1995; Harden et al. 2000). Thus there is a strong scientific imperative to acquire knowledge about climate-fire relationships in the boreal-forest biome.

Paleoecological analyses are particularly useful for elucidating the complex and potentially dramatic effects of climatic change on fire regimes in boreal regions, where fire-return intervals are long (e.g., Larsen and MacDonald 1998; Carcaillet et al. 2001; Lynch et al. 2003, 2004b). In Alaska, emerging sediment records indicate that boreal fire regimes responded to Holocene climatic change in a counter-intuitive way -- fire frequencies increased when regional climate became colder and/or wetter (Hu et al. 2005). This response occurred both when flammable black-spruce forests first became established during a widespread Holocene climatic cooling ~ 6-7000 years before present (BP) (Hu et al. 1993; Lynch et al. 2003), and when no apparent vegetational shift took place within the later Holocene (Tinner and Hu 2001; Lynch et al. 2004b). These paleorecords contribute to a growing body of evidence that climate-fire relationships are not straightforward and that future climatic forcing may lead to unexpected changes in boreal fire regimes (e.g., Carcailett et al. 2001; Flanagan et al. 2001). In particular, Alaskan paleodata stand in sharp contrast with the regional fire records of the past 50 years, which show increased fire occurrence under warmer/drier weather conditions (Hess et al. 2001; Kasischke et al. 2002; Duffy et al. 2005). This contrast implies that short-term historic observations do not capture the full spectrum of boreal-fire responses to climatic change, and thus that predictive models based on historic observations may be severely constrained by unrealistic assumptions of climate-fire relationships.

Paleorecords over the past 6000 years, when Alaskan boreal forests and the magnitude of climatic shifts were similar to those anticipated for the future, can greatly extend the observational period for inferring climate-fire interactions. However, the existing array of Alaskan sediment records is inadequate to assess the range of fire-regime responses in modern boreal forest types. This inadequacy results from three major deficiencies that will be confronted directly by our proposed research. First, only three quantitative fire reconstructions (Lynch et al. 2003, 2004b) have been published from the vast Alaskan boreal-forest region with a complex spatial pattern of modern fire regimes (Kasischke et al. 2002). Documenting changes in fire regimes in regions with long fire return intervals (FRI) requires careful consideration of sample sizes. Fortunately, the Alaskan database of historic fires (Alaska Fire Service 2003) permits the design of a statistically justifiable sampling scheme for detecting centennial-scale changes in fire regimes of key regions. Second, the lack of high-quality paleoclimatic reconstructions with spatial and temporal resolutions compatible with charcoal records has greatly hampered our understanding of climate-fire relationships. Novel techniques of sediment analyses that have been successfully applied in Alaska and adjacent Canada (Hu et al. 1998, 2001, 2003; Barley 2004) now make such reconstructions possible. Third, as typical of paleodata, the existing paleofire records do not offer a mechanistic understanding of how climate and vegetation control fire dynamics, greatly diminishing the value of paleo-information for helping project future fire-regime changes. One way to improve this understanding is to use computer models of ecosystem change to evaluate ecological mechanisms responsible for the fire-regime changes observed in the paleorecord. ALFRESCO, a spatially explicit model developed and well tested for Alaskan boreal ecosystems (Rupp et al. 2000a, 2000b, 2001, 2002), is ideally suited for this purpose because its spatial and temporal scales are similar to those of paleorecords. A newly developed model (CharSiM) of charcoal production, dispersal, and deposition will allow us to directly compare ALFRESCO-simulated fire regimes with sediment charcoal records (Section 4.4). Objective criteria can then be used to assess whether ecological mechanisms embodied in ALFRESCO explain observed paleofire records. When reparameterized to reflect the range of climate-vegetation-fire relationships in the paleorecords, ALFRESCO will provide an improved evaluation of Alaskan fire-regime responses to future climatic change.
The proposed project builds upon several years of exploratory studies (Section 4) and takes advantage of the complementary properties of paleoecological and modeling approaches. We will use this integrative approach to investigate how climate and vegetation influenced the fire regimes of the Alaskan boreal ecosystems at centennial time scales during the late Holocene (defined here as the past 6000 years). This period encompasses both directional shifts (e.g., neoglacialion) and oscillations (e.g., the Little Ice Age (LIA) and warmer times before and after) in the regional climate (Section 4.1). Juxtaposing investigations in the Yukon-Old Crow Basin and Copper River Basin, regions with similar vegetation and physiography but contrasting fire regimes (Figure 1; Sections 4.1 and 5.1) and past climatic anomalies (Section 4.1), will allow us to examine a broad range of boreal fire-regime responses to differing temperature and moisture combinations. The proposed project covers a number of intimately-linked research elements, including improving the quantification of fire regimes from charcoal records through modeling charcoal-fire relationships on the modern landscape, reconstructing patterns and mechanisms of climate-fire-vegetation relationships using a coupled data-modeling approach, and simulating future fire regimes with an improved version of ALFRESCO. Each of these elements is at the forefront of ongoing research in the respective areas, and together they promise to substantially advance our knowledge of climate-fire-vegetation interactions of boreal ecosystems for the past, present, and future.

3. OBJECTIVES, TASKS, AND BRIEF JUSTIFICATION

The proposed research has two major components. Each by itself represents a critical step in improving the understanding of boreal fire-regime responses to climatic change.

