Reconstructing fire regimes in tundra ecosystems to inform a management-oriented ecosystem model

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Abstract

We reconstructed fire history in one of the most flammable tundra ecosystems in Alaska, the Noatak River watershed, and interpreted records in the context of local vegetation change and regional climate. We also developed models linking monthly weather conditions to annual area burned in Alaskan tundra from 1950-2008. Both objectives served the additional goal of improving the Boreal ALFRESCO model, an ecosystem model representing vegetation change as a function of climate and disturbance by fire.

Fossil pollen records indicate that tundra vegetation in the Noatak study area showed subtle shifts over the past 6000 years, likely in response to previously-described millennial-scale variations in relative moisture (precipitation - evaporation). Different patterns between sites suggest that local factors modified the impacts of regional dryness ca. 4000 years ago and subsequent increases in relative moisture. Estimated fire return intervals (FRIs) since 6000 years before present (yr BP) varied from 30 to 720 years, with mean FRIs (summarized over 2000-yr periods) varying from 120 to ca. 500 years. These millennial-scale changes in mean FRIs were significantly linked to changes in vegetation, suggesting that white spruce, shrub birch, and grasses are associated with increased fire risk, whereas alder is associated with decreased fire risk. The taxonomic makeup of future tundra ecosystems, therefore, could have important impacts on fire risk. When characterized over the past 2000 years, estimated FRIs were shorter (average 134 yr [95% CI 109-162]) at warmer sites with greater tussock-shrub tundra abundance than at cooler, up-valley sites with a greater abundance of low shrub-tundra (mean FRI 295 yr [189-415]).

Results from modern fire-climate analyses indicate that annual area burned can be largely explained with climate variables representing summer temperature and precipitation ($r^2 > 0.83$). Models linking historical climate with tundra area burned in combination with estimated FRIs from the paleo data were used to parametrize tundra regions represented by the Boreal ALFRESCO model. Comparisons between historical simulation and the paleo record from the Noatak study suggest that the newly-informed Boreal ALFRESCO model provides improved estimates of tundra fire occurrence in the Noatak as compared to previous versions.

1 Background

Fire mangers in Alaska face significant challenges unique to this vast region. Alaska contains extensive ecosystems that are rare or absent from the contiguous United States. Arctic and subarctic tundra, for example, covers nearly one-third of the state, encompassing over 60 communities and 348 native allotments. Under warm, dry conditions tundra fuels are highly flammable, and over the past 60 years more than 2.3 million hectares (5.8 million acres) of Alaskan tundra have burned (Alaska Fire Service, 2009).

Despite the abundance of tundra fuel types, the empirical information on fire regimes required for fire and resource management in tundra is lacking. National fire initiatives such as LANDFIRE and Fire Regime Condition Class (FRCC) require knowledge of historic fire return intervals (FRIs) to make landscape-level fire and fuels management decisions, yet even this basic information is missing in virtually all tundra ecosystems.

Alaskan fire managers also face the unique challenge posed by climate-induced changes in vegetation and physical processes across tundra regions (e.g., Hinzman et al., 2005). Increases in shrub density documented over the past several decades (Silipaswan et al., 2001; Stow et al., 2004; Tape et al., 2006), for example, represent an important change to the fuel characteristics in tundra. Recent paleoecological evidence, which indicates high flammability of shrub tundra in the past (Higuera et al., 2008), also suggests the possibility that increasing shrub density could lead to increased area burned in tundra regions. A recent record-setting tundra fire, the 2007 Anaktuvuk River Fire, further highlights the potentially dramatic changes that climate warming could have on tundra burning (Jones et al., 2009; Hu et al., in revision). Thus not only are tundra fire regimes poorly understood, but their key vegetation and climate controls appear to be changing. These unknowns impose a major challenge to fire management efforts to anticipate the impacts of future vegetation and climate change on tundra fire regimes.

2 Project Objectives

The unique qualities of Alaskan tundra and our relative ignorance about fire regimes in this ecosystem pose special challenges for the design and implementation of landscape-level fire and fuels management. Confronting these challenges requires managers to understand the relationships between fuels, climate and fire and to consider landscapes in the context of historic variability. This project had three original objectives:

(1) Develop records of fire history in two of the most flammable tundra-dominated regions in Alaska (Seward Peninsula and Noatak River watershed) spanning the past 5000 years.

(2) Compare fire history records to both pollen-based vegetation records from selected sites and independent regional paleoclimate records to infer historic relationships between climate, vegetation, and fire regimes.

(3) Use newly-developed information on the drivers of tundra fire regimes to refine the tundra component of Boreal ALFRESCO, an increasingly-used ecosystem model designed to aid Alaskan land managers in assessing fuels and fire hazards.

Modified objectives The original objectives have been mostly achieved, but field work during Year 2 dictated some modifications. After surveying over 100 lakes via remote sensing and aerial reconnaissance in the Bering Land Bridge study area (BELA), we were only able to identify one lake with the appropriate basin characteristics for developing high-resolution charcoal records (i.e., $<$ 10 ha surface area, $\geq$ 4 m in depth). It was apparent in the field, and later confirmed through laboratory analyses, that the three other lakes sampled in BELA were thaw lakes, which were young ($<$ 1000 yr), and had a large amount of sediment mixing, slumping, and/or discontinuous sedimentation. Unfortunately, the single non-thaw lake yielded a record that was only ca. 3000 yr old. Consequently, we include results from the four BELA lakes in this report, but we emphasize our results from the Noatak study region. As soon as the BELA samples were deemed inappropriate, we channeled our resources into two additional objectives:

(M1) Develop pollen records of past vegetation change at all four lakes in the Noatak study region (instead of two in each region) to infer climate-vegetation-fire relationships over the past 6000 (instead of 5000) years.

(M2) Inform and improve the Boreal ALFRESCO model (Objective 3) without paleo records from the Seward Peninsula, by building statistical models linking annual area burned in Alaskan tundra to climate for the period 1950-2008 CE (common era, aka AD). These models were used to modify climate-fire algorithm in Boreal ALFRESCO.

3 Study Location and Description

3.1 Noatak National Preserve

We reconstructed fire and vegetation history using pollen and high-resolution charcoal records from four lakes spanning a 50-km east-west transect in the western Noatak River valley (Table 1; Fig. 1-2). Raven, Uchugrak, Poktovik, and Little Isac are all small (3-6 ha), shallow to deep (5-14 m) lakes with small, intermittent inlet and outlet streams (Fig, 1, 3).

Regional fire history since 1950 (Fig. 2 B-D) suggests fire cycles for areas including the study sites from 175 to 193 yr (Kobuk Ridges and Valley Ecoregion, Kasischke et al., 2002; Joly et al., 2009) to 480 yr ("Noatak Lowlands" Gabriel and Tande, 1983). Fires burned within 1.7 km west of Raven Lake in 1972 and 1984, and 1 km east of Poktovik Lake in 1972, and a 1300-ha fire burned around Uchugrak Lake in 1977 and a 260-ha fire burned around Little Isac Lake in 1984 (Fig. 1; AICC http://fire.ak.blm.gov/predsvcs/maps.php, 10 February, 2010).

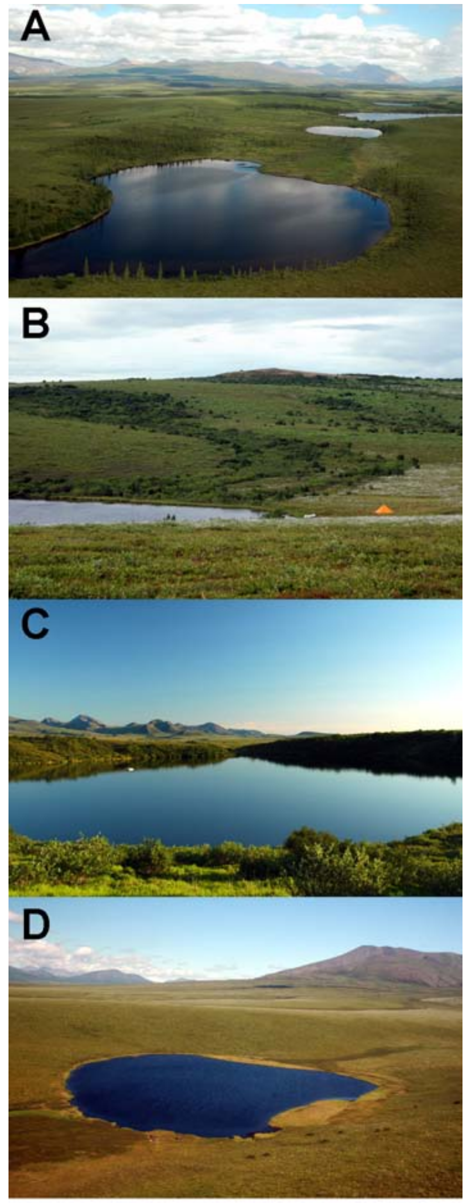

Fig. 1: **Landscape and vegetation surround each lake in the Noatak study area.** (A) Raven Lake, looking north, (B) Uchugrak Lake from the southern hillside, (C) Poktovik Lake, looking south/southwest towards the Noatak River, and (D) Little Isac Lake, looking northwest towards the Isacheluich Mountains. Photos by P. Higuera.

