EVALUATION OF FIRE REGIME SHIFTS IN BOREAL ALASKA THROUGH THE USE OF SEDIMENTARY CHARCOAL

by

Alexander O. Headman

A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Geography

The University of Utah

December 2016

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The thesis of **Alexander O. Headman**

has been approved by the following supervisory committee members:

Simon C. Brewer	, Chair	**5/14/2015** Date Approved
Mitchell James Power	, Member	**5/14/2015** Date Approved
Andrea R. Brunelle	, Member	**5/14/2015** Date Approved

and by **Andrea R. Brunelle** , Chair/Dean of

the Department/College/School of **Geography**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

In the field of ecology, regime shifts are often abrupt and catastrophic occurrences with far reaching effects on global and local ecosystems which result in distinct changes in the composition and function of an ecosystem. The boreal forest provides a long term stable ecosystem over the past 6000 years, with little anthropogenic influence, creating an ideal environment to study regime shifts with respect to regional and global climate changes. In the context of modern climate change, fire in the boreal forests appears to be expanding, however, little is understood concerning the impact of previous Holocene climate changes on fire regimes in the boreal forests. This study utilizes 14 long-term charcoal records from the boreal forests of Alaska to identify spatiotemporal patterns in regime shifts and identify possible climatic drivers and consequences of these shifts on the overall ecosystem.

Regime shift patterns are identified by testing for structural change in linear regression models. Comparison of identified break points to existing paleoclimate and pollen records is then made to infer possible drivers of changes.

Clusters of break points occur over the time interval associated with the expansion of the boreal forests, mid-Holocene climate changes, as well as smaller changes associated with the late-Holocene climate. Regional changes are seen to occur with shifts in vegetation and climate, while climate shifts tend to be more local and individual in nature.

TABLE OF CONTENTS

Chapters

LIST OF FIGURES

Figures

LIST OF TABLES

Tables

PREFACE

In the field of ecology, regime shifts are abrupt occurrences with far reaching effects on global and local ecosystems which result in distinct changes in the composition and function of an ecosystem. The use of the paleoecological record to identify and study the ecological thresholds at which these shifts occur provides four opportunities to improve knowing in the field of study: a) long-term ecological records which may feature several regime shifts in the same location; b) the identification of the point(s) in time where change takes place; c) the conditions and changes preceding the change; and d) the reaction of the system after the shift. In combination with paleo-climatological data, paleoecological records provide clues and context for these past regime shifts, which, in turn, can be used to help to provide context for future abrupt changes and understand the potential ramifications of those future shifts.

Ecological systems vary greatly in their stability, with some, such as longleaf forests of southeast North America, undergoing cycles in succession on a semiannual basis, while others, such as the boreal forest, undergoing the process over the course of centuries. In many ecosystems fire acts as a catalyst for this process. Fire regimes are broadly controlled by two factors in an ecosystem: biomass, or fuel, and climate. Changes in either factor can, theoretically, affect the severity or frequency of fire within the system. The very nature of fire’s role in the ecosystem indicates that a possible change to its regime can cascade to changes in the stability of the associated ecosystem. These changes can result in possible overgrowth and eventual increase in severity of fire, in the case of a decrease of fire frequency, or destruction of local woody vegetation and a shift to fast growing vegetation, such as grasses, in the case of an increase in fire frequency.

By interrogating one by-product of fire, charcoal, it is possible to reconstruct aspects of a particular fire regime and its change throughout time. Small, windborne fragments of charcoal that fall onto lakes may be preserved in the accumulating sediments, providing a stratigraphic record of previous fires within an area. Charcoal records from lake sediment cores allow the decomposition of charcoal abundance, typically expressed as influx (particles cm^{-2} $year^{-1}$) into critical aspects of a fire regime, such as fire frequency and intensity. Expanding this scope over a larger area with more sites allows for the reconstruction of fire regimes and a variety of temporal and spatial scales, and ultimately to explore the role of local (e.g., grazing) versus regional drivers (e.g., climate).

One of the outstanding questions with respect to several fire regimes, including but limited to, that of boreal forests, is their ability to withstand significant changes in climate. Many paleorecords show a significant change in charcoal accumulation with climate, but this is difficult to disentangle from accompanying vegetation change. In order to isolate the effects of climate without the alteration in vegetation, we require a system that has not undergone significant changes in vegetation despite being exposed to several changes in climate. The Northern American boreal forest provides an ideal location to perform this analysis. This system was established at ~6000 BP-~4000BP, and has remained remarkably stable throughout the Holocene. Sedimentary records from this region covering the mid-to late Holocene therefore provide the opportunity to study changes in fire regimes where climate may be assumed to be the principal driver.

The focus of this thesis is the analysis of regime changes in charcoal records from Boreal Alaska, with the goal of understanding the role of climate in these changes. Records from the Yukon River Basin, south of Yukon Flats and the Brooks Range are used to identify regime shifts in regional fire ecology, and these are coupled with paleoclimatic records and palynological records to provide context for these regimes shifts. Specifically, this project aims to answer the following questions:

1) Can local and regional scale fire regime shifts be identified using sedimentary charcoal records?
2) Are there spatial and/or temporal patterns to these shifts?
3) By linking the observed regime shifts to known climate and/or vegetation changes, is it possible to identify the drivers and/or consequences of these shifts?

A total of 14 charcoal records covering the mid-to-late Holocene were taken from the Global Charcoal Database, and compiled into a composite regional database for this project, with five located in the Brooks Range and nine in the Yukon River Basin.

Regime shifts were identified in both individual charcoal records and in composite regional using a method designed to test for structural changes in linear regression models, the StrucChange algorithm. The method fits a series of linear regression models to a time series, with different models fit before and after a given breakpoint. The set of all possible breakpoints in a series are tested, where a breakpoint is the midpoint between two consecutive samples. Models before and after the breakpoint are compared using an *F*-test, and where significant differences are found ($p < 0.05$) the breakpoint is retained. In a second step, the results from the individual sites are then grouped together to look for spatial or temporal patterns. Information on potential drivers of the identified shifts are taken from a set of regional temperature and precipitation records, as well as paleo-oceanographic records from the Bering Sea and Gulf of Alaska to provide information on sea-surface temperature, fresh water input, and sea ice extent. Information about changes in terrestrial vegetation paralleling the regime changes is taken from pollen records from the selected sites as well as regional synthesis of records from lakes and peat bogs.

Results suggest the most significant changes, which generate novel fire regimes, occur with large-scale reorganization of the regional vegetation. This is most evident with the on-set of fire regime changes co-occurring with the establishment in the boreal forest, first at Brooks Range sites, then at Yukon Basin sites ~5000BP-4000BP. The timing of regime shifts matches the establishment of *Picea* vegetation as it migrates from coastal and northern refuges toward the southeast. The change in fire regime is not synchronous, lagging the change in vegetation by 150-200 years. This lag corresponds approximately to the time period for *Picea* trees to fully mature, indicating that the boreal fire regime requires a fully mature forest to become established.

Other shifts in fire regimes appear linked to climatic changes, but these tend to be more local and individual in nature, with no region-wide shifts occurring. Many of these shifts are temporary in nature, with significant changes occurring over a short period, but returning to normal conditions, as the vegetation is replaced. These changes are suggestive of the existence of a hysteresis loop, where the climate forcing is sufficient to cause variation in the fire regime, but without enough energy to effect a permanent shift. This is primarily seen in the cluster of change points over the 3000BP-1500BP interval. Breakpoints in this time frame tend to be less visually distinct in the time series, and have larger confidence intervals. The temporal lag between the shifts in climate and breakpoints remains approximately 100-200 years.

In the Late Holocene, records show the boreal forests to be remarkably resilient to the effects of the Medieval Climate Anomaly and Little Ice Age. In the context of modern climate change, with variability in precipitation and temperature exceeding normal variability, no change point is seen in these records. Given that earlier shifts in the charcoal record lag climate changes by 100-200 years, this suggests, as with the effect of vegetation changes, that the impacts of current climatic change on the boreal fire regime may not be fully observed for several decades.

One of the impacts of the global increase in temperatures is the expansion of boreal forests into Arctic regions. The results of this study indicate that this will result in abrupt shifts in the fire regime across large areas of the Arctic, although this effect may not be seen until the expanded forest matures. Additionally, it identifies climatic factors with links to changes in fire regimes on the regional level, such as increased moisture and temperature variability, and these may be used to create more robust models of boreal fire regime changes.

In relation to the question posed in this study:

1) Regimes shifts are identifiable using the StrucChange algorithm;

2) Spatial and temporal patterns in these shifts were observed. This is less clear when the fire regime changes in response to climate, but not vegetation. One of the more

intriguing results is the identification of a lag period in the boreal ecosystem consistently show a 100-200 year interval between perturbations in the climate and regime shifts;

3) Possible drivers are identified through the use of additions of other paleoclimate records. These include freshwater increases in paleo-oceanographic records, as well as ratios of oxygen isotopes as a proxy record for temperature and precipitation. However, more work is needed to identify sensitivity of the ecosystem to different aspects of the climate system.

While the results were able to shed light on past changes in fire regime in this region, the methodology was limited by the length of the records used. In the case of a short temporal record the algorithm may detect changes that are not necessarily the result of a climate change, but rather local factors, such as local overgrowth or plant disease, and when considering the previous 100-200 years anthropogenic influence or fire suppression. The opposite may also be true in the case of a record covering a long length of time. Significant climate changes of the past, such as the Younger Dryas, may cause a large enough shift that minor perturbations in climate and fire regime, such as the Medieval Climate Anomaly (MCA) may not create a significant enough shift in the linear model to trigger a regime shift. The resolution of a record is also a limiting factor of this study. Records of significant time depth but low resolution create inaccuracies in the timing a regime shift. In final, the length of the successional process may be of significant length in time, on the order of centuries, in which case more recent changes, such as anthropogenic climate change, to regimes with long fire return intervals may not be detected at the time of the study.

Wildfire in the boreals is often large and dramatic, with consequences to global climates through a significant increase in atmospheric emissions, and long term as a net loss of one of the largest carbon sinks on the planet. This study strives to provide a context for their fire regimes in the basis of global and regional vegetation and climate, and how changes throughout the Holocene have affected them. Future research should expand site selection to include a wider array of sites, specifically those in the Canadian and Siberian boreal ecosystems, as their continentality is similar to the sites selected for this study. This will aid in further investigation of potential lag-times between climate change and regime shift. Future research should also include the testing of sensitivity of the boreal forest to regime shift to provide understanding of the limits of the fire regime in the boreal forests in the context of future climate scenarios, as well, as the consequences of these shifts.

I would first like to express my thanks, appreciation, and gratitude to my advisor, Dr. Simon Brewer for his exemplary teaching, mentoring, and patience in guiding me through this project. Additionally, to my committee members, Dr. Mitchell Power and Dr. Andrea Brunelle, who jump started a passion for paleoecology that has yet to dwindle.

In addition to these wonderful people, I would also like to thank the fine people working at the Bureau of Land Management and the United States Geological Survey, for their support during this project, as well as my fellow paleoecology students and friends at the Utah Museum of Natural History, Yoshi Maezumi, Lovina Turney, and Blake Wellard for their support, commiseration, ideas and discussion.

This project would not have been possible without the large number of projects contributing to open access data. Heartfelt thanks to the National Oceanic and

Atmospheric Association’s National Climate Data Center, Dr. Mitchell Power, Dr. Phillip Higeura, and many others for their contributions to open data.

Last, my wife Kristin, for putting up with me all this time, for her willingness to be a content editor, and for her unwavering support, sacrifices, encouragement, love, and th list goes on.

CHAPTER 1

INTRODUCTION

The circumpolar boreal forests represent a vast and important component of the Earth's system, representing almost 10% of the land surface (Kelly et al., 2013) and containing 800 Pg C with a net carbon sink of 0.54 Pg C year^{-1} (Apps et al., 1993). In recent decades, the boreals have undergone significant changes associated with climate change (ACIA, 2005; IPCC, 2013). This includes an increase in expansive wildfires responsible for releasing significant amounts of carbon into the atmosphere (Barrett et al., 2013; Kelly et al., 2013), with some estimates of increasing as much as 100% in the latter half of the 20th century (Barrett et al., 2013; Kasischke & Turtsky, 2006). While fire has always been the dominant disturbance within the boreal forests (Bond-Lamberty et al., 2007), models predict a still greater significant increase in boreal fires in response to anthropogenic warming (Flannigan et al., 2009).

While the significance of the boreal forests as net carbon sinks for the planet, representing ~30% of the terrestrial carbon (Apps et al., 1993; Kelly et al., 2013), cannot be understated, there are gaps in understanding the sensitivity and limits of the boreal fire regimes' response to climate changes. While it is well known that fire regimes shifts with changes in fuel composition (e.g., Higuera et al., 2009), it is less well known how boreal forests have specifically reacted to changes in climate over the course of the mid-late Holocene.

The late Quaternary is punctuated with climatic and ecological changes that are extraordinarily abrupt (Alley et al., 2003; Williams et al., 2011), be it the termination of the previous glacial period and the Younger Dryas Interval, or the North American hemlock population collapse (Bennett & Fuller, 2002; Davis, 1981; Orwig et al., 2002). While there are climatic factors at all manner of time scales (Overpeck et al., 2003), there are limits which ecological processes are able to operate, and, once crossed, require a substantial amount of time and energy to return to their former states (Lenton et al., 2008; Scheffer et al., 2001; Scheffer, 2009; Scheffer & Carpenter, 2003).

Dynamical systems theory provides a framework with which to consider how these regime shifts occur (Scheffer, 2009), both in space and time (Carpenter & Lathrop, 2008; Dakos et al., 2010). By identifying previous regime shifts in systems, it is possible to understand where these limits are, as well as the antecedent conditions that precipitated the shift in regime (McWethy et al., 2013).

Sedimentary charcoal is a frequently employed tool to reconstruct fire regimes in the past (Clark, 1988). Until recent years, these reconstructions were only available at the site specific level. The generation of large dataset repositories (NOAA NCDC Paleoclimate Data Center, 2015; Power et al., 2010) now allows for a larger spatial and temporal view of the effects of shifting climates beyond the historic record. Comparison studies with other available paleorecords, such as those of pollen and ice cores, can be combined with currently available charcoal records to provide an in-depth view of not only the operating conditions of a stable fire regime, but the conditions which lead to changes within that regime. Combining these records can also determine possible inferences of the sensitivity and adaptability to the system itself (Scheffer et al., 2012).

The aim of this study seeks to expand on current site-based studies within the boreal system and to look at this question of threshold points, with respect to shifts in fire regimes to determine if:

1. Local and regional scale fire regime shifts can be identified using sedimentary records,

2. There are spatial and/or temporal patterns to these shifts, and

3. These changes are linked to known climate and/or vegetation changes in the available paleorecord.

CHAPTER 2

BACKGROUND

Systems Theory

The concept of dynamical system theory is that all systems exist in equilibrium with the current conditions, however, when a change is introduced into the system, an alternative stable state can occur for which conditions exist (Scheffer & Carpenter, 2003). The response of a system, at this point, depends on if it undergoes the mechanics of positive or negative feedbacks (McWethy et al., 2013). While many disturbances can upset a system's equilibrium it does not necessarily result in a regime shift. However, a significantly large change, which permanently affects the feedback system which serves to maintain the system, or an alteration to the functionality of an ecosystem can be caused by a change in the stable state, resulting in a regime shift. While, in general, negative feedbacks typically work to maintain a system of equilibrium, the impediment of one or more factors within the system can consequently trigger positive feedbacks, which can precipitate a catastrophic change, should it escape the bounds of its ecologically acceptable operating limits.

An example of this positive feedback system is seen in temperate rainforests as described by McWethy et al. (2013), and Holz and Veblen (2011). In the described system, forests are cut back for croplands and/or fires are suppressed. In either case, the rainforest biome is cleared and a mixed forest/woodland biome replaces it; the lower density of the forest allows for a greater density of ladder fuels and increased flammability leading to more fires and less forest. Eventually, this feedback will precipitate into a collapse of the forest system and be replaced with grassland, where greater flammability acts as a stabilizing mechanic. This is an example of an abrupt change type alteration (Scheffer, 2009; Scheffer & Carpenter, 2003) and catastrophic change.

Catastrophic change, a change which occurs over an extremely short period of time relative to the system, in a system does not necessarily require an abrupt change. Often the slow application of an element can precipitate changes after a significant amount of time passes. The agent of changes eventually causes the system to cross a limit to where a linear response in a system shifts to an abrupt response. Where this limit is depends on the resilience of the system to change. Abrupt response can be triggered by a large shock, such as the introduction of a rapidly colonizing invasive species. An example of this is the effect of *Bromus tectorum* (cheatgrass) on the fire regimes of the American West as seen in Billings (1994) and D'Antonio and Meyerson (2002). Alternatively, the lowering of the resilience of a system can also trigger catastrophic change. An example of this is seen in the form of albedo driven changes; in the ice-albedo feedback system, long-term climate change affects local albedo, which multiplies the effects of insolation driven heating (Deser et al., 2000). Similar alterations in albedo may also drive desertification feedback, with decrease in vegetation cover and increasing albedo, reduce precipitation, which further reduces vegetation cover, which Renssen et al. (2003) suggest, may have been a factor in the collapse of vegetation in the Sahara/Sahel region.

While catastrophic change is the most dramatic example of regime shift, the resilience of some systems will reflect as a linear response due to change taking place over a long time period (Scheffer & Carpenter, 2003). Slow changes, however, imply only one possible equilibrium for the state to exist (Scheffer et al., 2001). The equilibrium idea seen in Scheffer et al. (2001) and Scheffer & Carpenter (2003), also speaks to the idea of system resilience and the energy needed to force change. By using the paleoecological record to look at past system changes it may provide insight and improved knowledge to help understand the possible changes in the next few decades.

Climate and Vegetation

Modern Boreal Climate and Vegetation

An advantage of using the boreal forests to study the impact of climate change on fire regimes is the remarkable stability of vegetation over the previous 6000 years (Anderson & Brubaker, 1994; Bartlein et al., 1992; Higuera et al., 2009; Miller et al., 2007) allowing for the study of the effects of shifting climate on fire regimes. Forests are spruce dominated with *Picea glauca* (white spruce) dominant on upslope areas in warmer and drier areas and *Picea mariana* (black spruce) dominant in lowland areas. River meanders and seasonal wetland areas support some deciduous broadleaf trees which include several species of *Populus* and *Betula* (Hagenstein et al., 2012).

Climate in the western boreal region is characterized by long cold winters with average temperatures below freezing 5-6 months of the year. Precipitation values are low throughout the year with the majority of effective moisture occurring during the late summer months (Manley and Daly, 2005). Low temperatures and permafrost combine with low evapotranspiration allowing for the establishment of wetland areas.

Large scale moisture patterns throughout the boreals are driven by the Pacific Decadal Oscillation (PDO) and the longitudinal movement of the Aleutian Low (AL) (Barron & Anderson, 2011; Bosnal et al., 2001; Fisher et al., 2008; Hare & Mantua, 2000; Mantua et al., 1997; Miller et al., 2007; Overland et al., 1999). Indices for these atmospheric-ocean phenomena are well linked to annual average temperature and precipitation over the extent of the region (Anderson et al. 2005; Barron & Anderson, 2011; Papineau, 2001). PDO cyclicity is variable between 15-25 year periods (Mantua et al., 1997), while the variability of the Aleutian Low is on a shorter time frame of 5-10 year periodicity (Overland et al., 1999).

Modern Boreal Fire Regimes

Boreal forests routinely burn, initiating secondary succession, with mean fire return intervals (mFRI) of approximately 150-170 years (Higuera et al., 2009). Fires in the boreals are generally large, stand replacing events (Kasischke & Turetsky, 2006). In addition to initiating succession, fires in the boreals renew soil nutrients and promote tree recruitment (Chapin et al., 2000; Kasischke & Turetsky, 2006). The majority of fires in the interior of the Alaska and Canada regions remain naturally caused (Kasischke & Turetsky, 2006), and are likely due to sparse human population.

Paleoclimate of the North American Boreals

Bartlein et al. (1991) propose using the framework of dividing the postglacial era into sections based on major controls for studying paleoclimates in Eastern Beringia. This includes the North American ice sheets (influencing air circulation and temperature), insolation values (influencing seasonality and temperature), greenhouse gas concentrations (influencing temperature), and ocean related feedbacks (reinforcing insolation). During the Late Quaternary period, the presence, size, and eventual absence of the North American ice sheets (Bartlein et al., 1991; COHMAP Members, 1988) is the major climatic driver in the Arctic from 18ka to 10ka. From 14ka-6ka insolation gradually takes over as the primary driver of climate in the Arctic. From 6ka to present insolation approaches modern values, resulting in warmer seas surface temperatures, and higher CO_2 and CH_4 concentrations (Berger, 1978; CLIMMAP Project, 1981; Ruddiman, 1987). In addition to the framework proposed by Bartlein et al. (1991), additional eras utilized for study framework by Miller et al. (2007) are neoglaciation at approximately 3000BP, the Medieval Climate Anomaly (MCA) approximately 1000-800BP (Miller et al. 2007), and the modern era of the previous 1000BP, including the Little Ice Age (LIA) and modern anthropogenic climate change (ACIA, 2005; IPCC, 2014; Kaufman et al. 2009).

Pleistocene-Holocene Transition (18ka-10ka)

Available records from the majority of Interior Alaskan sites show the area as ice free from 18ka to present (Anderson & Brubaker, 1993; Anderson & Brubaker, 1994; Brubaker et al., 2005). Anderson and Brubaker (1994) show this region dominated by herbaceous taxa of Gramineae, Cyperaceae, and *Artemisia*, with the addition of *Salix* pollen. A small population of *Populus* is seen throughout the longitudinal profile of the record, however, tree taxa represent a very small amount of total pollen (<10%) (Anderson et al., 1989; Higuera, 2009).