COMPONENT 1 -- Document the temporal trajectories of fire regimes in contrasting regions to elucidate how boreal fire regimes varied in response to changes in growing-season temperature and moisture, focusing initially on the neoglacial transition and the LIA oscillation. This research component is guided by our previous research findings and the recent literature. First, our research and modern climatological analyses (Mock et al. 2001) indicate that the Yukon-Old Crow and the Copper River Basins have experienced contrasting climatic variations during the late Holocene (Section 4.1). Sediment records from these areas, therefore, will provide a wide range of climatic conditions for observing fire-regime responses and may also indicate the potential for climate-caused divergences in fire regimes of the future. Second, our high-resolution charcoal records < 20 km apart in the Copper River Basin (Section 4.2) show unique temporal patterns in fire occurrence, indicating the need for a larger sample size in order to detect fire-frequency changes at centennial time scales. A major innovation of the proposed work is the use of a statistical framework for field sampling to ensure our ability to detect changes in fire frequency at these time scales. The specific objectives of COMPONENT 1 are:

- Collect multiple lake-sediment cores from each study region, based on statistical criteria for detecting neoglacial and LIA-scale changes in fire frequency.
- Develop high-quality chronological control by using $^{210}$Pb, $^{137}$Cs and AMS $^{14}$C dating.
- Analyze (1) macroscopic charcoal to estimate fire occurrence, (2) pollen assemblages to reconstruct vegetation, and (3) chironomid assemblages, oxygen isotopes and trace elements to reconstruct
temperature and effective moisture.

- Derive composite records of fire-frequency regimes, vegetation, and climate for each study region. Compare records between climatic periods (focusing on periods defined by climatic transitions, especially neoglaciation and LIA oscillations) to assess fire-regime responses to changes in temperature and moisture.

- Compare fire-vegetation-climate relationships between the two study regions to test if the spatial patterns of fire regimes varied with climatic fluctuations.

**COMPONENT 2: Evaluate the ecological mechanisms underlying fire-regime responses to centennial-scale climatic transients.** This component has two modeling aspects.

**2a -- Improve parameterization of CharSiM in order to understand the consequence of fire-regime changes to sediment-charcoal records.** Interpretations of fire history from macroscopic charcoal records rest upon several untested assumption about charcoal production, transport, and deposition (Clark 1988b; Clark et al. 1996b; Whitlock and Anderson 2003). These assumptions can be explicitly evaluated using CharSiM, a simulation model that numerically describes the major processes affecting charcoal-based fire records (Section 4.4). To our knowledge, CharSiM is the first attempt to translate conceptual models of charcoal production and delivery into a numerical modeling framework. Its primary application in the proposed research is as 1) a tool for evaluating alternative fire-regime interpretations from the charcoal records, and 2) a means for translating ALFRESCO fire output into charcoal stratigraphies, so that ALFRESCO-simulated fire data can be compared directly with paleofire records. Parameterization of CharSiM has been hampered by the scarcity of empirical data on charcoal processes. The specific objectives of COMPONENT 2a are:

- Estimate charcoal production and shapes of charcoal dispersal curves by installing charcoal traps along transects perpendicular to the edge of experimental and natural fires in Alaskan boreal forests.

- Improve our understanding of within-lake secondary charcoal deposition using sediment traps deployed in lakes that had watershed fires of varying ages over the past 50 years.

- Compare charcoal in short sediment cores from lakes within and near recently burned watershed as a complementary approach to further inform our understanding of charcoal dispersal and deposition in relation to fires.

**2b -- Elucidate ecological mechanisms responsible for fire-regime shifts in the past and enhance the capacity of ALFRESCO to project future changes, using an iterative approach of data-model comparisons.** ALFRESCO simulations of vegetation and fire responses to climatic change offer insights into the ecological processes causing fire-regime shifts recorded by charcoal in lake sediments. For example, our pilot study shows that a LIA-climatic cooling could have led to a wide range of fire regimes, depending on the amount of precipitation and the trajectory of climatic variation. The results also demonstrate the importance of fuel dynamics in relation to the sequence of climatic events in determining whether there is a lag in fire response to climatic change (Section 4.5). Such information cannot be obtained from paleorecords alone but is crucial for interpreting the causes of reconstructed fire-regime shifts, particularly at centennial time scales. Conversely accurate paleorecords can help guide the modification/further development of ALFRESCO to simulate conditions different from modern. Our specific objectives are:

- Use historic records to parameterize and calibrate ALFRESCO to simulate fire-vegetation-climate interactions in the two study regions.

- Simulate fire-regime dynamics of the past 6000 years from paleoclimate, paleovegetation, and paleofire data. Inform and re-calibrate ALFRESCO with an iterative approach.

- Translate ALFRESCO-simulated fire regimes into stratigraphic charcoal records using CharSiM.
• Compare simulated and observed charcoal records and identify key spatial and temporal processes of fire response to climatic change. If necessary, modify and improve ALFRESCO to accurately simulate the effects of climatic transients with magnitudes greater than those of the historic record.

• Simulate potential 21st-century fire-regime dynamics, based on a suite of forecast climatic scenarios, using the modified and improved ALFRESCO version.

4. STATE OF KNOWLEDGE

4.1. The Regional Paleoclimate Framework

The evolution of Earth's orbit to aphelion during Northern Hemisphere summer led to neoglacial advances of Alaskan glaciers ~ 3500 BP (Calkin 1988; Calkin et al. 2001). Following a minor glacier recession about 2000 BP, widespread LIA advances began around 700 BP and continued through the 19th century (e.g., Wiles and Calkin 1994; Calkin et al. 2001; Wiles et al. 2002, 2004). New methods for deciphering climatic change from lake sediments (Hu et al. 1998, 2001; Abbott et al. 2000) reveal the climatic changes associated with these glacial fluctuations. The most detailed temperature reconstruction, in the northern foothills of the Alaska Range, shows patterns similar to these glacial records over the past 2000 years (Hu et al. 2001). Specifically, paired oxygen-isotopic analyses of abiotic carbonate and benthic-ostracode shells reveal three intervals of growing-season warmth: AD 0-300, 850-1200, and post-1800, the latter two corresponding to the Medieval anomaly and climatic amelioration following the LIA. The LIA culminated at AD 1700, when summer temperature was ~1.7 °C colder than present. Our recent analyses of chironomids and oxygen isotopes at Omega Lake near the Yukon-Old Crow Basin and at Moose and Grizzly Lakes in the Copper River Basin indicate that LIA-related fluctuations in summer temperatures occurred in the two study areas of this proposal.

