THE ROLE OF CLIMATE VARIABILITY AND

DISTURBANCES ON FOREST ECOLOGY

IN THE INTERMOUNTAIN WEST

by

Vachel Ashley Carter

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

Doctor of Philosophy

Department of Geography

The University of Utah

August 2016

The University of Utah Graduate School

STATEMENT OF DISSERTATION APPROVAL

The dissertation of **Vachel Ashley Carter**

has been approved by the following supervisory committee members:

Andrea Brunelle	, Chair	**April 28, 2016** Date Approved
Simon Brewer	, Member	**April 28, 2016** Date Approved
Philip Dennison	, Member	**April 28, 2016** Date Approved
R. Justin DeRose	, Member	**April 28, 2016** Date Approved
John Shaw	, Member	**April 28, 2016** Date Approved

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

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

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

ABSTRACT

Disturbances play an integral role in regeneration and succession of many forested ecosystems in the Intermountain West region of the western United States. However, changes in climate have been shown to alter the occurrence, duration, and frequency of disturbances. The research presented here uses a paleoecological approach using multiple proxies from sediment cores from three different sites from the Intermountain West in order to assess the linkages among disturbances, climate, and vegetation composition. From the first site in the central Rocky Mountains, a paleoenvironmental data documents the sensitivity of past quaking aspen occurrence to increased temperatures, while frequent wildfire activity led to the persistence of a quaking aspen. From the second site located in south central Utah, a paleoenvironmental data documents how changes in the position of the El Niño Southern Oscillation dipole transition zone affects moisture availability across the state of Utah, which ultimately influences vegetation composition and wildfire frequency. Lastly, from the third site located on the north slope of the Uinta Mountains in northeastern Utah, paleoenvironmental data assesses the long-term primary control on wildfire activity from the region.

The results from this dissertation suggest that disturbance regimes have been in a state of constant change throughout the Holocene as a result of climate variability and in combination these led to changes in vegetation composition. The information contained

in this dissertation will be important for natural resource planning and management because it provides context regarding the natural range of disturbance and vegetation variability for three distinctly different forested settings located in the Intermountain West. Forest managers can use paleoenvironmental records as analogs to help place context of how forested ecosystems will respond to climatic changes. By providing forest managers with long-term information about forest composition and disturbance regimes at multiple sites, this dissertation can be used to enhance resource policy making, planning and management.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Dr. Andrea Brunelle, for her support, mentorship, and friendship. I would also like to thank my committee, Dr. Philip Dennison, Dr. Simon Brewer, Dr. John Shaw, and Dr. Justin DeRose. I am especially grateful for Dr. John Shaw for his support. Without him, this dissertation research would not have contributed research to the north slope of the Uinta Mountains. I would like to express my gratitude to Justin DeRose, Yoshi Maezumi, Vanessa Chavez, Shawn Blissett, and Josh Mueller for their valuable discussions that greatly improved the content of this dissertation. I would also like to acknowledge the long list of folks who helped assist in the field: Vanessa Chavez, Greg Freyer, Sara Goeking, Charlie Hastings, Kelsey Howard, Evan Kraklow, Yoshi Maezumi, Kate Magargal, Scott Matheson, Autumn McKnite, Ran Meng, Brian Munford, Yi Qi, Jessica Spencer, Victor Spencer, Victoria Simmons, and Corey Unger. I would not have been able to do this without the love and support of my family and friends; thank you. And finally, I am especially grateful for my husband, Evan. Thank you for unconditional love and support, and most importantly, preventing hangry outbreaks.

This research was financially supported by a National Science Foundation Doctoral Dissertation Research Improvement Grant (1558289), a USDA Forest Service Joint Venture Agreement #11-JV-1122168202, an award from the Rockies Express Pipeline LLC, two awards from the David C. Williams scholarship, two awards from the University of Utah Department of

Geography Donald R. Currey scholarship, and research support from the University of Utah Global Change and Sustainability Center.

CHAPTER 1

INTRODUCTION

Disturbances, such as wildfires, are integral components of forested ecosystems across the North American Rocky Mountains, playing an important role in regeneration, succession, and ecosystem function. Together, climate variability and site characteristics, such as biomass (i.e., fuel) composition, influence the distribution of vegetation and disturbance regimes (Courtney Mustaphi & Pisaric, 2013). Gradual changes in climate cause long-term shifts in both vegetation and disturbances (Scheffer et al., 2001). However, abrupt climatic changes cause more rapid ecological changes (Scheffer et al., 2001). For example, Marlon et al. (2009) demonstrated the link between abrupt, large-scale climate change during the late glacial-interglacial period between 15,000 and 10,000 cal yr BP, and changes in biomass productivity and wildfire activity in North America. These authors suggest that the unusually large fire episodes during this transitional period were directly linked to changes in fire weather and ignition frequency, and indirectly linked to changes in vegetation (fuel) flammability.