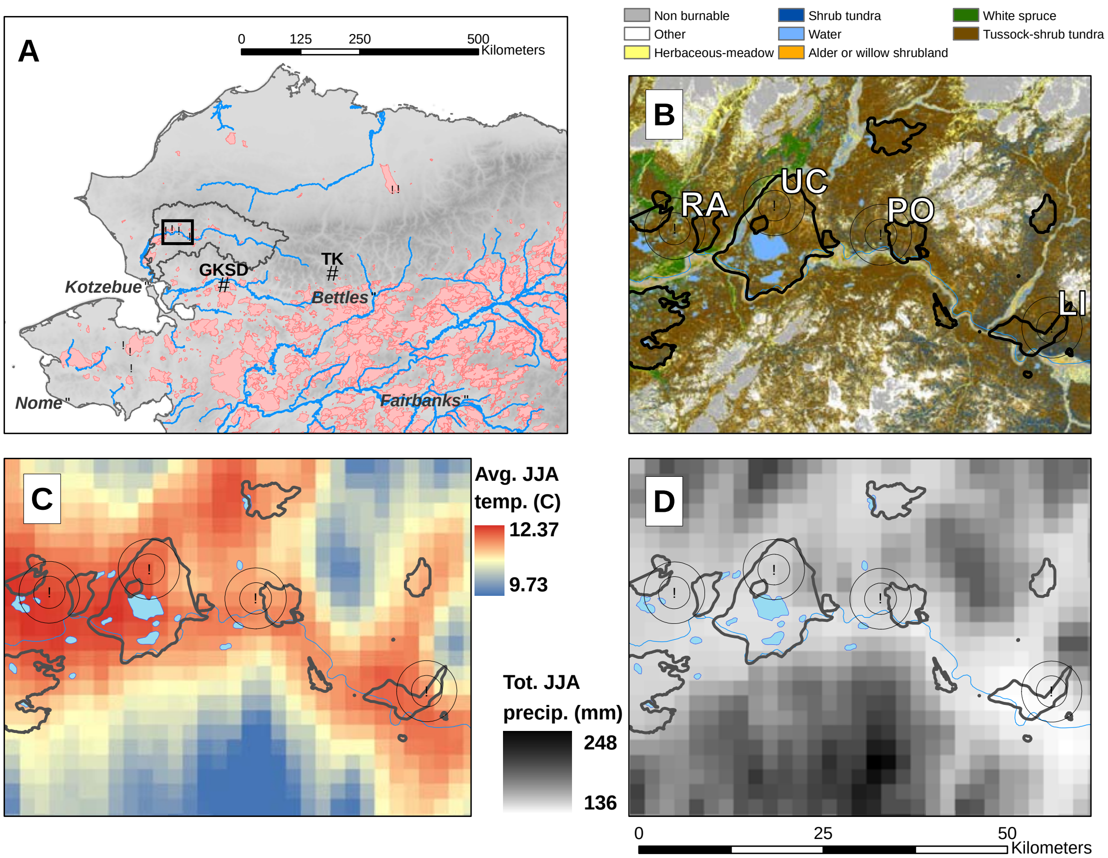

Fig. 2: **Regional location, local vegetation, and local growing season climate (June-August) for the Noatak River study area.** (A) Northern Alaska with rectangle identifying the study area within the Noatak National Preserve. Regional paleoclimate records referred to in the text are also identified: Great Kobuk Sand Dunes (GKSD; Mann et al., 2002) and Takahula Lake (TK; Clegg and Hu, 2010). Points of the Seward Peninsula identify lakes cored as part of this project; points on the North Slope, in the Anaktuvuk River Fire, identify tundra lakes cored as part of a complementary project. (B) Vegetation in the Noatak study area, summarized from Jorgenson et al. (2009) at 30-m resolution. Panel includes lakes used in this study, Raven (RA), Uchugrak (UC), Poktovik (PO), and Little Isac (LI), and perimeters of fires since 1950 CE (gray polygons; AICC http://fire.ak.blm.gov/predsvcs/maps.php, Feb 10, 2009). Circles around each lake have a 2- and 4-km radius, conservative estimates for the spatial scale of charcoal and pollen records, respectively. (C) June-August temperature and (B) precipitation at 2-km spatial resolution, as estimated by the Parameter-elevation Regression on Independent Slopes Model (PRISM). (C)-(D) also include features from (B).

Tab. 1: **Location and characteristics of lakes cored in the Noatak and Bering Land Bridge National Preserve.** Lake names are unofficial.

Lake Name	Latitude (N)	Longitude (W)	Elevation (m above sea level)	Perimeter (km)	Surface Area (ha)	Maximum Depth (m)
Noatak NP						
Raven	68° 00' 32.5"	162° 02' 08.5"	118	1.02	5.65	4.9
Uchugrak	68° 03' 07.4"	161° 43' 34.6"	216	0.84	3.69	9.2
Poktovik	68° 01' 54.4"	161° 22' 29.0"	160	1.33	6.30	13.4
Little Isac	67° 56' 27.9"	160° 47' 49.6"	210	0.71	2.93	5.4
Bering Land Bridge NP						
Laundry	65° 57' 48.1"	163° 52' 49.9"	72	0.73	3.05	3.3
Asinus Ears	65° 44' 31.5"	163° 20' 19.0"	485	0.56	1.52	3.0
Nimrod	65° 38' 20.6"	162° 59' 01.9"	261	0.82	2.35	3.0
Orion	65° 19' 38.4"	162° 49' 50.6"	244	0.53	1.84	6.9

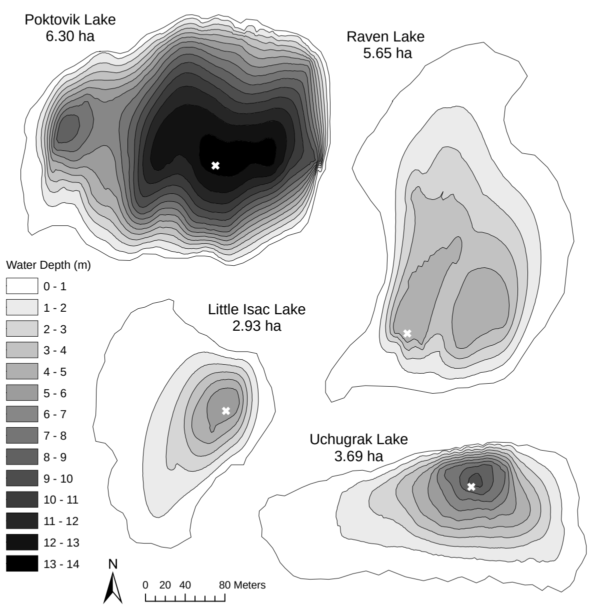

Fig. 3: **Bathymetric maps of each lake in the Noatak study area.** The approximate coring location is indicated by the white “x”.

Vegetation in the study area is dominated by tussock-shrub tundra, birch-Ericaceous shrub tundra, or willow shrub tundra types; white spruce also reaches its up-valley limit along the Noatak River and adjacent drainages. Local vegetation, within 2-8 km of each lake, differs slightly among sites, with generally a greater abundance of tussock-shrub tundra at down-valley sites of Raven and Uchugrak, and a greater abundance of low shrub-tundra at the up-valley sites of Poktovik and Little Isac lakes; white spruce is present only at Raven Lake (Fig. 4).

Based on the Parameter-elevation Regression on Independent Slopes Model (PRISM; 2 km^2 resolution, www.prism.oregonstate.edu/) data, average growing-season (June-August) temperature decreases and total precipitation increases slightly from down-valley (Raven) to up-valley (Little Isac) lakes (from ca. 12.25 to 11.90°C, and ca. 1.50-1.55 cm). The exception is Little Isac Lake, which has lower predicted precipitation than all other sites, despite being the furthest up-valley. This likely reflects a rain shadow from mountains to the southwest.

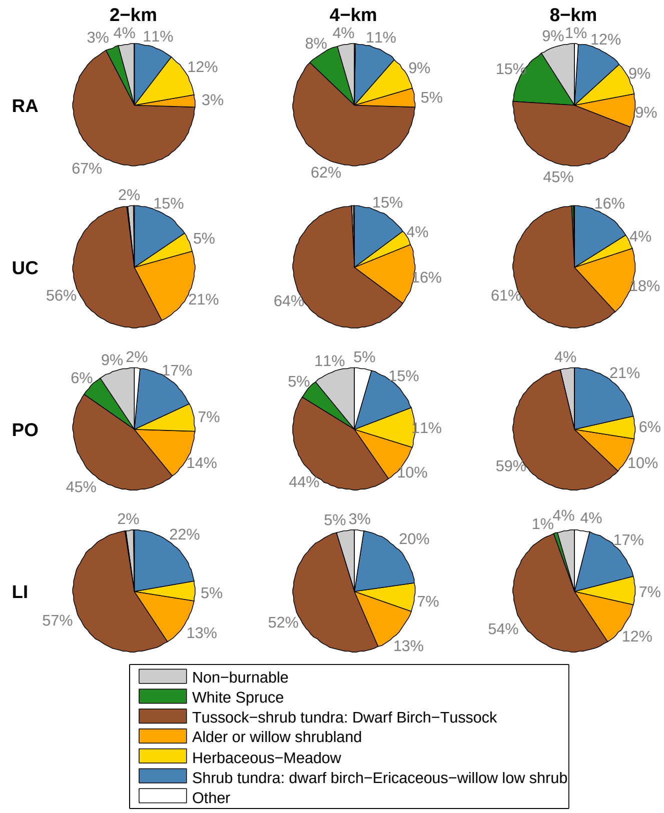

Fig. 4: **Vegetation around each lake in the Noatak study area.** Percent of general vegetation types around Raven (RA), Uchugrak (UC), Poktovik (PO), and Little Isac (LI) lakes, based on a current 30-m resolution vegetation map for the Noatak study area (Jorgenson et al., 2009). Each lake is shown in a row and the percent of vegetation is shown within a 2-, 4-, and 8-km radius around each lake. Note that Raven Lake (RA) has the highest percentage of tussock-shrub tundra and Uchugrak (UC) has the greatest amount of alder-willow shrubland at the 2-km radius.

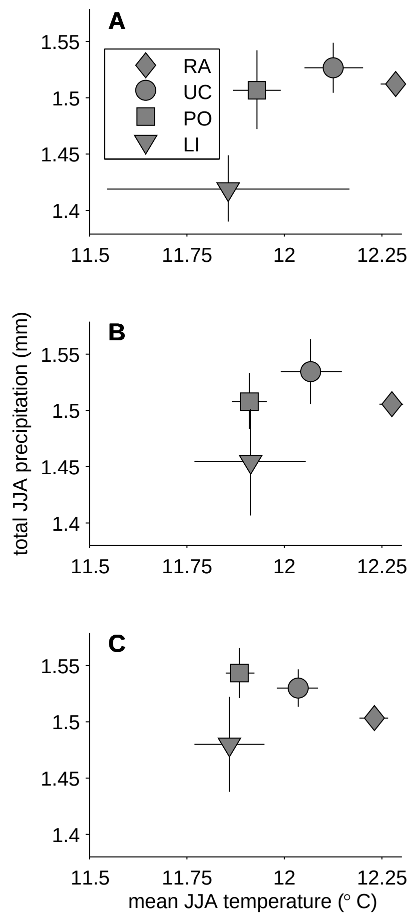

Fig. 5: **Growing-season climate around each lake in the Noatak study area.** June-August mean temperature and total precipitation, +/- 2 standard error units, as predicted by the PRISM dataset (see text) for (A) 2-km, (B) 4-km, and (C) 8-km radius around each lake. Lake codes are: Raven (RA), Uchugrak (UC), Poktovik (PO), and Little Isac (LI).