Effective moisture increased during the Neoglacial period, as evidenced by the retraction of dune fields in NW Alaska (Mann et al. 2002) and by the rise of lake levels in the interior (e.g., Abbott et al. 2000). However, subsequent variations in effective-moisture appear to have differed between Alaskan subregions. For example, ostracode trace-element ratios in the northwestern Alaska Range suggest that the LIA was wetter than previous and following periods, and our new carbonate-δ18O data in northern interior Alaska also reveal a wet LIA. Ostracode assemblages near Anchorage (Forester et al. 1989) and diatom-inferred lake levels in the Copper River Basin (C. Bigler, W. Tinner, and F. S. Hu; In preparation) suggest decreased effective moisture during the LIA. Contrasting precipitation anomalies between areas north and south of the Alaska Range have also been documented from instrumental weather records (Mock et al. 2001, Fig. 1). The selection of the two study areas for the proposed research exploits these contrasting climatic histories to address fire-regime responses to a wide range of temperature and moisture combinations.

4.2. Climate-fire-vegetation relationships in boreal forests: temporal and spatial patterns in Alaska

Historic observations and paleoecological studies reveal spatial and temporal variations in the fire regimes of Alaskan ecosystems (e.g., Kasischke et al. 2002; Lynch et al. 2003). Fire records from the past 50 years document the relationships of fire occurrence to spatial variations in growing-season temperature and precipitation, elevation, aspect, vegetation cover, and lightning ignition (Kasischke et al. 2002). The Yukon-Old Crow Basin has the shortest mean FRI (81 years, <800 m in elevation) among the interior ecoregions. Though Kasischke et al. (2002) did not address the Copper River Basin, this region is known to have a long FRI compared to boreal forest regions of interior Alaska, as only 24 fires burning a total area of 4058 ha have occurred in this area since 1950 (Alaskan Fire Service, 2003).

Fire-regime responses to climatic variations after black spruce arrival ~6000 BP are not well understood. Lynch et al. (2004b) found that fire frequencies in the Copper River Basin increased with neoglacial temperature decreases and moisture increases. In contrast, data from interior Alaska showed no change at the neoglacial onset ~3500 BP (Calkin 1988; Calkin et al. 2001), even though millennial-scale shifts did occur around 2500 BP and 1500 BP at separate sites (Lynch et al. 2003, 2004c).
Existing reconstructions in Alaska suggest that the timing and direction of fire-frequency changes differed between ecoregions (Hu et al. 2005). For example, the dramatic fire-frequency differences between the Copper River Basin and the Interior (Alaska Fire Service 2003) probably did not exist until ~4500 BP (Fig. 2). In addition, millennial-scale shifts in fire frequency were asynchronous at sites within the same modern region north of the Alaska Range (e.g., FRI increased at Dune Lake and decreased at Low Lake within the late Holocene; Fig. 2). Furthermore, the temporal pattern of fire occurrence at four sites in the Interior and the Copper River Basin, including two sites only 20-km apart, are statistically independent at a wide range of time scales (Hu et al. 2005). This lack of synchrony indicates the importance of accounting for stochastic influences on fire occurrence before invoking climatic explanations for changing fire frequencies through time. Because of this variability, describing fire-regime shifts at centennial time scales requires the combination of fire records from multiple sites within a given region (Section 5.1).

Overall, existing paleorecords from Alaska illustrate: 1) short-term historic observations are too limited to reflect the wide range of possible fire-regime responses to climatic change, and thus predictions of future fire regimes may be problematic if models are constrained by modern climate-fire relationships, and 2) boreal fire regimes in different regions did not respond in parallel to past climatic change and will unlikely do so in the future. However, existing paleorecords from Alaska are inadequate for assessing spatial and temporal patterns of fire-regime responses to centennial-scale climatic change (of the late Holocene). The proposed research will use a rigorous sampling design to overcome these limitations and document fire history at the spatial and temporal scales necessary to improve our understanding of climate-fire relationships in boreal Alaska.

4.3. Statistical considerations for detecting changes in fire-frequency regimes

The use of sediment records to reconstruct past fire occurrence is a relatively recent field. To date, most attention has been placed on analytical methods for quantifying charcoal and identifying fire events in individual sediment records. Few researchers (e.g., Clark et al. 1996b; Lynch et al. 2003; Gavin et al. in review) acknowledge the statistical requirements for characterizing differences in fire regimes over time or space—a primary motivation of paleofire research. Existing studies have primarily relied on one to several sites (<<5) to describe the fire regime of one “study region” that represents a specific physical and/or biological domain. In Alaskan boreal ecosystems, where Holocene FRI is typically >100 years and highly variable, this approach is sufficient only for describing fire-frequency regimes at millennial and longer time scales (e.g., Lynch et al. 2003). Detecting fire-frequency changes at finer time scales (e.g., several centuries of the LIA) requires a more robust sampling approach with explicit statistical criteria.

