Title:

Impacts of past warming episodes on fire frequency, carbon fluxes, and soil erosion in the Alaskan boreal forests: Lessons from the past

JFSP ID Number:

12-3-01-27

Principle Investigator:

Dr. Daniel H. Mann; University of Alaska Fairbanks

Student Investigator:

Benjamin V. Gaglioti; University of Alaska Fairbanks

Co-authors:

Dr. Bruce P. Finney; Idaho State University

Dr. Benjamin M Jones; US Geological Survey

Dr. John W Pohlman; US Geological Survey

Dr. Matthew J Wooller; University of Alaska Fairbanks

Abstract:
Wildland fire is a keystone disturbance in the boreal forest, affecting everything from public safety, to woodpecker populations, to permafrost. How settlement by European people impacted wildland fire regimes in Alaska is poorly understood because paleo-fire records near population centers are rare. High-resolution records of past fires are needed to detect recent changes in the tempo of burning in the boreal forest because the era of human settlement and fire suppression are relatively short there. Here, we describe the annually resolved record of burning in the watershed of a thermokarst lake near the city of Fairbanks, Alaska (established AD 1902). We use the sedimentary archive preserved in Ace Lake to reconstruct the frequency of local wildland fires over the past 500 years. Clastic-biogenic varves consisting of silt and algae are deposited in deep-water zones (>5 m) of the lake and preserved by meromictic conditions. These annual layers provide the age control for paleo-fire activity. To identify individual fires and to describe their relative magnitudes, we measured charcoal area as viewed in epoxy thin sections. Results show that the timing of charcoal peaks in the varve record correlates with ages of fire scars on spruce trees growing around the lake, as dated by tree-ring analyses. Four fires occurred after AD 1900, the last one in 1962. European settlement of the area was accompanied by a striking increase in fire frequency. During the 400 years prior to AD 1900 - before Fairbanks was founded - fires occurred on average every 58 years (35-98 year range). After European settlement, local fires became roughly twice as frequent (mean 21 years, 10-28 year range). This period of anomalously frequent fires followed by fire suppression starting in the 1960s has caused fuel loads to become synchronized around Fairbanks today. Our paleo-records suggest this large area of uniform fuel loading will soon be overdue to re-burn.

Purpose and Background of the Study:

Purpose

The original goal of this study was to determine what effects past warming episodes had on fire frequency, carbon fluxes, and soil erosion in a black spruce forest in Interior Alaska. Two limitations, realized after the study began, slightly modified this goal. First, it turned out that the annual sediment layers (varves) in the study lake did not extend back to the Medieval Warm Period (AD 950-1250), preventing a clear assessment of how fire frequency and its effects changed at the onset of that prior warming event. Second, it became apparent that because our study area is located near the city of Fairbanks, the wildland fire record there was influenced by human activities after the area was settled around AD 1902. It would be difficult to correlate fire frequency with climate because warming had occurred in concert with human settlement of the area. Our revised objectives became to determine how the wildland fire regime changed after the settlement of Fairbanks and, as initially proposed, to assess how wildland fires affected carbon fluxes and soil erosion in Interior Alaska.

Controls on Wildland fire Frequency in Interior Alaska

Wildland fire frequency in Interior Alaska is a function of the biophysical conditions in a given site in the form of a complex interaction between ignition, fuels, and weather. Mega-fire years - anomalously large fire seasons in the historical fire record - occur during the warmest and driest springs and summers (Duffy et al., 2005). Recent work shows that past warming events extending over decades to centuries caused enhanced fire frequency in the Yukon Flats (Kelly et al., 2013). Land cover also moderates the flammability of a landscape. Black spruce forests are more prone to frequent, stand-replacing fires than are deciduous forests because the structure and flammability of understory and arboreal fuels (Viereck, 1973a). The spatial distribution of surface water features has also been shown to modify fire frequency in Interior Alaska (Barrett et al., 2013). Because of this region's sparse human population and largely pristine vegetation cover, human effects on the wildland fire regime are rarely thought to be important there. Although human-caused wildland fires now occur relatively frequently near Alaska's road system and populated areas, there is a lack of information on wildland fire frequency prior to human settlement. Fastie et al., (2002) and Kurkowski et al., (2008) hypothesized there was a large increase in the number and extent of wildland fires ignited by humans in the Fairbanks area during the mining boom of the early 20th century. However, without precise estimates of paleo-wildland fire activity prior to and during human settlement, this trend remains anecdotal.

Permafrost and Wildland fire

Interior Alaska lies in the zone of discontinuous permafrost, and the relatively warm permafrost there is highly vulnerable to thaw after wildland fires because of the removal of insulating soil layers and lowered surface albedo (Viereck, 1973b; Swanson, 1996). The stability of permafrost soils are potentially of great importance because they store about 50% of the world's soil carbon, equal to twice the amount of CO_2 in the atmosphere (Tarnocai et al., 2009). Post-fire thaw could greatly enhance the decomposition of this carbon pool, causing a positive feedback to global warming and creating unstable ground that damages roads, pipelines, and buildings (Harden et al., 2006; Schuur et al., 2014). A critical question in the management of the Alaskan boreal forest is how climate change, fire regimes (the frequency, severity, and extent of burning), permafrost, and soil carbon will interact in the future (McGuire et al., 2009). Accumulating lake sediment incorporates both the charcoal originating from wildland fires (Clark, 1988a; Higuera et al., 2007) and the mineral material derived from permafrost thaw after these fires (Gaglioti et al., 2014). For this reason, the sedimentary archives in lakes can be used to infer the responses of a permafrost landscape to past wildland fires.

Lake Sediment Archives

Lake sediments are like chronologically arranged filing cabinets containing detailed records of past events in their watersheds (Cohen, 2003). Boreal lake sediments accumulate charcoal, mineral material eroding from thermokarst events (ground subsidence resulting from permafrost thaw), and non-charcoal carbon derived from plants and soils in their watershed and from within-lake primary productivity (Cohen, 2003). Well-developed techniques exist for the extraction and interpretation of the charcoal and various carbon fractions contained in lake sediments, and for dating the enclosing sedimentary layers (Cohen, 2003; Higuera et al., 2007).

Our study lake, Ace Lake, is unusual because its sediment consists of annually banded layers that can be used to infer the precise timing of environmental events such as local fires and erosion events (Clark, 1988b). Varved lakes provide the best opportunity for clarifying human impacts on the wildland fire regime in Alaska because the eras of human settlement and fire suppression are relatively recent and therefore require high-resolution records in order to be discerned.