Changes in local, regional, and global temperature and precipitation patterns can alter the occurrence, duration, frequency, and intensity of disturbances (Dale et al., 2001). Average global temperatures have risen 0.85^{o} Celsius since 1880 CE, with the 30-year period between 1983 and 2012 CE likely the warmest 30-year period of the last 1400 years (IPCC, 2014). Climate change is causing widespread vegetation mortality (Allen et al., 2010; McDowell et al., 2011) and will likely influence the distribution of plants that are currently at their latitudinal and altitudinal limits in the future (Elliott & Baker, 2004; Landhäusser et al., 2010; Luckman & Kavanagh, 2000; Mann et al., 1999). Climate change is already altering fuel loads and fuel moisture in subalpine forests of the western US, which has increased the forests' susceptibility to wildfires (McKenzie et al., 2004; Westerling et al., 2003). Westerling et al. (2006) have demonstrated the relationship between the earlier onset of winter snowmelt (i.e., the length of the fire season), as a result of above average spring and summer temperatures, and wildfire activity. Since 1984, the number of wildfires, as well as the area burned, has increased across much of the western US (Dennison et al., 2014), with notable exceptions near the 40° - 41° N latitude boundary in Utah, Colorado, and Wyoming, and this increase is largely manifest in rangeland fires as opposed to forest fires. Unfortunately, virtually all future climate models project an increase in annual temperatures in the Intermountain West region by the end of the 21st century. An increase in annual temperatures, specifically warmer spring temperatures, reinforces the tendency toward an earlier onset of winter snowmelt and a lengthening of the summer season, thus providing conditions that are conducive for wildfire activity in the future.

In the western US, the 40°N latitude marks an important and climatically complex dipole transition zone (Dettinger et al., 1998; Wise, 2010), defined by winter season precipitation that can be associated with the El Niño Southern Oscillation (ENSO). During periods of ENSO activity, there can be a north-to-south 'seesaw' of precipitation variability as seen by anomalously wet conditions in the desert southwest-southern Rocky

Mountains and anomalously dry conditions in the Pacific Northwest-northern Rocky Mountains during El Niño years, and vice versa during La Niña years (Wise, 2010). The Intermountain West and central Rocky Mountains are positioned roughly on the fulcrum of the dipole transition zone in a weak-to-no ENSO correlation zone (Figure 1). The dipole transition zone has been documented to shift in latitude on decadal timescales (Westerling & Swetnam, 2003). However, it is unclear as to how ecosystems and wildfire activity respond to the position of the dipole in the Intermountain West and central Rocky Mountains.

Given the close relationship between climate, disturbances, and vegetation, it is important to understand the long-term interrelationship among the three (i.e., the natural range of variability of each). The natural range of variability is a term that is used to characterize the past spatial and temporal variability commonly using the presettlement period as a type of baseline that can be used as a reference or benchmark in ecosystem management (Keane et al., 2009). One way to understand the natural range of climate variability or natural range of disturbance events (i.e., wildfire frequency) is to use a paleoecological approach that uses sedimentary proxies, such as pollen or macroscopic charcoal preserved in lake sediments, as tools to reconstruct ecosystem function over time and space. Paleoecological reconstructions are helpful to land managers because they provide valuable information about past ecological states and process responses, and how future ecosystems may respond to future climate change and future changes in forest disturbance regimes (Millar et al., 2007). Without fully integrating anticipated impacts of climate change, it will be difficult or impossible for public land management agencies to fulfill their mission to sustain ecosystem function for present and future generations. This dissertation research is intended to provide managers with long-term information about how vegetation and wildfire respond to changes in climate variability over time from individual sites from the Intermountain West region. This long-term information can be applied to both current and anticipated future changes. This work has three primary research objectives and individual working hypotheses that will each be addressed in the subsequent chapters (manuscripts);