The collection of species seen during the Last Glacial Maximum (LGM) and their coexistence on the landscape of this region are associated with modern tundra assemblages (Anderson et al., 1989). Anderson et al. (1989) note the increase in non-analogue communities between 14000BP-9000BP could be the result of extremely rapid climate change associated with the glacial-interglacial transition, which resulted in the inability of plant communities to firmly establish. Their site studies of vegetation communities of Interior Alaska during the late-glacial (12ka-10ka) show a slight increase in analogue vegetation communities with modern communities of Interior Alaska, possibly suggesting a late-glacial climate of cold dry winters and cool wet summers, similar to the modern climate of the North Slope, Alaska (Manley & Daly 2005). However, the rapid decrease of ice sheets (Bartlein, 1991; Clark et al., 2009; Cronin, 2013) may have resulted in a climate space unique to the time period.

Two major global climate events occurred during this transition era, the Heinrich Event H1 at ~16ka (Cronin, 2013; Hemming, 2004) and the Younger Dryas Interval (YDI) at 13ka (Alley, 2000). During the YDI, a decrease in levels of *Populus* pollen indicates a return to a drier climate (Mann et al., 2002). However, the majority of pollen records show very little evidence of the YDI having a large effect at the regional scale (Anderson & Brubaker, 1994; Higuera, 2009) when compared with the large alteration in vegetation seen in paleoclimatic records from the Atlantic region (Shuman et al., 2002;

Williams et al., 2002).

Kaufman et al. (2004) argue that the onset of the Holocene Thermal Maximum affected the Alaskan region earlier than in Canada due to the presence of the rapidly shrinking Laurentide Ice Sheet. Rapid expansion of *Populus* and *Picea,* at and above the modern tree-line (Anderson & Brubaker, 1994; Brubaker, 2005; Higuera, 2009), rising lake levels (Mann et al., 2002), and dendroclimatological studies based on ring width of *Populus balsamifera* (Edwards & Dunwiddle, 1985) show a warmer climate than modern values and a wetter climate than LGM values throughout the North American Boreals.

The transition to more regular fire intervals for Alaskan sites occurred during the vegetation transition from herb dominated tundra to shrub dominated tundra at approximately 14ka. Mean fire return interval (mFRI) during the shrub interval is approximately 137 years (Higuera et al., 2009). Higuera et al. (2009) argue that this change in fire regime can be linked to vegetation changes since climate records indicate the same cool and dry conditions throughout the majority of the time interval despite the rise in and expansion of *Betula* pollen (Anderson & Brubaker, 1994). Anderson and Brubaker (1994) do note, however, during the expansion of the *Betula*, there is a coincident gradual rise in the moisture for sites in western Alaska. Compared to the herb dominated tundra, *Betula* requires greater moisture to thrive. Its sudden and rapid rise possibly indicates dry summer conditions coupled with increasing wet conditions during the early spring flowering period of *Betula*. It is difficult to interpret whether changes in fire regime were driven by climate or vegetation during this period versus later period due to the scarcity of pollen data within the region, and the existence of nonanalogue vegetation communities (Anderson et al., 1989).

Early Holocene and Pre-Boreal Period (12ka-6ka)

Climate during the early Holocene interval comes under the increasing control of summer insolation (Bartlein et al.., 1991; Higuera et al.., 2009; Kaufman et al.., 2004). Temperatures, in general were 1°-2°C warmer with up to 40% less precipitation than modern (Anderson et al.. 2001; Edwards et al. 2001; Kaufman et al. 2004, Viau et al. 2008).

During this time period, Kaufman et al. (2004) note that the change in the interior of Alaska shows a gradual transition in climate with the onset of the Holocene Thermal Maximum, (HTM). Alaskan sites mentioned in Kaufman et al. (2004) are those with a continuous record through the Pleistocene-Holocene transition period, which are shown to have an earlier onset (~12ka) and termination (~9ka-11ka) of the HTM in Alaska when compared with Arctic sites in interior Canada. Legacy glaciers from the Pleistocene in the region retreated behind their modern limits, with coastal glaciers receding inland. The existence of an ice-free region during the late Holocene is likely a physiographic reason for the early onset of the HTM, as well as a reason for the smooth transition between Pleistocene-Holocene paleorecords.

The vegetation records of Higuera et al. (2009) and Anderson and Brubaker (1994) do not show a dramatic change in vegetation during this time frame. The most notable is the rapid expansion of *Populus* throughout interior Alaska, with *Betula* pollen continuing to maintain the same presence over the majority of the sites.

Anderson and Brubaker (1994) interpret the increase in deciduous forest as vegetation establishing along streams and along well drained slopes. Additionally, geomorphic evidence for increased stream aggradation (Hopkins, 1982) supports a drier than normal climate throughout eastern Beringia. This is an important consideration for interpretation of paleofire records in Higuera et al. (2009), which paradoxically show a decline in fire activity at ~10.5ka as climate warmed and precipitation decreased. The Yukon River Basin records from Alaska shows very little charcoal activity during this time frame, suggesting that the vegetation in the Brooks Range and the Yukon River Basin was likely covered in sparser vegetation centered near natural fire breaks within a mountain valley. However, in areas where coastal waters influence climate, this time frame shows an increase in fire activity (Anderson et al., 2006; Berg et al., 2006). The anomalously dry conditions in the Kenai combined with denser fuel loads would allow for greater fire frequency. Modern climate variability show a greater trend towards more year round moisture, and low temperature variability in the coastal regions with fewer fires (Agee, 1996; Manley & Daly, 2005) with dry, highly variable temperature conditions in the Yukon River Basin region (L'Heureux et al., 2004).

As a comparison, the Canadian continental region, prior to the onset of HTM at 6ka (Kaufman, 2004), shows wetter and warmer conditions expanding west to east from 12.5ka-7.5ka (Abbott et al.., 2000; Mann et al.., 2002). Anderson et al. (2005) show a rapid increase in lake levels between 10ka-8ka. The recession of the Laurentide Ice Sheet, the late arrival of HTM conditions in Northwest Territories, and with the onset of modern climate variation (Anderson et al., 2005; Barron & Anderson, 2011; COHMAP, 1998; Higuera et al., 2009; Miller et al., 2007), coupled with the expansion of the boreal forest in the region, is likely the reason for low fire frequency in the charcoal record prior to 7.5ka.

A decline in pollen accumulation during this time period and the rapid decline of

Betula in southeast Yukon Territory (Cwynar & Spear, 1995) also support a drying climate over much of the region. However, this drying event is not synchronous across the Yukon Territory. While sites in the southeast show dry and cool conditions, sites in central Yukon Territory do not show the same dry period (Cwynar & Spear, 1991; Cwynar & Spear, 1995; Lauriol et al., 2009). Further evidence of this regional split is seen in Richie (1981), which shows a loss in biodiversity from pollen records from central Yukon Territory and expansion of *Picea* in northern Yukon Territory. Laruiol et al. (2009) explain this regional difference as an increase in moisture from northern sources of the Beaufort Sea and the postglacial sea level rise coupled with the insolation maximum.

CHAPTER 3

METHODOLOGY

Site Selection

The spatial extent of the boreal forests in Alaska span a large enough area, with homogenous vegetation, that the effects of changing fuel types on associated fire regimes are negligible and fire behavior is similar across all sites. Records from the Global Charcoal Database (Power et al., 2008) within an established closed forest boreal ecosystem were selected for this study, which covered a minimum of the previous 2000 years with at least five dating controls distributed throughout the core(s) used in the age model so as to establish adequate coverage for the resolution of the study. Sites containing values for charcoal accumulation within the database were utilized using the values given, sites where differing unit were used in the study were interpolated to accumulation rates using CharAnalysis (Higuera et al., 2008). These sites record dominant weather patterns generated from the Northeastern Pacific. This study includes five sites from the Brooks Range, AK, USA at a latitude of 65°N and a longitudinal gradient from 150°-154°W, and nine sites from the Yukon River Basin, AK, USA in a latitudinal gradient from 64°-66°N and a longitudinal gradient from 147°-149°W. The sites have a Pacific-influenced climate on the windward side with respect to the continental dividing ranges (see Table 1, Figures 1-3).

Due to its long period of stability, the boreal system is an ideal area to study the impacts of regional and global climate imposed shifts on fire regimes. Pollen records show the establishment of the closed forest boreal ecosystem at approximately 6000-5000BP (Higuera et al., 2009). Utilization of temporally transgressive records with respect to the establishment of the boreal forests allow for testing of the efficacy of this analysis against a robust known change in the region. Therefore, any future change could be interpreted according to climate conditions.

Paleoclimatic Comparison Datasets

Climate and weather patterns within the Pacific basin have been well studied in both the modern climate and in the paleo context. The wealth of information has allowed for the creation of viable reconstructions of the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) (e.g., Barron & Anderson, 2011; Fisher et al., 2008; Wilson et al., 2010), the two dominant modal patterns affecting the northeastern Pacific. Records of glacial advance and retreat (Miller et al. 2010), as well as, pollen-based records (Viau & Gajeweski, 2009; Viau et al., 2008) in the region provide a proxy record for temperature reconstruction, whereas oxygen and deuterium isotope records provide a record for moisture reconstruction (Anderson et al., 2001; Fisher et al. 2004; Fisher et al. 2008; Viau et al., 2008). In addition to the use of pollen records as a proxy for climate reconstruction, pollen is also used to establish the time frame for the boreal forest establishment and the vegetation fluctuation and stability. Using these existing records, we can establish a viable reconstruction of climate and vegetation throughout the mid-to-late Holocene period/era to provide context for records of fire activity.

Statistical Analyses

Time series analysis for the charcoal series was performed using R and the StrucChange package (Zeilus et al., 2012). The algorithm utilized by StrucChange builds upon the classical linear regression model with the assumption that between stable relationships, wherein the coefficients within the linear regression do not change, there exists *m* points in the series where the model coefficients change, resulting in a new model for part of the series and thus, a breakpoint in the linear regression (Bai, 1994; Bai & Perron, 2003; Zelius et al., 2012). This is given by the equation:

$$(1)\quad y_i = x_i^T \beta_j + u_i \quad (i = i_{j-1} + 1, \dots i_j \;\; j = 1 \dots., m + 1)$$

where *i* denotes the index point in the time series and *j* the section of the series modeled by that coefficient. The determination of a breakpoint is derived via an estimation based in the minimization of the residual sum of squares (RSS) within the series (Zelius et al., 2012). This is compared to determinations in the computed *F* statistic (Chow test) between points prior to the estimated breakpoint and after the breakpoint for significance ($p < 0.05$).

Since the number of breakpoints in any given series is *m*, where $m+1$ is the number of datapoints (*n*), it is therefore essential to utilize a method that restrains the number of breaks to a realistic amount. For the StrucChange package, BIC score is the default method for scoring the applicable number of breakpoints, with the option of utilizing AIC score. Both of the method provide a score for each set of breakpoints, based on the RSS of the total model, but penalized by the number of coefficients (and therefore breakpoints) used. Considering the scope and goals of this study, BIC score is the more favorable method because of its reliance on posterior probability. There were no series in the study, at either the site level, or regional level analysis where the number of determined breakpoints exceeded four. The values of the AIC score were computed, however, there were no situations where AIC scores would have favored a different selection. The initial exploratory phase considered $m=10$ for any given series, which was later refined $m=5$ for the final analysis.

The calculation of confidence intervals is based on equations from Bai (1997). For charcoal data confidence intervals are based on Gaussian distribution, and the final confidence interval is presented here as the 95% interval within which the breakpoint exists.

Individual sites were run through the StrucChange algorithm utilizing the entire available record. In instances where the best fit model showed no significant changes, the results are not reported; however, data from these sites are included in the regional analyses.

Regional analysis is based on the spatial aggregate of the sites, divided into two regions: the Brooks Range and the Yukon River Basin regions as indicated in Table 1. Charcoal data for analysis on regional scale is transformed using a Box-Cox transformation seen in Power et al. (2008). This allows for the cross-comparison of records when charcoal reporting methods differ among sites. All records are clipped to the temporal extent of 7000BP to allow for the greatest number of records. The time domain also allows us to control for fire regime changes influenced by possible vegetation shifts prior to the establishment of the closed boreal ecosystem. Records are averaged and loess smoothing windows from 100 years to 500 years were applied prior to applying the StrucChange algorithm.

Table 1 Selected sites for study

Site Name	Lat	Long	Elev (m)	samp #	Age (Years BP)	Citation
BROOKS RANGE						
Code	67.158	-151.861	250	470	7409	Higuera et al.. 2009
Last Chance	67.079	-150.752	250	64	2167	Higuera, P., unpublished
Wild Tussock	67.128	-151.382	290	551	7828	Higuera et al.. 2009
Ruppert	67.071	-154.246	230	1062	13948	Higuera et al.. 2009
Xindi	67.112	-152.492	240	580	18001	Higuera et al.. 2009
YUKON RIVER BASIN						
Deuce	66.055	-148.162	170	64	1269	Lynch et al.., 2002
Dune Lake	64.417	-149.9	134	373	9219	Lynch et al.., 2002
Jan	66.03	-147.553	223	206	13400	Edwards, M.E., Unpublished
Oops	65.442	-147.632	488	184	6410	Finney and Krumhardt, 2004
Picea Lake	65.881	-145.588	269	565	10369	Kelly et al.., 2013
Reunion Lake	66.009	-146.108	306	1783	5405	Kelly et al.., 2013
Screaming Lynx	66.068	-145.404	276	1514	10642	Kelly et al.., 2013
West Crazy Lake	65.891	-145.62	239	927	2770	Kelly et al.., 2013
Windy Lake	66.041	-145.75	245	400	2808	Kelly et al.., 2013

Sites are publicly available through contribution to the NCDC at NOAA. Retrieved from at http://www.ncdc.noaa.gov/data-access/paleoclimatology-data.

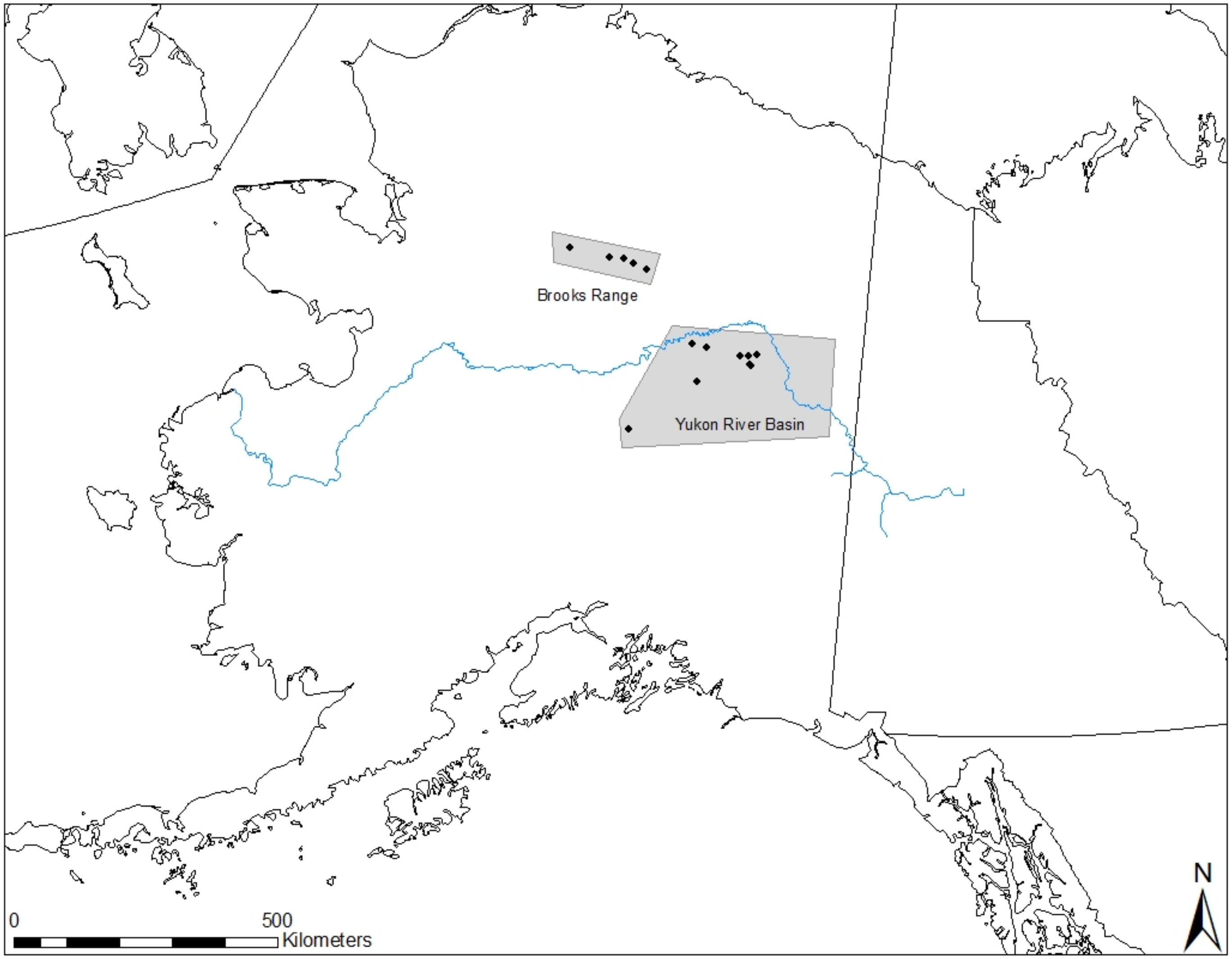

Figure 1 Map of selected sites for this study. The grey boxes indicate regional groupings.

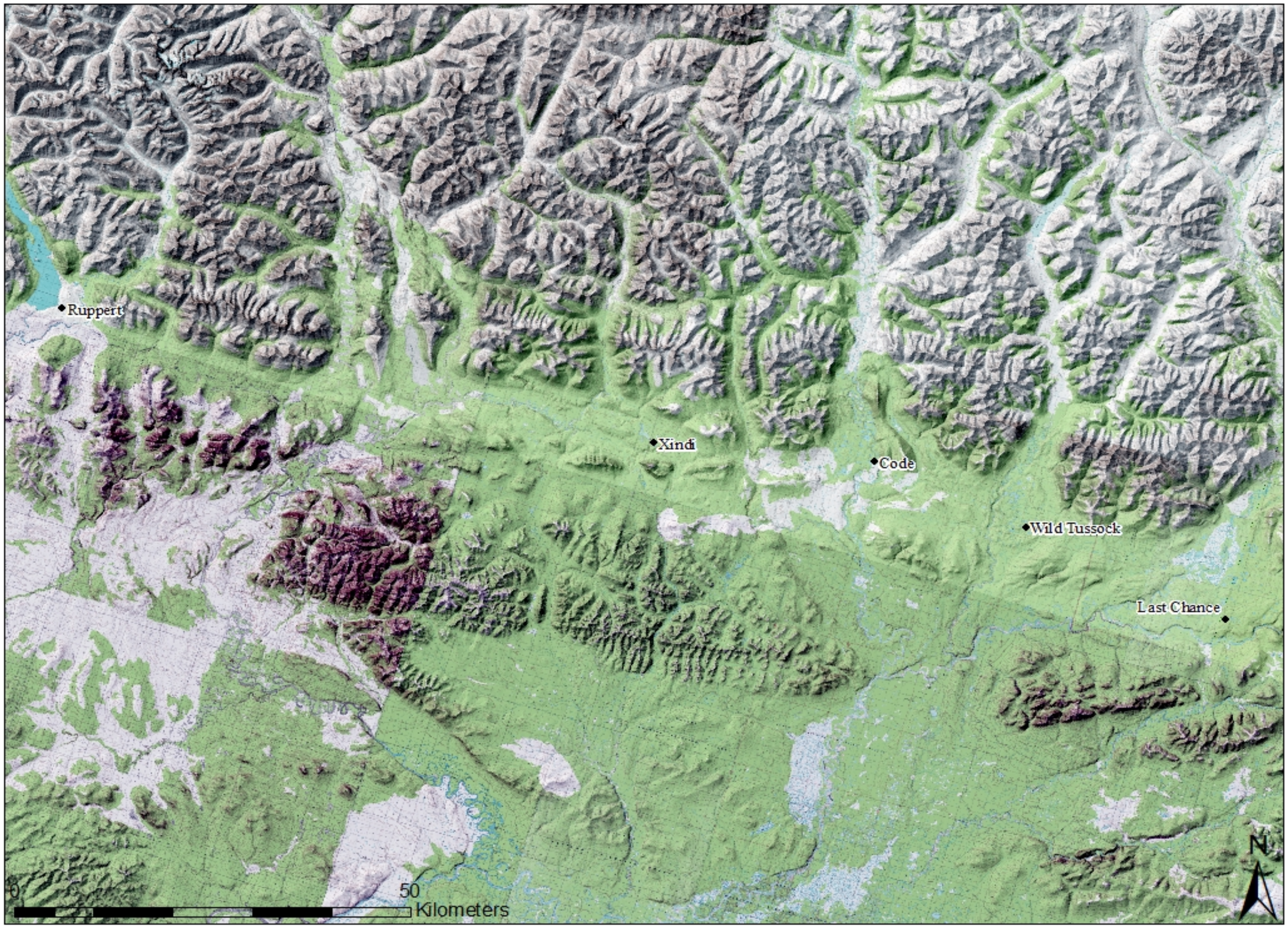

Figure 2 Detail map of the Brooks Range sites.