Study Location and Description:

Study Location

The study area is Ace Lake and its watershed near Fairbanks, Alaska (Figure 1). Fairbanks has a subarctic, continental climate with mean July and January temperatures of 17° and -22° C, respectively. Ace Lake is typically ice-covered between October and May, and ice thickness reaches a maximum of around 75 cm. The lake surface area is 7.4 hectares, has a maximum depth of 9 meters, and was formed due to ground subsidence from permafrost thaw (thermokarsting). The surrounding watershed covers an area of approximately 165 ha. Ace Lake is relatively productive compared to other lakes in the region (Alexander and Barsdate, 1974). It has inputs from both ground and surface water. Leaning trees indicative of ongoing thermokarst show that the lake is expanding along its northern shore. Nearby Deuce Lake flows into Ace and may be the source for some of its groundwater input (Alexander and Barsdate, 1974). Permafrost underlies most of the watershed, and the active layer (topmost layer that thaws every year) is 0.3-1 m thick. Vegetation cover in the watershed is primarily black spruce (*Picea mariana*) forest with ericaceous shrubs (Ericaceae) and feather mosses in the understory. Occasional stands of white spruce (*Picea glauca*) and birch (*Betula neoalaskana*) occur in the watershed on well-drained soils, with willow (*Salix* spp.) and rose (*Rosa acicularis*) in the understory. Lake shorelines are lined with emergent wetland vegetation including cattails (*Typha angustifolia*), sedges (Cyperaceae), and willows (*Salix* spp.). Littoral zones of the lake have abundant stands of spatterdock (*Nuphar advena*).

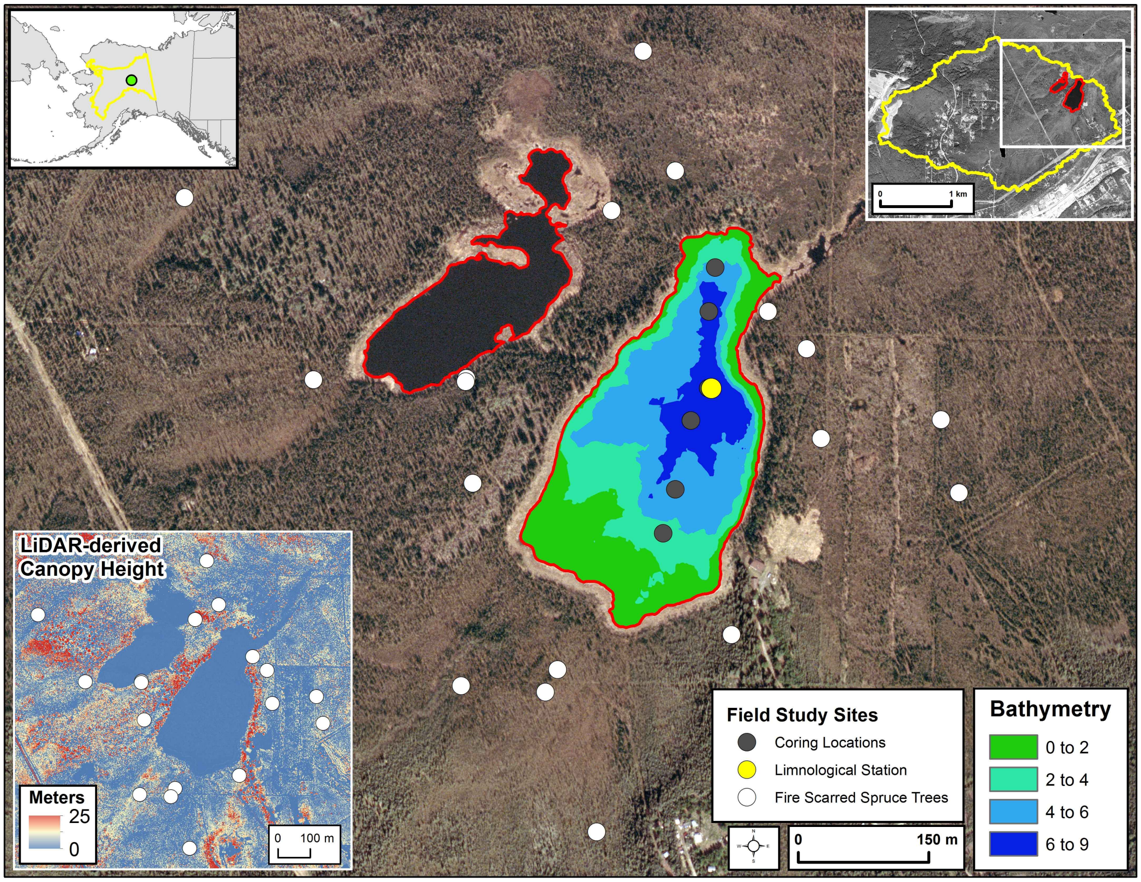

Figure 1 Main: 2012 aerial image of Ace Lake (to right) and its watershed (outlined in blue) with sampling locations and lake bathymetry. Deuce Lake lies northwest of Ace Lake. Top left: Alaska with boreal forest outlined in yellow and location of Ace Lake in green. Bottom left: LiDAR derived forest canopy height with locations of fire-scarred spruce trees. Top right: Aerial image of Ace Lake with watershed outlined in yellow.

Study Description: Limnology and Lake Sediment

To better understand the sedimentary regime and charcoal record in Ace Lake, we analyzed and monitored a variety of limnological properties in the course of this study. The bottom-waters of Ace Lake were known to be anoxic through most of the year (Alexander and Barsdate, 1974). Such conditions exclude macro-invertebrates, which prevents them from disturbing the sediment through bioturbation, which allows the preservation of annual sediment layers known as varves (Anderson, 1985). These varves provide the chronology for our detailed record of wildland fires, so documenting their existence and figuring out how and why they formed was an important first step in this study.

Seasonal changes in physical and chemical parameters in the water column at the deepest point (8.9 meters) in Ace Lake indicate that the lake was stratified during most of the sampling periods in 2013 (Figure 2). The lake became homo-isothermal (similar temperature throughout the water column) in May and October 2013; however, the hypoxic / anoxic hypolimnion (bottom layer of densest water) observed during these times suggested lake turnover did not occur. The lack of overturn in May 2013 was due to a nearly 100% ice cover that protected the water column from any wind disturbance that was capable of initiating overturn. In October 2013, a solute-rich hypolimnion maintained a density gradient in the water column that apparently was resistant to wind-driven overturn before the lake froze again.