1. Determine the role of climate and wildfire on quaking aspen (*Populus tremuloides*) communities from a site in southeastern Wyoming.
    a. $Hypothesis_1$: Warmer temperatures will exert primary control over aspen pollen production.
    b. $Hypothesis_2$: Wildfire activity will exert primary control over aspen pollen production.
2. Determine whether the position of the El Niño Southern Oscillation dipole transition zone influences vegetation and wildfire activity in south central Utah.
    a. $Hypothesis_1$: The position of the dipole transition zone is non-stationary through time, and affects vegetation composition and wildfire frequency in south central Utah.
    b. $Hypothesis_2$: The position of the dipole transition zone is stationary through time, and does not affect vegetation composition and wildfire frequency in south central Utah.
3. Determine the dominant controls of wildfire regimes on the north slope versus the south slope of the Uinta Mountains, Utah.

a. Hypothesis$_1$: Fire regimes on the north slope are more responsive to changes in winter moisture, while fire regimes on the south slope are more responsive to changes in summer moisture.

b. Hypothesis$_2$: Fire regimes on the north slope are not responsive to changes in climate, but rather respond to changes in vegetation composition (i.e., fuels).

In order to address these research objectives, sediment cores were collected from Long Lake, located in southeastern Wyoming in the Medicine Bow Mountains, from Fish Lake, located in south-central Utah on the boundary between the Great Basin and the Colorado Plateau, and from Salamander Pond, located on the north slope of the Uinta Mountains in northeastern Utah (Figure 2). These sites are located within the Intermountain West and central Rocky Mountain regions of the US, which are characterized as topographically complex areas with heterogeneous temperature and precipitation patterns (Mock, 1996). Additionally, these sites lie within and/or near the ENSO dipole transition zone. The position of the ENSO dipole transition zone is non-stationary, thus its position putatively influences vegetation composition and wildfire activity. Therefore, these sites are located in the ideal location to examine Holocene changes in the position of the ENSO dipole transition zone and its affect on vegetation composition and wildfire activity.

Chapter 2 (Manuscript 1), "Climate variability and fire effects on quaking aspen in the central Rocky Mountains, USA," was written for the *Journal of Biogeography*. This chapter analyzes the sediment core collected from Long Lake, Wyoming in order to understand how climate variability and wildfire regime influence quaking aspen during a unique period of time referred to as the *Populus* period (Carter et al., 2013; Carter et al., *in review*). This chapter presents pollen and charcoal data as evidence of changes in vegetation composition and wildfire regimes during the *Populus* period. This chapter incorporates data from the modern pollen-climate analog as a proxy for reconstructing changes in temperature and precipitation.

Chapter 3 (Manuscript 2), "Hydroclimate variability and fire-vegetation responses over the past 1,300 years at Fish Lake, south central Utah," was written for *The Holocene*. This chapter analyses the sediment core collected from Fish Lake, Utah in order to understand how vegetation and wildfire regimes have responded to changes in moisture patterns over the past 1,300 years. This chapter presents pollen and charcoal data as evidence of changes in vegetation and wildfire regimes, as well as incorporates reconstructed temperature data from tree-rings collected from the Colorado Plateau (Salzar & Kifmueller, 2005), and reconstructed Palmer Drought Severity Index (PDSI) data as a proxy for changes in seasonal moisture patterns.

Chapter 4 (Manuscript 3), "Climate-fire-vegetation linkages from the north slope of the Uinta Mountains," was written for either *The Holocene* or *Quaternary Research*. This chapter analyses the sediment cores collected from Salamander Pond, Utah in order to understand how vegetation and wildfire activity have changed over the past 9,600 years. In addition, this record was compared to two Holocene length records from the south slope of the Uinta Mountains in order to determine changes in wildfire behavior with changes in precipitation patterns through time. This paper presents pollen and charcoal as evidence of changes in vegetation composition and wildfire regimes through time.

Chapter 5 summarizes the major findings from this dissertation and discusses the climate-vegetation-fire linkages throughout the Intermountain West and central Rocky Mountains, as well as presents future research that might be developed from this work.