3.2 Bering Land Bridge National Preserve

The four lakes selected on the Seward Peninsula were located within the eastern/interior portions of Bering Land Bridge National Preserve (BELA; Fig. 2 A), BELA a cold, wind-swept landmass on the northern part of the Seward Peninsula. Vegetation is primarily tundra, with moist sedge-tussock shrub tundra communities at lower elevations and alpine Dryas-lichen tundra communities in the high mountains. Vegetation is primarily composed of sedge tussocks interspersed with scattered stringers of willows and dwarf birch. Patches of low-growing Ericaceous and willow-birch shrubs occur on better-drained areas. Isolated pockets of balsam poplar also occur within the region.

Summer temperatures on the coast are usually in the low 50's °F, with mid 60's to 70's and occasional 80's or 90's in the interior. Average January lows are -15° F on the coast and -50° F in the interior (Weather from NPS BELA web page). The four lakes that were selected to core were from north to south: Laundry, Asinus Ear, Nimrod, and Orion. Of the four lakes only Nimrod Lake sits within a recent fire perimeter (1977 Kugruk Fire, 261,909 acres). All lakes, except for Orion, are likely to be thaw lakes, which prohibit high-resolution fire history records.

3.3 Lake core sampling, and charcoal and pollen analysis

Fire and vegetation history were reconstructed from continuous records of charcoal accumulation and pollen from overlapping cores collected from each lake. Sediment cores were sliced at 0.25-0.5 cm intervals (c. 10-20 yr per sample) and subsampled for both charcoal and pollen analysis. Charcoal was identified at 10-40 X magnification from continuous subsamples of 3-5 cm^3 from every level. Samples were prepared by washing sediments through a 180-μm sieve and bleaching them for $<$ 24 hours (Higuera et al., 2009). Sediment samples of 1 cm^3 were prepared for pollen analysis according to standard procedures (Faegri and Iversen, 1975). Pollen was counted (400-1000 X magnification; terrestrial pollen sum $>$ 275 grains) at 250- to 500-year intervals to characterize past changes in tundra vegetation.

Chronologies for lake cores are based on a total of 158 samples of ^{210}Pb activity in the uppermost sediments and 53 AMS ^{14}C ages of terrestrial macrofossils from deeper sediments. ^{210}Pb portions were developed using the constant-rate-of-supply (CRS) model (Binford, 1990), and ^{14}C portions were developed base on calibrated ages (to years before present, 1950 CE) using the IntCal 04 dataset in CALIB v5.01 (Reimer et al., 2004; Stuiver and Reimer, 1993).

3.4 Inferring fire history from sediment-charcoal records

Charcoal concentrations were converted to charcoal accumulation rates (CHAR) based on sediment chronologies. CHAR time series were then separated into peak and background components, and a threshold was selected to identify peaks related to "local" fires (Higuera et al., 2009, 2010). Threshold selection criteria were applied consistently across all records, and criteria were determined based on statistical properties of the records and comparisons with documented fires.

Identified charcoal peaks were treated as estimates of local fire events, defined as one or more fires occurring within the 15-yr sample resolution, within ca. 1 km of each lake. This definition is consistent with comparison between the upper-most peak identified in each record, and documented fire history since 1950 CE. **At each site, estimates of fire events were used to calculate two metrics of fire occurrence: (1) fire-event frequency (fires events per given time intervals) and (2) the fire-event return interval (FRI; years between fire events). The lat-**

ter is a conservative estimate of a site-specific fire return interval, since the record may contain more than one fire within the 15-yr sample resolution.

FRIs were summarized in two ways. First, we plotted a time series of FRIs for each site, along with the 2000-yr mean FRI (+/- 95% CI). These time series illustrate if and how much fire regimes have changed over the past 6000 years. Second, we summarized the characteristic FRIs at each lake over the past 2000 years with the mean and median FRI, and parameters of a Weibull model fit to the distribution of FRIs.[1] Weibull distributions are commonly used to describe the frequency component of fire regimes, and they allow more powerful statistical tests than other methods (Johnson and Gutsell, 1994). Weibull models are also advantageous because they can be used to express the frequency component of a fire regime in several different ways, including hazard of burning, and the Weibull *c* parameter indicates if there is an increased probability of burning with time-since-fire (when $c > 1$). Weibull models were fit to each FRI distribution using maximum likelihood techniques (Johnson and Gutsell, 1994; Higuera et al., 2009).

To test for differences in FRIs across the study area, we compared FRI distributions for the past 2000 years between each site using a likelihood-ratio test (Johnson and Gutsell, 1994; Higuera et al., 2009). Statistically-similar distributions were combined into pooled distribution, and then pooled distribution were compared to test the null hypothesis of no difference.

[1] The time span of 2000 years is arbitrary: it is long enough to encompasses > 10 FRIs at most sites, but it is not too long so as to encompass periods of significant climate and/or vegetation change. We are not implying that climate and vegetation were static over this period, but rather, that this period represents a good trade off between the competing needs describe above.

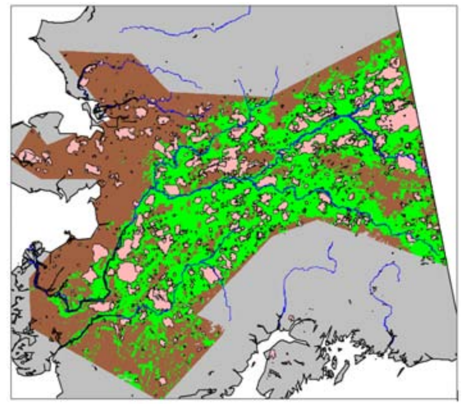

Fig. 6: **National Land Cover Database vegetation classifications for Alaska**. Forest and tundra vegetation is identified by green and brown, respectively, and fire perimeters from 1950-2004 are identified by light-red polygons. The overall domain of the NLCD coverage corresponds to the domain used for Boreal ALFRESCO simulations.

3.5 Modern fire-climate relationships and Boreal ALFRESCO

To improve the way Boreal ALFRESCO represents the link between climate and area burned in tundra vegetation, we constructed a model that predicts tundra area burned in Alaska from 1950-2008 CE based on monthly climate values. Two tundra classification (hereafter “domains”) were used for these models: (1) the National Land Cover Database (NLCD; Fig. 6; http://www.mrlc.gov/) , and (2) the Circumpolar Arctic Vegetation Map (CAVM; Fig. 7; Walker et al., 2005). The NLCD domain was used for consistency and efficient integration into the Boreal ALFRESCO model. The CAVM domain was used to isolate non-alpine tundra and limit the impacts of forest-tundra vegetation on climate-fire models

For both domains, historical monthly average temperature and precipitation data from the Western Region Climate Center (www.wrcc.dri.edu/summary/Climsmak.html)

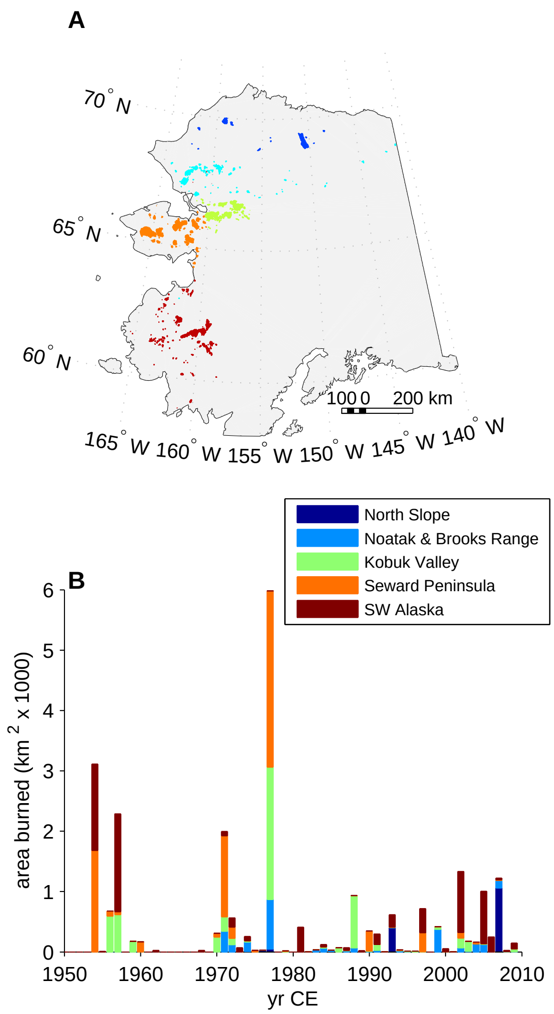

Fig. 7: **Alaskan tundra fires from within the Circumpolar Arctic Vegetation Map (CAVM).** Tundra area burned is stratified by Ecoregion (Nowacki et al., 2001) within the CAVM (Walker et al., 2005) in space (top) and time (bottom; 1950-2009). Compared to the NLCD dataset used for Boreal ALFRESCO, this dataset includes more areas of Arctic tundra but no alpine tundra from interior Alaska. Figure modified from Hu et al. (2010). ("CE" = common era, aka "AD")

were used to predict tundra area burned. For the NLCD domain, monthly temperature and precipitation from Bettles, Delta Junction, Fairbanks, McGrath, Nome, Northway, and Tanana were used (following Duffy et al. 2005). For the CAVM domain, average June through September temperature and precipitation from Barrow, Bettles, McGrath, Nome, and Kotzebue were used.[2] The larger spatial coverage of the NLCD domain is consistent with the footprint of the climate data used for the backcast (Modified Objective M2, see section 2) and eventual projections using future climate scenarios.