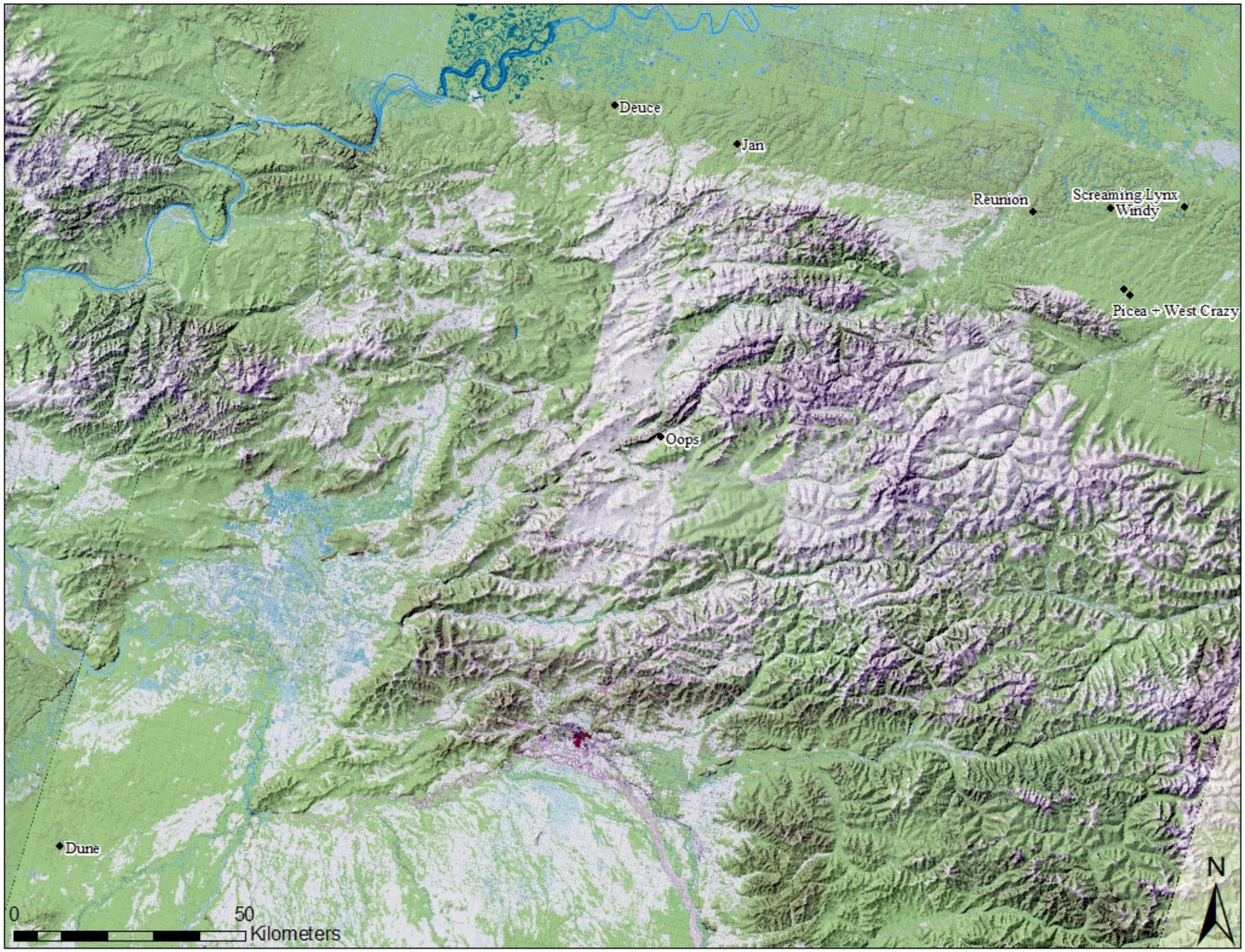

Figure 3 Detail map of the Yukon River Basin sites.

CHAPTER 4

RESULTS

Brooks Range Site Level Analysis

Of the five sites, as part of the Brooks Range, four were identified as having breakpoints in their linear model whereas Xindi had no significant breaks. Records without breaks are assumed to have been subject to similar conditions. However, the change at these sites, possibly due to local factors such as physiographic setting, did not occur at a rapid enough rate so as to trigger a breakpoint in StrucChange. Likewise, limitations may exist within the StrucChange algorithm which could affect results on sites with less than adequate resolution. This is discussed in greater detail in the discussion section.

Code Lake

Code Lake site shows three significant breakpoints over the 7409 year record (Figure 4). The earliest breakpoint being 4960BP with 95% confidence interval (CI) and 5% CIs for this point at 5343BP and 4891BP. The trend for the time preceding the breakpoint shows a slight incline with relatively low charcoal accumulation until approximately 6000BP. The interval between the breakpoint at 4960BP and the following breakpoint at 2651BP shows a marked increase in the amplitude of charcoal accumulation compared to the previous interval with the slope showing a steady increase in charcoal accumulation.

The second break point of 2651BP, [3730BP and 2444BP], shows a long period of little fire activity during the interval between ~3480BP to ~3250BP, which is followed by a marked increase in the amplitude and frequency of charcoal accumulation. During the time interval between 2651BP and the final breakpoint of 1496BP, the trend shows is an overall downtrend in overall charcoal accumulation, but the amplitude of peaks are higher than the preceding interval.

The final breakpoint of 1496BP [1740BP and 840BP], is marked with a continuous decline in activity and lower overall amplitude versus the previous period. One significant spike occurs at ~421BP. A slight uptrend is seen towards the end of the interval, however it is not seen as a significant deviation from the overall linear trend of the interval.

Last Chance Lake

Last Chance site shows a single significant breakpoint in its 2160 year record (Figure 5). The breakpoint occurs at 1847BP [1880BP and 1542BP]. The number of samples prior to the breakpoint limits significant commentary regarding trends. The linear trend shows declining fire activity prior to the breakpoint with higher amplitude than the interval after the breakpoint. The interval after the breakpoint is characterized by low amplitude and low accumulation of charcoal, however, there is a slight increase in activity towards the end of the interval.

Ruppert Lake

Ruppert Lake shows three breakpoints over the 13,948 year record (Figure 6). The first significant breakpoint occurs at 9260BP [10,512BP and 9620BP]. For the interval preceding the breakpoint, the trend shows an increase in charcoal accumulation with a higher frequency of peaks relative to the preceding interval. The interval after the first significant breakpoint and prior to the next breakpoint is marked with a relatively flat trend and little to no fire activity. Overall, the amplitude and frequency over this interval are the lowest of any point during the entire record.

The second breakpoint at 5165BP [5693BP and 5119BP], is marked by a large increase in the slope of the trend, as well as the amplitude and frequency over the interval between 5165BP and 1726BP. The third breakpoint at 1726BP [2750BP and 1580BP], shows an increase in the frequency of fires with the exception of two of the sample points, which have a lower overall amplitude. This interval also shows a declining trend line over the interval from 1726BP to the present.

Wild Tussock Lake

Wild Tussock Lake shows two breakpoints over its 7828 year period (Figure 7). The first breakpoint occurs at 4774BP [5809BP-4057BP]. The interval preceding the breakpoint shows similar frequency compared to the interval following. Amplitude, with the exception of three peaks, is overall lower than any of the following intervals. The following interval shows another period with a relatively flat trend. The second breakpoint occurs at 2323BP [3505BP and 1691BP]. The interval after this break is marked with a steady increase of the trend's and higher overall amplitude than either of the preceding intervals. Frequency remains similar to the previous intervals, if not slightly lower. Out of any of the sites in the Brooks Range which reflect breakpoints, this record has the largest range of confidence intervals relative to the breakpoint.

Brooks Range Regional Scale

All of the Brooks Range records were utilized in the regional scale analysis (Figure 8), including Xindi, which did not show any significant breakpoints at the site level. Loess smoothers were applied at 100-year intervals through a 500-year smoother window. There was no significant difference between any of the loess smoother intervals in the outcome of the analysis (+- 20 years for any given point, either 5% confidence interval or breakpoint). The results reported here are from the 500-year smoother window.

Records for the analysis were trimmed to 7000 years, which covers the majority of the records, including Last Chance which, due to its length, is not included in the interval between 7000BP and 2160BP. In the preliminary investigation, trimming the records to include Wild Tussock and Code made no significant difference on the outcome of the analysis.

The initial breakpoint in the regional scale analysis, based on the 500-year smoother window, is located at 5337BP [5350BP and 5333BP]. The interval prior to this point shows relatively low fire activity with occasional high amplitude, but these spikes are of low frequency. Over the term of this early interval there is a steady decline in fire activity up to the breakpoint. The interval after the breakpoint shows a marked increase in charcoal accumulation. Frequency is higher, with amplitude that is similar to the previous interval. The most notable difference between the two intervals is the extreme decrease in samples with was zero accumulation. There is a marked drop in the smoothing line prior to the second breakpoint at 2830BP.

The second breakpoint in the regional scale analysis is at 2830BP [2847BP and 2783BP]. The interval after this breakpoint is marked by a sharp increase in charcoal accumulation, which is then followed by a gradual decline. Both amplitude and frequency appear to increase over the interval, with very few points with zero accumulation between 2872BP and the third break point at 1864BP.

The third break point at 1864BP [1872BP and 1853BP], shows an overall decline in the accumulation trend. Despite the increase in amplitude compared to the previous interval, the frequency declines. The latter part of the interval, has conditions similar to the interval preceding 1864BP, in terms of frequency and amplitude, however the overall accumulation continues to decrease.

The fourth and final breakpoint at 891BP [950BP and 885BP], shows a marked increase in charcoal accumulation with a frequency and amplitude similar to that of the interval between 5332BP to 2872BP. A significant rise in the smoother line is seen beginning at approximately 200BP.

Yukon River Basin Site Level Analysis

Nine sites were selected in the Yukon River Basin area. Out of these nine sites, six sites showed significant breakpoints at the site level, with Reunion, Jan, and Deuce Lakes showing no break points.

Dune Lake

Over its 9810 year record, Dune Lake shows a single breakpoint at 4384BP, [5807BP and 4255BP] (Figure 9). The interval prior to the breakpoint shows very little charcoal accumulation, a lower frequency, and no significant peaks in amplitude. The time frame from ~5800BP onward shows a marked increase in frequency, amplitude, and overall accumulation. Notably, this site's sample frequency prior to 5807BP is 43 samples over a 4000 year time frame, or one sample per 100 years. The interval after the breakpoint shows a significant increase in the amplitude of the spikes in regard to charcoal accumulation. Overall accumulation increases over the period of the latter interval, however, due to low sample frequency in the preceding interval, no significant determination can be made with the respect to frequency. A shift in the sedimentation likely causing this disparity in sampling frequency during the change interval may indicate in a change in local ecological conditions, and therefore, a regime shift.

Oops Lake

Oops Lake also shows a single breakpoint over its 6410 year period at 4101BP [4620BP and 4012BP] (Figure 10). Prior to the breakpoint, the trend shows a steady increase in charcoal accumulation, with low frequency and amplitude compared to the following interval. The interval after the breakpoint shows a parabolic trend with an increase up to approximately 2300BP, after which overall accumulation steadily declines to present. Amplitude and frequency remain relatively constant over the entire interval.

Picea Lake

Picea Lake shows two breakpoints over the 10,369 year record (Figure 11). The first breakpoint is at 3163BP [3603BP and 3023BP]. Prior to this breakpoint very little charcoal accumulation takes place. With only one significant peak at any point prior to ~4500BP and most values being fairly close to zero accumulation. After the breakpoint the base charcoal accumulation rises to nonzero values. Both frequency and amplitude are significantly higher than the majority of the values prior. Throughout the time frame charcoal accumulation is in a downtrend from its initial jump at the break point.

Picea Lake's second break point occurs at 1483BP [2223BP and 1403BP]. After the breakpoint there is a significant uptrend in charcoal accumulation and amplitude. Frequency is similar to that of previous time frame. The lower 5% CI is a long tail extending to a point where the down trend of the previous time frame flattens out. It is at the breakpoint where the uptrend in charcoal accumulation resumes.

Screaming Lynx Lake

Screaming Lynx Lake shows a single breakpoint in its 10,642 year record (Figure 12). This breakpoint occurs at 3708BP [4098BP and 3693BP]. Prior to this breakpoint there are no significant peaks, with a slight increase in frequency beginning at ~5000BP. After the breakpoint charcoal accumulation significantly increases in amplitude of peak, with frequency remaining similar to the ~5000BP point. The trend remains fairly even throughout the latter portion of the record with increasing peak amplitude into the modern era.

West Crazy Lake

West Crazy Lake and Windy Lake, with records of 2770 years and 2808 years, respectively, were selected based on their record length covering a decent portion of the latter part of the total record. Using these two records allows for a better view of changes over the previous 3000 BP when the boreal forest ecosystem is already established.

West Crazy Lake shows two breakpoints (Figure 13). The first breakpoint at 768BP [798BP and 753BP] shows a significant increase in charcoal accumulation from the previous era. All of the peaks in this era are larger than previous time frames and begins a period of unusually high frequency and amplitude in the accumulation rate. The second breakpoint at 348BP [378BP and 303BP] marks a return to conditions prior to the first breakpoint. The two initial peaks at the beginning of this time frame are lower baseline than the previous time frame, with similar amplitude. Overall the time frame shows a strong decline in charcoal accumulation with only the time since 1950AD reflecting an increase.

Windy Lake

Windy Lake shows one breakpoint in its record at 1112BP [1517BP and 977BP] (Figure 14). The record shows a significant increase in charcoal accumulation after the breakpoint with a general uptrend, increase in frequency, and amplitude in the latter part of the record. Prior to the breakpoint there is only one significant peak at ~1500BP, which marks the beginning of the breakpoint confidence interval. With the exception of this peak the record shows very little charcoal accumulation over the entire interval.

Yukon River Basin Regional Scale

Similar methods were followed as with the Brooks Range sites, with the sites Reunion Lake, Jan Lake, and Deuce Lake being excluded from the analysis. Site density increases to the present with four lakes covering the entire record, six lakes covering the boreal ecosystem (~6000BP-present) (Figure 15). The remaining three lakes are included progressively from approximately 3000BP to 1269BP based on their bottom dates (see Table 1).

The application of loess smoothers at 100-year intervals through 500 years, shows no significant change in results between the intervals. Overall four breakpoints are identified with breakpoints varying by +-60 years between the 100 year and 500 year loess smoother intervals (Figure 16). Results are reported using the 500 year loess smoother window.

The first breakpoint occurs at 5131BP [5136BP and 5116BP]. The interval prior to the breakpoint shows a rise in the accumulation trend with relatively low frequency and amplitude compared to all time frames after the breakpoint. The interval after the breakpoint shows a shallower rise in accumulation, but a dramatic increase in the frequency and amplitude of spikes.

The second breakpoint occurs at 3541BP [3556BP and 3526BP]. The interval following the breakpoint shows a concave parabolic trend with a sharp rise in accumulation peaking at approximately 3400BP and a low point following at ~2800BP, frequency and amplitude remain similar to the time frame prior to the breakpoint. Taking out the concave pattern, accumulation rates remain relatively flat, with a slight down trend between the peak and following break point.

The third breakpoint is at 2543BP [2503BP and 2544BP]. This break shows a steeply sloping trend showing increasing accumulation over the entire interval with a dramatic increase towards the end of the interval. Amplitude remains fairly similar, if slightly lower than the preceding interval, with an increase in frequency towards the end of the interval. Overall there is an upward trend in accumulation, however, it is not as steep as the upward trend after the first breakpoint.

The fourth and final breakpoint at 1563BP [1592BP and 1563BP] shows a sharp increase and then sharp decline in accumulation before resuming an uptrend to approximately 800BP. There is a trough in the decline at the beginning of the 20th century, with frequency and amplitude increasing substantially to the present.

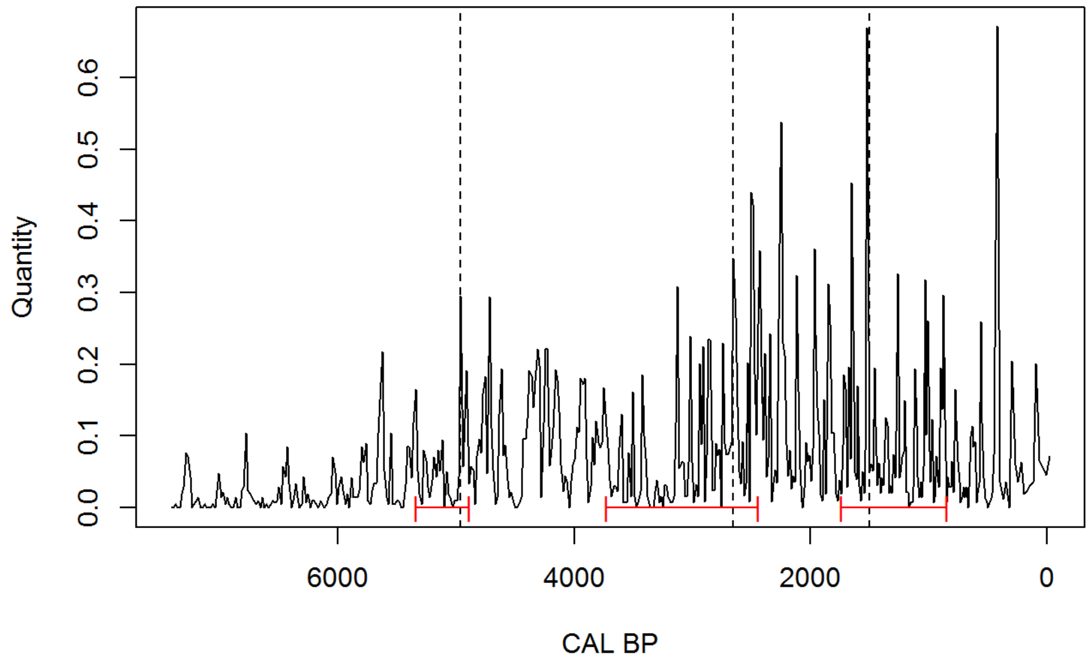

Figure 4 Results from Code Lake. Y-axis indicates charcoal accumulation ($cm^{-2}year^{-1}$); X-axis is calibrated years before 1950CE. The dashed line indicates the 95% confidence interval of the breakpoint identified in StrucChange, with the red line below showing the full confidence interval.

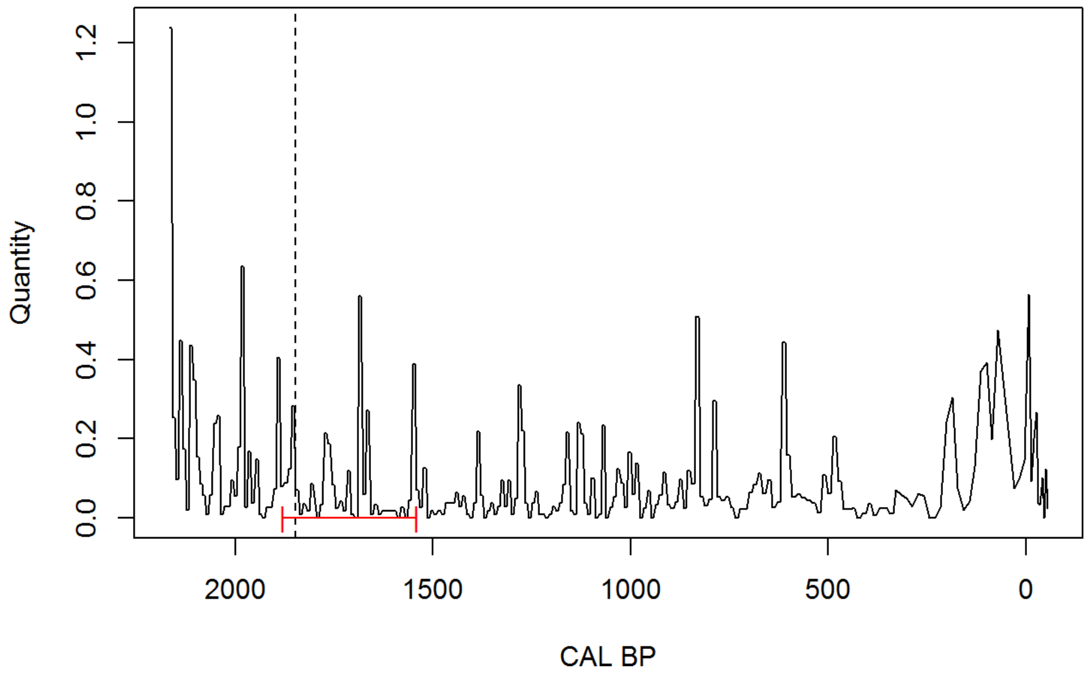

Figure 5 Results from Last Chance Lake.

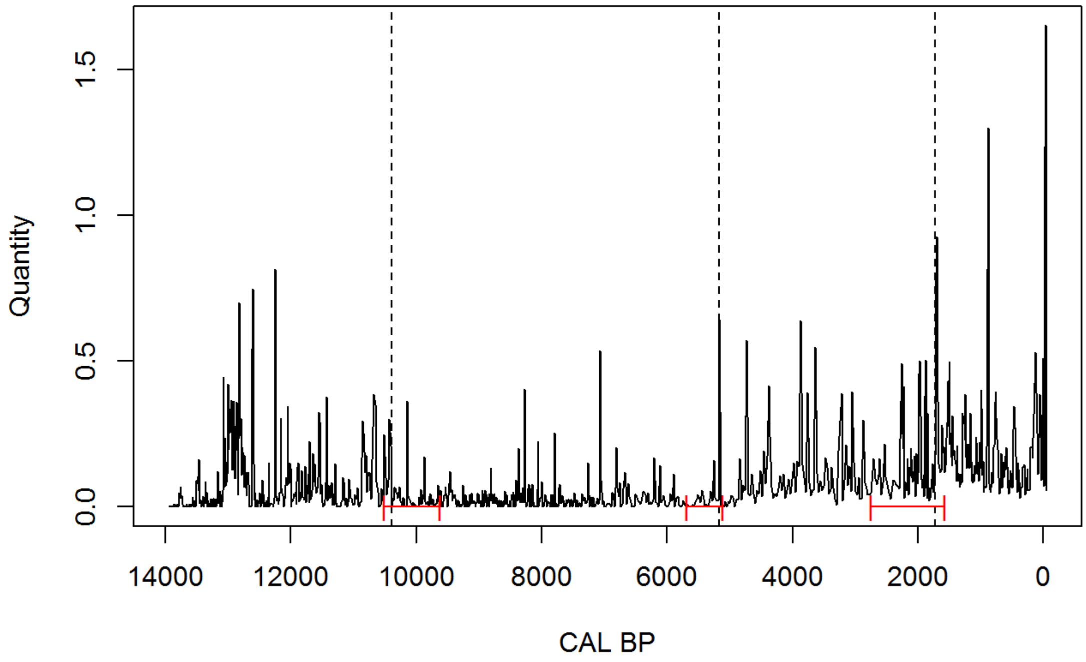

Figure 6 Results from Ruppert Lake.