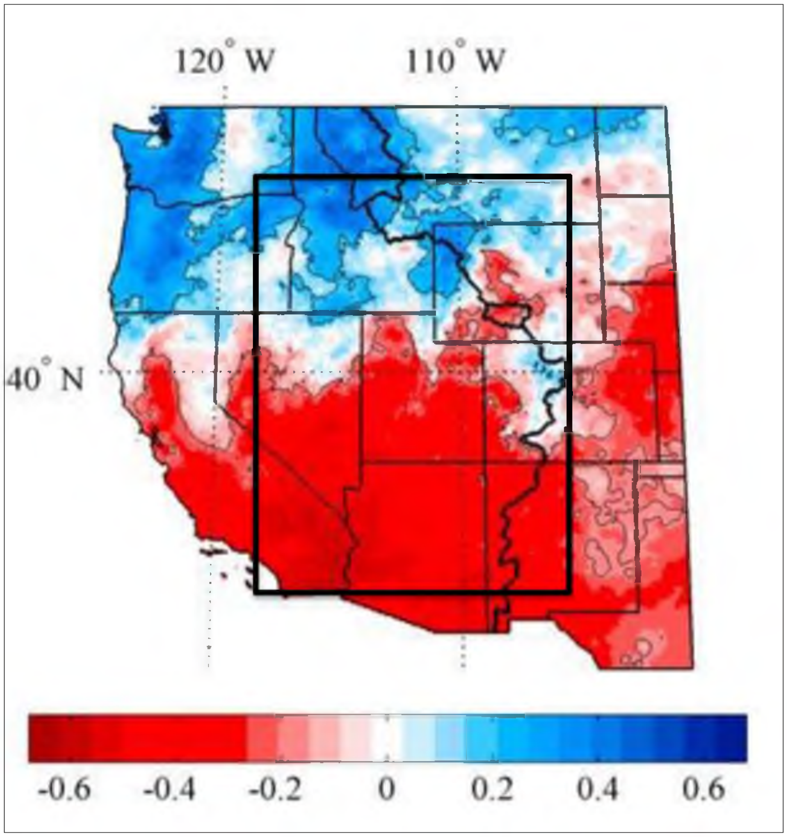


Figure 1. Correlation coefficient map showing the relationship between the Southern Oscillation Index (for June through November) and winter precipitation (for October through March). The black box indicates the Intermountain West region, which is located in the center of the El Niño Southern Oscillation dipole transition zone. Modified from Wise, 2010.