Tundra area burned was modeled using Generalized Boosting Models (GBM), applied in a way that accounts for stochasticity associated with the model-construction process. In general, the GBM approach seeks to minimize the discrepancy between the observed data (annual tundra area burned) and a proposed model (utilizing climate data).

To select the most important monthly variables, the following steps were repeated 5000 times. A random selection of 15 of the 59 years used in the analysis was removed before a GBM was developed. A GBM model was constructed and used to estimate values for the years not included in model construction. The importance of each explanatory variable (i.e., monthly climate) was stored, in a metric similar to the significance levels associated with explanatory variables in multiple regression analyses. This process results in a distribution of estimates for area burned for each year, and a distribution of estimates for the relative influence associated with each potential explanatory variable. The mean estimate of relative influence was computed across the 5000 iterations, and the four explanatory variables with the highest values were selected. These four variables were then used to fit a final GBM to predict annual area burned.

[2] This model was constructed as part of a complementary project investigating linkages between June-September sea-ice extent and tundra area burned (Hu et al., 2010).

The final GBM model serves two complementary purposes. First, it indicates which climate variables are the most important controls of historic tundra area burned. This information can be used to qualitatively, and eventually quantitatively, anticipate future fire seasons based on observed or predicted climate. Second, the climate-fire relationships contained within the GBM were directly implemented into the Boreal ALFRESCO model. Thus, tundra area burned in the model can now be determined by a tundra-specific climate-fire relationship.

4 Key Findings

Key findings focus on fire and vegetation history over the past 6000 years as inferred from the sediment records (4.1), and tundra fire-climate relationships from 1950-2008 CE and improvements to the Boreal ALFRESCO model (4.2).

4.1 Fire and vegetation history

4.1.1 Fire-event return intervals ranged from 30 to 720 years (Fig. 8)

Charcoal records from the Noatak study area provide unambiguous evidence of past burning at all sites, with estimated fire-return intervals (FRIs) ranging from 30 to 720 years (Fig. 8). Long term (2000-yr) average FRIs in many periods were statistically similar to those found in comparable studies from Alaskan boreal forests (Lynch et al., 2002; Higuera et al., 2009).

Charcoal records from Bering Land Bridge National Monument were not appropriate for high-resolution fire history information, with the exception of Orion Lake. At a minimum, the fact that charcoal was found in all cores indicates that biomass has burned in this study area for the duration of these records (Fig. 9).

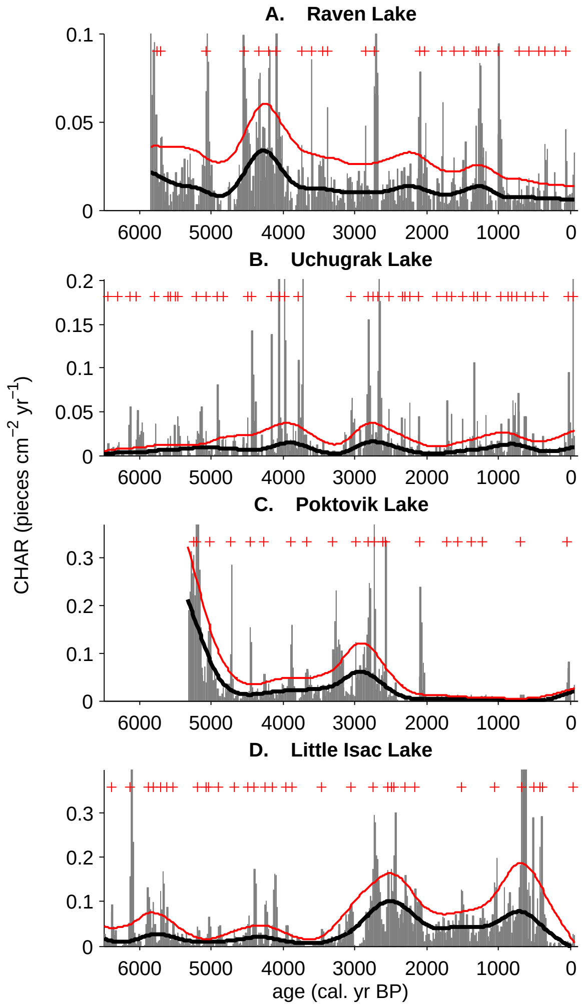

Fig. 8: **Charcoal records from the Noatak study area.** Samples are interpolated to constant, 15-yr intervals. The black line is the background trend, estimated with a 500-yr center-weighted moving average (robust to outliers), and the red line is the threshold value for peak identification. Samples exceeding the threshold are identified with a red “+” and were likely created from local fire events. The upper-most peaks at Uchugrak (B) and Little Isac (D) lakes correspond to historic fires in 1977 and 1984, respectively. The most recent identified peaks at Raven (A) and Poktovik (C) lakes predate the historic record.

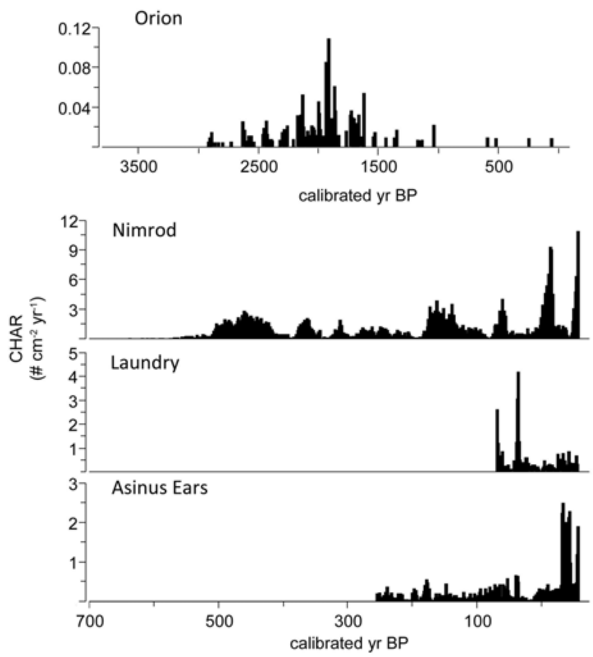

Fig. 9: Charcoal records from sites in the Bering Land bridge study area. Charcoal samples are interpolated to constant, 15-yr intervals. Orion Lake is the only lake with continuous, non-mixed sediments, and it suggests ca. eight fires between 3000-1500 years before present (cal. yr BP) with few if any local fires since 1500 cal. yr BP. The other three lakes are likely thaw lakes, confirmed by laboratory analyses and radiocarbon dating indicating either age reversals and/or sediment unconformities. These records are not appropriate for high-resolution fire history information. For example, the upper two peaks at Nimrod Lake are inconsistent with known fire history since 1950. Laundry Lake may record two fires since ca. 100 yr BP, and Asinus Ears may record 1-2 fires within the last 50 years, these interpretations are very tenuous.

4.1.2 Estimated mean fire return intervals for the past 2000 years vary between 140 yr (110-160) at down-valley sites and 260 yr (190-420) at up-valley sites (Fig. 10)

Over the past 2000 years, fire return intervals (FRIs) differed across the study area, with significantly shorter FRIs at two down-valley sites (Raven and Uchugrak lakes) compared to the two up-valley sites (Poktovik and Little Isac; Fig 10). The pooled distribution of FRIs from Raven and Uchugrak lakes had a mean and median (95% confidence intervals) of 134 yr (109-162) and 135 yr (105-150), respectively. In contrast, the pooled distribution from Poktovik and Little Isac lakes had a mean and median (95% confidence interval) of 295 yr (189-415) and 180 yr (150-465), respectively. The larger confidence intervals for estimates at the up-valley sites reflect the small sample size of 11 FRIs.Variations in FRIs between up-valley and down-valley sites are consistent with the modern temperature gradient across the study region (Figs. 2 C, 5).

4.1.3 Estimated fire-return intervals varied through time (Fig. 11)

Mean fire-return intervals (FRIs) for the last 2000 years do not represent the entire 6000-yr record. For example, at Poktovik Lake, FRIs have been increasing since 2000 years ago (Fig. 11), and at Raven Lake, FRIs have been slowly decreasing since 6000 years ago. From 6000 to 2000 years ago, the down-valley sites of Raven and Uchugrak experienced longer FRIs, and the up-valley sites of Poktovik and Little Isac experienced shorter FRIs, relative to recent millenia. These changes are well explained by changes in vegetation, described below.

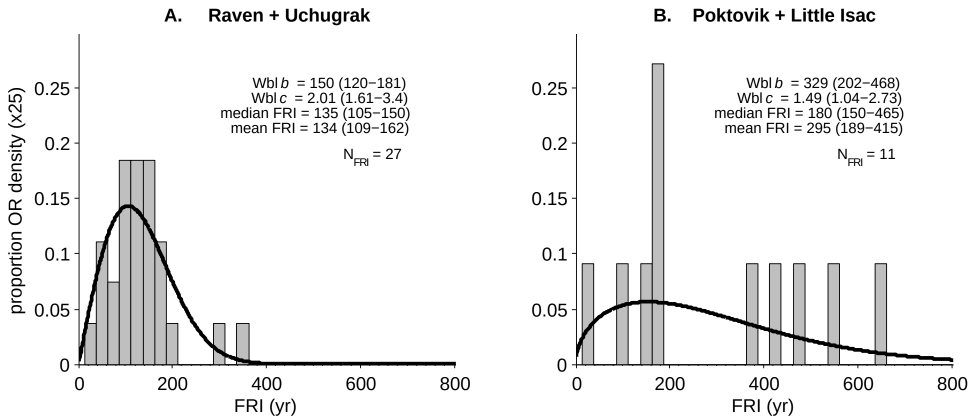

Fig. 10: **Fire return intervals from the Noatak study area over the past 2000 years.** (a) Pooled FRIs from Raven and Uchugrak lakes; (b) pooled FRIs from Poktovik and Little Isac lakes. Weibull model fit (via maximum likelihood techniques), and mean and median FRI are included fro each set of sites.