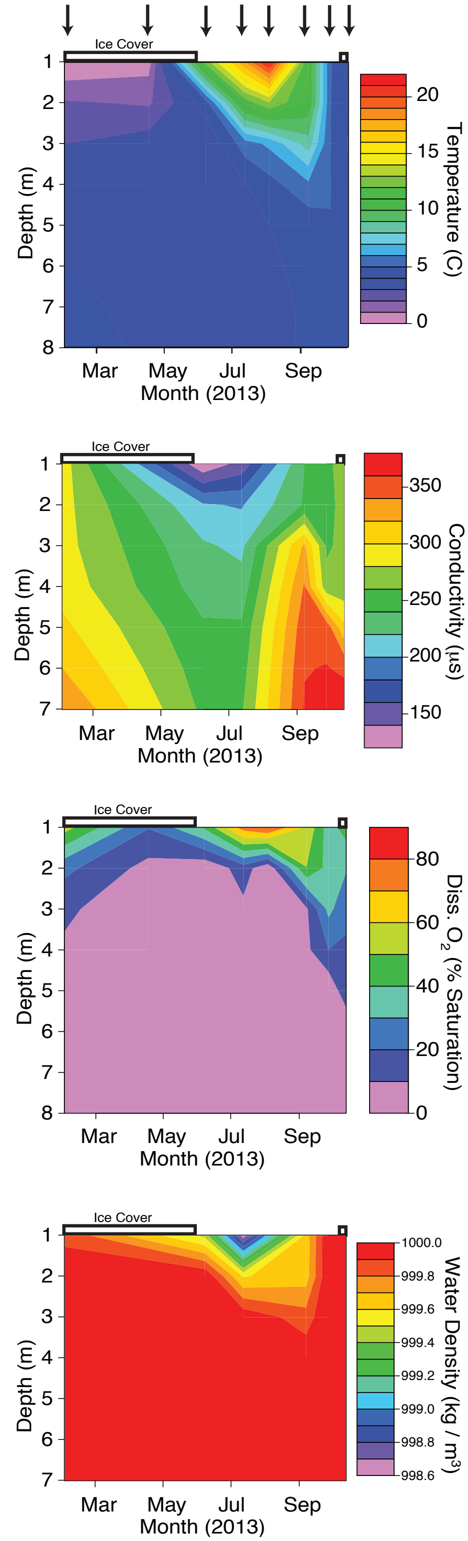

Figure 2. Physical and chemical properties of the Ace Lake water column during 2013. Arrows at the top are times of sampling.

We assessed the variability of sedimentary features in different parts of the Ace Lake basin in order to determine the location of lake inception and how its shoreline expanded over time. This information was then used to determine where we should core in the lake basin to obtain the longest record of sedimentary charcoal record. Six sedimentary units consisting of organic-poor silt that were either massive or laminated were crosscorrelated visually and by radiocarbon (^{14}C) dating at seven coring locations along a north south transect across the lake basin (Figure 3). The three older (lower) silt units were only found in cores taken at the southern part of the lake (locations A, B, and C). Increasingly younger (upper) silt units were present in the northern coring locations (Figure 3). Estimates of the age of lake formation come from the lowest dated plant macrofossil (a spruce needle) at core location B that had a calibrated age range of AD 970-1030. This suggests the lake basin first formed by thermokarsting near coring location B in the southern end of the lake. The basin has then expanded northward over the last 1 ka. Basin-expansion rates along the northern edge of the lake are estimated at 0.36 m / year between AD 970 and AD 1160, 0.79 m / year between 1160 AD and AD 1320, and 0.14 m / year between AD 1320 and AD 1966 (Figure 3).

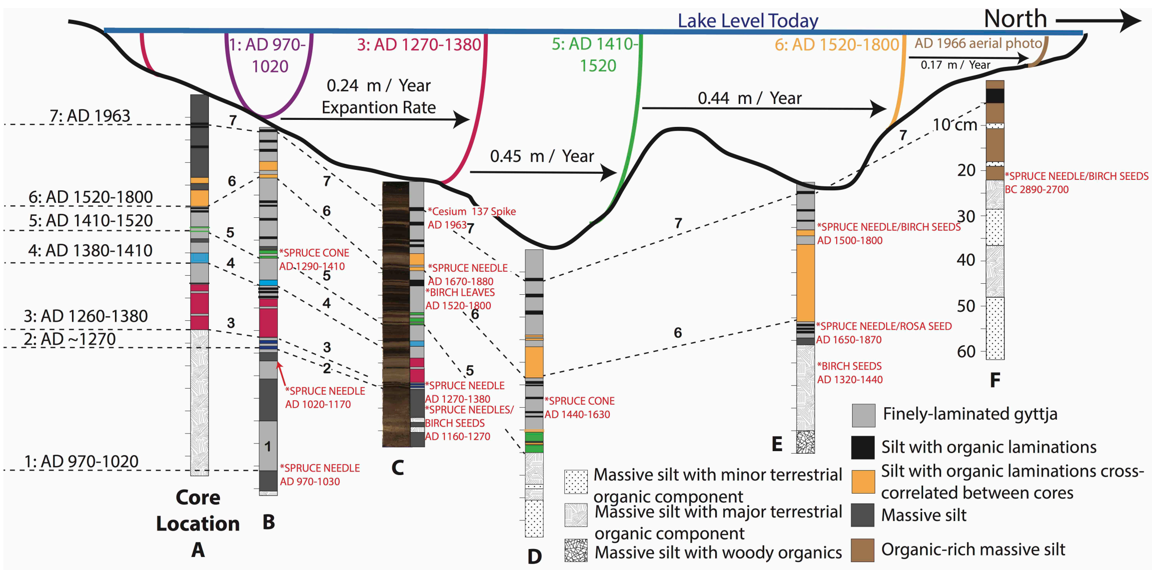

Figure 3. Sedimentary facies in Ace Lake revealed along the coring transect shown in Figure 1. Dotted lines show where sedimentary structures correlate in different cores. ^{14}C dates are in red. Age and position estimates of shorelines of Ace Lake in colored text at the top. Rates of shoreline expansion are in black.

To verify the chronology of sediment accumulation and ultimately the age control over the record of wildland fires, we compared varve counts with radiometric dates obtained by ^{210}Pb and ^{14}C. We interpolated the radiogenic age-depth estimates from individual dates using the methods of Blaauw and Heegaard (2012). Varves were observed in epoxied thin-sections from the sediment core collected from location C and were counted and measured using a compound microscope and Olympus Cell Sens Standard XV microscope imaging software (© 2011) (Figure 4). Four hundred and ninety three algal-capped laminations were counted in the top 45 cm of the thin-sectioned core taken from location C in the lake basin (Figure 5). This varve chronology and its 10% error envelope overlapped with the ^{210}Pb

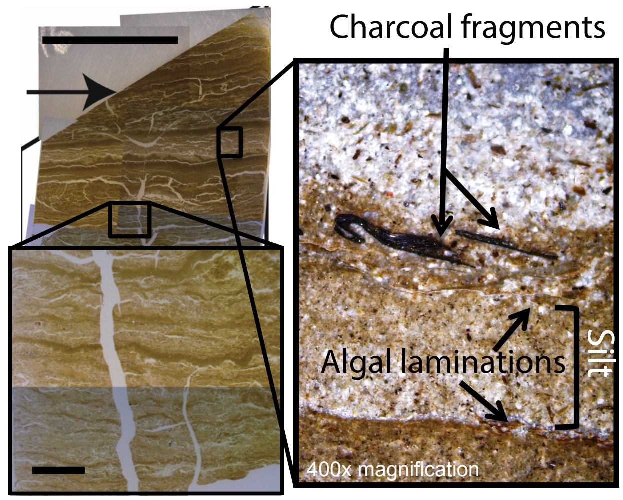

Figure 4 Close-up of a thin section of part of the varved sediment record from Ace Lake pointing out some of the common features, including varves (bottom left) and charcoal fragments (right). Top left: Scale bar is 1 cm. Bottom Left: Scale bar is 1 mm.