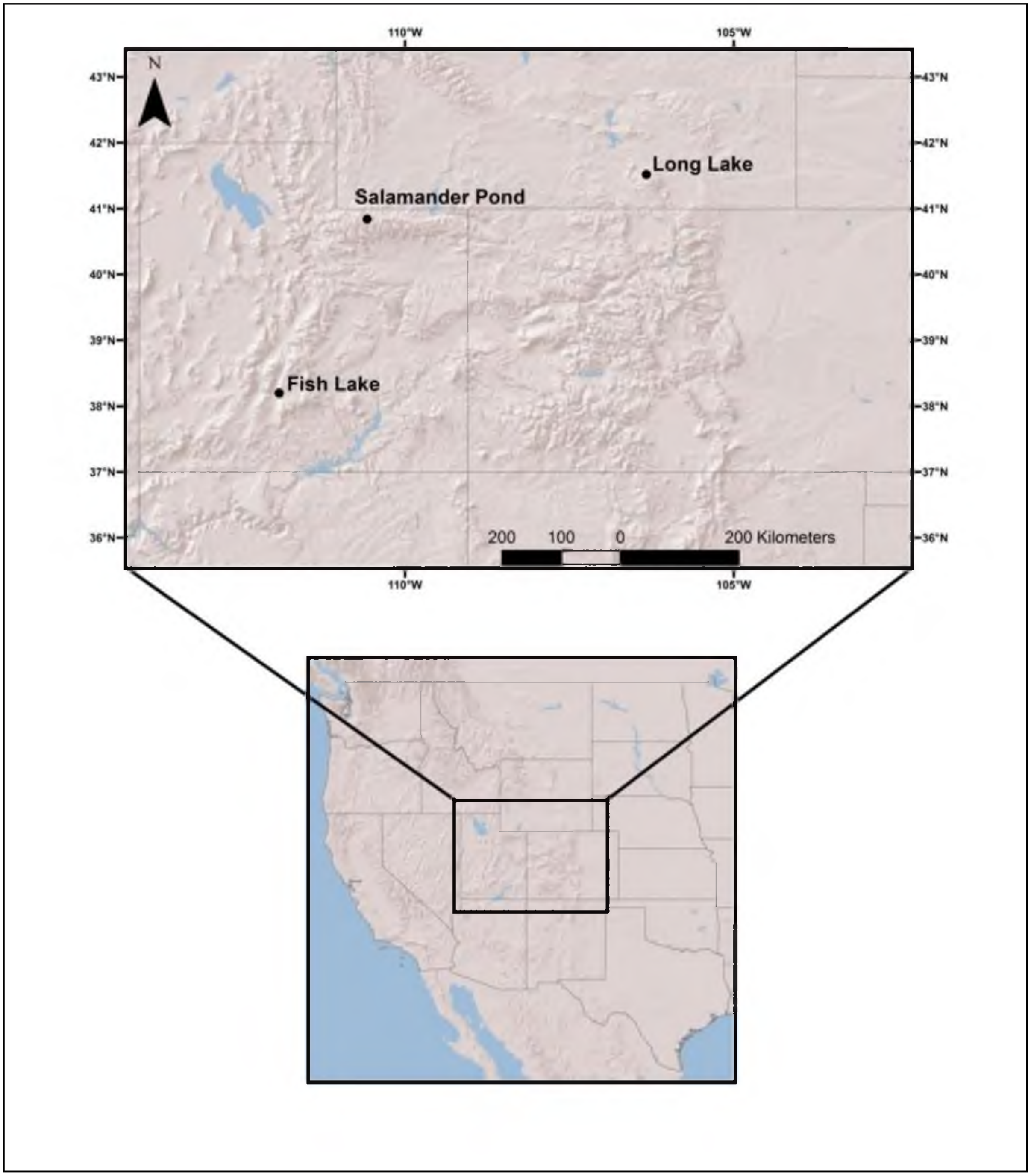


Figure 2. Study sites from this dissertation located across the Intermountain West and central Rocky Mountain region of the western United States.

CHAPTER 2

CLIMATE VARIABILITY AND FIRE EFFECTS ON QUAKING ASPEN IN THE CENTRAL ROCKY MOUNTAINS, USA.

Introduction

Quaking aspen (*Populus tremuloides* Michx; hereinafter referred to as 'aspen') is the most widely distributed deciduous tree species in North America (Little, 1971; Perala, 1990). Despite its wide distribution, aspen are typically found where annual precipitation exceeds evapotranspiration and mean annual temperatures are relatively cool. Aspen do not function well where conditions are generally warm and relatively low humidity (Dang et al., 1997; Jones, 1985; Morelli & Carr, 2011). Aspen are generally confined to higher elevations and south-facing slopes in the colder parts of its range (Jones et al., 1985).

Numerous studies have detailed the large-scale decline in aspen communities across parts of the western United States (U.S.) (Anderegg et al., 2013a; 2013b; Kashian et al., 2007; Rehfeldt et al., 2009; Worrall et al., 2008; 2010; 2013) as a result of drought (Hanna & Kulakowski, 2012; Hogg et al., 2008). It is unknown whether the recent decline of aspen is within the natural range of variation of aspen population dynamics over longer time periods (Kulakowski et al., 2004; Morelli & Carr, 2011). Although some aspen stands have been impacted by drought, aspen in other parts of western North

America have increased throughout the 20^{th} century as a result of increased disturbances, mainly fire activity (Kulakowski et al., 2004). Unfortunately, the relationship between climate variability, fire, and aspen demographics remains poorly understood (Anderegg et al., 2013b; Hanna & Kulakowski, 2012; Worrall et al., 2010), especially prior to the 20^{th} century.

Mueggler (1989) has shown that fire is critical for aspen regeneration and persistence in particular stands in Utah, southeastern Idaho, and western Wyoming. Shinneman et al. (2013) state that understanding the importance of fire in aspen communities is a fundamental issue. Generally, aspen communities are thought to be either stable or seral, each being supported by distinct fire regimes (Jones & DeByle, 1985; Mueggler, 1989; Shinneman et al., 2013). Within stable aspen ecosystems, lightning-caused fires are uncommon (Jones & DeByle, 1985; Shinneman et al., 2013) and the spread of fire is limited due to high moisture content within aspen stands (Smith et al., 1993). In seral aspen ecosystems, conifers are more abundant and play an important role in fire susceptibility by increasing the amount of biomass in a stand over time and acting as fuel ladders, which leads to increased fire severity (Brown & DeByle, 1987). However, both seral and stable aspen communities can burn when climatic conditions are favorable, especially when aspen communities include conifers (Shinneman et al., 2013).