4.1.4 Tundra vegetation change over the past 6000 years was subtle and differed between sites (Fig. 12)

The regional expansion of white spruce ca. 3000 years ago is the only change in the tundra species composition in the study region, indicated in the pollen record by an increase in spruce percentages at all sites (Fig. 12; see also Anderson, 1985, 1988). White spruce expansion was likely in response to increased regional moisture, as indicated by a paleoclimate record in the central Brooks Range (Takahula Lake, Fig. 2 A; Clegg and Hu, 2010), and white spruce was never more abundant than on the modern landscape.

All other taxa have been present over the past 6000 years, and pollen records suggest subtle shifts in their relative abundances (Fig. 12). These shifts include increased relative abundance of grasses and sedges, and decreased relative abundance of birch and alder pollen. Pollen percentages at Little Isac Lake differed in several aspects: alder increased (ca. 4500 years ago), grasses decreased, and birch was consistently higher.

Differences between Little Isac and other sites imply that tundra vegetation in the Noatak study region did not respond uniformly to climatic variations over this period. These differences were likely caused by the similar site-specific factors that create vegetation differences across sties on the modern landscape (Figs. 2, 4), including micro-climate (Fig. 5), soils, and aspect.

4.1.5 Variation in vegetation was significantly correlated to fire history (Table 2)

Over the past 6000 years, fire frequency at millennial time scales were significantly correlated with pollen percentages of select taxa ($0.22 < r < 0.83$; Table 2).[3] When included as predictors in a multiple linear regression model, pollen per-

[3] Two lines of evidence suggest that vegetation change was influencing the fire regime, rather than the other way around. First, correlations compared vegetation for individual pollen samples, representing ca. 10-20 years, to fire frequency summarized in the surrounding 425-1000 years. It is unlikely that every pollen sample represented post-fire successional changes across all samples at all sites, as would be required for the vegetation record to reflect the impacts of fire on vegetation. Second, correlations were higher when comparing pollen samples to fire frequencies in time intervals *after* rather than before each pollen sample, suggesting that fire frequencies did not explain subsequent vegetation as well as vegetation explained subsequent fire frequencies.

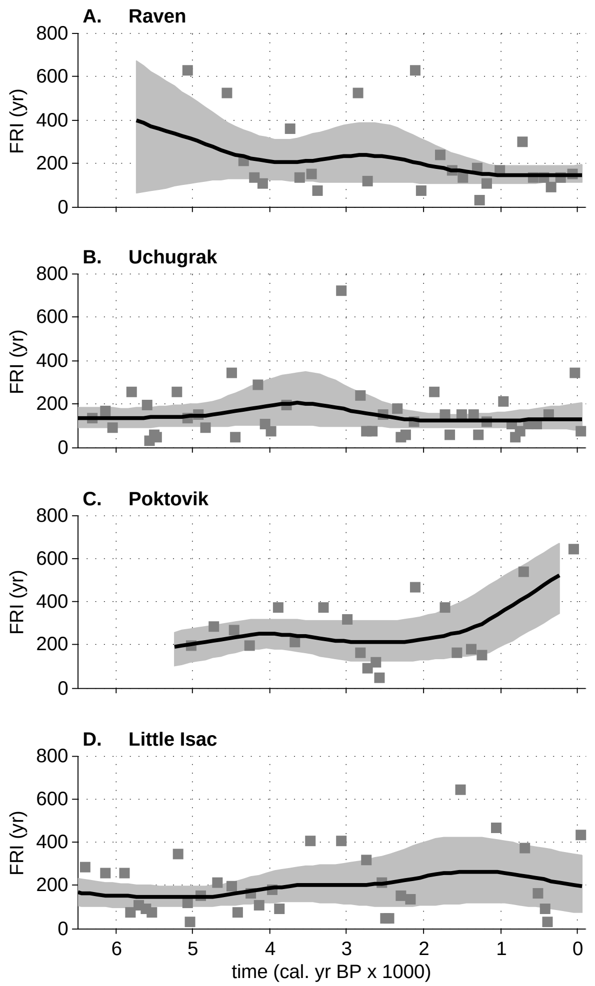

Fig. 11: **Fire-return intervals (FRIs) through time.** FRIs (gray squares) at each lake (A-D) in the Noatak study area with smoothed 2000-yr mean (black line) and 95% confidence intervals (gray shaded area). The mean FRI at any point in time is based on all return intervals within 1000-yr before and after the point; estimates within the first and last 1000 years, therefore, are extrapolated estimates based only on 1000 years.

centages of white spruce, birch, alder, sedges, and/or grasses explained between 17-83% of the variability in millennial-scale fire frequencies over the past 6000 years (Table 2). Spruce, birch, and grasses were positively related to fire frequencies, while alder and sedges were negatively related to fire frequencies.

4.2 Modern tundra fire-climate relationships and Boreal ALFRESCO

4.2.1 Monthly climate variables explains 83-88% of the inter-annual variability in tundra area burned (Fig. 13; Table 3)

The GBM models predicting tundra area burned from the NLCD and CAVM domains explained 83% and 88% of the inter-annual variability in the tundra area burned from 1950-2008, respectively (Fig. 13). Within the CAVM domain, which used average June-September temperature and precipitation, models predicting region-specific area burned generally performed as well or better than models for the entire domain (Table 3). This suggests that there is some regional variability associated with the response of tundra burning to a climate signal.

For the NLCD model, where monthly climate variables were not predetermined, the four explanatory variables with the highest relative influence were (in order): August temperature, January precipitation, July precipitation, and June precipitation. The NLCD-based model forms the basis for backcasts of tundra area burned for comparisons to the paleo data.

4.2.2 Tundra-specific climate-fire relationships and paleo data help improve the Boreal ALFRESCO model

The climate-fire relationships developed from the NLCD domain have been implemented into

Tab. 2: **Relationships between inferred fire frequency and pollen percentages over the past 6000 years.** Bold/italic values indicate $p < 0.05$; plain text indicates $p < 0.10$. For multi-taxa models predicting fire frequency based on pollen assemblages (bottom three rows), only taxa that did not co-vary and explained were included as potential candidate variables. For example, at Raven Lake, percentages of white spruce and birch pollen were significantly correlated; because white spruce is present at Raven Lake today, its increase represent an important change in local fuels and was thus included in the multi-taxa model whereas birch was not included. Taxa included in the final model are indicated by the asterisk (*) in the top five rows. For both correlations and multi-taxa models, relationships were evaluated over multiple time scales, but we present only those that maximized r^2_{adj} (Window$_{max}$cor).

		Raven	Uchugrak	Poktovik	Little Isac
Taxa-specific correlations	*Picea*	***0.83****	--	--	***-0.57***
	Betula	***-0.75***	-0.22	0.58*	0.55*
	Alnus	***-0.73***	--	--	***-0.56***
	Cyperaceae	--	0.45*	-0.63*	--
	Poaceae	***0.50****	--	--	0.70*
Multiple-linear regression model results	r^2_{adj}	0.83	0.17	0.54	0.68
	p_{adj}	0.002	0.009	0.002	0.004
	Window$_{max\ cor}$	2000 yr	750 yr	1000 yr	2000 yr

* Taxon selected for multiple linear regression model, based on forward-selection criteria.

Tab. 3: **Generalize Boosting Model (GBM) results linking climate and tundra area burned.** Coefficient of determination (r^2) for GBM models relating monthly or seasonal climate variables to annual tundra area burned in the National Land Cover Dataset (NLCD) and Circumpolar Arctic Vegetation Map (CAVM; Walker et al., 2005) domains. Composite climate data used for explanatory variables are described by location (i.e., climate stations) and time (i.e., months).

		Composite climate data	
Tundra domain	**Subregion***	Bettles-DeltaJunction-Fairbanks-McGrath-Nome-Northway-Tannana	Barrow-Bettles-McGrath-Nome-Kotzebue
		Mean Aug. temp., Jan., July, June precip.	Mean June-Sep. temp. and precip.
NLCD	All	0.83	--
CAVM	All	0.88	0.92
	Seward, SW Alaska	--	0.77
	North Slope, Noatak, Brooks Range, Kobuk	--	0.93
	Seward	--	0.99
	North Slope, Noatak	--	0.98
	SW Alaska	--	0.92

* Subregions correspond approximately to Ecoregions of Alaska.