A likelihood ratio test utilizing Maximum Likelihood Estimates (Clark 1996; Grissino-Mayer 1999) provides a means to test the null hypothesis that two distributions of FRI (i.e. fire-frequency regimes) are identical (Section 5.1). Populations can be discriminated based on a pre-determined confidence level (alpha) and a permutation test (for small sample sizes). This approach is more powerful than other non-parametric approaches (e.g. Kolmogorov-Smirnov test), but does not have a straightforward associated power calculation. The statistical power, the probability of correctly rejecting the null hypothesis, can be calculated based on a large number of comparisons (e.g., 1000) between populations from different fire-frequency regimes, at varying sample sizes (Fig. 3). The ability to detect changes in fire-frequency regimes depends on (1) the magnitude and direction of change, (2) the mean FRI at a site,
and (3) the number of sites representing a given region. We will use this information to design our sampling scheme (Section 5.1).

4.4. CharSiM: improving the interpretation of sediment-charcoal records and linking fossil-charcoal data with ALFRESCO

Testing the assumptions underlying interpretations of sediment-charcoal records is critical for understanding the accuracy of fire-history reconstructions. While modern studies of fire-charcoal relationships provide insight to fire-history interpretations (e.g., Whitlock and Millspaugh 1996; Clark et al. 1998; Higuera et al. 2005), their application is inherently limited by their site-specific nature. As recognized by the paleofire community (Whitlock and Anderson 2003), modeling offers a powerful means to assess the sensitivity of sediment-charcoal records to a variety of natural and analytical variables.

The CharSiM model was developed to inform our understanding of fire-charcoal relationships and to improve the accuracy of fire-history interpretations from sediment-charcoal records (Higuera et al. 2004b, 2004c). The model generates a charcoal stratigraphic record based upon the frequency, size, and location of fires on a simulated landscape, as well as parameters of charcoal production and dispersal, primary and secondary charcoal deposition, sediment mixing, and sediment sampling. It is parameterized to represent boreal forests, using empirical fire-size data from Alaska (Alaska Fire Service, 2003) and charcoal production/dispersal data from boreal forests in Canada and Siberia (Clark et al. 1998; Lynch et al. 2004a). One application of the model is to improve the understanding of methodological choices made in the analysis of charcoal records. For example, the accuracy of different analytical choices can be quantified because simulated charcoal stratigraphies can be analyzed with varying background smoothers and charcoal threshold values (Clark et al. 1996b; Long et al. 1998) to identify fire events, and these results can be compared to the “true” fire history that generated the charcoal record (Fig. 4).

The current version of CharSiM is limited by the lack of empirical data on charcoal production, dispersal and secondary charcoal transport. With insufficient data on these processes, the application of CharSiM, or any similar modeling effort, will remain limited. Consequently, COMPONENT 2a aims to
collect empirical data to improve the parameterization of CharSiM to more accurately represent modern processes of charcoal production and transport. It can then be used to derive stratigraphic charcoal records from ALFRESCO simulations of boreal fire-regime dynamics in relation to climatic and vegetational changes. This linkage will allow us to examine mechanistic processes connecting changes in climate and vegetation, to changes in fire regimes, to variations in sediment charcoal records (Section 5.5).

4.5. ALFRESCO: Investigating mechanistic processes in boreal-fire response to climatic transients

The use of ALFRESCO to simulate Holocene ecosystem dynamics provides opportunities to gain insight into climate-fire-vegetation interactions (e.g., feedbacks, lead-lag relationships), which cannot be determined directly from sediment records. Previous research with ALFRESCO highlighted both direct and indirect (through changes in fire frequency and extent) effects of climate on the expansion rate, species composition, and extent of treeline in Alaska (Rupp et al. 2000a, 2001). In addition, simulations of boreal-forest dynamics revealed that fire-frequency changes due to climatic variation, anthropogenic ignitions, and indirect effects of vegetation succession strongly influence landscape-level vegetation pattern, which in turn exerts key feedbacks to future fire regimes (Rupp et al. 2002; Chapin et al. 2003; Turner et al. 2003).

The ability of ALFRESCO to accurately simulate the spatio-temporal dynamics of the landscape, however, is greatly limited by the “calibration space” provided by the short period of historical data (e.g., fire observations, tree fire scars, weather records). This problem hinders accurate simulations across the range of variability in black-spruce ecosystems over the past 6000 years and anticipated for the future. The potential consequence is reduced model robustness to long-term biophysical trends (e.g., vegetation composition and distribution) and short-term environmental extremes (e.g., abrupt temperature change and drought).

Paleoecological records (e.g., pollen, charcoal, and climate proxies) provide an instrument for extending the observation period to encompass an expanded range of natural variability and increase model robustness. The relatively coarse temporal resolutions of ALFRESCO simulations match well with those of paleorecords. In addition, the input and calibration requirements of ALFRESCO (e.g., growing season climate, 

Figure 5. ALFRESCO-simulated area burned (A, C, D, &F) in response to hypothetical LIA summer temperature anomalies (°C) (B&E, thin wiggle lines are raw data partially based on Briffa et al. 1992, and thick lines 10-yr moving averages) and precipitation anomalies (30% above and 30% below present level for AD 1400-1650 and for post-AD 1650, respectively, in B; 30% below present throughout the period of post-AD 1400 in E).
vegetation composition, and fire frequency) can be met with sediment data.