Shinneman et al. (2013) reviewed primarily tree-ring-based studies to understand the relationship between aspen communities and historic fire regimes. Of 46 studies analyzed, 12 reconstructed the mean fire return interval (FRI), and only one estimated fire rotation (>140 years) near an aspen stand using stand-origin dates over a large study area (Romme et al., 2001). Despite their review, the natural range of variability of burning in aspen prior to the 20th century remains poorly understood, likely due to the fact that aspen stems are easily killed by fire and not ideal for dendrochronological evaluations of fire (Brown & DeByle, 1987; Jones & DeByle, 1985; Shinneman et al., 2013).

Because dendrochronological aspen fire history reconstructions are limited to the age of extant wood, other sources of ecological and historical evidence are needed in order to understand the full range of natural variability of aspen dynamics (Rogers et al., 2013). A paleoecological approach that specifically examines charcoal and pollen preserved in lake sediments is one methodology that provides a means to better understand the full range of natural variability of climate and fire in sustaining aspen populations. While aspen pollen (herein referred to as '*Populus*') is normally poorly represented in sedimentary records, the record presented in this study contains an unusual amount of *Populus* pollen, indicating an extremely high abundance of aspen on the landscape. This unique record allowed us to examine the possible climate-fire relationships on aspen abundance prior-to, during, and after a period of anomalously high *Populus* pollen referred to as the *Populus* period. The *Populus* period is a unique vegetation transition period between 3950 and 3450 cal. yr BP when a lodgepole pine-dominated system transitioned to an aspen-mixed conifer forest in the Medicine Bow Mountains of southeastern Wyoming (Carter et al., 2013). The objectives of this study are to determine how aspen was influenced by climate variability, specifically warmer temperatures, and by fire.

Material and Methods

Study Site

Long Lake (41° 30.099′ N, 106° 22.087′ W, 2700 m a.s.l.) is a small lake (~12 ha) with a 22 ha catchment (Dennison et al., 2010) located in the Medicine Bow range of southeastern Wyoming (Figure 3). The modern forest surrounding Long Lake is dominated by lodgepole pine (*Pinus contorta*), with Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*). The present-day aspen ecotone is ~200 m downslope from Long Lake (Figure 3).

Core Recovery and Chronology

A 4.85 m long core (LL07D) and 56 cm short core (LL07C) were collected in September 2007. Carter et al. (2013) describe core recovery. Sediments were transported back to the Records of Environment and Disturbance (RED) Lab at the University of Utah and refrigerated at 2°C.

Age-depth relationships were updated from Carter et al. (2013) with an additional ^{14}C accelerator mass spectrometry (AMS) date at depth 129 cm to fully constrain the timing of the *Populus* period, and a cesium (Cs) peak date that provides modern temporal constraint (Table 1). ^{14}C AMS dates were converted to calibrated years and new age-depth relationships were determined using the classical age-depth model (CLAM) with a smoothing spline with a smoothing parameter of 0.3 (Blaauw et al., 2010) (Figure 4).

Pollen Analysis

Pollen analysis was conducted to provide a high-resolution vegetation reconstruction. Long Lake serves as an excellent depositional environment with anoxic conditions that provided excellent pollen preservation, which is demonstrated by the overall high levels of preservation (calculated by the ratio of pollen to the tracer, *Lycopodium*) and the sheer abundance of *Populus tremuloides* pollen counted in this study. Individual one-cm^3 pollen samples were processed contiguously between depths 1 and 36 cm (represents the modern period), and 94 and 176 cm (represents the period between 4500 and 2000 cal. yr BP) following standard acid-base methods (Faegri et al., 1989). A known number of *Lycopodium* spores were added to each sample as an exotic tracer in order to quantify total pollen concentration values. A minimum of 300 pollen grains or *Lycopodium* tracers were counted per sample using light microscopy at 500X magnification. Pollen records are described in terms of influx and ratios. Pollen influx (particles/cm^2/yr) provides information about individual pollen taxon abundance, while pollen ratios allow for comparison between two types of pollen taxon or a group of pollen taxa. In this study, genus names (i.e., *Populus*) are used when referring to pollen influx and/or ratios, while common names (i.e., aspen) are used when discussing environments. Two groups of ratios were compared in this study and were calculated using the formula $(a-b)/(a+b)$ (Maher, 1963, 1972); 1) a = total *Pinus* pollen, b= *Populus* pollen; and 2) a = the sum of all arboreal pollen (AP), b = the sum of all non-arboreal pollen (NAP) (see Table 2). The total *Pinus* pollen represents the sum of *Pinus* undifferentiated, *P.* subgenus *Pinus*, and *P.* subgenus *Strobus* based on the modern phytogeography of the conifer species present in the Medicine Bow Mountains. Ratio data are presented in standard units where higher (lower) values indicate greater (lesser) abundance of *Pinus* pollen relative to *Populus* pollen and AP pollen relative to NAP pollen.