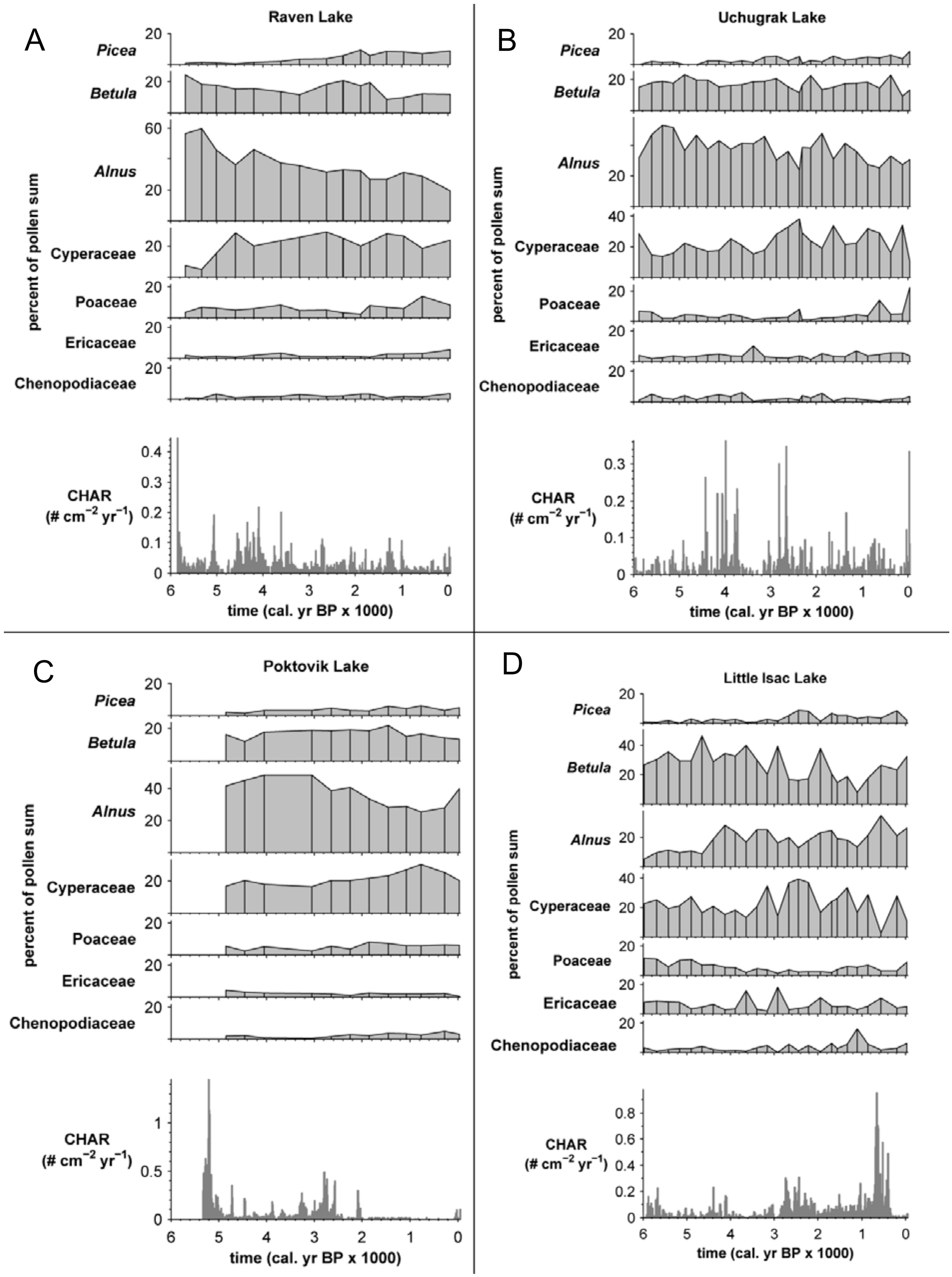

Fig. 12: **Pollen percentages of major taxa and raw charcoal accumulation rates from the Noatak study area.** Taxa include white spruce (*Picea*), birch (*Betula*), alder (*Alnus*), sedges (Cyperaceae), and grasses (Poaceae) at (A) Raven, (B) Uchugrak, (C) Poktovik, and (D) Little Isac lakes.

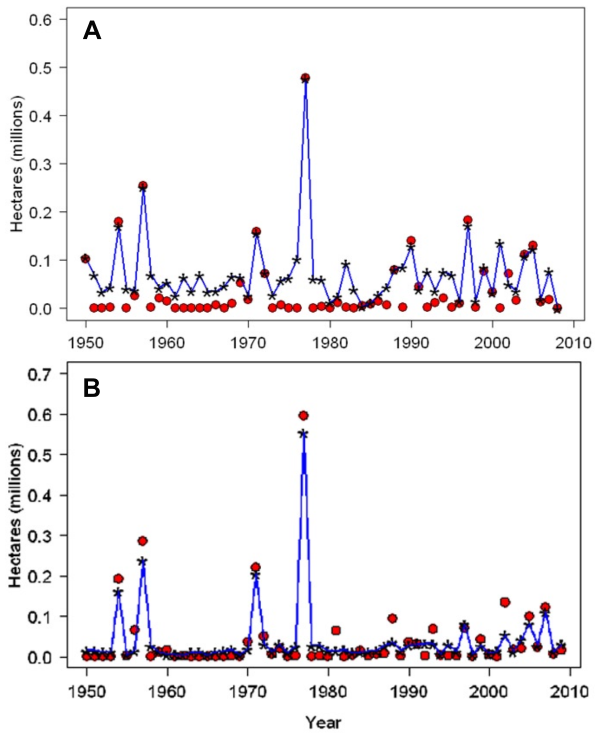

Fig. 13: **Predicted and observed tundra area burned, 1950-2008.** Annual area burned in (A) NLCD-defined and (B) CAVM-defined tundra regions in Alaska (red dots) and estimated area burned from the final GBM models (black asterisks). The NLCD model is based on August temperature and January, July, and June precipitation and explains 83% of the variability in annual area burned. The CAVM model is based on average June-September temperature and precipitation and explains 88% of the variability in annual area burned.

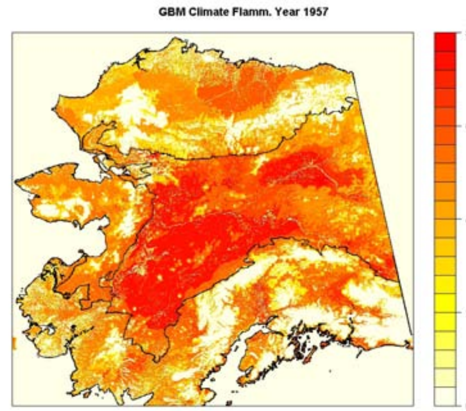

Fig. 14: **Flammability map from the Boreal ALFRESCO model.** Relative flammability (from 0-8) across Alaska in summer 1957, as represented by the GBM model in the Boreal ALFRESCO model. Areas of tundra, as defined by the NLCD dataset (Fig. 6), have burn probabilities that are defined independently of boreal forest vegetation.

Boreal ALFRESCO through flammability maps that account for fire-climate relationships specific to tundra (Fig. 14). These maps are used to determine the probability of tundra burning, given the same monthly input data used for the GBM model. Previously, the flammability for the entire Boreal ALFRESCO domain was determined from climate-fire relationships developed primarily for boreal forests.

Preliminary calibrations against observational and paleo records suggest that the new tundra-specific climate-fire relationships represent a substantial improvement with respect to tundra burning. For example, backcasts of tundra area burned to 1985 are generally consistent with modern records (Fig. 15). Site-specific fire-return intervals from the pixes in Boreal ALFRESCO representing Raven Lake also show improved agreement to actual data. Prior to implementing the new fire-climate relationships, these pixels burned with median return intervals > 500 years, significantly longer than what the paleo data suggest was the case at Raven Lake over the past 2000 years. After implementation of the new fire-climate relationships, median FRIs are $<$ 500 years. Further calibration is needed, and data-model comparisons (e.g., Brubaker et al., 2009) will help diagnose if and why there are discrepancies between Boreal ALFRESCO and the paleo data.

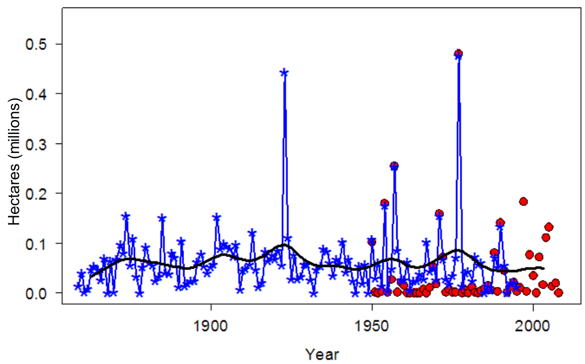

Fig. 15: **Backcast of annual tundra area burned from 1859-1995.** Backcasted values are presented as blue asterisks and historical data from 1950-2008 are presented as red dots for reference. Historical climate data used for the backcast come from the Potsdam Institute for Climate Impact Research (PICIR). This dataset is a modified version of that presented in (Leemans and Cramer, 1991). The modification is presented in McGuire et al. (2001) and covers the period 1859-1995. The black line represents a smoothed spline estimate of the decadal average of annual are burned.

5 Management Implications

Historic fire return intervals [Key Findings 4.1.1-4.1.3] The baseline information on historic fire return intervals from this study provides an important context for evaluating management strategies (e.g., suppression actions, management plans in the context of future change). This also helps fulfill requirements from the Department of Interior Fire Reports (Wildland Fire Management Information) and fuels project reporting in the National Fire Plan Operations and Reporting System.

Prioritizing fuels treatments for fire or property protection is often based on the likelihood of fire occurrence in an area, as judged by the historical record. For example, given that tundra areas in this study have experienced relatively short fire return intervals in the past, FMOs may shift priorities to treat these areas sooner than previously considered (e.g., Weddle, personnel communication, March 2010). Likewise, the estimated FRIs presented here will be important when developing prescribed fire plans for the lower Noatak watershed.

Although our study provides much-needed data describing fire return intervals (FRIs) within the study area, it is equally important that managers recognize FRIs varied markedly through time, and that tundra vegetation has been resilient to a wide range of fire return intervals over the past 6000 years. Long-term variability in FRIs implies that no single point or interval in time is any more meaningful or representative of a fire regime than others. Particularly in the context of ongoing environmental change, understanding the full range of historic variability in tundra fire regimes helps place ongoing and future change within context.

Subsistence resource management. In a recent publication on the Western Arctic Caribou Herd in Alaska, Joly et al. (2009) state:

> The management of wildfires is a contentious issue, not least of all because of its implications for caribou winter range. [Therefore] understanding the fire regime of this region and its impacts on the [Western Arctic Caribou Herd] will be critical information utilized in the development of a fire management plan for the winter range of the herd.

The concern over the impact of fire on caribou winter range has gone on for nearly 50 years (see Joly et al., 2003; Rupp et al., 2006). Caribou and reindeer utilize a high proportion of fruticose lichens (if available) in their winter diet, and some studies suggest that post-fire recovery of these lichens is fairly slow (15-40 yr) and that other species may invade areas once occupied by lichens (e.g., Racine et al., 2004; Jandt et al., 2008). Yet other studies have maintained that although wildland fire may result in short term impacts to caribou populations by destroying forage lichens, it may be needed in the long term to maintain high lichen productivity (Klein, 1982; Schaefer and Pruitt, 1991, as cited by Joly et al., 2003).

Currently land management agencies are considering more proactive fire management strategies to protect caribou winter range habitat, including wildfire suppression. Some agencies already have large areas designated with an elevated suppression response, to protect reindeer grazing allotments as well as other natural, cultural, and subsistence resources (Fire Management Plan for Western Arctic Parklands, National Park Service, 2004 [revised 2009].). This study provides information on the fire regimes in tundra ecosystems that can assist agencies in their decisions on fire management and potentially identify whether suppression actions have altered the natural fire regime in the area.