A linked paleodata-model approach would: (a) increase our understanding of the underlying mechanisms and processes that drive boreal-fire response to climatic transients; and (b) improve our ability to simulate future response to forecasts of climatic warming. The utility of this approach is illustrated by our exploratory ALFRESCO simulations of fire responses to various hypothetical scenarios of temperature/precipitation variation in the past 1000 years (Fig. 5). Results show that a LIA climatic cooling could have led to a wide range of fire regimes, depending on the amount of precipitation and the trajectory of climatic variation. The area burned per year or per fire increased significantly during the LIA compared to during the past 150 years if a LIA cooling (by <1 °C) was coupled with decreased precipitation (by 30%), whereas these fire metrics decreased markedly if the cooling was accompanied by increased precipitation (by 30%). Furthermore, drastically different fire regimes may exist under the same climate, depending on the climate and fire regime of the preceding centuries. For example, area burned per year/fire was on average ~4X greater under a warm/dry climate preceded by cold/wet conditions than under the same climate preceded by cold/dry conditions (Fig. 5). This “legacy effect” occurred because cold/wet conditions diminished fire occurrence, leading to large contiguous patches of black spruce forests on the landscape and thus abundant flammable fuels that burned readily when climate became warmer/drier.

The first result contrasts with our preliminary paleoecological evidence for increased fire in cooler/wetter periods (Sections 2 and 4.2). Resolving such differences between paleodata and ALFRESCO simulations requires rigorous documentation of fire frequency and paleoclimatic change during the LIA, combined with a mechanistic assessment of the ecosystem processes driving vegetation and fire responses. The intensive sampling, unique sediment analyses, and data-model linkages of the proposed research are designed to meet these requirements.

5. Proposed Research

5.1. Strategies for selecting ecoregions, lakes, and core subsampling

5.1.1. Ecoregions. Our study areas correspond to the Copper River Basin and Yukon-Old Crow Basin ecoregions of Nowacki et al. (2001).

Three factors guided our choice of study areas: 1) Because ecoregions are defined by similar vegetation, physiography, climate and other factors, they can be considered homogeneous sampling units for the statistical purposes; 2) The black-spruce dominance and similar physiography of these areas imply that fire-vegetation interactions and the effects of landscape factors on fire regimes should be similar. Thus between-region differences in fire regimes can be attributed directly to climatic differences; 3) The contrasting patterns of modern fire regimes and climatic anomalies of these areas provide an opportunity to explore how a wide range of temperature and moisture combinations affect boreal fire regimes.

5.1.2. Lake sampling. Lake-sampling is
Lake Sampling: Based on Figure 3, 22 and 11 lakes are needed to detect changes in fire-frequency regimes at LIA-time scales in the Copper River and Yukon-Old Crow Basins, respectively. Fortunately, short cores (7.6 cm diameter, 1-1.5 m long, equivalent to the past ~1200 years) can be used to examine the LIA climatic oscillation, and several lake records are already in hand from the Copper River study area. Assuming 2000 year windows for neoglacial fire-regime changes, 5 long cores will be required in the Copper River Basin and only 2 long cores in Yukon-Old Crow Basin. Based on the 95th-percentile fire size observed in the modern fire-size record (≈ 360 km²), sites will be a minimum of 21 km apart to assure that multiple lakes do not record the same fire events (and thus pseudo sample fires).

Core Subsampling and Description: Cores will be sliced in 0.25-cm thick sections using a fine-interval, core-sampling instrument. Previous research indicates that 0.25 cm should represent ~10 yr of sediment accumulation, although the actual temporal resolution may be doubled because of sediment mixing. Each 0.25-cm section will be subsampled for charcoal analysis. Subsamples for pollen and geochemical analyses will be removed at variable intervals, as needed (contiguous samples at transitions and at larger intervals for less dynamic periods).

Core Subsampling and Description: Cores will be described in the laboratory and measured for magnetic susceptibility (roughly correlated with the inorganic content of lake sediments), as well as organic and inorganic carbon.

5.2. Geochronology

Age models for each sediment core will be based on ¹³⁷Cs, ²¹⁰Pb and ¹⁴C measurements. ²¹⁰Pb and ¹³⁷Cs analyses will be used for ≤ 150 year-old sediments and AMS ¹⁴C for older sediments. We will target terrestrial plant macrofossils, including macroscopic charcoal (<180 µm), which provide the most reliable ages (Lynch et al. 2004b; Oswald et al. in press) and should be abundant through the late Holocene. AMS ¹³C dating efforts will benefit through the collaboration of Dr. Thomas Brown (see attached letter). Dating the Copper River Basin sites will be greatly aided by tephras (e.g., “White River Ash”) that are common in lake sediments of that region (Hu personal observation).

5.3. Reconstructing climate, fire, and vegetation shifts based on sediment records

5.3.1. Climatic Reconstructions. We will use the quantitative proxy-temperature data from δ¹⁸O and chironomid assemblages to assign four temperature classes (Rupp 2000a, 2000b) for ALFRESCO. These data in conjunction with trace-element ratios will help differentiate the signals of moisture vs. temperature so that relative moisture classes can be assigned. Since the temperature and precipitation classes of ALFRESCO have defined effects on vegetation and disturbance, a complete climatic record (i.e., explicit growing-season temperature and precipitation values) is not required. Similarly, because ALFRESCO uses climate to drive ecosystem changes, only climatic trends (i.e., departures from the norm) are
important. State-of-the-art techniques, anchored by modern calibration studies, will be used to extract information on past summer temperature and effective moisture.

**Modern Calibration:** We will evaluate each proxy indicator by comparing proxy data from $^{210}$Pb- and $^{137}$Cs-dated records to instrumental weather data, as we have done for carbonate $\delta^{18}$O at a site near the Yukon-Old Crow Basin. In the Copper River Basin, the calibration study will be further bolstered by a 400-yr summer temperature reconstruction from tree-rings (Davis et al. 2003). Because accurate paleoclimatic interpretations of isotope data depend on understanding the unique limnological and hydrological characteristics of each lake, we will study the hydroclimatological controls on the modern isotope budgets by analyzing water samples from the lakes, inlet and outlet streams, and precipitation for $\delta^{18}$O and $\delta^D$. We will engage local residents to collect precipitation and lake-water samples for the analyses of $\delta^{18}$O and $\delta^D$ time series to establish local meteoric water lines and to assess relationships among $\delta^{18}$O and $\delta^D$ and atmospheric temperature.