chronology (AD 1969 - AD 1959) from a nearby core at the depth levels of 6.5-8 cm. In addition, the ^{137}Ce spike that occurred globally in AD 1963 corresponds to a varve age of AD 1962 ± 5 varve years in our record (Figure 5 inset). Age estimates based on the ^{210}Pb

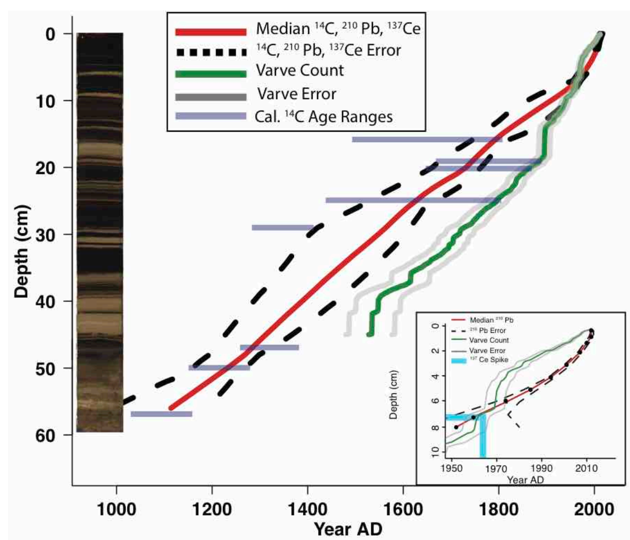

Figure 5 Core "Ace-12-TS" photo with age-depth modeling results. Inset box it a close-up of the radiometric and varve age-depth model since AD 1900. The 137Ce spike occurring in AD 1963 is shown in blue.

chronology are uncertain below the 8-cm level. The varve chronology overlapped with the calibrated age ranges of three out of the five ^{14}C ages from contemporaneous levels (Figures 5). Overall, the varve chronology is younger than the median and error of the radiogenic isotope chronologies throughout most of the record. We hypothesize that this disparity could be due to errant turbidity currents removing an occasional varve layer. Alternatively, overturn of the water column might occur in rare years, which would allow bioturbation to occur, which might have obscured some of the varves. Both of these processes would yield varve years that were not counted and so underestimate the varve age-depth model.

Study Description: Wildland Fire Record

We sampled cross-sections from living spruce trees growing around Ace Lake that had cambial scars at the base of their trunks indicative of fire scaring (Schweingruber, 1988). Four wildland fires occurring in the 20th century were detected in fire-scarred spruce trees. Fire ages and number of trees scarred by these fires were: AD 1903 (n=5), AD 1913 (n=6), AD 1939 (n=3), and AD 1962 (n=3) (Figure 6). The locations of these dated, fire-scarred trees in the Ace Lake watershed suggest that the 1903, and 1913 fire were widespread, while the 1939 and 1962 fires may have been confined south and north of the lake, respectively (Figure 1).

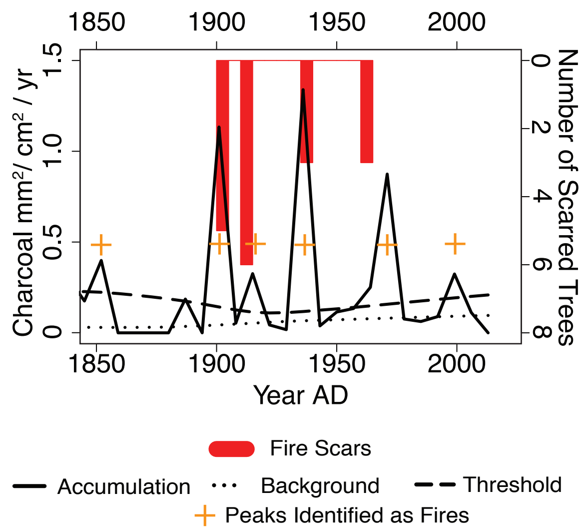

Figure 6 Histogram time series of fire scarred spruce trees and time series of macroscopic charcoal since with modeled charcoal components deconstructed and inferred peaks since AD 1850.

We quantified macroscopic and microscopic charcoal area in sediment thin sections viewed under 50-200x magnification through a compound microscope. This quantification was conducted every 1 mm in core depth over a core-width of 2 cm. We then converted the charcoal area and count measurements to a temporal record by assigning a varve year to each sample depth. Charcoal influx and charcoal-peak identification for verifying the presence of past wildland fires was calculated using the CHAR analysis extension of MatLab software developed by Higuera et al., (2011). This analysis deconstructs a macroscopic charcoal record into background charcoal, the normal rate of charcoal production deposition between fires, and peak charcoal flux, the latter being derived from local wildland fires, which are those occurring within ~1 km of the lake (Higuera et al., 2007; Peters and Higuera, 2007).

The CHAR program performs best when it is validated by independent datasets that allow the charcoal record to be calibrated against a record of fires derived from some other source. The number of charcoal peaks in the lake charcoal record from Ace Lake that were considered significant outliers, and therefore representing wildland fires, varied depending on the width of the interpolated window used. An unreasonably large number of fires (n=23) were identified when using a window length of 2 years (the mean sampling resolution used; Figure 7), and six wildland fires were identified when the interpolated window length was 15 years. Thus a wider interpolated window causes individual charcoal peaks to be smoothed and disappear beneath the charcoal-influx background. Moreover, a wider interpolated window causes two adjacent charcoal peaks to be considered as one (number of peaks/fires detected) reducing the number of charcoal peaks detected.

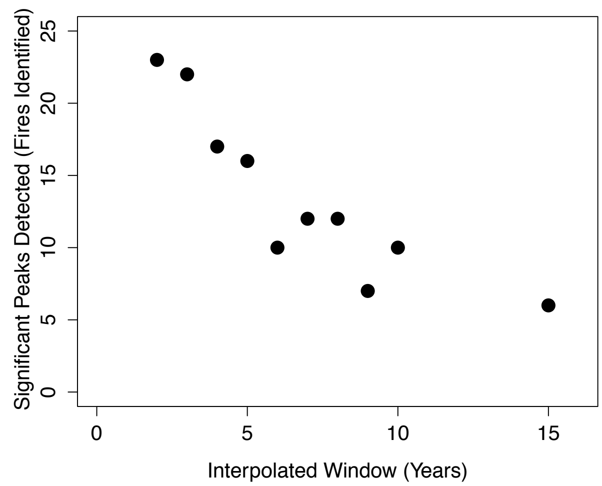

Figure 7 The number of peaks identified as fires in the Ace Lake charcoal time series plotted against the size of the interpolated window used for the data.