Both recent a analysis of fire cycles using current fire perimeter data (Joly et al., 2009) and sediment-charcoal estimates of fire return intervals (this study), indicate that fires are relatively common in the current winter and migratory ranges of the Western Arctic Caribou Herd. The paleo fire data suggests that if caribou utilized these areas over the past 6,000 years, then they have certainly co-existed with fire.

Response of tundra vegetation to climate change [Key Findings 4.1.4] Vegetation in the Noatak National Preserve, whether in the context of fire management or otherwise, should not be expected to respond uniformly to ongoing and future climate change. Site-specific and species-specific response to climate change is a common theme in retrospective studies (e.g., Lloyd and Fastie, 2002; Gavin et al., 2003; Oswald et al., 2003)g., and our paleo-vegetation records from the Noatak suggest that relatively close sites (e.g., within 50 km) can experience different directional changes over millennial time scales. In the context of ongoing and predicted vegetation changes in arctic tundra (e.g., Hinzman et al., 2005; Tape et al., 2006), historic variability implies that these changes will be accompanied by significant site-specific variability.

Vegetation-fire relationships [Key Finding 4.1.5] Climate change in arctic tundra is affecting taxa differentially (Chapin et al., 1995; Stow et al., 2004), and alder is one species that has been projected to increase (e.g., Sturm et al., 2001; Tape et al., 2006). These changes in fuels could have important impacts on the probability of future tundra fires. For example, paleoecological records from the south-central Brooks

Range suggest that increase abundance of shrub birch led to increased fire frequencies in the early Holocene, presumably by increasing the abundance of flammable fuels on the landscape (Higuera et al., 2008).

Records from the Noatak study regions suggest that (1) vegetation change in tundra will likely modify tundra fire regimes, and (2) the direction of this impact will depend upon the species composition of future tundra vegetation. Increased white spruce, birch, and grasses could increase fire risk, whereas increased alder may decrease fire risk.

Tundra fire regimes under future climate change [Key Findings 4.2.1-4.2.2] Land management agencies are hindered by a limited understanding of how future climate changes could impact fire regimes in Alaska. Models that links the impacts of climate and vegetation on fire regimes help understand potential future conditions, given alternative climate scenarios. Boreal ALFRESCO is one such model that is increasingly being used by Alaskan land managers in this context.

Prior to this study, Boreal ALFRESCO was under-predicting fires within tundra regions (Springsteen, in preparation). The improvements made in this study to the climate-fire relationship for tundra fires will make Boreal ALFRESCO more applicable in tundra ecosystems. This in turn will help land managers as they consider the impacts of increasing temperatures on tundra fire regimes and the cascading effects this could have on other ecosystem processes.

The climate-fire model developed in this study, primarily to inform Boreal ALFRESCO, does not allow for forecasts of upcoming fire seasons, because the model is built to simulate annual area burned give future (or historic) monthly climate variables. However, given that January precipitation was identified as an important predictor of tundra area burned, it is possible that predictive models could be developed specifically to forecast upcoming fire seasons in tundra ecosystems (e.g., Preisler and Westerling, 2007).

6 Relationship to Other Recent Findings

Results from the Noatak study area add to a growing body of evidence indicating that tundra ecosystems can burn frequently, with return intervals similar to those found in modern boreal forests (Higuera et al., 2008). The positive effect of birch shrubs on fire occurrence observed at the two up-valley sites in this study is also consistent with these paleo records from the early Holocene (Higuera et al., 2008; Tinner et al., 2008).

New to this study are the first estimates of fire return intervals (FRIs) in modern tundra ecosystems. Our estimated FRIs are generally shorter than those previously estimated based on a 25-60 yr observational record (Racine et al., 1985; Kasischke et al., 2002; Joly et al., 2009). These difference may reflect one or more of several possibilities: (1) stochastic variability in the relatively short period of previous analyses may have resulted in over estimates of the tundra fire cycles, (2) tundra fires may have been slightly more common prior to 1950 CE than since, and/or (3) charcoal-based FRIs may overestimate local fire occurrence. The limitations of sediment-charcoal records (Higuera et al., 2010) make them biased towards under-predicting fire occurrence (e.g., combining > 1 fire in one peak; missing peaks due to sediment mixing), suggesting that (3) is likely not the case.

Recent tundra fires in other regions of Alaska, e.g., the Anaktuvuk River (AR) Fire (Jones et al., 2009), have raised questions about the precedence of tundra burning in the past. Indeed, sediment-charcoal records from this research team indicate that the AR Fire was locally unprecedented within the last 5000 years (Hu et al., 2010). Thus, fire regimes in tundra ecosystems are clearly diverse, with some regions (e.g., the Noatak) burning as often as boreal forests, and others regions rarely burning over millennial time scales.

The climate-fire relationships quantified in this study are the first step to help understand the mechanisms creating spatial variability in tundra fire history across Alaska (and Arctic-wide). Largely, these relationships are consistent with many recent studies linking summer warmth and drought to fire occurrence in forested ecosystems (e.g., Duffy et al., 2005; Morgan et al., 2008; Balshi et al., 2009; Littell et al., 2009).

7 Future Work Needed

Our understanding on tundra fire regime is in its infancy. General principles of fire behavior from forest ecosystems apply to tundra ecosystems as well: e.g., strong linkages between weather, climate, vegetation, and fire occurrence. However, tundra fire regimes also display a great range of variability, both across the modern tundra landscape and in the past. It remains unclear to what extent this variability is due to climate alone, vs. the interactive effects of climate and fuels. Understanding the role that fuels play in affecting fire risk therefore remains an important research goal in tundra ecosystems. Limited evidence from the paleo record and little research otherwise suggests that variability in fuels could substantially change fire risk. For most practical purposes, tundra fuels are underrepresented in current operational models, and this further limits our ability to anticipate fire hazard and fire risk as both climate and vegetation change in tundra ecosystems.

8 Deliverables Cross-walk

The status of original deliverables and additional deliverables achieved in this study are listed in Table 4.

9 Acknowledgments

We thank numerous National Park Service personnel from the Western Arctic Parklands and Denali Fire Crew for logistical support and field assistance, Triet Vuong and Jennifer Beamer for lab assistance, and Mark Olson and Brendan O'Brien for ALFRESCO implementation.

Tab. 4: Deliverables cross-walk.

Deliverable	Description	Delivery Date	Status / Additional Deliverable
Cooperators Meeting	Present fire history records from first field season; request feedback from collaborators.	Winter 2008	Delivered, University of Illinois
Annual Report	Project status report to JFSP and agency partners	Spring 2008	Delivered
Study Site Data Delivery	Provide preliminary results of fire history records from first field season to agency cooperators.	Spring 2008	Delivered
Conference proceeding, poster presentation		Summer 2008	Higuera, PE, M Chipman, JL Allen, S Rupp, and FS Hu (2008) Tundra fire regimes in the Noatak National Preserve, northwestern Alaska, since 6000 yr BP. Pages 144 in 93th **Annual Meeting of the Ecological Society of America, Milwaukee, WI.**
Conference proceeding, poster presentation		Fall 2008	Higuera, PE, M Chipman, JL Allen, S Rupp, and FS Hu. (2008) Tundra fire regimes in the Noatak National Preserve, northwestern Alaska, since 6000 yr BP. In, **Alaska Park Science Symposium Fairbanks, AK.**
Conference proceeding, oral presentation		Fall 2008	Higuera, PE, M Chipman, JL Allen, S Rupp, M Urban, FS Hu (2008) Tundra fire regimes in the Noatak National Preserve, northwestern Alaska, since 6000 yr BP. **Meeting of the International Association of Wildland Fire, Jackson Hole, WY.**
Conference proceeding, poster presentation		Fall 2008	Chipman, ML, PE Higuera, JL Allen, S Rupp, and FS Hu (2008) Tundra fire regimes in the Noatak National Preserve, northwestern Alaska, since 6000 yr BP. **Proceedings of the American Geophysical Union annual meeting, San Francisco, CA.**
Cooperators Meeting	Present fire history records from second field season, present results of model development; request feedback from collaborators.	Winter 2008	Delivered, summer 2008
Annual Report	Project status report to JFSP and agency partners	Spring 2009	Delivered
Study Site Data Delivery	Provide preliminary results of fire history records from first field season to agency cooperators.	Spring 2009	Delivered
Conference proceeding, oral presentation		Spring 2009	Higuera, PE, ML Chipman, JL Allen, TS Rupp, M Urban, and FS Hu (2009) Beyond boreal forests: Holocene fire history in Alaskan tundra. Page 40 in **Wildfires in boreal ecosystems: past, present and future fire regimes, Quebec Canada.**
Journal Articles	Write and submit fire history results for publication in peer-reviewed journal.	Summer 2009	Delayed
Conference proceeding, oral presentation		Summer 2009	Chipman, M, PE Higuera, JL Allen, MA Urban, S Rupp, and FS Hu (2009) Tundra fire-regime response to late-Holocene climate and vegetation change in the Alaskan Arctic. **Annual meeting of the Ecological Society of America, Albuquerque, NM.**
Journal Articles	Write and submit modified Boreal ALFRESCO results for publication in peer-reviewed journal.	Fall 2009	(1) Higuera, PE, Chipman, M, Barnes, J A, Urban, M, Hu, FS. Tundra fire regimes in north-western Alaska and links to late Holocene vegetation and climate change. **In prep.** for Ecological Applications. (2) Hu, FS, PE Higuera, JE Walsh, WL Chapman, PA Duffy, LB Brubaker, and ML Chipman Tundra Burning in the Central Alaskan Arctic: Linkages to Climatic Change and Sea-Ice Retreat. *Journal of Geophysical Research-Biogeosciences* **in revision.**
Tech. Transfer	Workshop with collaborators and land managers (NPS, FWS, BLM, and State) to convey our findings, distribute manuscripts and data, and demonstrate software and model improvements.	Fall 2009	Higuera, PE, M Chipman, JL Allen, S Rupp, M Urban, and FS Hu (2009) Tundra fire regimes of Alaska: the Holocene perspective. **Alaska Fire Science Consortium Workshop, Fairbanks, AK.**
Conference proceeding, poster presentation		Fall 2009	Chipman, ML, PE Higuera, JL Allen, S Rupp, M Urban, and FS Hu (2009) Tundra fire regimes in the Alaskan Arctic and the link to late-Holocene vegetation change. **Proceedings of the American Geophysical Union annual meeting, San Francisco, CA.**
Conference proceeding, oral presentation		Fall 2009	Higuera, PE, M Chipman, JL Allen, LB Brubaker, C Whitlock, M Urban, and FS Hu (2009) Holocene climate-vegetation-fire interactions: lessons from high-latitude and high-elevation ecosystems. **Proceedings of the American Geophysical Union annual meeting, San Francisco, CA.**
Conference proceeding, oral presentation		Winter 2009	Higuera, PE (2010) Interactions of climate, vegetation, and fire during the Holocene: insights to future change. **Bonanza Creek LTER Symposium, Fairbanks, AK.**

10 References

References

Anderson, P. M. 1985. Late Quaternary Vegetational Change in the Kotzebue Sound Area, Northwestern Alaska. Quaternary Research **24**:307–321.