### 5.3.1.1. Chironomid assemblages

Analysis of midge (chironomid, chaoborid, and ceratopogonid) assemblages is the “most promising biological method for reconstructing past temperature” (Battarbee 2000). Midge larvae are highly sensitive to summer lake-water temperature, which mirrors air temperature in lakes without string thermal stratification, and fossil midge assemblages preserved in lake sediments have been used extensively to quantify temperature changes (e.g., Levesque et al. 1997; Brooks and Birks 2001; Palmer et al. 2001; Porinchu et al. 2003; Larocque and Bigler 2004). Transfer functions of July temperature and other variables were recently developed for Alaska and adjacent regions (e.g., Walker et al. 2003; Barley 2004), and they will be utilized in the proposed research. We recognize that the statistical uncertainty of midge-temperature transfer functions may hamper quantitative temperature reconstructions. However, a number of studies from high altitude and latitude regions demonstrate the ability of this proxy to provide reliable quantitative reconstructions of Holocene temperature variations (e.g., Pellatt et al. 1998; Rosen et al. 2001; Seppä et al. 2002; Heiri et al. 2003). Our own pilot study using midge assemblages at several Alaskan sites reveals both the cooling trend from early to late-Holocene (Higuera et al. 2004a) and striking signals of LIA-related temperature oscillations (Clegg, Walker, and Hu, unpublished data).

### 5.3.1.2. Oxygen isotopes

The second approach for estimating summer temperature combines $\delta^{18}$O of benthic ostracodes ($\delta^{18}$O$_{bo}$) and the oxygen-isotope composition of inorganically precipitated carbonates ($\delta^{18}$O$_c$) (Kelts and Talbot 1990). This approach was recently applied to quantify temperature changes during the last 2000 yr in the Alaska Range (Hu et al. 2001). $\delta^{18}$O$_c$ indicates summer-epilimnion conditions, because carbonate precipitation occurs in the uppermost water layers due to increased photosynthetic CO$_2$ uptake and warmer water temperature (Kelts and Hsu 1978). $\delta^{18}$O$_c$ is thus determined by both lake-water $\delta^{18}$O and epilimnion-water temperature. Although $\delta^{18}$O$_{bo}$ also indicates growing-season conditions for the ostracode taxa that calcify during the summer (Delorme 1969, 1991), it reflects lake
water $\Delta^{18}O$ and is largely independent of surface water temperature. As a result of these differences in controlling factors, $\Delta^{18}O$, and $\Delta^{18}O_{bo}$ can be compared to isolate a temperature signal.

5.3.1.3. Trace elements. Together with stable-isotope analysis of the same samples, the trace-element composition of ostracode shells offers a powerful means to tease out effective-moisture vs. temperature signals (Chivas et al. 1985, 1986; Ito 2002). The trace-element chemistry of lake water is a sensitive monitor of climatic changes. In particular, when the water concentration of Ca is held constant by the inorganic precipitation of calcite, increased aridity should result in increased Mg/Ca and Sr/Ca ratios. This relationship exists because Mg and Sr concentrations are undersaturated with respect to the mineral forms commonly precipitated within lakes and thus become elevated when drought severity increases (Chivas et al. 1985, 1986; Engstrom and Nelson 1991; Hu et al. 1998; Ito 2002). These changes in water chemistry are recorded in the calcitic shells of ostracodes, as ostracodes incorporate trace elements into their shells in proportion to their concentrations in the host water. Effective-moisture signals from these trace-element ratios can be verified independently with $\Delta^{18}O$ data from the same samples.

5.3.2. Reconstructing fire-regimes.

We will use statistical approaches to quantify two key components of fire regimes that have direct links to climate: (1) fire frequency, and (2) presence or absence of synchrony in fire occurrence across multiple sites at $\geq$100-year time scales.

Estimates of local fire occurrence will be used to calculate FRI, which will then be grouped into populations based on time periods and/or geographic regions. This grouping assumes that the characteristics of each time and/or space domain are similar, an assumption that is testable using our paleoclimate and paleovegetation proxies. For example, we might group all FRI at sites in the Yukon-Old Crow Basin from years that define a climatic periods of interest (e.g. LIA and Medieval Warm Anomaly). For each population, FRI will be fit with a Weibull model using Maximum Likelihood Estimation (e.g. Clark 1989; Lynch et al. 2003) and differences in Weibull parameters tested for statistical differences. Fire occurrence data will be used to test for synchrony in fire timing across groups of sites using a modification of the bivariate Ripley’s $K$-function (Gavin et al. in review). This

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**Macroscopic Charcoal Analysis:** Sediment charcoal will be prepared, identified and quantified using standard methods (Whitlock and Anderson 2003), with background charcoal estimated using a center-weighted running average that is robust to outliers (e.g. rLOWESS filter) over a to-be-determined time period. Positive residuals will estimate the peak charcoal component (Carcaillet et al. 2001; Gavin et al. 2003a; Lynch et al. 2003, 2004b). Charcoal peaks will be identified based on a sensitivity analysis (e.g., Gavin et al. 2003a; Lynch et al. 2003), and on comparisons to recent known fire events. These methods will be modified as necessary, depending on the insights from and techniques developed in the CharSiM modeling component of this study.