The independently derived record of recent fires we obtained from the fire-scarred trees enables us to calibrate the CHAR program appropriately. A 7-year interpolated window yielded charcoal peaks contemporaneous with the fire-scar ages identified on trees in the Ace Lake watershed (Figure 8). Use of this 7-year window minimized the number of "false fires" - charcoal peaks not observed in the fire-scar record (Figure 8). Lower interpolated window lengths (<7 years) identified charcoal peaks that were not observed by the fire-scar record in the watershed. Higher interpolated window lengths (>7 years) missed wildland fires that were recorded in the fire-scar record. There was one charcoal peak that was identified in the lake charcoal record, but not in the fire scar or historical record during the late 1990's. This may have been the result of the landowner burning brush near Ace Lake or by the reworking of charcoal-rich sediment within the lake basin. This suspect charcoal peak was omitted from the fire frequency analysis. Two charcoal peaks that were identified from AD 1838 and 1852 were combined as one fire because the second charcoal peak was deposited within a fining upward silt layer probably representing the deposit left by a turbidite (an underwater landslide) that reworked charcoal from somewhere else on the lake bottom. We used the 7-year window length to determine the wildland fire history around Ace Lake over the last 500 years.

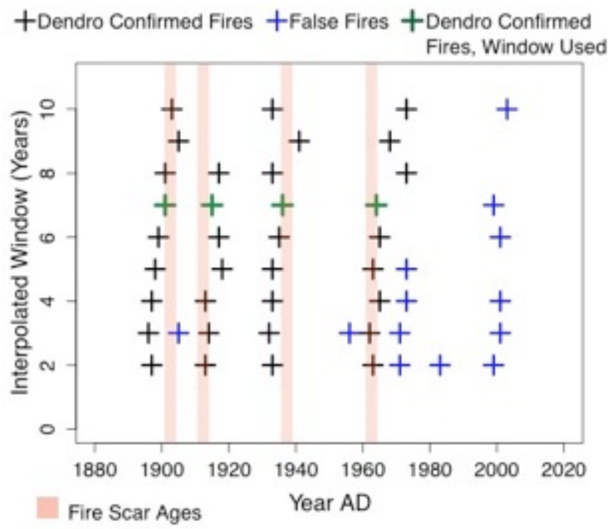

Figure 8 Timing of sedimentary charcoal peaks identified as fires under different interpolated window sizes compared with fire-scar record from trees. A seven-year window resulted in the maximum agreement between the two data sources, and so we used this window length to analyze the time series of sedimentary charcoal.

Wildland Fires and Organic Sediment Sources

To test whether organic sediment sources changed before and after fires, we examined the elemental (C:N ratios) and the stable carbon and nitrogen isotope values ($\delta^{13}C$, $\delta^{15}N$) of lake sediment organic matter. C:N ratios and C and N isotopes have been used widely to trace the sources of organic matter entering lakes (Meyers and Ishiwatari, 1993), as well as to describe the cycling of carbon (Finney et al., 2012) and nitrogen (Talbot, 2001).

The elemental and isotope records from Ace Lake show no consistent pattern of response to burning in the lake's watershed. Some fires triggered no detectable response of C:N ratios and C and N isotopes in the sedimentary record. Others might have triggered enhanced input of terrestrial organic matter to the lake, while other fires were followed by increased autochthonous (algae) organic matter input to the lake. The magnitude of the charcoal peaks had no consistent relationship with the limnological response. Most of the variability in organic matter source was determined by the abundance of silt being deposited in the lake at the time, and silt deposition is not directly related to burning but instead is controlled by thermokarst processes within the lake basin itself.

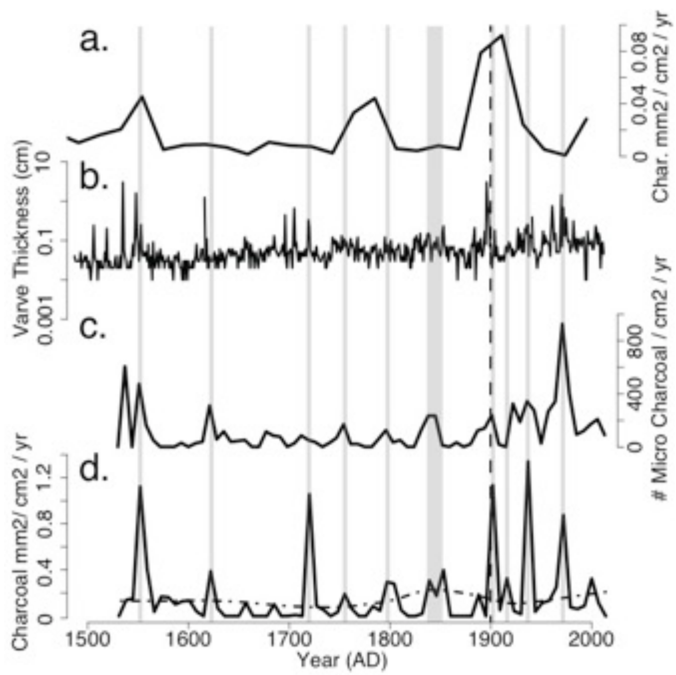

Figure 9 Wildland fire record of the Ace Lake watershed over the last 493 years. a) Sedimentary charcoal record in Deuce Lake sediment (Lynch et al., 2004). b) Varve thickness on a log scale. c) Micro charcoal record from Ace Lake with smoothing function. d) Macrocharcoal record from Ace Lake with threshold level indicated by dashed line. Gray bars indicate the timing of peaks we identified as fires.

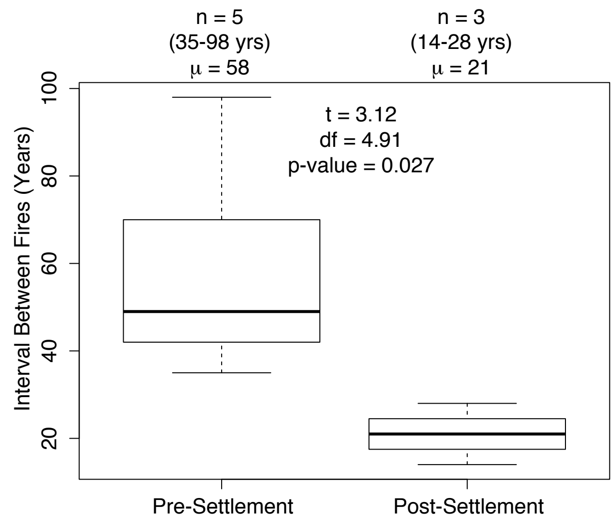

Figure 10 Box-plot of fire frequency before and after white settlement in Fairbanks, Alaska, occurring in AD 1902.