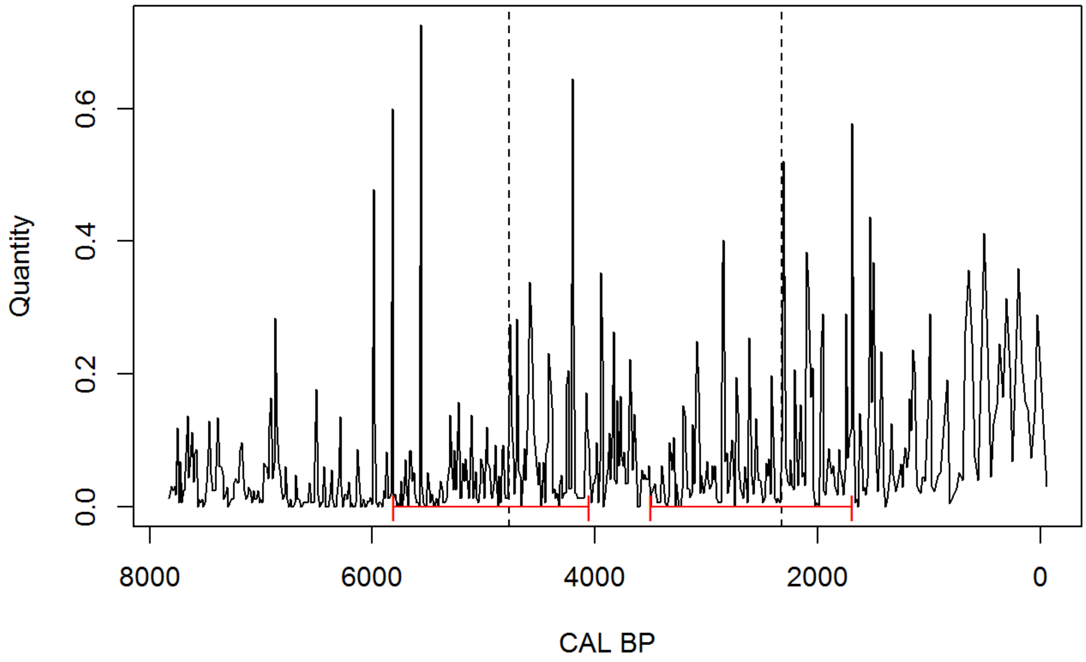

Figure 7 Results from Wild Tussock Lake.

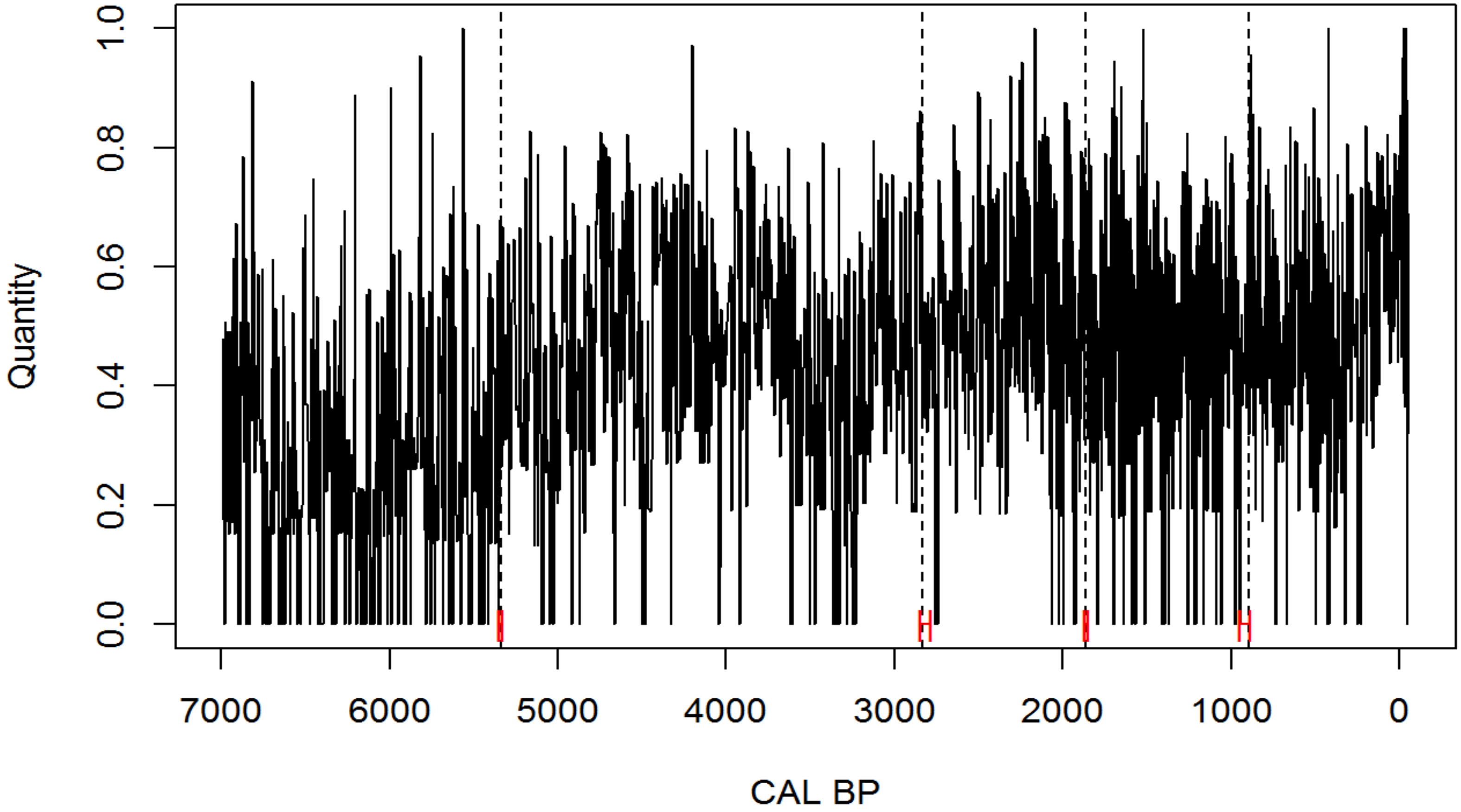

Figure 8 Results from the Regional Scale Analysis of the Brooks Range sites. The Y-axis represents the Box-Cox transformed values for the charcoal accumulation to normalize data for comparison between sites.

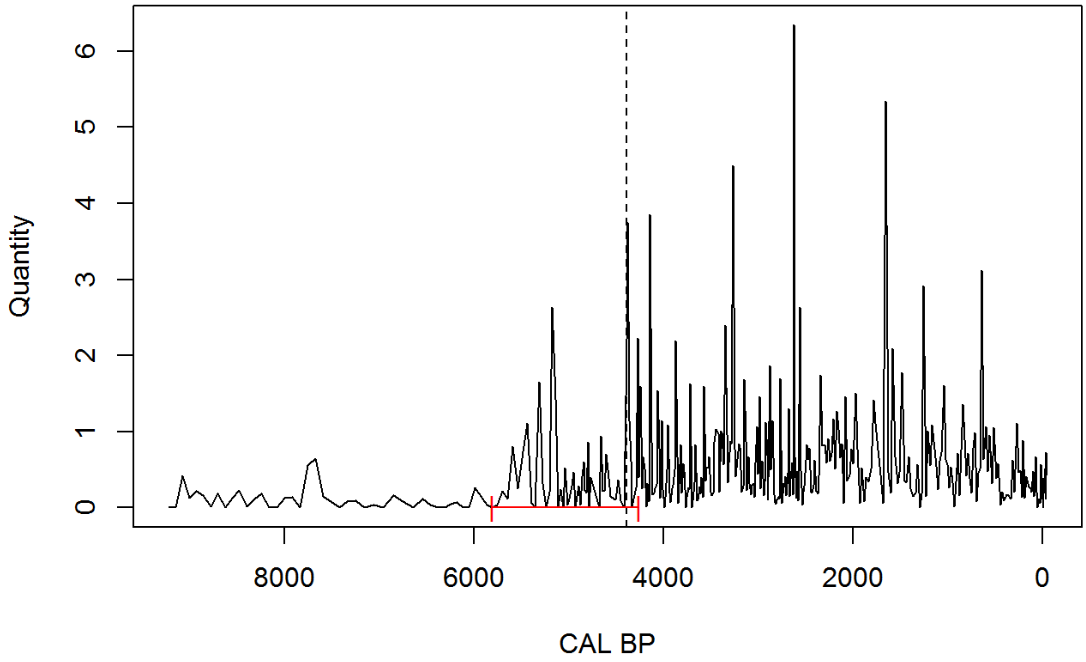

Figure 9 Results from Dune Lake.

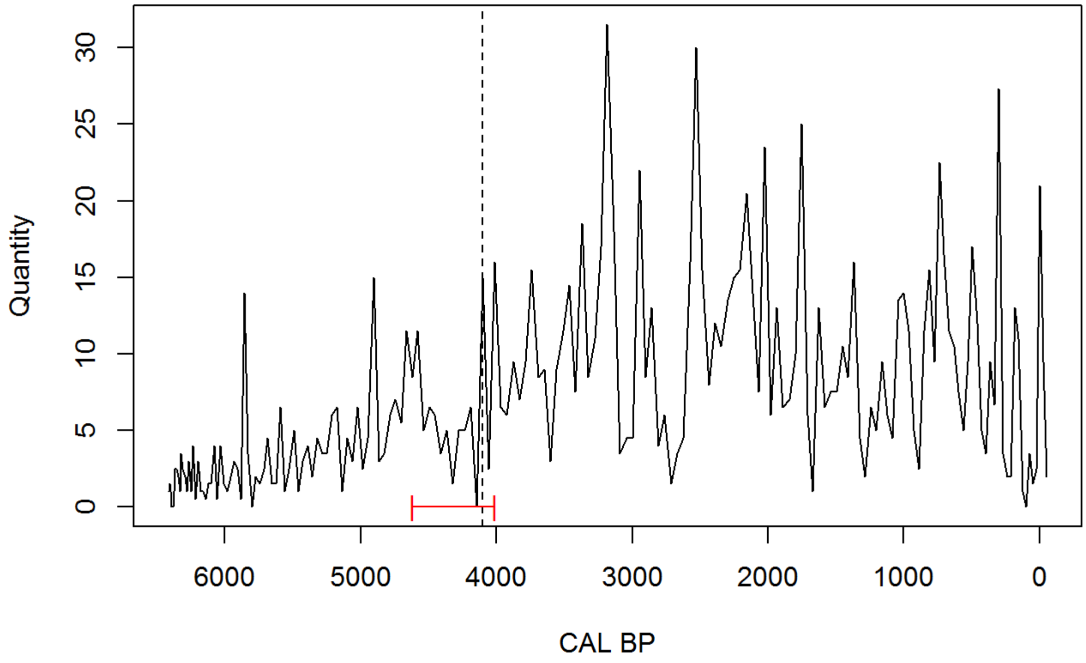

Figure 10 Results from Oops Lake.

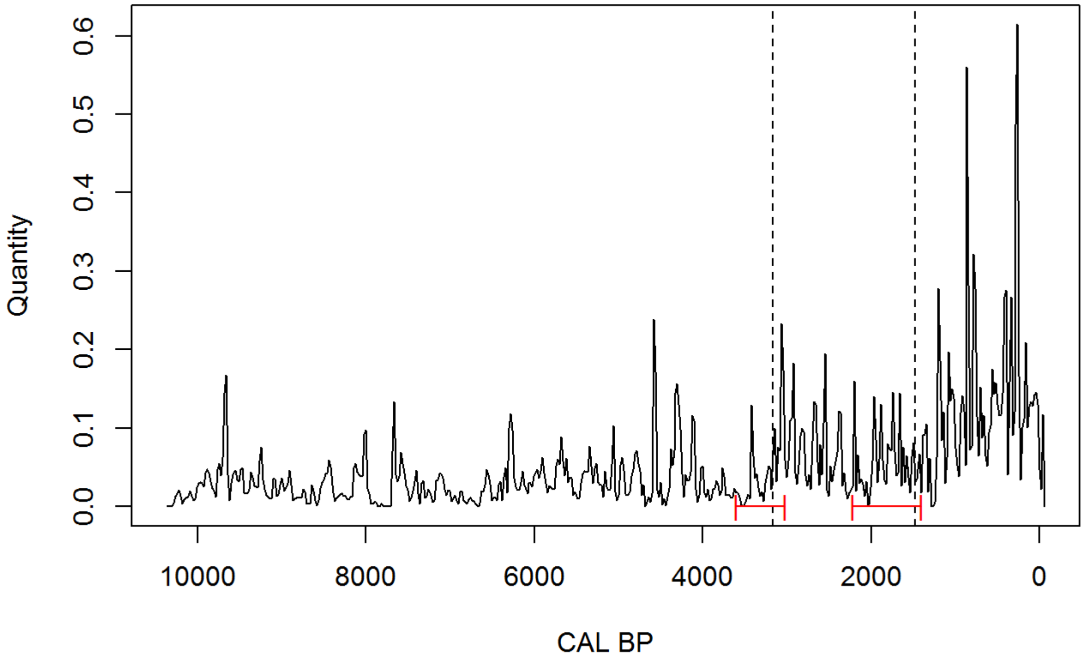

Figure 11 Results from Picea Lake.

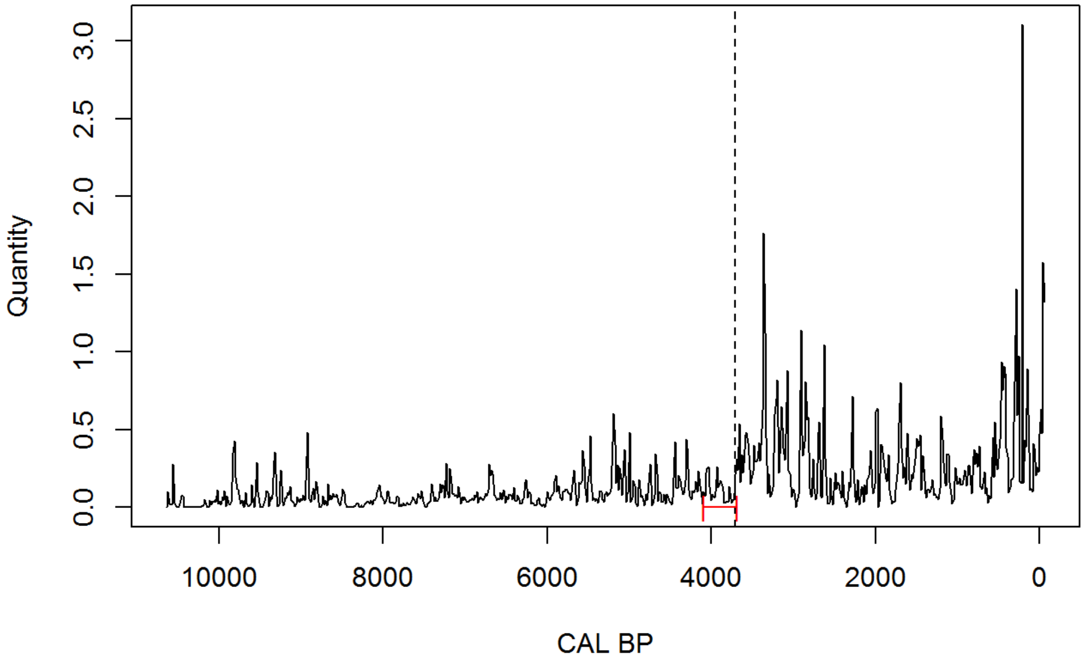

Figure 12 Results from Screaming Lynx Lake.

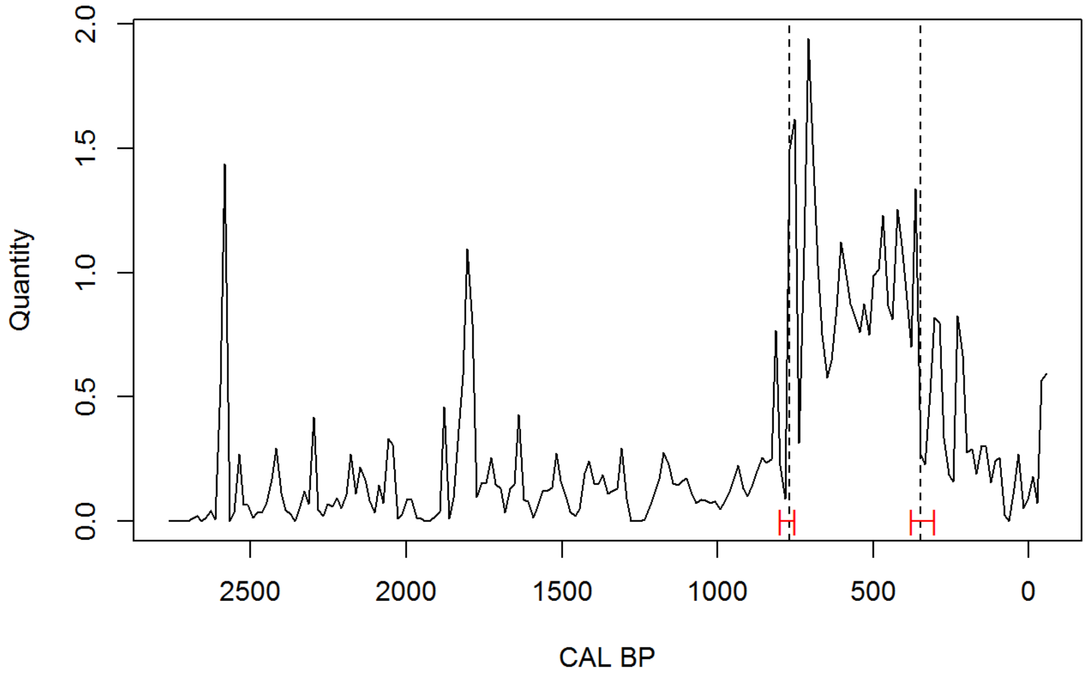

Figure 13 Results from West Crazy Lake.

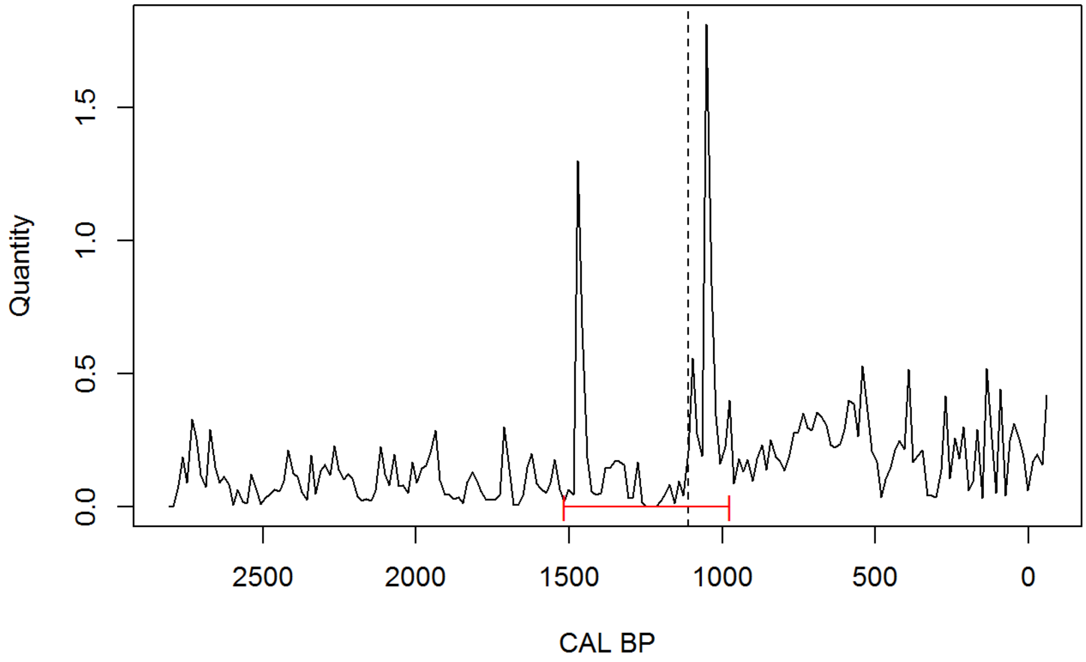

Figure 14 Results from Windy Lake.