Zonal boundaries that indicate major changes in vegetation composition were determined by CONISS (Grimm, 1987). Carter et al. (2013) identified three major pollen zones prior-to, during, and after the *Populus* period (LL:III 9000 - 4000 cal. yr BP; LL:IV 4000 - 3100 cal. yr BP; and LL:V 3100 - present (2007 CE) cal. yr BP). However, in this study we have added subzones to zones LL:IV and LL:V (LL:IVa, LL:4b-5a, and LL:5b) in order to keep descriptions consistent (see Carter et al., 2013), but also reflect the new age-depth model discussed in the 'Core Recovery' section (see Table 1). Subsequent analytical methods discussed below will also be presented based on the new subzones.

Charcoal Analysis

Macroscopic charcoal was used to reconstruct the fire history. Individual 5-cm^3 charcoal samples were contiguously analyzed following standard methods (Long et al., 1998). Sediments were screened through 125 μm and 250 μm sieves as fraction sizes >125 μm do not travel far from their source and represent local fire activity within the catchment (Clark et al. 1988; Gardner & Whitlock, 2001). Total charcoal counts were converted into charcoal concentrations (particles cm^{-3}) and then transformed to charcoal influx (CHAR; particles/cm^2/yr). Charcoal concentrations were binned into 5-yr intervals using CharAnalysis (Higuera et al., 2009; Huerta et al., 2009). The CHAR time-series was decomposed into two components; a slow moving background component, which represents the continual input of charcoal from varying local and extra-local fire activity, and a peaks component, which represents instantaneous charcoal input into the lake from a local fire event. The background component was determined using a 500-yr Lowess smoother, robust to outliers. Fire return interval (FRI), the number of years between each fire episode, was smoothed using a 1000-yr moving window. Fire peak magnitude (particles/cm^2/episode) represents the amount of charcoal produced above the background charcoal level for each fire episode.

Climate Reconstruction

The modern pollen analog approach (Overpeck et al., 1985) was used to apply modern pollen-climate relationships to the fossil pollen spectra as a means to interpret past climatic conditions (Minckley, 2003; Minckley et al., 2008; Whitmore et al., 2005; Williams et al., 2006; William & Shuman, 2008). Two temperature variables, mean temperature of the warmest month (MTWA) and mean temperature of the coldest month (MTCO), and two moisture variables, the ratio of actual evapotranspiration to potential evapotranspiration (AE/PE) and annual precipitation (AnnP), were selected for the climate reconstruction (Minckley et al., 2008). We also used two bioclimate variables, growing season precipitation (GSP), which is the sum of the reconstructed precipitation from April through September, and the annual dryness index (ADI), using the ratio of growing degree-days (5^o base) to annual precipitation, which Worrell et al. (2013) and Rehfeldt et al. (2009) suggest are important bioclimate predictors for the presence or absence of aspen. *Populus* pollen abundance was not used in the association between modern and fossil pollen assemblages because it currently is not apart of the modern pollen data set. Climate reconstructions were based on the weighted average modern climate values from the seven closest pollen analogs for each fossil spectra (see Minckley et al., 2008; Williams & Shuman, 2008). Results were presented as anomalies from present day reconstructed climate.

Statistical Analysis

The Kruskal-Wallis rank sum test was used to assess differences between subzones based on the six climate variables (MTCO, MTWA, AnnP, AE/PE, ADI, and GSP), two fire history variables (CHAR and FRI), and *Populus* pollen influx. Tukey's Honest Significance Difference (HSD) test was used to identify which pairs of subzones exhibited significant differences (Table 3).

Results

Zone LL:III Pre-Populus Period (4500 - 3950 cal. yr BP)

The high abundance of *Pinus* pollen (mean, 5658 grains/cm^2/yr) and non-arboreal pollen (NAP) (mean, 3346 grains/cm^2/yr) indicate an open lodgepole pine forest with abundant understory vegetation (Figure 5b). Low *Populus* pollen (mean, 55 grains/cm^2/yr) indicates the aspen ecotone was lower in elevation than Long Lake. Fire activity was low (n=2) during this zone. CHAR averaged 1.5 particles/cm^2/yr, and peak magnitude averaged 148 particles/cm^2/episode (Figure 6b). Reconstructed temperature variables indicate modern-like temperatures (MTWA mean, 15°C ± 1.6; MTCO mean, -9°C ± 1.2), and relatively high precipitation (AE/PE mean, 0.47 ±0.3; AnnP mean, 442 ± 57 mm; GSP mean, 347 ± 31 mm) (Figure 7).