**Weibull Distributions:** A likelihood ratio will provide a test statistic to test the null hypothesis that the Weibull A and B parameters for each population are identical, using a permutation test to assess statistical significance. This method is similar to techniques used by Clark et al. (1996) and Lynch et al. (2003), but it provides a more powerful statistic for discriminating between distinct populations and allows us to state the power of our test, given that the null hypothesis is not rejected.

**Synchrony:** The bivariate Ripley’s $K$-function will be used to evaluate records for synchrony over multiple time windows ($\geq$ 100 yrs.) to identify the temporal scale of synchrony (e.g. 500 years vs. 1000 years). We will perform synchrony analyses individually for millennial-scale time periods for which paleoclimate proxies indicated distinct climatic regimes. Comparing results at sites within and between our study regions will provide information about the spatial scales of synchrony, if it exists.
Vegetation Reconstructions: Pollen assemblages in each sediment sample will be compared to modern pollen samples from the PAIN database (>400 sites in Alaska, Bigelow et al. 2003). Based on site location, each modern sample will be assigned to a corresponding ecoregion. The 10-20 modern samples (lakes) most similar to fossil samples will be used to assign fossil samples to a modern ecoregion. Past vegetation changes will be detected when the closest modern analogues change between ecoregions.

5.3.3. Reconstruction vegetation. The characteristics of past boreal forests at the ecoregion scale will be reconstructed using analogue analyses, a widely applied approach to quantifying the similarity of fossil and modern pollen assemblages (e.g., Anderson et al. 1989; Gavin et al. 2003b).

5.4. Modern processes of charcoal production, dispersal, and deposition
Charcoal production and dispersal processes will be measured both directly and indirectly through (1) experimental and wildfire monitoring and (2) comparisons between charcoal in $^{210}$Pb/$^{137}$Cs-dated recent sediments and known fire history.

During each fire season over the next three years, we will sample 1-4+ fires in boreal Alaska. We have communicated with Karen Murphy (U.S. Fish and Wildlife Service, regional fire ecologist; see attached letter), who has agreed to allow us to access and sample prescribed and wildland fires on Fish and Wildlife Service-managed lands, given appropriate circumstances. We will sample fires located in black spruce or black and white spruce forests with minimal relief and “typical” fuel loads and site characteristics. Ideally, there will be abundant and/or distinct natural fuel breaks (e.g. rivers or lakes) or other characteristics that will facilitate predicting the fire edge. For wildland fires, information provided by the Alaska Fire Service (e.g. fire maps, estimates of fire intensity, fuel types, and weather conditions) will help determine which fires to sample and when sampling will take place.

Our site selection for sediment cores will take advantage of fires that have occurred during the past 50 years, as documented by the Alaska Fire Service, particularly in the Yukon-Old Crow Basin. $^{210}$Pb/$^{137}$Cs dating will facilitate comparisons between the timing, size and location of known fire events to the timing, presence/absence, and size of charcoal peaks in the sediment records (e.g., Lynch et al. 2004a; Higuera et al. 2005). Given the proposed sampling for short cores (Section 5.1), we anticipate being able to sample a variety of fire sizes and fire distances. In total, we propose to collect at least 10 short cores from lakes that have experienced a nearby fire within the last 50 years. In these lakes we will also measure secondary charcoal deposition by setting up sediment-traps in the center of each lake. Data from sediment traps can be directly compared with charcoal accumulation rates from further down core, corresponding to local fires, and with charcoal accumulation from experimental and wildland fires.
## 5.5. ALFRESCO modeling and integration with paleo-data

We will address five main modeling objectives specific to ALFRESCO. **First**, we will parameterize and calibrate the model for our two study regions. This is a straightforward and necessary task required before any simulations can be conducted. The initial model calibration will be based on historic observations and contemporary empirical relationships. **Second**, we will perform simulations of the past 6000 years based initially on the modern calibration. We will utilize a portion of the paleorecord to inform ALFRESCO and provide reasonable initial conditions (i.e., vegetation composition, fire frequency, and growing season climate) for the model “spin-up” process. Driving climate datasets will be generated from the paleoclimate record. The **third** objective, assessment of these simulations, will be carried out in two ways: (1) a simple comparison of fire frequencies between the model output and the charcoal record, and (2) generate charcoal stratigraphy from the simulation results using CharSiM. This component requires modifications to account for the different spatial scales of ALFRESCO (1 km$^2$) and CharSiM (0.1 km$^2$), but once done,

| Model Calibration: The model will be calibrated to species-specific stand age distributions (Yarie 1981; Rupp et al. unpublished data). A three-parameter Weibull distribution will be employed to model stand ages (Rupp et al. submitted). The Weibull distribution has been commonly employed in the fitting of both fire-frequency and time-since-last-fire data (Johnson 1979, 1992; Grissino-Mayer 1999). We will use Maximum Likelihood Estimation to estimate model parameters. Our calibration will aim to match both the observed fire regime (1950-2003) and current vegetation (based on AVHRR remotely sensed data), under current climate conditions. Model ‘Spin-up’: A 1000 yr ‘spin-up’ simulation will be performed to allow for realistic patch size and age-class distributions to be generated over multiple fire cycles. We chose 1000 years because that represents five times the length of the longest reported fire frequency for these ecosystem types (30-200 yr; Yarie 1981; Van Cleve et al. 1991; Chapin et al. 2003). The ‘spin-up’ assures ecologically realistic initial conditions for our scenario simulations. Without this step the initial distribution and composition of vegetation and their associated ages may not conform to observations or basic ecological principles (Rupp et al. 2000a). We will use a small subset of the paleorecord to inform and initialize this step of the modeling process. The final (year 1000) vegetation and age maps from the ‘spin-up’ will serve as initial input for our various scenarios. **Current Climate-Fire Relationship:** The historic effects of climate on fire were computed using a two-parameter regression analysis similar to that used by Kasischke et al. (2002). We stratified interior Alaska by ecoregion (Gallant et al. 1995, Nowacki et al. 2001), climate (Fleming et al. 2000) and fire frequency (Kasischke et al. 2002). Fire frequencies and climate variables were computed directly (and respectively) from the Bureau of Land Management, Alaska Fire Service (AFS) large-fire database (Kasischke et al. 2002; http://agdc.usgs.gov/data/afs/fire/index.html) and monthly statewide maps of precipitation and temperature (Fleming et al. 2000; http://agdc.usgs.gov/data/projects/hlct/hlct.html). We performed this analysis statewide to ensure we captured the full spectrum of climate variability and to provide the ability to accurately simulate the response of the fire regime to a changing climate in a specific location. **Modifications to Climate-Fire Relationship:** The current model regression will be systematically modified in an attempt to produce simulation results that are similar to the paleorecord and that do not violate fundamental ecological/biological relationships. Once this is achieved we can compare differences between the historic and paleo algorithm and document the effects on landscape dynamics. |