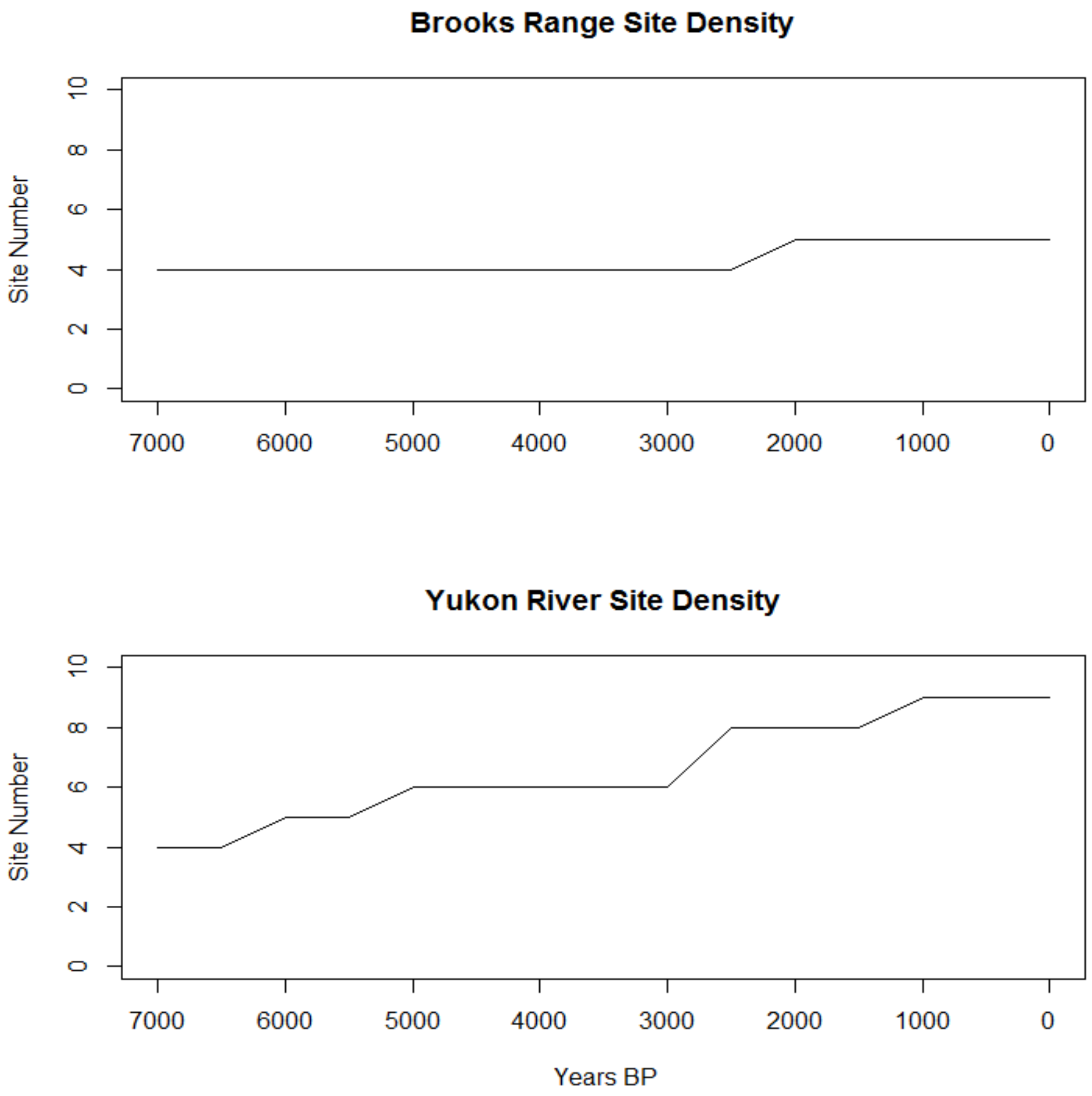

Figure 15 Number of records utilized in the regional analysis throughout time. Y-axis indicates the number of sites available in the region at point in time.

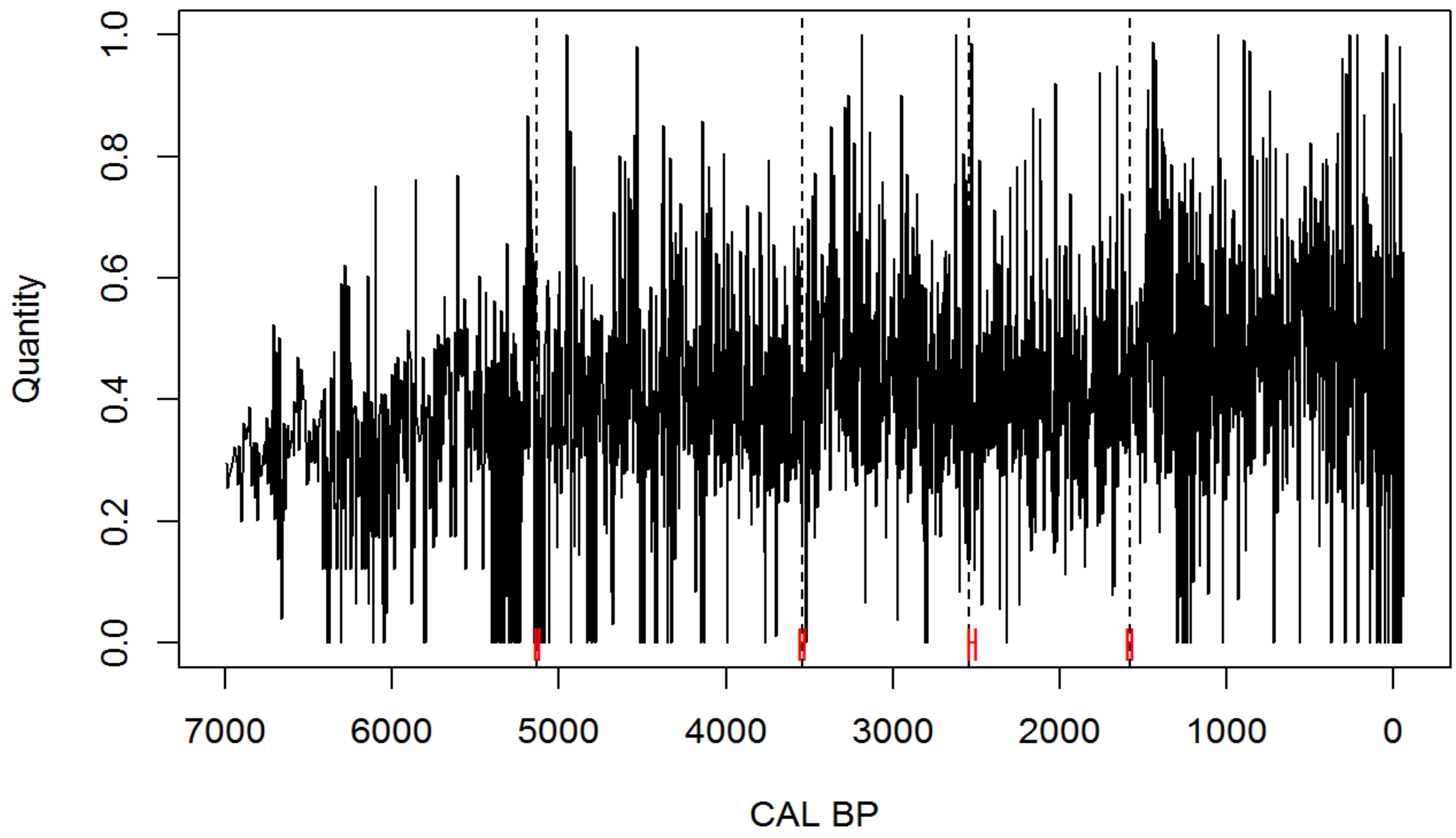

Figure 16 Yukon River regional analysis results.

CHAPTER 5

DISCUSSION

Change Point Clusters

The results the site scale analysis show clusters of breakpoints during the time frame of 5500BP-4000BP, with six change points detected, and an additional six breakpoints between 2500-1500BP (Figure 17). At the regional scale, the primary difference appears in the addition of a later cluster between 500-1000BP (Figure 18). Comparing with the site level, there are three breakpoints in the 4000BP-5500BP interval and three breakpoints in the 1500BP-2500BP interval.

Boreal Migration Period (5500BP – 4000BP)

The first cluster of breakpoints coincides with the migration of the boreal forest into the region (Anderson et al., 1989; Higuera, 2009) and the beginning of what is considered the closed boreal system. The second cluster of breakpoints, around 2000BP, suggests a possible link between the climatic changes linked to solar forcing (Bond et al., 2001) and ocean dynamics.

Brooks Range

At the site level, the Brooks Range sites from Higuera et al. (2009) show an influx of boreal analogue pollen assemblages. At approximately 5500BP, this occurs at Xindi, Code, Ruppert, and Wild Tussock Lakes. The first change point associated with these sites is seen between 5165BP-4774BP. At the regional level, this same breakpoint is seen in the Brooks Range at 5337BP. The mFRI of these lakes that Higuera et al., (2009) calculated in Char Analysis has a median value of 171 years. The time between the rise of *Picea* pollen, the beginning of the boreal forest analogue seen in Higuera et al., (2009) and the initial breakpoint is approximately 150 years. This time gap also correlates to the time frame necessary to renew stands of *Picea mariana* (Fryer, 2014).

Higuera et al. (2009) note climate across the Brooks Range sites during the middle Holocene is poorly resolved, however, slow changes appear to occur throughout the interval. Viau et al. (2008) suggest that throughout the interval, mean annual precipitation (MAP) is in decline, however, there are no abrupt changes. Mean July temperatures remain relatively stable throughout the period. The agreement between StrucChange tests and the records from Higuera et al. (2009) reflects several important factors in the setup of the fire regime. First is the steady rise in *Picea*, indicating the establishment of the boreal ecosystem, whereas the slow decline in MAP over this time frame (Viau et al., 2009) does not coincide with a decrease in pollen accumulation in the Higuera et al. (2009) records. This suggests a buildup of fuels during the first 100 year lag interval. After the change point at any of the Brooks Range sites, the fire regime notably changes, with charcoal accumulation increasing, but mFRI decreasing. Larger and more frequent fires, after the detected breakpoint, are consistent across the Brooks

Range sites which detect an additional breakpoint during this interval. This increase in fire frequency, coupled with the steady decline in MAP, suggests a slow change in moisture availability, which eventually enabled the dynamics in fire regime to reach a new equilibrium.

Yukon River Basin

Lynch et al. (2002; 2004) show a similar spike in *Picea* pollen at approximately 5300BP to that of the Brooks Range sites, however the breakpoints associated with the sites in this region, Oops and Dune Lakes, occur at 4384BP and 4102BP, respectively. Lynch et al. (2002) note the climate during this initial establishment phase is significantly wetter than before or after this time period. The sites from Kelly et al. (2013) reflect a similar pattern, with *Picea* pollen arriving later, and a delayed drop in *Betula* pollen than at the Brooks Range sites.

Compared with the vegetation migration of the boreal ecosystem in Anderson and Brubaker (1994), this time interval coincides with the migration of *Picea* from its position in the Northeastern portion of Alaska; with a migration pattern first spreading across the Brooks Range and then Southward towards the Yukon Basin sites. The time frame between 7.5ka-4ka is characterized by relatively lower MAP than the following time period. Region conditions suggest a precipitation regime similar to a negative Pacific Decadal Oscillation (PDO) phase (Barron & Anderson, 2011; Fisher et al., 2008), supposedly creating wetter-than-normal conditions in the region. However, Anderson et al. (2005) suggest that this region is connected to a weaker or westward shifted Aleutian Low (AL). Assuming a westward shifted AL, a decrease in moisture advection would prevent storm tracks from reaching interior sites. A brief rise is seen in the moisture halfway through the regional decline in MAP, as the boreal forests were being established (Viau et al. 2008). This coincides with a drop in δ^{18}O levels from Jellybean Lake (Anderson et al., 2005) and a Mt. Logan ice core (Fisher et al., 2008), which suggests a short lasting cold period, adding to the delayed onset of the boreal system in the Yukon River Basin.

This initial boreal associated breakpoint is seen when the mean July temperature spikes after the aforementioned brief cold period. At this point, Screaming Lynx, Dune, and Oops Lakes all reflect a breakpoint. During this interval, Reunion Lake shows a breakpoint at 4516BP, however, the confidence interval shows a long tail. Based on visual inspection, Reunion Lake's fires may have shifted between 4516BP and 3500BP to a boreal analogue fire regime, which remains in the 50% confidence interval range. This shift suggests the regional decline in moisture was not zonally synchronous and supports the hypothesis of Anderson et al. (2005) of enhanced meridonal flow along the Canadian Coast, with few southern precipitation sources reaching the inland Yukon River Basin sites. The initial breakpoint at Picea Lake is also considerably later than the other sites. The record does show an increase in fire activity for a brief period at ~4300BP, but a long return interval does not force a significant enough change to trigger a breakpoint.

Considering the negative-like PDO conditions, the Brooks Range sites were more likely controlled by patterns coming off the Bering Sea (Mantua et al., 1997) that reached inland, creating greater inter-annual moisture variability and contributing to the earlier onset of the boreal fire regime in the Brooks Range. Like the Brooks Range sites, the Yukon River Basin sites reflect the slow decline in regional MAP, with stable temperatures that eventually gave rise to the boreal fire regime and a new equilibrium within the system. This effect is delayed because of the closer proximity to moisture sources associated with a westward shifted AL.

The spatial variability between the two regions (Figure 19) shows a strong gradient in the onset of the boreal fire regimes. However, when the comparison is made at the regional level, both regions show similar timing in the onset of the boreal fire regime, with only a 200 year difference between the Brooks Range and Yukon River sites. This lag period is likely caused by the climatic factors such as the negative-like PDO conditions and westward shifted AL, coupled with the southward spread of *Picea* species. It is possible the inclusion of Reunion Lake with its associated large confidence intervals and early onset in the Yukon River sites, and its abnormal early onset when compared with the other sites, may have some influence on the regional record. However, the influence is likely minimal, considering that the same time span is covered by four sites (Figure 18). Visual inspection of the time series indicates a slight rise in charcoal records around this time period with the exception of Reunion Lake. This rise in accumulation is not significant or sudden enough to trigger a breakpoint in the Yukon River records. Likewise, the exclusion of values associated with the time period prior to 7000BP from Screaming Lynx, Dune, and Picea Lakes may have affected the onset time of this breakpoint. It is notable that this large change at individual sites precedes the majority of the breakpoints in both regions, where the trimming of records has little effect on the overall regional records. This suggests that the individual site level response in fire regime is driven by regional climate and vegetation shifts and this is detectable prior to the reflection of the change at the site level.

Regional and Global Comparison

The spread of the boreal forest across the North American continent is synchronous with the end of the Early Holocene Thermal Maximum (EHTM). Kaufman et al. (2004) place the end of the EHTM across the study sites between 8000-9000BP. The slow moving end of this warm interval allowed for the migration of *Picea* from northern refuges (Brubaker et al., 2005). Considerable variation in the GISP2 Holocene temperature reconstruction also occurs during this time period (Alley et al. 2000), with variations larger than records from Viau et al. (2009) (see Figures 20 and 21). The amplitude of variation difference likely results from the influence of the Pacific Ocean on the records of Viau et al. (2009). However, there is a delay in onset between fluctuations of the land records and the GISP2 records for approximately 100 years, showing the sites to be climatically "upstream" from the GISP2 records (Fisher et al., 2008).

Ocean diatom records show a large rise in the influx of warmer Pacific waters and a decline in the sea ice extent in the southern margins of the Bering Sea (Caissie et al., 2010; Harada et al., 2014) with modern conditions setting up at ~5500BP. Several isotope records place the onset of modern ocean driven climate in the northern latitudes at approximately 4000BP (Anderson, 2001; Barron & Anderson, 2011; Fisher et al. 2008). Land and pollen records place this onset around 6000BP-5000BP as the *Picea* progressively settled into the landscape (Anderson & Brubaker, 1994; Higuera et al., 2008; Lynch et al., 2002, 2004). From this point forward, the majority of records are characterized by lower variation when compared to the EHTM or previous eras that had little to no variation in overall pollen composition.

Boreal Transition Period Summation

The initial breakpoint cluster reflects changes in both the variation in the region's vegetation composition, and the climate changes associated with the end of the EHTM and the middle Holocene. This breakpoint is unique as it is seen across the majority of sites. Over the entirety of the records, it is the most spatially coherent, supporting the idea of changing fuel type and vegetation mediated fire regime change in the Alaskan boreal forest, shown in Higuera et al. (2009), being the greatest drivers of fire regime change.

The lag interval of ~150 years correlates with the decline in MAP, the response of the fire regime, and the rearrangement in vegetation to modern assemblage; reinforcing the small confidence intervals on the regional scale, and suggesting the breakpoint is indeed a regime shift. This shows the abrupt nature of the change between two stable states, as small changes over a long period of time clearly crossed a bifurcation point and the system entered a new stable state, as described in Scheffer (2009). After this transition point, very few sites and neither of the study regions return to the pre-boreal state.

The Mid-Holocene Transitions (3200BP-1500BP)

The second cluster of breakpoints at the site level scale occurs between 2650BP and 1483BP (Figures 17 and 22). The majority of the sites which reflect this breakpoint are in the Brooks Range, suggesting the events affecting this change are specific to the Brooks Range. The regional analysis for this interval shows two distinct breakpoints in both regions. The first two breakpoints occur at 2830BP in the Brooks Range sites and

2543BP in the Yukon River Basin sites. The second breakpoints occur at 1864BP and 1563BP at the Brooks Range sites and the Yukon River Basin sites, respectively. In the case of the Yukon River Basin sites, an additional breakpoint exists at 3541BP.

As suggested by the regional breakpoints and the large temporal span covered by this time frame, the period of study is broken into two separate intervals. The first interval starts at the onset of the time frame, around 3500BP. As it is discussed in the following section, this point is significant in the both areas, despite the breakpoints in the Brooks Range sites only being loosely near that point in time. The second interval begins at the termination of this time frame, which is associated with the final breakpoint in the Yukon River sites analysis.

Brooks Range

Breakpoints identified during this time interval encompass the records of Code, Last Chance, Ruppert, and Wild Tussock Lakes. Unlike the majority of the breakpoints identified in the boreal transition period, the breakpoints associated with this change are less constrained in terms of their confidence intervals. This suggests the changes affecting the fire regime in this period are not as dramatic as the change affected by both climate and vegetation. Rather, these changes occur over a longer period of time and are exclusively based in climatic factors. These factors are, likewise, not as dramatic as the transition between the EHTM and the boreal period.

The beginning of the confidence interval brackets at Code and Wild Tussock Lakes agree with an approximate beginning of this period at ~3500BP. The breakpoints for Code and Wild Tussock Lakes are determined to be at 2650BP and 2323BP, respectively, which roughly coincides with the breakpoint at the regional scale. The breakpoints at this site overlap with the confidence interval seen at Ruppert Lake. In all instances described, there is a general uptick charcoal accumulation at the sites' respective breakpoints. While this does not necessarily suggest greater fire frequency, it does suggest fires being more widespread, which causes an overall increase in the quantity of the background charcoal. The majority of sites show greater amplitude in the peaks at the beginning 3200BP-1500BP interval when compared to the preceding interval. In the case of Wild Tussock Lake this increase continues until the modern era.

The pollen records from Higuera et al. (2009) show very little change in the composition of the vegetation across the majority of the sites, with the only discernable difference being a very slight increase in *Cyperaceae* pollen. This also holds true with Xindi Lake, which did not show any breakpoint in the site level during the boreal migration interval, but did experience the vegetation change. Wild Tussock Lake is an exception to this, showing a drop in *Picea* pollen and a return to a forest-tundra assemblage (Higuera et al., 2009).

The beginning of the confidence intervals, at the site level during this breakpoint, is associated with a rise in global temperatures at ~3500BP as seen in the GISP2 record. Local effects of this warm period show an abrupt increase in MAP and July temperature (Viau et al.. 2008). While Viau et al. (2008) show an abrupt decline in regional MAP at approximately 2800BP, Jellybean Lake (Anderson et al., 2005) shows a long, yet significant, increase in d^{13}C, adding to the theory of a wetter period. A significant increase is also seen in the d^{18}O values at Jellybean Lake, to their highest values at ~2200BP. Perhaps more relevant to the Brooks Range sites is a significant increase of freshwater diatoms in the Bering Sea at ~2500BP (Caissie et al., 2010), which indicates greater output from streams in the Brooks Range. A decline in sea ice extent (Brachfield et al., 2011) would also contribute to the overall trend in a wetter climate and serve as evidence for warmer conditions.

The Brooks Range sites are continental, which results in greater seasonal temperature differences. The wetter conditions seen regionally over this time period caused a period of growth resulting in an accumulation of fuels, coupled with an increase in temperature, in particular, July temperatures, there is an increase in charcoal accumulation and more intense charcoal peaks than the previous era. While the mFRI shows very little change, the change in the regional charcoal accumulation and the background accumulation at the Higeura et al. (2009) sites suggest more widespread fire. Considering this hypothesis with the Viau et al. (2008) records, which indicate a decline in MAP over this interval, it is probable there is a degree of variability in moisture patterns in the area leading to variations on annual-decadal time scales, which, considering the resolution of their reconstructions would not be reflected in their records.

The termination of the era at ~1800BP is clearly seen at Code Lake, Last Chance Lake, and Ruppert Lake, overlaps with the confidence intervals from Wild Tussock. Unlike the beginning of the interval, there is little cohesion of trends between the sites at the end of the interval. The records from Code and Last Chance Lakes show a decrease in fire activity when compared with the previous interval, from 3200BP to 1800 BP, while Ruppert Lake shows a slight increase before an overall decline into the modern era. Ruppert Lake also shows higher amplitude peaks after this interval, while most lakes maintain peaks similar to previous era.

CharAnalysis from Higuera et al. (2009) shows an increase in mFRI over this latter interval for Ruppert Lake, while the majority of the other lakes show a decrease in mFRI, although the decrease is not incredibly significant from the previous era. Pollen continues to show little to no change across all sites, with the exception of Wild Tussock Lake where *Picea* pollen returns and the assemblage is once again analogous to the modern boreal forest.

Regional climate records from Viau et al. (2008) show a short and sharp drop in regional temperature beginning at 2000BP. Jellybean Lake (Anderson et al., 2005) also shows an abrupt drop in $\delta^{18}O$ levels at approximately 2000BP. The drop in $\delta^{18}O$ levels at Jellybean is preceded by a decline in $\delta^{13}C$ levels, suggesting drought-like conditions, or at least a decrease in overall precipitation levels. The reconstructions from Viau et al.. (2008) agree with this decline. Regional MAP with regional precipitation levels hit a minimum at approximately 2100BP.