Over the last 500 years, ten charcoal peaks are identified as wildland fires (Figure 9). Four of these fires occurred in the 20th century between AD 1900 and AD 1970. Before the twentieth century, intervals between the six pre-20th century fires ranged from 35-98 years (58 year mean). During the 20th century intervals between the four fires ranged from 11-28 years (21 year mean; Figure 10). Wildland fires were significantly more frequent in the 20th century starting with the wildland fire that is recorded by five fire-scarred trees in AD 1903 (Figure 10).

Key Findings and Relationship to Other Work:

1) **The sampling resolution typically used to reconstruct fire history from lake sediment records (1 sample / >10 years) may be too coarse to accurately reconstruct past wildland fires in the boreal forest.**

Results of this study suggest that limited sampling resolution may be an unrecognized limitation for identifying relatively frequent wildland fires in the boreal forest using non-varved, lake-sediment charcoal records. Similar to other time-series data, the degree of temporal smoothing affects the magnitude and frequency of charcoal spikes derived from lake sedimentary records. The distribution of these spikes then dictates how many wildland fires are identified as being above the background Char variability and thereby estimates fire frequency (Higuera et al., 2007). These estimates of fire frequency in the past are then used to inform both management decisions and conceptual models of climate-vegetation-fire dynamics (Swetnam et al., 1999). Sensitivity tests on our Ace Lake results show that as the interpolation window is widened, fewer fires are identified from the same charcoal time-series. We found that using a customarily employed window length of more than 10 years failed to identify charcoal peaks that were contemporaneous with fire-scar ages in spruce trees growing around the lake. These larger window lengths erroneously reduced fire frequency. In addition, different sampling resolutions or interpolated window lengths from different time periods, sediment cores, and geographic regions may preclude valid comparisons between vegetation types and between different climatic regimes that have affected the same site over time. High-resolution sampling, thin-section charcoal quantification, and/or varved lake sediment records are needed to address the potential problems of sampling resolution in the interpretation of lake charcoal records.

2) **Past wildland fires in this boreal forest watershed were not followed by consistent patterns of change in sediment sources or paleolimnology. Instead,**

changing rates of lake-basin expansion that were unrelated to fires probably controlled the observed changes in sedimentation regime occurring in Ace Lake.

The impacts of wildland fires on lake chemistry, ecology, and sediment sources range from no detectable impact (McLauchlan et al., 2014), to significant changes in primary productivity (Planas et al., 2000) and mercury input (Kelly et al., 2006). Lewis et al., (2014) found little detectable impact of wildland fires on thermokarst lakes in the Yukon Flats area of Alaska. Our data support Lewis et al., (2014) observations that the chemistry, biota, and ecology of thermokarst lakes in Interior Alaska are insensitive to fires in their watersheds. However, this is counter to other observations that nitrogen cycling in boreal streams can be greatly impacted by wildland fires (Betts and Jones, 2009). The caveat to our results from Ace Lake is that there could have been a change to the sediment sources or limnology of Ace Lake after fires in its watershed, but it was not observed in the specific indices we measured. That said, the stable isotope indices we used here are the same ones used in other studies in other regions that do show strong effects of burning on limnology. Therefore, we conclude that wildland fires did not have drastic, lasting effects on the limnology of Ace Lake.

Wildland fires may have little effect on limnology in Interior Alaska for several reasons. Summer rainstorms and the degree of permafrost thaw limit soil erosion in Interior Alaska, and, even during enhanced thaw after wildland fires, the lack of intense rain in probably restricts the amount of soil erosion occurring. Additionally, like many thaw lakes in the region, there is no major stream entering Ace Lake that is able to transport sediment from the steeper, upper reaches of the watershed that are theoretically more vulnerable to erosion after fires. Even if drainages and gullies tapped these portions of the watershed, the soils there may be particularly impervious to erosion because thick organic mats that do not fully combust during fires act to stabilize the underlying soils. These organic mats are thickest on north-facing slopes under black spruce forest, which makes up most of the land-cover in the Ace Lake watershed. Black spruce forest of this type is also known to replace itself within a few years after fires (Kurkowski et al., 2008), which may also limit how much sediment erodes after fires (Yoshikawa et al., 2002).

Instead of wildland fires being the primary driver of sediment-source changes in Ace Lake, shorelines eroding by thermokarsting are probably responsible for the variability we observe in elemental and isotope records from the lake sediment. Shoreline erosion from thermokarst processes reworks the thick loess deposits underlying the surrounding landscape directly into Ace Lake. This thermokarst-mobilized sediment is laid down as the silt bands observed at every coring location. Many of these silt bands are wedge-shaped, widening towards the actively eroding, northern edge of the lake. Causes of episodes of enhanced shoreline erosion and subsequent silt transport and deposition in the lake's basin are likely related to a complex suite of factors including lake-level changes caused by beavers damming the lake outlet, the expanding lake margin encountering zones of particularly ice-rich permafrost, and variations in the heat flux into the ground caused by minor climate changes. Fires could also play a role; however, the fact that the mineral-rich layers found in sediment cores do not always correspond to charcoal spikes indicates that wildland fires are not the sole cause of mineral-rich sedimentation in Ace Lake.

3) **During the ~400 years before Fairbanks was founded in AD 1904, fires occurred on average every 58 years (35-98 year range). After European settlement, fires became significantly more frequent (mean 21 years, 10-28 year range). This indicates an important human impact on the fire regime during and after the gold-mining era.**

Fairbanks was first settled with the discovery of gold there in 1902 by Felice Pedroni. The resultant gold rush was accompanied by rapid population growth, and the miners used fire in a variety of ways. Large fires were used to thaw vertical shafts through near-surface layers of frozen silt in order to reach the underlying gold-bearing gravels (Cole, 1984). Miners also set wildland fires around populated areas to ease firewood harvesting by de-limbing and drying spruce poles (Lutz, 1959). Fires were also set to improve moose habitat, to clear land, and in a vain attempt to reduce the mosquito population (Lutz, 1959).

Ace Lake is centrally located in the Fairbanks Mining District. It appears on maps made in 1903 alongside the trail that connected the river town of Chena to the mining camps north of Fairbanks. By 1911, a railroad had been built along this trail (Cole, 2008; Figure 11). Watersheds near Ace Lake were targeted for mining activity, and it is likely that the area around Ace Lake was as well (Cole, 2008). Human activity around Ace Lake in late-prehistoric times was probably minimal because it is well away and not easily accessible from the resource-rich Tanana River where human activity is well documented (Potter, 2007), and, therefore, human impact went from nearly non-existent to abundant in the span of a few years during settlement. This rise in population correlated with a significant change in wildland fire frequency that is circumstantial evidence for a human-wildland fire connection. Before 1950, Fires were generally not fought unless they posed some risk to infrastructure (DeWilde and Chapin, 2006), which, in the early part of the 20th century, was mainly centered ~10 km south and east of Ace Lake in the towns of Chena and Fairbanks. These circumstances make it likely that people were responsible for setting some or all of the wildland fires occurring in the 20th century around Ace Lake.