| the simulated and observed sediment charcoal records can be objectively compared using statistical methods (e.g. a Kolmogorov-Smirnov test; e.g. Clark et al. 1996a). This entire process will be iterative and may require modifications to ALFRESCO before accurate simulations can be accomplished. **Our fourth** objective addresses this iterative process directly. We want to develop simulations that accurately reflect the paleorecords across the full range of documented climatic variation. Our goal here is to gain a better understanding of past climate-fire-vegetation interactions and improve the robustness of ALFRESCO for simulating forecast climatic warming scenarios. We know from previous research that ALFRESCO is sensitive to climate (i.e., a drought index that integrates growing-season temperature and precipitation), vegetation composition and distribution, and successional transition rates (Rupp et al. 2001, 2002). It is likely that climate-fire, climate-vegetation, and/or fire-vegetation relationships were different from modern empirical relationships. ALFRESCO provides the tool to test alternative relationships that can explain some of the mechanisms behind the paleorecords. CharSiM provides the assessment tool...
necessary to directly compare simulated landscape dynamics to charcoal stratigraphy. Modification of ALFRESCO to develop a more robust model will also serve to increase the accuracy and confidence in prognostic simulations of climatic warming scenarios.

Following the successful simulations of the past 6000 years, including relevant modifications, parameterizations, and calibrations, we will use ALFRESCO to simulate the potential landscape dynamics for the next century – our fifth objective. These projected future realizations (through 2100) will be based on a suite of spatially explicit climate scenarios as part of the recent Arctic Climate Impact Assessment (ACIA 2004). All the scenarios suggest strong directional warming and a general increase in precipitation, although the increased evaporation caused by warmer temperatures will likely offset higher precipitation and in many cases actually make soils drier. The climate scenarios represent significant departures from those experienced in the past 50 years. Understanding past system response to similar magnitude changes will be critical for the development of accurate simulations of the next century.

6. BROAD IMPACTS

6.1. Benefits to Society and Education

In addition to their far-reaching consequences on vegetational dynamics, biogeochemical cycling, and atmospheric chemistry, boreal fires have a wide range of societal, economic, and conservation implications at regional scales (Chapin et al. 2003, 2004; Bergeron et al. 2004). Understanding natural variability of fire regimes is critical for developing management guidelines (Cissel et al. 1999; Bergeron et al. 2001, 2004; Whitlock et al. 2003). Beyond the brief observational period, resource managers in Alaska must rely on fire-history dataset. The paleo-fire records from the proposed work should greatly enhance management’s knowledge base through expanding both the temporal and spatial perspectives of the existing sparse fire-history data set. Among our specific products, the prognostic simulations of the 21st century fire regime will provide information directly relevant to fire management planning and policy in a vast area of boreal forests (including the Yukon Flats National Wildlife Refuge).

The proposed project will advance the education of students and the general public. We intend to provide the intellectual, analytical, and financial resources for one postdoctoral, two graduate, and a number of undergraduate students. In particular, we will target students from groups under-represented in science to participate in this project. We have been successful in attracting such students to our research programs; e.g., Hu’s laboratory currently sponsors two female minority research fellows. The prospective postdoc (P. Higuera) is Hispanic American – he has been an integral part of our research team during the pilot study and preparation of this proposal. Higuera has demonstrated great promise as a scientist (see CV), and this project will facilitate his successful transition from an outstanding graduate student to an independent arctic researcher. In addition, Hu teaches introductory biology courses, and his lab routinely sponsors 10-20 honors students for undergraduate research each year. The proposed research will serve well to expose a large group of outstanding Midwestern students to the excitement of arctic research.

Beyond our direct impact on students, this project involves the collaboration of scientists from federal management units in Alaska (see attached letter from Karen Murphy, US Fish and Wildlife Service). This partnership will promote an improved understanding of the range of past, present, and future climate-fire relationships by federal and state natural resource managers.

6.2. Dissemination and Archival of Results

We will disseminate our research results at national/international meetings and through peer-reviewed publications. We will also work with relevant national/international programs (e.g., PARCS, International Multiproxy Paleofire Database) to make our data available to the broad research community in a timely fashion and produce educational materials for outreach to the general public. These products will be posted on our lab websites with links to national/international outlets, such as World Data Center for Paleoclimatology. We will also disseminate our research products to federal and state fire managers in Alaska, including the US Fish and Wildlife Service, Alaska Fire Service, and National Park Service.
REFERENCES CITED


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