Barron and Anderson (2011) associate this interval with a phase change from PDO- conditions to PDO+ conditions, while Anderson et al. (2005) associate the time period with an incredibly weak and west shifted AL. Both these condition would contribute to low energy storms dominating over Alaska. Sea ice extent during this time frame increases and the output of Alaskan streams decrease (Brachfield et al., 2009; Caissie et al., 2010; Harada et al. 2014). In contrast to the wet/warm period preceding this breakpoint, the region becomes dry and cold.

Yukon River

In contrast to the Brooks Range sites, the Yukon River basin sites show very little explicit change at the site level. Picea Lake shows two breakpoints at 3163BP and 1483BP, with a confidence interval that covers the end of the time interval. This first breakpoint is interesting in that it spans both the boreal migration associated interval and the middle Holocene interval (see Figures 11 and 16). Considering this breakpoint from the 95% confidence interval forward, like the Brooks Range sites, the change point at Picea Lake is associated with higher fire frequency and intensity than the previous interval. However, unlike the previous Brooks Range sites, there is a significant increase in fire activity associated with the termination of this period.

While its sole breakpoint is calculated at 1112BP, Windy Lake shows some association with this time period. Windy Lake increases in activity, with a significant peak at ~1450BP, which provides some evidence of the terminus of this era.

Pollen at Dune Lake (Lynch et al. 2002) shows an abrupt decrease in *Picea,* which is followed by an equally abrupt recovery from 1000BP-800BP. This perhaps contributes to the early regional breakpoint, considering this is a significant vegetation change. However, the lack of charcoal peak and the lack of associated breakpoint in this analysis, suggests the sudden decline in population and recovery at Dune Lake is not associated with fire. Kelly et al. (2013) show a significant increase in *Picea* pollen towards the beginning of the era. While the associated boreal migration initially presents in these records at ~5000BP, there is a significant increase in *Picea mariana* pollen at ~3800BP.

Three regional breakpoints are associated with this time period. The first at

3541BP reflects the onset of this period. At this breakpoint, there is a significant jump in fire activity compared with the previous era, which is explained by two factors. The first factor is the later establishment of the boreal forests in the region and the significant increase in *Picea* at ~3800BP. The lag in climatic conditions and the amount of time necessary for forest migration to occur causes a level of overlap between the boreal migration and the climate changes associated with this middle Holocene period. The second factor is the climatic change. In the case of the Yukon River sites, these warmer and wetter conditions are associated with a short jump in activity at the beginning followed by an overall decline in charcoal accumulation, rather than the increase seen in the Brooks Range. Considering the boreal forest stand began in this region later than in the Brooks Range, the overlap with climatic changes has a more significant impact on the forests, which possibly resulted in a longer succession period after the disturbance. This would explain the abrupt increase and then decline seen between the 3541BP breakpoint and 2503BP breakpoint.

The 2503BP breakpoint is considerably less complicated by vegetation factors. Lynch et al. (2002) use this point as the onset of the modern fire regime. While this analysis places the onset of the modern fire regime at Dune Lake at 4384BP, the 2503BP breakpoint is associated with an overall increase in fire activity. Kelly et al. (2013) show the vegetation of the area as roughly stable from the 3800BP point forwards, as well as an increase in mFRI from the previous interval.

Regional and Global Climate Association

The two differences between the Brooks Range regional analysis and the Yukon River sites are the timing of the onset/terminus and the response of the associated fire regimes to the terminus. The lag between the shifts in fire regime between the Brooks Range and Yukon River sites, approximately 1200 years, is roughly equivalent to the timing differences seen in the boreal migration interval, reinforcing the idea of ocean dynamics as the primary driver of the regional climate conditions and the fire regimes associated with the area. The beginning of the interval shows widespread warming in the area and a steady increase in annual precipitation (Figures 20 and 21), while the middle of the period sees this trend reverse. During this reversal, several records suggest a switch from warm/wet conditions to a cool/dry phase (Anderson et al., 2005; Barron & Anderson, 2011; Viau & Gajeweski, 2008; Viau et al., 2009). This is particularly evident in the Brooks Range where records show a steady increase in background charcoal.

The GISP2 record shows an abrupt spike at roughly this same time, the so-called Minoan Warm Period. This suggests that the warm time period, at the beginning of the middle Holocene interval in regional records, is part of a global-scale event. Unlike the temperature increase seen in GISP2, the temperature spikes correlated with this period in Viau et al. (2009) reflect an overall decline in temperature; however, this point in the GISP2 record is the largest spike in temperature in the previous 7000 years[1]. A significant amount of the difference is likely explained by the Greenland core, with a location on the far interior of the ice sheet, while the paleoclimate reconstructions discussed for this study have a bias of ocean mediated effects on climate.

---

[1] Alley et al. (2000) state the top of this record 1905 AD and therefore does not consider 20th century warming.

Fire regimes during this time frame were less affected by the temperature variation than with the variation in precipitation. Warming associated declines in sea ice extent likely contributed to wetter conditions, resulting in a buildup of fuels at the Brooks Range. These fuels were more prone to ignition due to the vast majority of moisture associated with the region originating from the Bering Sea. While similar conditions exist at the Yukon River sites, an overall decline in charcoal accumulation is seen, suggesting the source of increasingly wet conditions over the interval differed from the Brooks Range sites. Barron and Anderson (2011) show Jellybean Lake (Anderson et al., 2005) and Mt. Logan records (Fisher et al., 2008) are out of phase during this time period. While Barron and Anderson (2011) suggest this to be a period of PDO+ conditions, there is some disagreement between sources. Sea ice records from Harada et al. (2014), Caissie et al. (2010), and Davies et al. (2011) suggest extremely widespread warm conditions in the Pacific from 3000 to 1500 BP.

The termination of this early warm period is synchronous across this region, with temperatures going to their low point at approximately 2000BP. Likewise, GISP2 shows a brief spike in temperature before a drop off. Both regions experience breakpoints associated with this temperature change, with Brooks Range at 1872BP and Yukon River Basin at 1563BP. At these later breakpoints, the fire regimes of the two regions react in opposite manners. The overall trend of Yukon River Basin sites is an increase in fire activity, while there is an overall decline in the Brooks Range region. Barron and Anderson (2011) provide a possible explanation for this divergence by showing a phase change from PDO- to PDO+ and eventually a shift from weaker/west AL to a stronger eastward AL(Anderson et al., 2005). This would result in higher temperatures associated with PDO+ phase in the Yukon River sites region (Mantua et al., 1997), but also higher winter precipitation associated with the AL shift. Considering the Jellybean Lake record, this breakpoint is more associated with an increase in precipitation than with temperature, suggesting an increase in a build-up of fuels.

Meanwhile, the Brooks Range sites continue to be affected by conditions in the Bering Sea, which show an increase in sea ice extent (Harada et al., 2014) and a decrease in fresh water discharge during this time period (Caissie et al., 2010). Persistent dry conditions over the Brooks Range eventually cause a breakpoint to trigger at the end of the interval, following a slight rise in July temperature. While the overall deposition of charcoal declines and the background charcoal declines, this particular breakpoint marks greater variability in the fire record than all of the previous period. This suggests an increase in large fires that are followed by periods of recovery versus smaller, more frequent fires that occur during the wet interval.

Mid-Holocene Transition Period Summations

With respect to theories of regime shift and systems theory, this middle Holocene interval represents an intriguing array of changes. When considering changes at the site level in the Yukon River Basin, changes occur very slowly over a long period. Picea Lake is a great example of two types of catastrophic changes. The first change period, affected by both vegetation and climate change, shows an abrupt transition between states. There is less agreement in the second period concerning the confidence interval. This confidence interval suggests the application of an external force at the beginning, as charcoal accumulation changes from a downward trend to a flat trend. As time progresses, eventually a threshold response occurs and the fire records reflect a dramatic change. This change occurs after a series of climatic shifts in the region, however, there are no sudden changes immediately preceding this breakpoint in the paleoclimate reconstructions. In the case of the Yukon River Basin region, a series of small changes in the system built towards a dramatic shift in the fire regime. Arguably, more breaks within this region could be identified if examined records only included the previous 2000 years.

The Brooks Range records reflect several more changes than Yukon River Basin. Additionally, the Brooks Range sites show wider confidence intervals than any of the change points associated with the boreal migration, suggesting the changes of this particular time period more slowly. While the changes at the Brooks Range site level are more plentiful than that of the Yukon River Basin, they are far less dramatic. They do, however, reflect a situation where a discernable difference can be seen in fire regime and charcoal deposition records, with the only significant change being that of global and regional climates.

The Late Holocene (1500BP-Present)

Breakpoints after the cluster at ~2000BP become less frequent. Considering the length of the records involved, this is not surprising. Since the conditions which determine breakpoints are linked to the entire length of record, many of the more subtle climate linked changes of the late Holocene (e.g., The Medieval Climate Anomaly (MCA) and Little Ice Age (LIA)) do not create a large enough effect on fire regimes to trigger a breakpoint in the algorithm. While at the regional level, Brooks Range is the only region with a breakpoint in this area, however, there are no specific sites which show a specific breakpoint over the Late Holocene. Yukon River Basin's final breakpoint at the regional level occurs during the changes associated with the previously discussed time frame (see Figure 23). In an effort to investigate the effects at the site level in the Yukon River Basin, Windy Lake and West Crazy Lake were added to the overall analysis of conditions.

Brooks Range

While there are no breakpoints associated with the Late Holocene at the site level, the Brooks Range Regional analysis shows a breakpoint at 891BP. This breakpoint coincides roughly with the termination of the MCA at 800BP (Miller et al., 2010). The stable period prior to this breakpoint shows a decline in charcoal accumulation in the Brooks Range, with areas of peaks in the 100-year loess smoother window. This suggests that regionally synchronous fires became less common during the latter half of the 1st millennium, while after the breakpoint regionally synchronous fires increase, with a significant increase seen beginning at approximately 200BP.

Pollen records indicate very little change in vegetation dynamics during the time period (Higuera et al., 2009). What is notable about the pollen record is the significant increase in pollen accumulation rates at Xindi Lake in the previous 200 years. A similar effect is seen in the pollen record for Code Lake with a spike similar to that associated with the climate shift seen at the onset of the warm interval of 2300BP, although the change is less dramatic than the spike associated with the boreal shift.

The reconstructions of Viau et al. (2009) show the time frame immediately associated with this breakpoint sees an abrupt change in both precipitation and temperature. A spike in July temperatures and a drop in precipitation would both contribute to favorable conditions for the widespread fires to occur. Other climate records associated with the MCA show a decrease in sea-ice extent (Harada et al., 2010) and a general retreat of glaciers in Alaska (Wiles et al., 2008). General PDO+ conditions dominated the region (Barron & Anderson, 2011), bringing warmer Pacific waters into not only the Gulf of Alaska, but into the Bering Sea (Caissie et al. 2008; Harada et al., 2010), also strengthening the AL (Anderson et al., 2005). Warm Bering Seas, a stronger AL, and PDO+ conditions all would increase precipitation over the Brooks Range. Viau et al. (2009) show this increase in moisture began at the onset of the MCA and terminates at the end the MCA. The termination of the MCA, however, is not associated with lower temperatures in the region, with respect to the July temperatures. Lower moisture level and an increasing July temperature triggers this initial breakpoint. Visually, however, this breakpoint is less dramatic as climate shifts from the MCA into the LIA. While Viau et al. (2009) show an increase in July temperature, higher resolution records examined in Kaufman et al. (2009) suggest a widespread cooling of summer Arctic temperatures from 1250CE-1850CE. Jellybean Lake's d13C suggest a drought during the beginning of this interval, but little change after the recovery.

Higuera et al. (2009) and Kelly et al. (2013) show the charcoal accumulation of the past 1000 years to exceed the variability of the records at the majority of these sites when compared with the entire Holocene record. When compared with the StrucChange analysis, it is apparent this change is associated with the end of the MCA, but considering only the past 200 years of records, the more significant change occurs into the present at the site level. While this is speculative, if more records were available that focused on the modern era in the Brooks Range, and possibly farther into the 21st century, it is likely the previous 200 years would trigger a change point.

Yukon River

The Yukon River Basin region shows less variability at the regional scale. While there is some variability at the beginning of the MCA, a resulting period of little regional fire activity is promptly followed by a period of regionally synchronous fires. After this period there is a steady increase in charcoal accumulation through to the middle of the LIA. While the loess smoother indicates a decline in fire activity going into the present, there appears to be greater variability toward the end of the period.

At the site level, Windy Lake picks up this abrupt increase in fire activity, with charcoal accumulation increasing from the breakpoint at 1112BP to present. Likewise, West Crazy Lake picks up the transition between MCA and LIA with an increase in activity occurring at 768BP and ending at 348BP. Both these records suggest that the increase and then decline in activity is associated with a shift in available moisture content. Abnormally wet conditions through the MCA, followed by abnormally dry conditions through the LIA, would result in a situation where fuel accumulation and lower moisture content overrides the lower temperatures of the LIA.

Much like the Brooks Range sites, there is very little variability in the pollen assemblages of sites in the region. Lynch et al. (2004) show a similar increase in *Picea* pollen toward the end of the record, suggesting the termination of the LIA and the effects of anthropogenic warming may affect tree density in the boreal forest.

Climate in the region shows similar variability to the Brooks Range. The long PDO+ conditions more likely affected these sites than the warmer waters in the Bering Sea (Barron & Anderson, 2011; Papineau, 2001). The shift in PDO+ conditions at the beginning of the LIA, and associated drop in moisture, are proposed as the primary drivers behind the sudden shift in fire dynamics at the sites.

Kelly et al. (2013) show the regional variability of fire regimes to spread outside the Holocene normal. Again, like the Brooks Range sites, this variability is likely too short of an interval in time to be detected by the StrucChange algorithm. The inclusion of several other sites in Kelly et al. (2013), which did not span enough time to be considered within the scope of this study, also support the notion of modern climate variability to be considered a breakpoint.

Late Holocene Summation

The effects of climate variability of the late Holocene show the Arctic to be more resilient than other areas of the world (Kaufman et al., 2009; Miller et al., 2010). While changes did occur over the time frame, they are less significant in terms of the range of the previous 7000 years. However, the changes associated with this period are occurring faster, and indeed are crossing a threshold resulting in a different equilibrium over a short period of time, which is evident in the tightly constrained CIs in the records of West Crazy Lake and Windy Lake. Since there are changes in Alaskan paleoclimate records associated with the MCA and LIA (Miller et al., 2008), it is possible changes in the fire regime would be more prominent if records were clipped to simply contain the previous 2000 years.

While no breakpoints associated with anthropogenic warming of the 20th century are specifically detected, Kelly et al. (2013) show the variations in the fire regime are beyond the scope of the rest of the Holocene. The expansion of the boreal system into former Arctic terrain and the increase in fires in Tundra associated with the 20th century also support the idea of the modern time being a period associated with a breakpoint. It is not surprising that the 20th-century variability could be considered a breakpoint considering the mFRI for the boreals is approximately 170 years. Climate change has occurred with such speed that the charcoal records have not caught up to the trend. With regard to abrupt changes during the previous time period, it is possible for the lag period between shifts in climate to not be reflected in the charcoal record, with enough depth, to recognize a breakpoint in the modern era for another 100 years.

Methodological Limitations

There are some limitations in the use of StrucChange for determining regime shifts with charcoal data. First is, the length of the record. For example with a short record of time, the algorithm detects deviations which may or may not have been influenced by extra-local environmental factors, rather than changes that are site specific. Short-term droughts lasting years to decades, or an overabundance of fuels on the forest floor, increases flammability of the area, potentially over several years, as well as creates charcoal deposition over a significant portion of the record via slope wash or large fire plumes (Clark, 1988) in the event of a fire. In the absence of annual or regular sediment deposition, or short-resolution and low-resolution records, the detection of fire regime shifts indicated in StrucChange should be compared to modern fire regime analogues when making conclusions at the site level. An example of this is seen with comparison between the results from Picea Lake and West Crazy Lake, which are geographically close to each other. Picea Lake reflects changes based on the entire record, while West Crazy Lake shows two change points in the past 1000 years. Picea Lake does not reflect these change points as previous changes in the charcoal deposition are more significant to its own record. At the regional scale, this issue is ameliorated by records covering the same time frame.

Another limitation is resolution of the record. Records with a large time depth but low-resolution reflect regime shift with some degree of accuracy, however, the range of the confidence interval records widen significantly. When applied in this study, a short term climate change forcing a change in the fire regime would be visible, however, a longer term change would reflect as a more abrupt shift. Again, at the regional scale, analysis improves by using multiple records within the same time span. The regional portion of this study focuses on the previous ~6000 years for which there is a minimum of two records available for any point in time (Figure 15).

For the purposes of this study, StrucChange proves an adequate method to link changes within the paleorecords with known global changes. At the individual site level, this style of analysis is best complimented with palynological studies to establish possible factors beyond climate which influence fire regimes. Regional analysis and reflected changes could no doubt be improved with more sites, assuming they are of adequate resolution and depth so as to establish initial conditions.

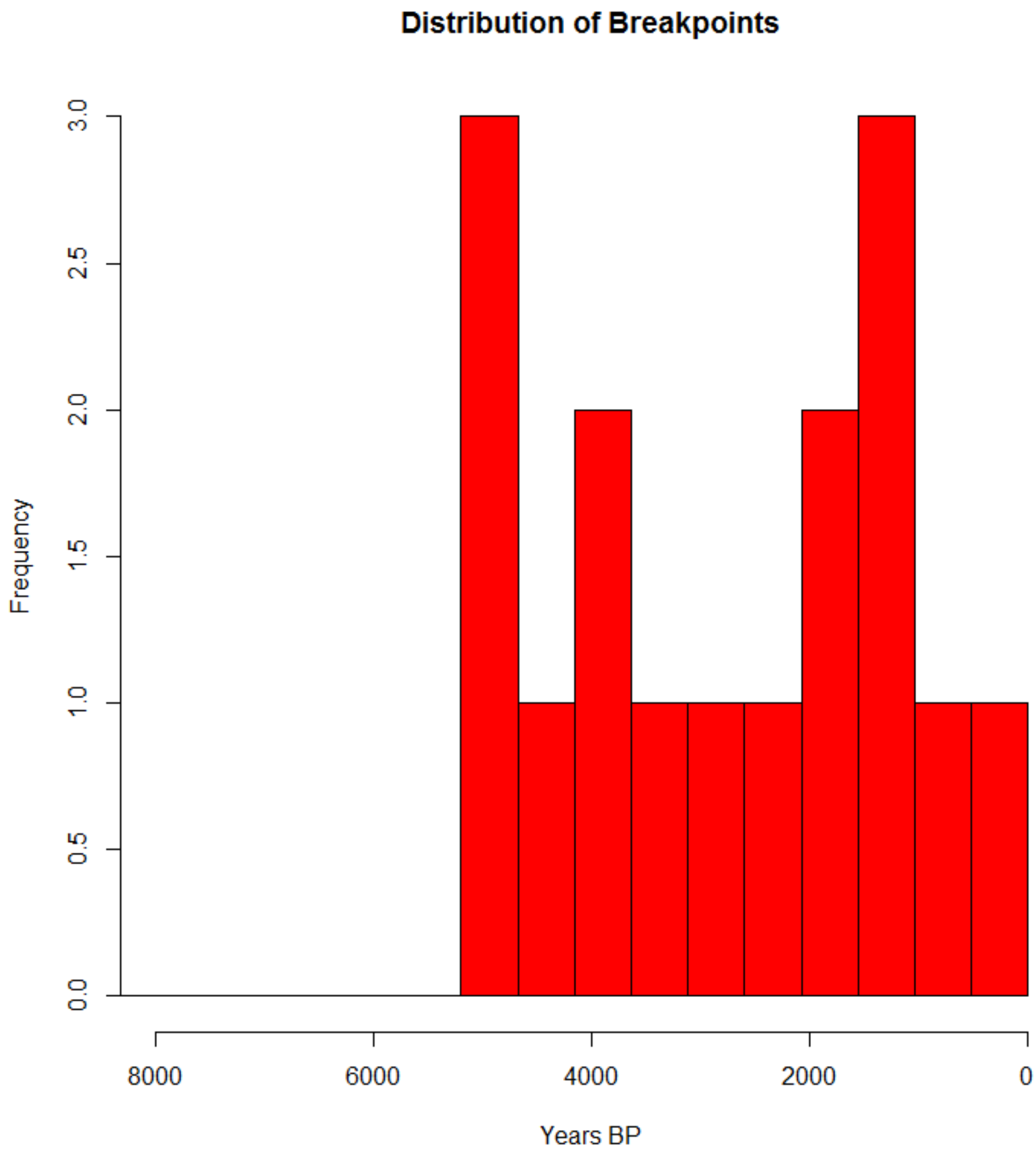

Figure 17 Distribution of site-level breakpoints. Binned in 500-year intervals from 7000BP-present. Y-axis indicates the number of sites reflecting breakpoints during the interval.