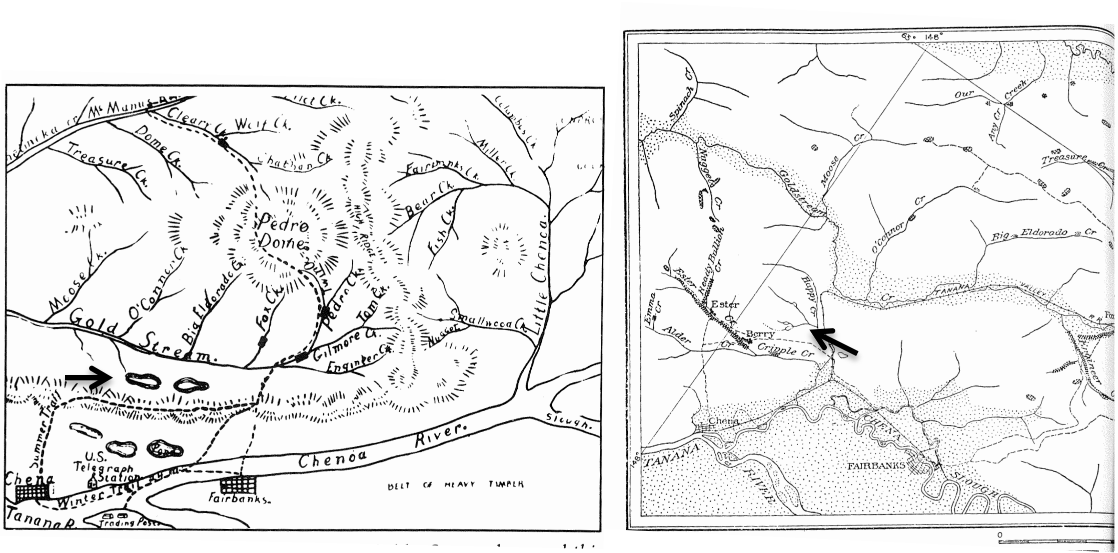

Figure 11 Maps of Fairbanks drawn in 1903 (Left) and 1911 (Right). Ace Lake is noted by the black arrows. Left: Note the east-west oriented trail (dotted line) from the town of Chena to the gold claims North of Fairbanks that passes the Ace Lake watershed and Right: the Chena-Fairbanks railroad that replaced it (hatched line).

Management Implications:

1) **The frequent, widespread wildland fires around Fairbanks in the first fifty years of the 20th century, followed by intense fire-suppression after 1950, may require special fuel-management considerations in the near future.**

The forests around Fairbanks were reset to an early stage of secondary succession in the first half of the 20th century and they are now accumulating a synchronized fuel load. The city of Fairbanks and its far-flung suburbs are now intimately comingled with aging forest stands. Because much of the area was repeatedly burned during the mining era, the mosaic of stand ages that would have otherwise acted to control fire spread has been significantly reduced. Large areas of even-aged stands have the potential to ignite and burn. The Ace Lake fire records show that the forest growing around Fairbanks today will soon surpass the normal wildland fire frequency. Fire managers in Alaska are well aware of this problem and have conducted a number of fuel treatment applications to safeguard communities in the most at-risk areas (Ott and Jandt, 2005). Our results support and hopefully will further inform these fuel-management efforts.

2) **Changes in wildland fire frequency may need to persist for centuries in order for them to have lasting effects on vegetation and permafrost in black spruce forests.**

The relatively frequent wildland fires of the 20th century can serve as a test for how Alaska's boreal forest might respond to future warming, which may include more frequent mega-fire seasons due to increased aridity (Wolken et al., 2011). Such changes could hold clues to how management may need to be modified in the future. Even after the barrage of wildland fires documented from the 20th century, there is still abundant black spruce in the Ace Lake watershed, and active layers remain relatively thin there. This contradicts recent models that infer more frequent wildland fires during warming trends will trigger a regime shift Interior Alaska's forests whereby black spruce is replaced by deciduous woodland (Mann et al., 2012; Kelly et al., 2013). Oviously, no such shift occurred around Ace Lake watershed, even when the fire frequency doubled there after AD 1900. For north-facing, black spruce forest with thick soil organic layers - like what around Ace Lake, an ecological regime shift driven by changing climate seems highly unlikely in the near future.

Future Work Needed:

Our project is a large step forward in providing a long-term context for fire-management issues in Alaska's urban areas, and it should be replicated in other Alaskan municipalities. This project can be built upon in several ways. First, the human-wildland fire link could be further detailed by investigating a comparable record using a varved lake located distant from any population center. Such a record would allow us to figure out if post-industrial warming of climate after ca. AD 1900 (the end of the Little Ice Age) contributed to the increase in fire frequency seen at Ace Lake and that we attribute to human activity. We recommend that future projects such as this one should incorporate dendrochronology-based fire records and use high-resolution sampling to recognize the wildland fires that may be missed in low-resolution studies. We would also like to pursue a high-resolution record that goes further back in time than the Ace Lake record in order to answer our original question of how fire frequency responds to past warming events such as the Medieval Warm Period (AD 1000-1300). To better connect these paleo-records to wildland fire management, future projects would benefit from the involvement of a fire-fuels specialist. This project component could assess the relationship between time-since-last-fire and fuel loads in and outside of human population centers like Fairbanks. Our results describing prehistoric fire frequencies near Fairbanks can be used to better manage fuels and to better design fire-control efforts.

Status of Deliverables:

Conference Presentation: Finished 2013.

Citation: Gaglioti, B., Mann, D. H., Finney, B., Pohlman, J., Jones, B. M., Arp, C. D., & Wooller, M. J. (2013, December). Long-term impacts of boreal wildland fire on carbon cycling dynamics in Interior Alaska. In *AGU Fall Meeting Abstracts* (Vol. 1, p. 0536).

Manuscript: Pending, expected submission date: January 2015

Expected Citation: Gaglioti, B., Mann, D. H., Finney, B., Jones, B. M., Pohlman, J., Wooller, M. J., & (*in prep*.) Using a varved lake record to detect human impacts on boreal wildland fire in Interior Alaska. To be submitted to *The Holocene.*

Dissertation: To be completed in autumn 2015. The above manuscript will be a chapter in my dissertation.

References:

Alexander, V., Barsdate, R.J., 1974. Limnological studies of a subarctic lake system. Internationale Revue der gesamten Hydrobiologie und Hydrographie 59, 737–753.

Anderson, R.Y., 1985. Meromictic lakes and varved lake sediments in North America. US Geological Survey Report, Department of the Interior

Barrett, C.M., Kelly, R., Higuera, P.E., Hu, F.S., 2013. Climatic and land cover influences on the spatiotemporal dynamics of Holocene boreal fire regimes. Ecology Eco Soc America 94, 389–402.