Anderson, P. M. 1988. Late Quaternary Pollen Records from the Kobuk and Noatak River Drainages, Northwestern Alaska. Quaternary Research **29**:263–276.

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

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

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

Chapin, F. S., G. R. Shaver, A. E. Giblin, K. J. Nadelhoffer, and J. A. Laundre. 1995. Responses of arctic tundra to experimental and observed changes in climate. Ecology **76**:694–711.

Clegg, B. C., and F. S. Hu. 2010. A centennial-scale record of Holocene effective moisture in the sotuhern Brooks Range, Alaska. Quaternary Science Reviews **29**:928–939.

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

Faegri, K., and J. Iversen. 1975. Textbook of Pollen Analysis. Hafner Press, Copenhagen.

Gabriel, H. W., and G. F. Tande. 1983. A regional approach to fire history in Alaska. Technical Report, BLM.AK.TR.83.09, 34 p .

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

Higuera, P. E., L. B. Brubaker, P. M. Anderson, T. A. Brown, A. T. Kennedy, and F. S. Hu. 2008. Frequent Fires in Ancient Shrub Tundra: Implications of Paleorecords for Arctic Environmental Change. PLoS ONE **3, 0001744**. URL `http://dx.doi.org/10.1371%2Fjournal.pone.0001744`.

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

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

Hinzman, L. D., N. D. Bettez, W. R. Bolton, F. S. Chapin, M. B. Dyurgerov, C. L. Fastie, B. Griffith, R. D. Hollister, A. Hope, H. P. Huntington, A. M. Jensen, G. J. Jia, T. Jorgenson, D. L. Kane, D. R. Klein, G. Kofinas, A. H. Lynch, A. H. Lloyd, A. D. Mcguire, F. E. Nelson, W. C. Oechel, T. E. Osterkamp, C. H. Racine, V. E. Romanovsky, R. S. Stone, D. A. Stow, M. Sturm, C. E. Tweedie,

G. L. Vourlitis, M. D. Walker, D. A. Walker, P. J. Webber, J. M. Welker, K. Winker, and K. Yoshikawa. 2005. Evidence and implications of recent climate change in northern Alaska and other arctic regions. Climatic Change **72**:251–298.

Hu, F. S., P. E. Higuera, J. E. Walsh, W. L. Chapman, P. A. Duffy, L. B. Brubaker, and M. L. Chipman. 2010. Tundra Burning in the Central Alaskan Arctic: Linkages to Climatic Change and Sea-Ice Retreat. Journal of Geophysical Research - Biogeosciences **in revision**.

Jandt, R., K. Joly, C. R. Meyers, and C. Racine. 2008. Slow recovery of lichen on burned caribou winter range in Alaska tundra: Potential influences of climate warming and other disturbance factors. Arctic Antarctic and Alpine Research **40**:89–95.

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

Joly, K., B. W. Dale, W. B. Collins, and L. G. Adams. 2003. Winter habitat use by female caribou in relation to wildland fires in interior Alaska. Canadian Journal of Zoology **81**:1192–1201.

Joly, K., T. S. Rupp, R. Jandt, and F. S. Chapin. 2009. Fire in the range of the Western Arctic Caribou Herd. Alaska Park Science. pages 85–91, December issue.

Jones, B. M., C. A. Kolden, R. Jandt, J. T. Abatzoglou, F. Urban, and C. D. Arp. 2009. Fire Behavior, Weather, and Burn Severity of the 2007 Anaktuvuk River Tundra Fire, North Slope, Alaska. Arctic Antarctic and Alpine Research **41**:309–316.

Jorgenson, M. T., J. E. Roth, P. F. Miller, M. J. Macander, M. S. Duffy, A. F. Wells, G. V. Frost, and E. R. Pullman. 2009. An ecological land survey and landcover map of the Arctic Network. National Park Service, NPS.ARCN.NRTR.2009.270, Fort Collins, Colorado .

Kasischke, E. S., D. Williams, and D. Barry. 2002. Analysis of the patterns of large fires in the boreal forest region of Alaska. International Journal of Wildland Fire **11**:131–144.

Klein, D. R. 1982. Fire, Lichens, and Caribou. Journal of Range Management **35**:390–395.

Leemans, R., and W. P. Cramer. 1991. The IIASA database for mean monthly values of temperature, precipitation and cloudiness of a global terrestrial grid. International Institute for Applied Systems Analysis, RR-91-18 .

Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling. 2009. Climate and wildfire area burned in western U. S. ecoprovinces, 1916-2003. Ecological Applications **19**:1003–1021.

Lloyd, A. H., and C. L. Fastie. 2002. Spatial and temporal variability in the growth and climate response of treeline trees in Alaska. Climatic Change **52**:481–509.

Lynch, J. A., J. S. Clark, N. H. Bigelow, M. E. Edwards, and B. P. Finney. 2002. Geographic and temporal variations in fire history in boreal ecosystems of Alaska **108**:0–17.

Mann, D. H., P. A. Heiser, and B. P. Finney. 2002. Holocene history of the Great Kobuk Sand Dunes, northwestern Alaska. Quaternary Science Reviews **21**:709–731.

McGuire, A. D., S. Sitch, J. S. Clein, R. Dargaville, G. Esser, J. Foley, M. Heimann, F. Joos, J. Kaplan, D. W. Kicklighter, R. A. Meier, J. M. Melillo, B. Moore, I. C. Prentice, N. Ramankutty, T. Reichenau, A. Schloss, H. Tian, L. J. Williams, and U. Wittenberg. 2001. Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO2, climate and land use effects with four process-based ecosystem models. Global Biogeochemical Cycles **15**:183–206.

Morgan, P., E. K. Heyerdahl, and C. E. Gibson. 2008. Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. Ecology **89**:717–728.

Nowacki, G., P. Spencer, T. Brock, M. Fleming, and T. Jorgenson, 2001. Ecoregions of Alaska and Neighboring Territories.

Oswald, W. W., L. B. Brubaker, and F. S. Hu. 2003. Holocene pollen records from the central Arctic Foothills, norther Alaska: testing the role of substrate in the response of tundra to climate change. Journal of Ecology **91**:1034–1048.

Preisler, H. K., and A. L. Westerling. 2007. Statistical model for forecasting monthly large wildfire events in western United States. Journal of Applied Meteorology and Climatology **46**:1020–1030.

Racine, C., R. Jandt, C. Meyers, and J. Dennis. 2004. Tundra fire and vegetation change along a hillslope on the Seward Peninsula, Alaska, U.S.A. **36**:1–10.

Racine, C., W. A. Patterson, and J. G. Dennis. 1985. Tundra fire regimes in the Noatak River Watershed, Alaska. Arctic **38**:194–200.

Reimer, P. J., M. G. L. Baillie, E. Bard, A. Bayliss, J. W. Beck, C. J. H. Bertrand, P. G. Blackwell, C. E. Buck, G. S. Burr, K. B. Cutler, P. E. Damon, R. L. Edwards, R. G. Fairbanks, M. Friedrich, T. P. Guilderson, A. G. Hogg, K. A. Hughen, B. Kromer, G. McCormac, S. Manning, C. B. Ramsey, R. W. Reimer, S. Remmele, J. R. Southon, M. Stuiver, S. Talamo, F. W. Taylor, J. Van der Plicht, and C. E. Weyhenmeyer. 2004. IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon **46**:1029–1058.

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

Schaefer, J. A., and W. O. Pruitt. 1991. Fire and Woodland Caribou in Southeastern Manitoba. Wildlife Monographs pages 1–39.

Silipaswan, C. S., D. L. Verbyla, and A. D. Mcguire. 2001. Land cover change on the Seward Peninsula: The use of remote sensing to evaluate the potential influences of climate warming on historical vegetation dynamics **27**:542–554.

Springsteen, T. S., A Rupp, in preparation. Summary report for Alaska National Parks: Projected vegetation and fire regime response to future climate change in Alaska. CESU Report.

Stow, D. A., A. Hope, A. D. Mcguire, D. L. Verbyla, J. Gamon, F. Huemmrich, S. Houston, C. Racine, M. Sturm, K. Tape, L. Hinzman, K. Yoshikawa, C. Tweedie, B. Noyle, C. Silapaswan, D. Douglas, B. Griffith, G. Jia, A. Petersen, L. Zhou, and R. Myneni. 2004. Remote sensing of vegetation and land-cover change in arctic tundra ecosystems. Remote Sensing of Environment **89**:281–308.

Stuiver, M., and P. J. Reimer. 1993. Extended 14C database and revised CALIB radiocarbon calibration program. Radiocarbon **35**:92–98.

Sturm, M., C. Racine, and K. Tape. 2001. Climate change - Increasing shrub abundance in the Arctic. Nature **411**:546–547.

Tape, K., M. Sturm, and C. Racine. 2006. The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. Global Change Biology **12**:686–702.

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

Walker, D. A., M. K. Raynolds, F. J. A. Daniels, E. Einarsson, A. Evlvebakk, W. A. Could, A. E. Katenin, S. S. Kholod, C. J. Markon, E. S. Melnikov, N. G. Moskalenko, S. S. Talbot, and B. A. Yurtsev. 2005. The circumpolar Arctic vegetation map. Journal of Vegetation Science **16**:267–282.