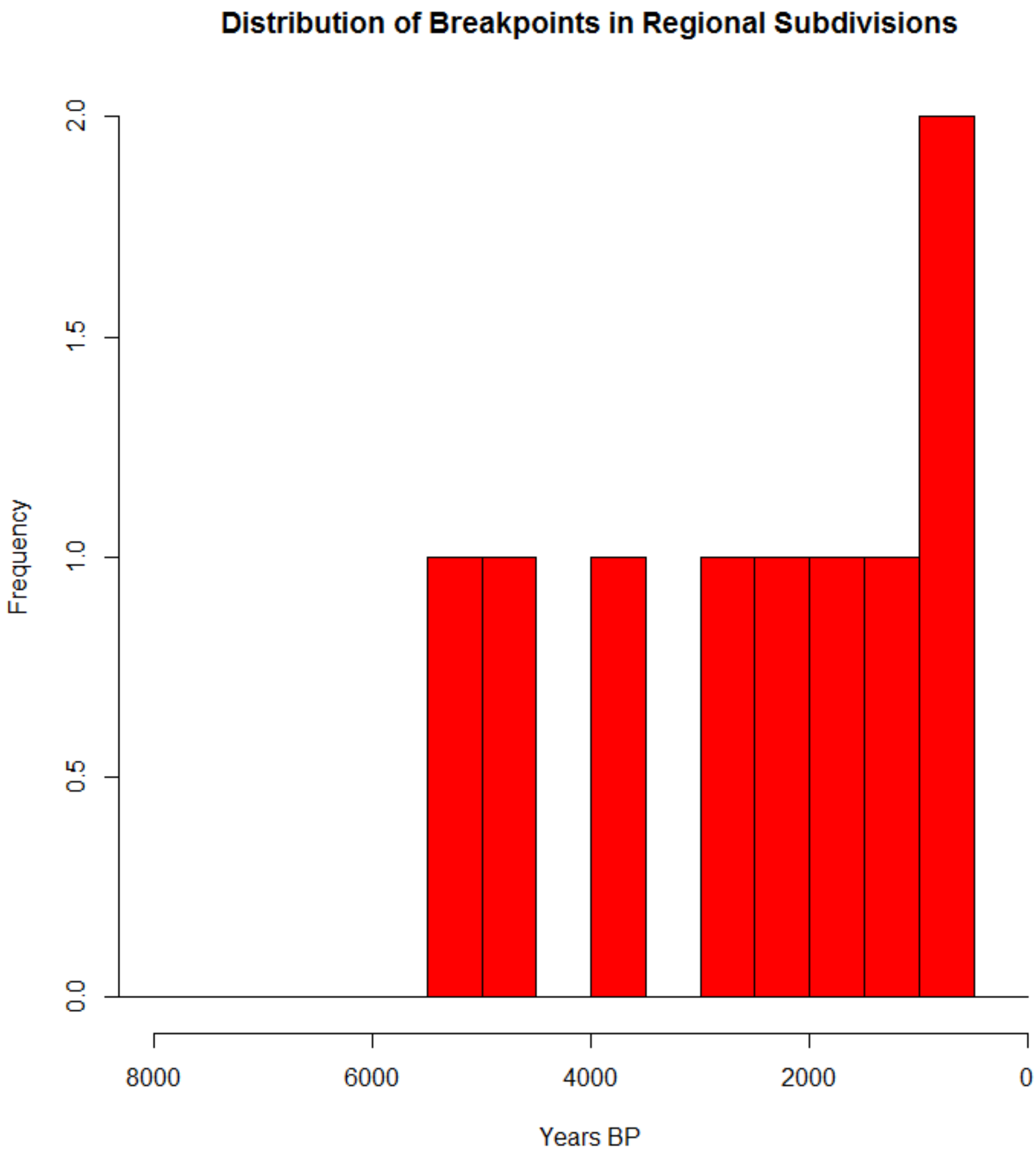

Figure 18 Distribution of region-level breakpoints.

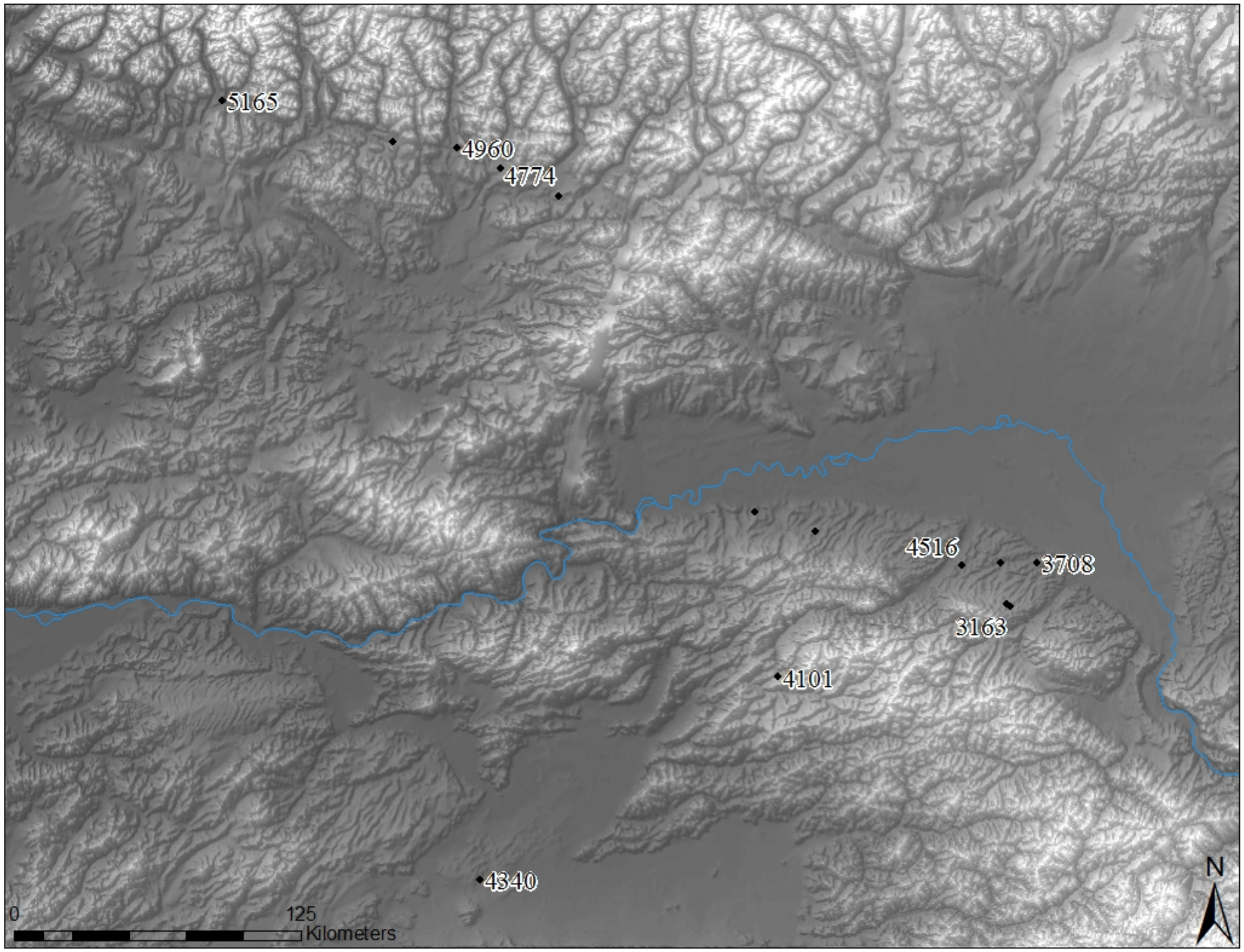

Figure 19 Map showing the breakpoints associated with the boreal forest establishment across all sites.

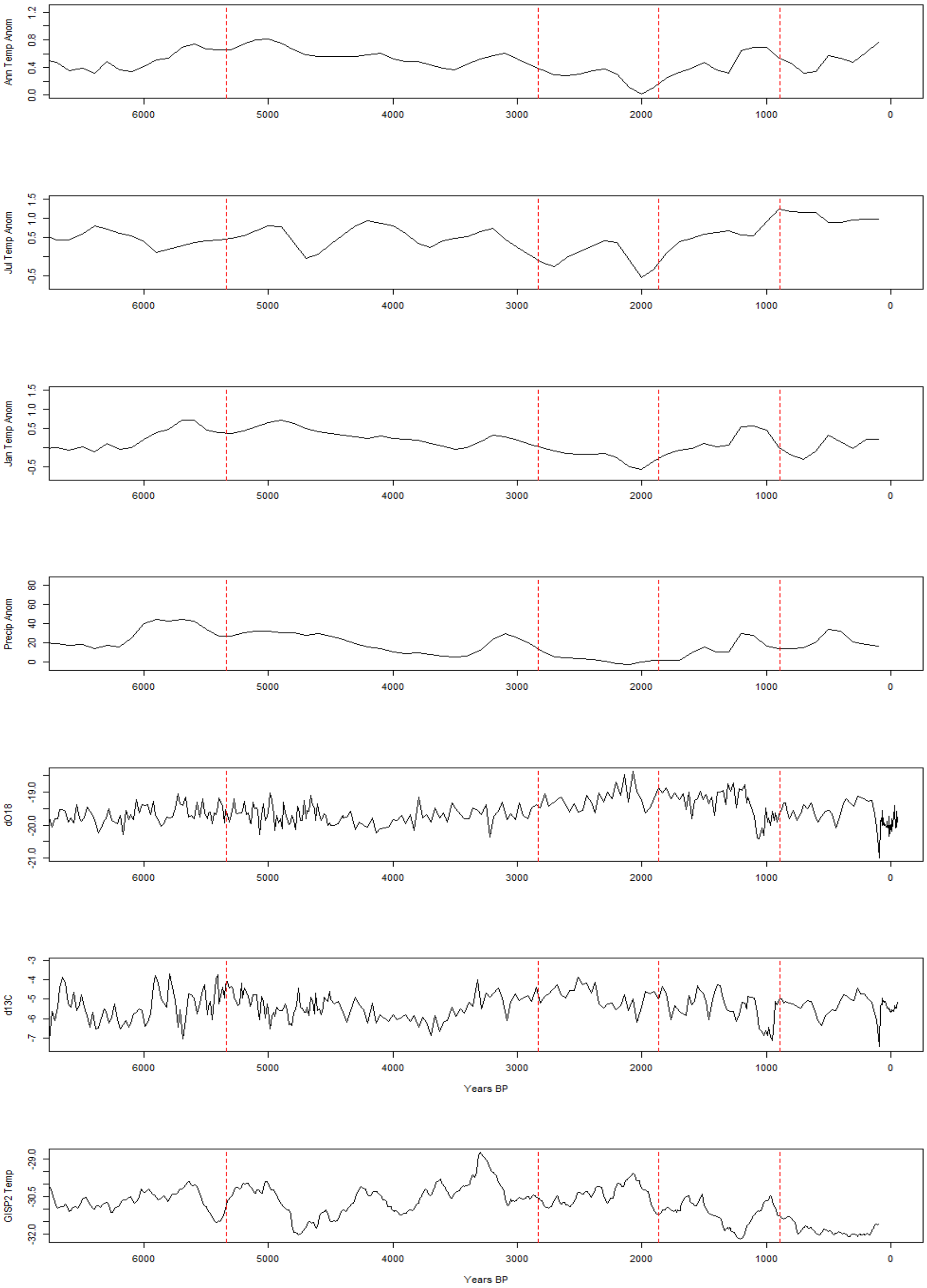

Figure 20 Selected paleoclimate reconstructions from Viau et al.. (2008), d18O and d13C records from Jellybean Lake (Anderson et al. 2005), and GISP2 temperature reconstructions (Alley, 2000). Red lines reflect the breakpoints from the Brooks Range regional analysis.

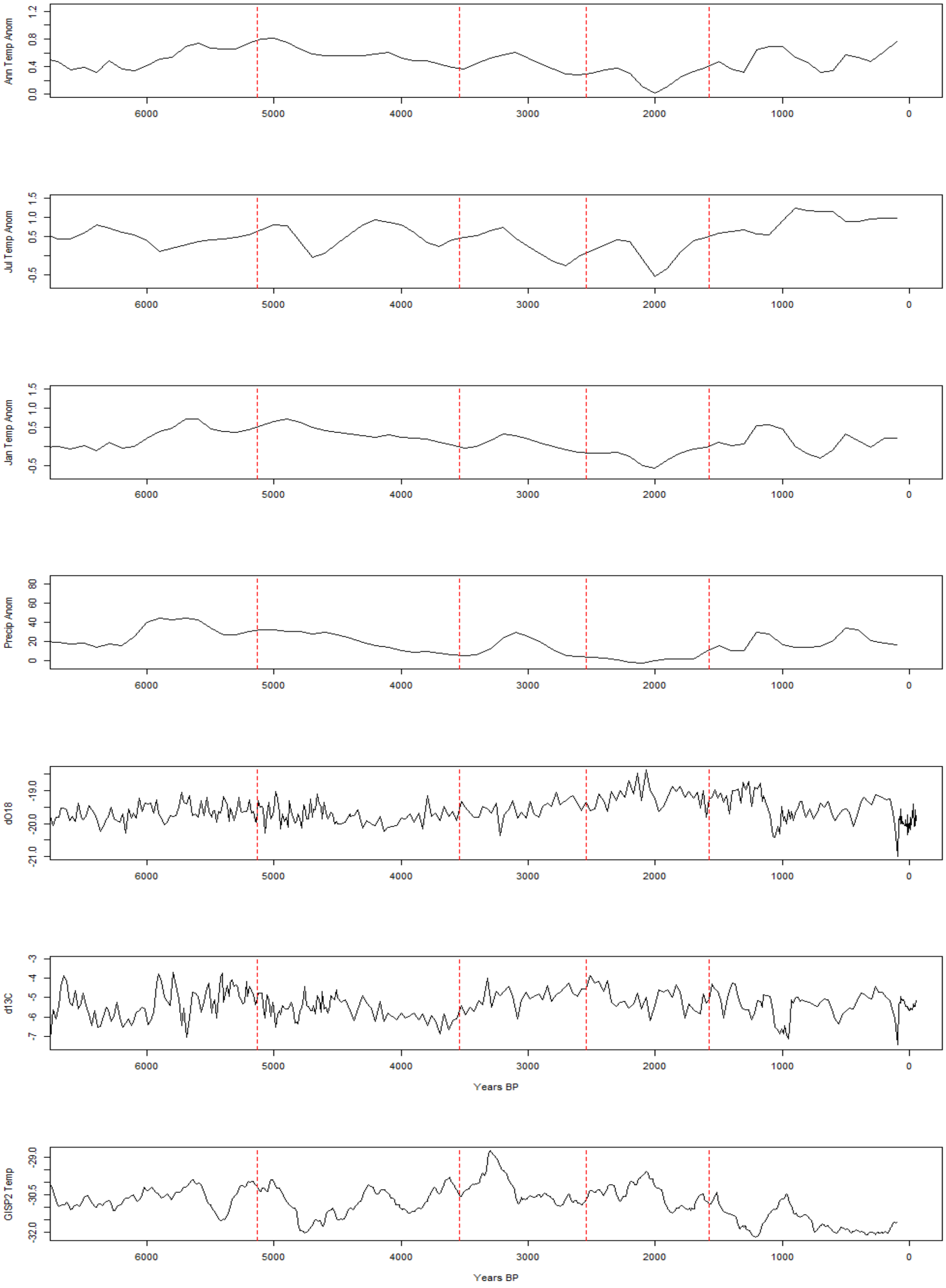

Figure 21 Selected paleoclimate reconstructions from Viau et al.. (2008), d18O and d13C records from Jellybean Lake (Anderson et al. 2005), and GISP2 temperature reconstructions (Alley, 2000). Red lines reflect the breakpoints from the Yukon River regional analysis.

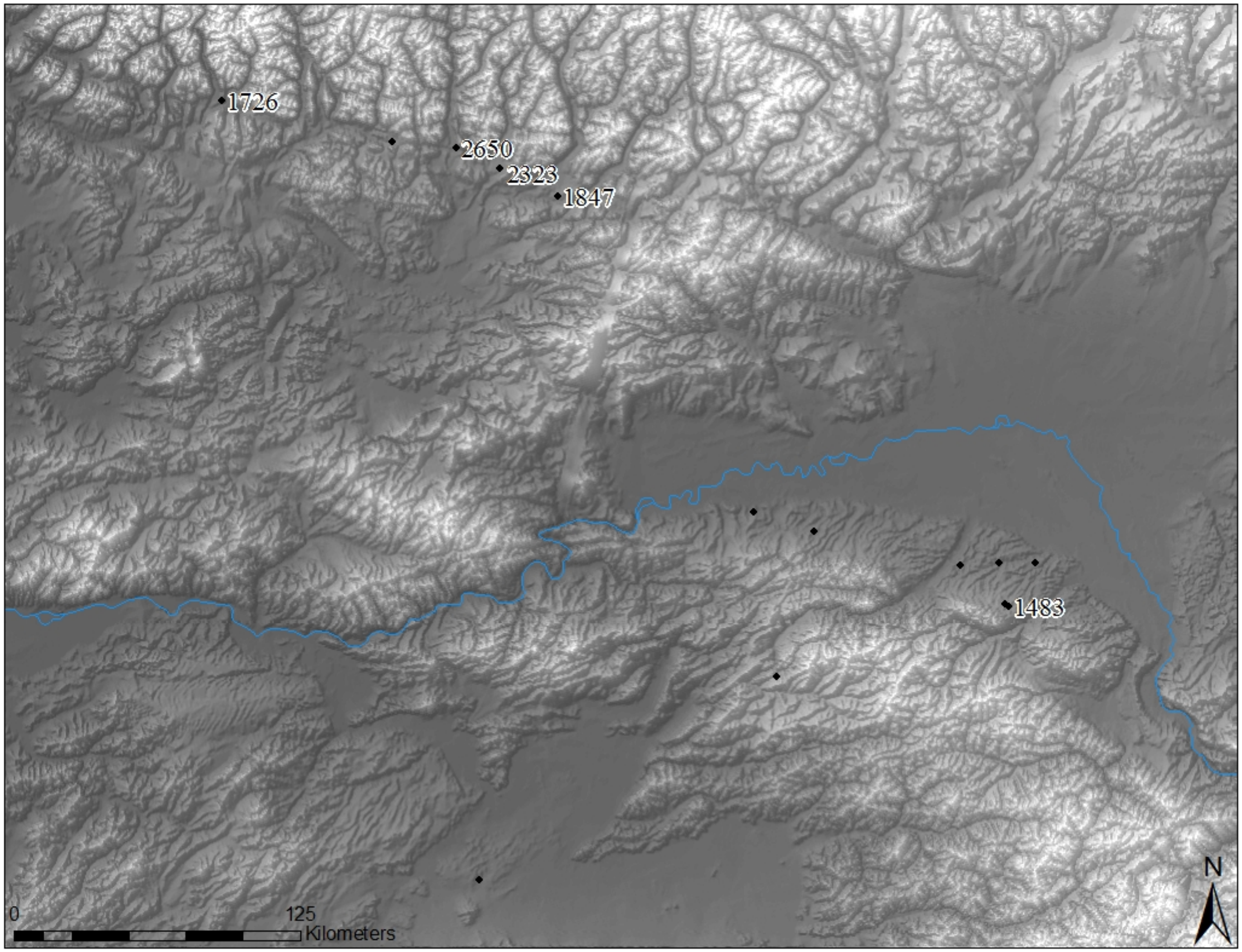

Figure 22 The spatial distribution of breakpoints seen during the mid-Holocene interval.

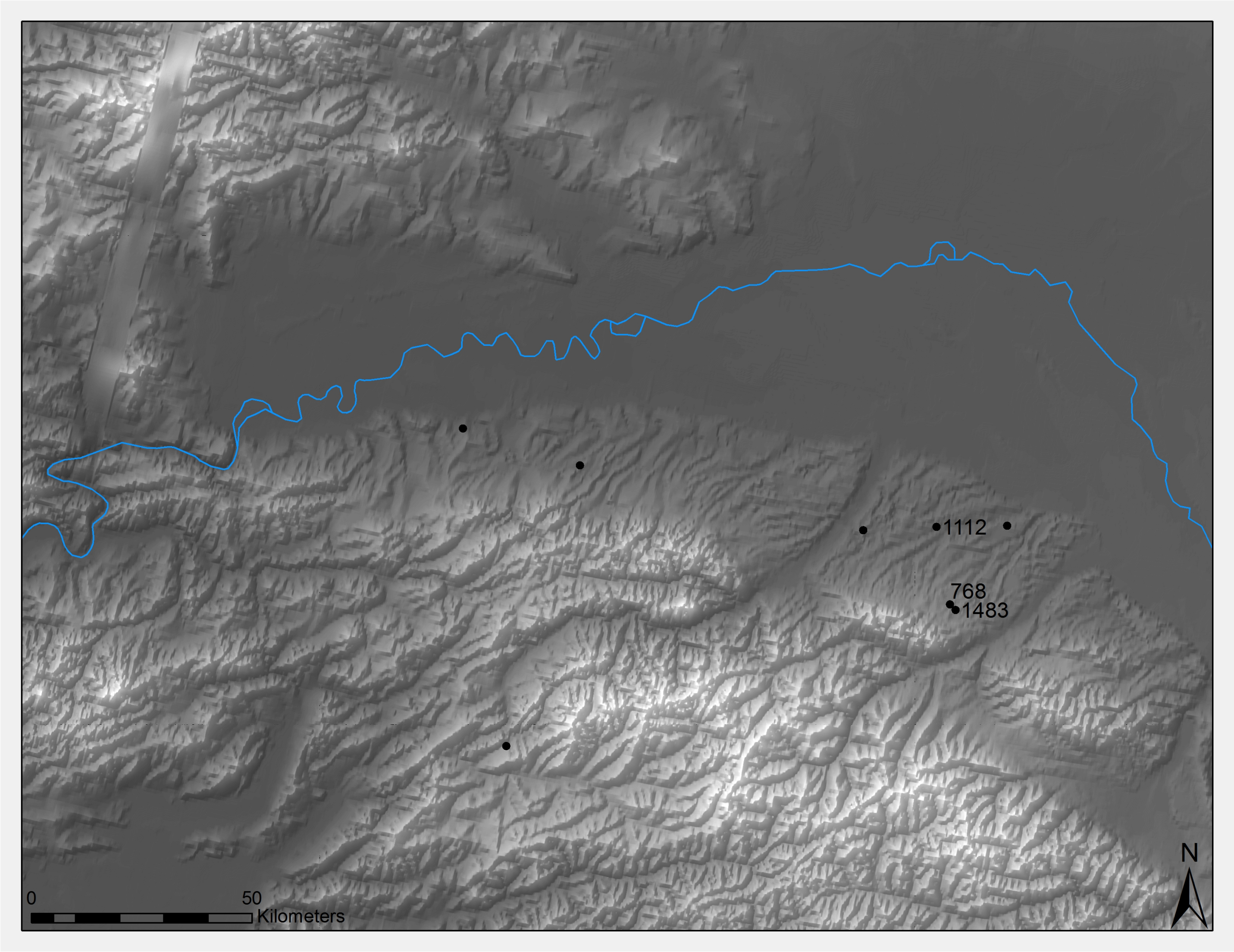

Figure 23 The late Holocene associated breakpoints at the site level in the Yukon River Basin. Brooks Range sites are not included in the figure as there are no site-level breakpoints associated with late Holocene.