Betts, E.F., Jones, J.B., 2009. Impact of wildland fire on stream nutrient chemistry and ecosystem metabolism in boreal forest catchments of interior Alaska. Arctic, Antarctic, and Alpine Research INSTAAR 41, 407–417.

Blaauw, M., Heegaard, E., 2012. Estimation of age-depth relationships. *in Tracking Environmental Change Using Lake Sediments* Springer 379–413.

Clark, J.S., 1988a. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. Quaternary Research Elsevier 30, 67–80.

Clark, J.S., 1988b. Stratigraphic charcoal analysis on petrographic thin sections: application to fire history in northwestern Minnesota. Quaternary Research Elsevier 30, 81–91.

Cohen, A.S., 2003. Paleolimnology: the history and evolution of lake systems. Oxford University Press, USA.

Cole, D., 2008. Fairbanks: A Gold Rush Town that Beat the Odds. University of Alaska Press.

Cole, T., 1984. Crooked past: The history of a frontier mining camp, Fairbanks, Alaska. University of Alaska Press.

DeWilde, L., Chapin, F.S., III, 2006. Human impacts on the fire regime of interior Alaska: interactions among fuels, ignition sources, and fire suppression. Ecosystems Springer 9, 1342–1353.

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

Fastie, C.L., Lloyd, A.H., Doak, P., 2002. Fire history and postfire forest development in an upland watershed of interior Alaska. Journal of Geophysical Research: Atmospheres

Wiley Online Library 107, FFR 6–1–FFR 6–13.

Finney, B.P., Bigelow, N.H., Barber, V.A., Edwards, M.E., 2012. Holocene climate change and carbon cycling in a groundwater-fed, boreal forest lake: Dune Lake, Alaska. Journal of Paleolimnology 48, 43–54, doi:10.1007/s10933-012-9617-2.

Gaglioti, B.V., Mann, D.H., Jones, B.M., Pohlman, J.W., Kunz, M.L., Wooller, M.J., 2014. Radiocarbon age-offsets in an arctic lake reveal the long-term response of permafrost carbon to climate change. Journal of Geophysical Research: Biogeosciences 119, 1630–1651, doi:10.1002/2014JG002688.

Harden, J.W., Manies, K.L., Turetsky, M.R., Neff, J.C., 2006. Effects of wildland fire and permafrost on soil organic matter and soil climate in interior Alaska. Global Change Biology Wiley Online Library 12, 2391–2403.

Higuera, P.E., Gavin, D.G., Bartlein, P.J., Hallett, D.J., 2011. Peak detection in sediment–charcoal records: impacts of alternative data analysis methods on fire-history interpretations. International Journal of Wildland Fire CSIRO 19, 996–1014.

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

Kelly, E.N., Schindler, D.W., Louis, V.L.S., Donald, D.B., Vladicka, K.E., 2006. Forest fire increases mercury accumulation by fishes via food web restructuring and increased mercury inputs. Proceedings of the National Academy of Sciences National Acad Sciences 103, 19380–19385.

Kelly, R., Chipman, M.L., Higuera, P.E., Stefanova, I., Brubaker, L.B., Hu, F.S., 2013. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. Proceedings of the National Academy of Sciences National Acad Sciences 110, 13055–13060.

Kurkowski, T.A., Mann, D.H., Rupp, T.S., Verbyla, D.L., 2008. Relative importance of different secondary successional pathways in an Alaskan boreal forest. Canadian Journal of Forest Research NRC Research Press 38, 1911–1923.

Lewis, T.L., Lindberg, M.S., Schmutz, J.A., Bertram, M.R., 2014. Multi-trophic resilience of boreal lake ecosystems to forest fires. Ecology Eco Soc America 95, 1253–1263.

Lutz, H.J., 1959. Aboriginal man and white man as historical causes of fires in the boreal forest, with particular reference to Alaska. New Haven, Yale University.

Mann, D.H., Rupp, T.S., Olson, M.A., Duffy, P.A., 2012. Is Alaska's boreal forest now crossing a major ecological threshold? Arctic, Antarctic, and Alpine Research INSTAAR

44, 319–331.

McGuire, A.D., Anderson, L.G., Christensen, T.R., 2009. Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs 79(4) 523-555.

McLauchlan, K.K., Higuera, P.E., Gavin, D.G., Perakis, S.S., Mack, M.C., Alexander, H., Battles, J., Biondi, F., Buma, B., Colombaroli, D., 2014. Reconstructing disturbances and their biogeochemical consequences over multiple timescales. BioScience Oxford University Press bit017.

Meyers, P.A., Ishiwatari, R., 1993. Lacustrine organic geochemistry—an overview of indicators of organic matter sources and diagenesis in lake sediments. Organic Geochemistry Elsevier 20, 867–900.

Ott, R.A., Jandt, R. 2005. Fuels treatment demonstration sites in the boreal forests of Interior Alaska. BLM Forestry Report

Peters, M.E., Higuera, P.E., 2007. Quantifying the source area of macroscopic charcoal with a particle dispersal model. Quaternary Research Elsevier 67, 304–310.

Planas, D., Desrosiers, M., Groulx, S.-R., Paquet, S., Carignan, R., 2000. Pelagic and benthic algal responses in eastern Canadian Boreal Shield lakes following harvesting and wildland fires. Canadian Journal of Fisheries and Aquatic Sciences NRC Research Press 57, 136–145.

Potter, B.A., 2007. Models of faunal processing and economy in Early Holocene interior Alaska. Environmental Archaeology Maney Publishing 12, 3–23.

Schuur, E.A.G., Vogel, J.G., Crummer, K.G., Lee, H., Sickman, J.O., Osterkamp, T.E., 2014. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature Nature Publishing Group 459, 556–559, doi:10.1038/nature08031.

Schweingruber, F.H., 1988. Tree rings-basics and applications of dendrochronology. D. Reidel Publishing Company.

Swanson, D.K., 1996. Susceptibility of permafrost soils to deep thaw after forest fires in interior Alaska, USA, and some ecologic implications. Arctic and Alpine Research JSTOR 217–227.

Swetnam, T.W., Allen, C.D., Betancourt, J.L., 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications Eco Soc America 9, 1189–1206.

Talbot, M.R., 2001. Nitrogen isotopes in palaeolimnology, Springer.

Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., Zimov, S., 2009.

Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochemical Cycles 23.

Viereck, L.A., 1973a. Wildland fire in the taiga of Alaska. Quaternary Research Elsevier 3, 465–495.

Viereck, L.A., 1973b. Ecological effects of river flooding and forest fires on permafrost in the taiga of Alaska. Ecology 60–67.

Wolken, J.M., Hollingsworth, T.N., Rupp, T.S., Chapin, F.S., III, Trainor, S.F., Barrett, T.M., Sullivan, P.F., McGuire, A.D., Euskirchen, E.S., Hennon, P.E., 2011. Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. Ecosphere Eco Soc America 2