CHAPTER 6

CONCLUSION

Various types of changes are seen throughout the records in this study, with short term variability in climate affecting the fire regime change for longer time periods. Additionally, long term changes also result in a breakpoint 100-200 years after the change in climate. Also, the regional variability and time lag between the sites show that response to change is not necessarily synchronous, with the Northern Latitudes being affected first. Considering the expansion of boreal forests into Arctic regions (ACIA, 2005), major shifts in fire regime will eventually affect larger areas of the Arctic and with the previously discussed potential time lag. The majority of changes in the fire regimes of the Arctic regions will continue to persist, even when considering the best-case scenario in the IPCC (2013) climate models.

This study sought to approach the following questions of fire regime analysis using sedimentary analysis utilizing variations in linear models:

1. Could fire regime shifts be detected on the local and regional scale?
2. Are there spatial and/or temporal patterns to these shifts?
3. Can these events be connected to variations in climate changes and/or vegetation changes in the paleorecord?

Conclusions reached from these questions suggest major changes in fire regimes are indeed detectable and relate well to the existing record. Connections to climate and vegetation changes, both spatial and temporal in nature, have been suggested with respect to the clusters in breakpoints and the differences between the Brooks Range and Yukon River Basin. The former is controlled by climatic factors closely associated with conditions in the Bering Sea and the latter is associated with conditions in the Pacific Ocean. With respect to the spatiotemporal patterns, this study suggests the Northern Latitudes are more susceptible to changes in the climate, with changes progressing south as climate patterns shift.

Concerning associated climate and vegetation changes in the record, this analysis shows the fire regimes in continental boreal forests to be more sensitive to changes in climate than their vegetation may suggest. The most significant change detected in the record coincides with the establishment of the boreal forest ecosystem. The temporal difference in regional breakpoints, between the Brooks Range and Yukon River Basin, closely mirrors the migration of the boreal ecosystem from northern and western glacial refuges (Anderson & Brubaker, 1994; Brubaker et al., 2005).

One of the primary objectives with modern views in systems theory is the ability to correctly identify thresholds, in both where they occur in the record (Andersen et al., 2008; Schaffer, 2005; Schaeffer et al., 2001; Shuman et al., 2005), the disturbances in the stable states and the limits at which systems will respond to the change (Carpenter & Lathrop, 2008; Schaeffer, 2005). The goal of this study was to identify periods of the past where climate and vegetation dynamics contribute to a shift in the fire regime and review the stable state conditions between them, and possible perturbations wherein the regime shifted. This approach does not, however, attempt to identify the ecological thresholds of the current fire regimes within the boreal ecosystem with respect to future changes. Further research is necessary and encouraged to investigate the scope of changes in the circumpolar regions in Canada beyond the North American continent, in particular, in continental Siberia. Additionally, further research should focus on the sensitivity of the boreal system to climate change, the increase in these large fires and what the implications are for atmospheric carbon circulation and the climate feedbacks associated with carbon, with questions focusing on how this will impact boreal system and the planet as a whole. Additional research is also necessary to understand how fire dynamics will response to the northward expansion of the boreals and the loss of tundra ecosystems, and how this will affect issues such as habitat concerns, permafrost, and human interaction with the Arctic environment.

Considering many factors in a changing climate, current changes of the boreal fire regime of the past century (Flannigan et al., 2009; Kelly et al., 2013), and possible future changes (Flannigan et al., 2005, 2009), the identification of these previous changes is the first step in a process towards identifying the sensitivity of the primary disturbance factor in the world’s largest forest system.

APPENDIX

Table 2: StucChange breakpoints, their corresponding sites, regions and dates.

Region	**Site**	**5%**	**95%**	**5%**	**Bottom Date**
Brooks Range	Code	850	1496	1740	7409
Brooks Range	Code	2444	2650.278	3730	7409
Brooks Range	Code	4890.6171	4959.7788	5342.7173	7409
Brooks Range	Last Chance	1542.3129	1847.3647	1880.2362	2167
Brooks Range	Ruppert	1580	1726	2750	13948
Brooks Range	Ruppert	5119	5165	5693	13948
Brooks Range	Ruppert	9620	10388	10512	13948
Brooks Range	Wild Tussock	1691	2323	3504	7828
Brooks Range	Wild Tussock	4057	4774	5809	7828
Yukon River Basin	Dune	4255.317	4384.448	5806.9814	9219
Yukon River Basin	Oops	4012.052	4101.52	4620.426	6410
Yukon River Basin	Picea	1403	1483	2223	10369
Yukon River Basin	Picea	3023	3163	3603	10369
Yukon River Basin	Reunion	2086	4516	4546	5405
Yukon River Basin	Screaming Lynx	3693	3708	4098	10642
Yukon River Basin	West Crazy	303	348	378	2770
Yukon River Basin	West Crazy	753	768	798	2770
Yukon River Basin	Windy	977	1112	1517	2808

REFERENCES

ACIA (2004). Impacts of a warming arctic-Arctic climate impact assessment. Cambridge: Cambridge University Press.

Abbott, M. B., Finney, B. P., Edwards, M. E., & Kelts, K. R. (2000). Lake-level reconstruction and paleohydrology of Birch Lake, central Alaska, based on seismic reflection profiles and core transects. *Quaternary Research*, *53*(2), 154-166.

Agee, J. K. (1996). *Fire ecology of Pacific Northwest forests*. Washington, D.C.: Island Press.

Alley, R. B. (2000). The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews*, *19*(1), 213-226.

Anderson, L., Abbott, M. B., & Finney, B. P. (2001). Holocene climate inferred from oxygen isotope ratios in lake sediments, central Brooks Range, Alaska. *Quaternary Research*, *55*(3), 313-321.

Anderson, L., Abbott, M. B., Finney, B. P., & Burns, S. J. (2005). Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada. *Quaternary Research*, *64*(1), 21-35.

Anderson, P. M., Bartlein, P. J., Brubaker, L. B., Gajewski, K., & Ritchie, J. C. (1989). Modern analogues of late-Quaternary pollen spectra from the western interior of North America. *Journal of Biogeography*, 573-596.

Anderson, P. M., & Brubaker, L. B. (1993). Holocene vegetation and climate histories of Alaska. *Global climates since the last glacial maximum*, 385-400.

Anderson, R. S., Hallett, D. J., Berg, E., Jass, R. B., Toney, J. L., De Fontaine, C. S., & DeVolder, A. (2006). Holocene development of boreal forests and fire regimes on the Kenai Lowlands of Alaska. *The Holocene*, *16*(6), 791-803.

Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., ... & Vinson, T. S. (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution*, *70*(1-4), 39-53.

Bai, J. (1994). Least squares estimation of a shift in linear processes. *Journal of Time Series Analysis*, *15*(5), 453-472.

Bai, J., & Perron, P. (1998). Estimating and testing linear models with multiple structural changes. *Econometrica*, 47-78.

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*, *94*(2), 389-402.

Barron, J. A., & Anderson, L. (2011). Enhanced Late Holocene ENSO/PDO expression along the margins of the eastern North Pacific. *Quaternary International*, *235*(1), 3-12.

Bartlein, P.J., Anderson, P.M., Edwards, M.E., McDowell, P.F. (1992). A Framework for interpreting paleoclimatic variations in eastern Beringia. *Quaternary International*, *10*(12), 73-83.

Bennett, K. D., & Fuller, J. L. (2002). Determining the age of the mid-Holocene Tsuga cana densis (hemlock) decline, eastern North America. *The Holocene*, *12*(4), 421-429.

Berg, E. E., & Anderson, R. S. (2006). Fire history of white and Lutz spruce forests on the Kenai Peninsula, Alaska, over the last two millennia as determined from soil charcoal. *Forest Ecology and Management*, *227*(3), 275-283.

Berger, A. (1978). Long-term variations of daily insolation and Quaternary climatic changes. *Journal of the Atmospheric Sciences*, *35*(12), 2362-2367.

Billings, W. D. (1994). Ecological impacts of cheatgrass and resultant fire on ecosystems in the western Great Basin. In S.B. Monsen & S.G. Kitchen (Eds.), *Proceedings of Ecology and Management of Annual Rangelands* (pp. 22-30). Ogden, UT: USDA Forest Service Intermountain Research Station General Technical Reports.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., ... & Bonani, G. (2001). Persistent solar influence on North Atlantic climate during the Holocene. *Science*, *294*(5549), 2130-2136.

Bond-Lamberty, B., Peckham, S. D., Ahl, D. E., & Gower, S. T. (2007). Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature*, *450*(7166), 89-92.

Bonsal, B. R., Zhang, X., Vincent, L. A., & Hogg, W. D. (2001). Characteristics of daily and extreme temperatures over Canada. *Journal of Climate*, *14*(9), 1959-1976.

Brachfeld, S., Barletta, F., St-Onge, G., Darby, D., & Ortiz, J. D. (2009). Impact of diagenesis on the environmental magnetic record from a Holocene sedimentary sequence from the Chukchi–Alaskan margin, Arctic Ocean. *Global and Planetary*

Change, *68*(1), 100-114.

Brubaker, L. B., Anderson, P. M., Edwards, M. E., & Lozhkin, A. V. (2005). Beringia as a glacial refugium for boreal trees and shrubs: new perspectives from mapped pollen data. *Journal of Biogeography*, *32*(5), 833-848.

Caissie, B. E., Brigham-Grette, J., Lawrence, K. T., Herbert, T. D., & Cook, M. S. (2010). Last Glacial Maximum to Holocene sea surface conditions at Umnak Plateau, Bering Sea, as inferred from diatom, alkenone, and stable isotope records. *Paleoceanography*, *25*(1), PA1206.

Carpenter, S. R., & Lathrop, R. C. (2008). Probabilistic estimate of a threshold for eutrophication. *Ecosystems*, *11*(4), 601-613.

Chapin, F. S., McGuire, A. D., Randerson, J., Pielke, R., Baldocchi, D., Hobbie, S. E., ... & Running, S. W. (2000). Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology*, *6*(S1), 211-223.

Clark, J. S. (1988). Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. *Quaternary Research*, *30*(1), 67-80.

Clark, P. U., Dyke, A. S., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., ... & McCabe, A. M. (2009). The last glacial maximum. *Science*, *325*(5941), 710-714.

CLIMAP Project. (1981). *Seasonal reconstructions of the Earth's surface at the last glacial maximum*. Geological Society of America.

COHMAP Members (1988). Climatic changes of the last 18,000 years: Observations and model simulations. *Science*, *241*, 1043-1052.

NOAA NCDC Paleoclimatology and World Data Center for Paleoclimatology (2015). *IGBP PAGES/World Data Center for Paleoclimatology, NOAA/NCDC Paleoclimatology Program.* Retrieved from https://www.ncdc.noaa.gov/data-access/paleoclimatology-data.

Cronin, T. M. (2013). *Paleoclimates: understanding climate change past and present*. New York City, NY: Columbia University Press.

Cwynar, L. C., & Spear, R. W. (1991). Reversion of forest to tundra in the central Yukon. *Ecology*, 202-212.

Cwynar, L. C., & Spear, R. W. (1995). Paleovegetation and paleoclimatic changes in the Yukon at 6 ka BP. *Géographie physique et Quaternaire*, *49*(1), 29-35.

Dakos, V., van Nes, E. H., Donangelo, R., Fort, H., & Scheffer, M. (2010). Spatial correlation as leading indicator of catastrophic shifts. *Theoretical Ecology*, *3*(3), 163-

174.

D'Antonio, C., & Meyerson, L. A. (2002). Exotic plant species as problems and solutions in ecological restoration: a synthesis. *Restoration Ecology*, *10*(4), 703-713.

Davies, M. H., Mix, A. C., Stoner, J. S., Addison, J. A., Jaeger, J., Finney, B., & Wiest, J. (2011). The deglacial transition on the southeastern Alaska Margin: Meltwater input, sea level rise, marine productivity, and sedimentary anoxia. *Paleoceanography*, *26*(2).

Davis, M. B. (1981). Quaternary history and the stability of forest communities. In D. C. West, H. H. Shugart & D. B. Botkin (eds.), *Forest succession* (pp. 132-153). New York City, NY: Springer.

Deser, C., Walsh, J. E., & Timlin, M. S. (2000). Arctic sea ice variability in the context of recent atmospheric circulation trends. *Journal of Climate*, *13*(3), 617-633.

Edwards, M. E., & Dunwiddie, P. W. (1985). Dendrochronological and palynological observations on Populus balsamifera in northern Alaska, USA. *Arctic and Alpine Research*, *17(3)* 271-277.

Edwards, M. E., Mock, C. J., Finney, B. P., Barber, V. A., & Bartlein, P. J. (2001). Potential analogues for paleoclimatic variations in eastern interior Alaska during the past 14,000 yr: atmospheric-circulation controls of regional temperature and moisture responses. *Quaternary Science Reviews*, *20*(1), 189-202.

Fisher, D. A., Wake, C., Kreutz, K., Yalcin, K., Steig, E., Mayewski, P., ... & Burns, S. J. (2004). Stable isotope records from Mount Logan, Eclipse ice cores and nearby Jellybean Lake. Water cycle of the North Pacific over 2000 years and over five vertical kilometres: sudden shifts and tropical connections.*Géographie physique et Quaternaire*, *58*(2-3), 337-352

.

Fisher, D., Osterberg, E., Dyke, A., Dahl-Jensen, D., Demuth, M., Zdanowicz, C., ... & Rupper, S. (2008). The Mt Logan Holocene—late Wisconsinan isotope record: tropical Pacific—Yukon connections. *The Holocene*, *18*(5), 667-677.

Flannigan, M., Stocks, B., Turetsky, M., & Wotton, M. (2009). Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology*, *15*(3), 549-560.

Hagestein, R., Richetts, T., Sims, M., Kavanagh, K. & Mann, G. (2012). Interior Alaska-Yukon lowland taiga ecoregions. WWF - Endangered Species Conservation World Wildlife, Retrieved April 3, 2014 from http://worldwildlife.org/ecoregions/na0607.

Harada, N., Katsuki, K., Nakagawa, M., Matsumoto, A., Seki, O., Addison, J.A., Finney, B.F., Sato, M., 2014. Holocene sea surface temperature and sea ice extent in the Okhotsk and Bering Seas. *Progress in Oceanography, 126*, 242–253

Hare, S. R., & Mantua, N. J. (2000). Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography*, *47*(2), 103-145.

Hemming, S. R. (2004). Heinrich events: Massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Reviews of Geophysics*, *42*(1).

Higuera, P. E., Brubaker, L. B., Anderson, P. M., Hu, F. S., & Brown, T. A. (2009). Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. *Ecological Monographs*,*79*(2), 201-219.

Holz, A., & Veblen, T. T. (2011). The amplifying effects of humans on fire regimes in temperate rainforests in western Patagonia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *311*(1), 82-92.

Hopkins, D. M. (1982). Aspects of the paleogeography of Beringia during the late Pleistocene. *Paleoecology of Beringia*, 3-28.

IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Kasischke, E. S., & Turetsky, M. R. (2006). Recent changes in the fire regime across the North American boreal region—spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters*, *33*(9).

Kaufman, D. S., Ager, T. A., Anderson, N. J., Anderson, P. M., Andrews, J. T., Bartlein, P. J., ... & Wolfe, B. B. (2004). Holocene thermal maximum in the western Arctic (0–180 W). *Quaternary Science Reviews*, *23*(5), 529-560.

Kaufman, D. S., Schneider, D. P., McKay, N. P., Ammann, C. M., Bradley, R. S., Briffa, K. R., ... & Vinther, B. M. (2009). Recent warming reverses long-term Arctic cooling. *Science*, *325*(5945), 1236-1239.

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*, *110*(32), 13055-13060.

Lauriol, B., Lacelle, D., Labrecque, S., Duguay, C. R., & Telka, A. (2009). Holocene evolution of lakes in the Bluefish Basin, northern Yukon, Canada. *Arctic*, 212-224.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences*, *105*(6), 1786-1793.

L'Heureux, M. L., Mann, M. E., Cook, B. I., Gleason, B. E., & Vose, R. S. (2004). Atmospheric circulation influences on seasonal precipitation patterns in Alaska during the latter 20th century. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *109*(D6).

Lynch, J. A., Clark, J. S., Bigelow, N. H., Edwards, M. E., & Finney, B. P. (2002). Geographic and temporal variations in fire history in boreal ecosystems of Alaska. *Journal of Geophysical Research: Atmospheres (1984–2012)*,*107*(D1), FFR-8.

Lynch, J. A., Hollis, J. L., & Hu, F. S. (2004). Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska. *Journal of Ecology*, *92*(3), 477-489.

Mann, D. H., Peteet, D. M., Reanier, R. E., & Kunz, M. L. (2002). Responses of an arctic landscape to Lateglacial and early Holocene climatic changes: the importance of moisture. *Quaternary Science Reviews*, *21*(8), 997-1021.

Manley, W.F., and Daly, C., 2005, Alaska Geospatial Climate Animations of Monthly Temperature and Precipitation. Retrieved from http://instaar.colorado.edu/QGISL/AGCA.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, *78*(6), 1069-1079.

McWethy, D. B., Higuera, P. E., Whitlock, C., Veblen, T. T., Bowman, D. M. J. S., Cary, G. J., Haberle, S. G., Keane, R. E., Maxwell, B. D., McGlone, M. S., Perry, G. L. W., Wilmshurst, J. M., Holz, A. and Tepley, A. J. (2013), A conceptual framework for predicting temperate ecosystem sensitivity to human impacts on fire regimes. *Global Ecology and Biogeography, 22*, 900–912.

Miller, G. H., Brigham-Grette, J., Alley, R. B., Anderson, L., Bauch, H. A., Douglas, M. S. V., ... & Wolff, E. W. (2010). Temperature and precipitation history of the Arctic. *Quaternary Science Reviews*, *29*(15), 1679-1715.

Orwig, D. A., Foster, D. R., & Mausel, D. L. (2002). Landscape patterns of hemlock decline in New England due to the introduced hemlock woolly adelgid. *Journal of Biogeography*, *29*(10-11), 1475-1487.

Overland, J. E., Adams, J. M., & Bond, N. A. (1999). Decadal variability of the Aleutian Low and its relation to high-latitude circulation. *Journal of Climate*, *12*(5), 1542-1548.

Overpeck, J., Whitlock, C., & Huntley, B. (2003). Terrestrial biosphere dynamics in the climate system: past and future. In K. D. Alverson, R. Bradley, & T.F. Pedersen (eds.), *Paleoclimate, global change and the future* (pp. 81-103). Berlin: Springer.

Papineau, J. M. (2001). Wintertime temperature anomalies in Alaska correlated with ENSO and PDO. *International Journal of Climatology*, *21*(13), 1577-1592.

Power, M. J., Marlon, J., Ortiz, N., Bartlein, P. J., Harrison, S. P., Mayle, F. E., ... & Kennedy, L. (2008). Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. *Climate Dynamics*, *30*(7-8), 887-907.

Renssen, H., Brovkin, V., Fichefet, T., & Goosse, H. (2003). Holocene climate instability during the termination of the African Humid Period. *Geophysical Research Letters*, *30*(4), 1184.

Ritchie, J. C. (1981). Problems of interpretation of the pollen stratigraphy of northwest North America. In W.C. Mahaney (Ed.), *Quaternary Paleoclimate* (pp. 377-391). Norwich, UK: GeoAbstracts.

Ruddiman, W. F., & Wright, H. E. (Eds.). (1987). *North America and adjacent oceans during the last deglaciation* (pp. 137-154). Boulder, CO: Geological Society of America.

Scheffer, M. (2009). *Critical transitions in nature and society*. Princeton, NJ: Princeton University Press.

Scheffer, M., & Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology & Evolution*, 18(12), 648-656.

Scheffer, M., Carpenter, S. R., Lenton, T. M., Bascompte, J., Brock, W., Dakos, V., ... & Vandermeer, J. (2012). Anticipating critical transitions. *Science*, *338*(6105), 344-348.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591-596.

Shuman, B., Webb Iii, T., Bartlein, P., & Williams, J. W. (2002). The anatomy of a climatic oscillation: vegetation change in eastern North America during the Younger Dryas chronozone. *Quaternary Science Reviews*, *21*(16), 1777-1791.

Viau, A. E., & Gajewski, K. (2009). Reconstructing millennial-scale, regional paleoclimates of boreal Canada during the Holocene. *Journal of Climate*, *22*(2), 316-330.

Viau, A. E., Gajewski, K., Sawada, M. C., & Bunbury, J. (2008). Low-and high-frequency climate variability in eastern Beringia during the past 25000 years. *Canadian Journal of Earth Sciences*, *45*(11), 1435-1453.

Wiles, G. C., Barclay, D. J., Calkin, P. E., & Lowell, T. V. (2008). Century to millennial-scale temperature variations for the last two thousand years indicated from glacial geologic records of Southern Alaska. *Global and Planetary Change*, *60*(1), 115-125.

Williams, J. W., Post, D. M., Cwynar, L. C., Lotter, A. F., & Levesque, A. J. (2002). Rapid and widespread vegetation responses to past climate change in the North Atlantic region. *Geology*, *30*(11), 971-974.

Zeileis, A., Leisch, F., Hornik, K., Kleiber, C., Hansen, B., & Zeileis, M. A. (2012). Package 'StrucChange'. Vienna: R Foundation for Statistical Computing.