However, between 4300 and 4100 cal. yr BP, *Picea* pollen (mean, 152 grains/cm^2/yr), *Populus* pollen (mean, 63 grains/cm^2/yr), and NAP pollen (mean, 3861 grains/cm^2/yr) all increased coincident with a decrease in AE/PE (mean, 0.43 ± 0.3), AnnP (mean, 394 ± 58 mm), GSP (mean, 330 ± 42 mm), and an increase in MTWA (mean, 16°C ± 1.8) and MTCO (mean, -8°C ± 1.1), indicating a drought. High ADI (mean, 0.45 ± 0.17) further indicates warm and dry conditions during this time.

Zone LL:IVa The Populus Period (3950 - 3450 cal. yr BP)

The abrupt yet significant increase in *Populus* pollen (mean, 40,014 grains/cm^2/yr; peak influx value of 206,000 grains/cm^2/yr) distinguishes this zone (Figure 5b), which is significantly different than the pre-*Populus* period zone (p=<0.001) (Table 1). The increase in aspen suggests the aspen ecotone migrated upslope into the Long Lake watershed. However, total *Pinus* pollen (mean, 13,571 grains/cm^2/yr), *Abies* pollen (mean, 333 grains/cm^2/yr), *Picea* pollen (mean, 162 grains/cm^2/yr), and NAP pollen (mean, 5171 grains/cm^2/yr) all increased during this zone, likely a result of increased precipitation (AE/PE mean, 0.50 ± 0.2; AnnP mean, 468 ±35 mm; and GSP mean, 358 ± 19 mm). The reconstructed ADI values (mean 0.28 ± 0.11) also suggest wetter conditions than the previous zone (Figure 7b). Fire activity increased during the *Populus* period (n=5) with a mean FRI of 109 years, which is significantly different than the pre-*Populus* period (p=<0.001). CHAR (mean, 3.0 particles/cm^2/yr) and peak magnitude (mean, 225 particles/cm^2/episode; range 31 & 549 particles/cm^2/episode) both increased during this zone, and demonstrate that fire events were more severe during the *Populus* period (Figure 6b). Temperatures were similar to those experienced prior to the drought between 4300 and 4100 cal. yr BP, with a mean MTWA of 15°C ± 1.2, and a mean MTCO of -9°C ± 1.1, respectively.

Zone LL:IVb and LL:Va Post-Populus Period (2000 - 3450 cal. yr BP)

The significant decline in *Populus* pollen (mean, 30 grains/cm^2/yr) defines the end of aspen dominance, suggesting that the aspen ecotone migrated downslope in elevation. However, total *Pinus* pollen (mean, 4767 grains/cm^2/yr), *Abies* pollen (mean, 63 grains/cm^2/yr), *Picea* pollen (mean, 43 grains/cm^2/yr), and NAP pollen (mean, 2005 grains/cm^2/yr) also gradually decreased throughout this zone (Figure 5b). While fire activity was abundant (n=8) in this zone, the FRI lengthened to 166 years and the severity of the fires decreased as indicated by low CHAR (mean, 1.2 particles/cm^2/yr), and peak magnitudes (mean, 80 particles/cm^2/episode; range 1.0 and 183 particles/cm^2/episode) (Figure 6b). Temperatures during the post-*Populus* period remained similar to the *Populus* period, while precipitation decreased slightly (AE/PE mean, 0.48 ± 0.3; AnnP mean, 443 ± 39 mm; GSP mean, 351 ± 22 mm). Reconstructed ADI values increased (mean, 0.35 ± 0.12), suggesting slightly drier conditions than the previous zone (Figure 7b).

Zone LL:Vb The Modern Period (550 cal. yr BP - present)

The high abundance of total *Pinus* pollen (mean, 5376 grains/cm^2/yr) and NAP pollen (mean, 3006 grains/cm^2/yr) suggests a landscape dominated by an open lodgepole pine forest with abundant understory vegetation. Low *Populus* pollen (mean, 81 grains/cm^2/yr) suggests that the aspen ecotone was located downslope from Long Lake (Figure 5a). Fire activity was abundant (n=6) and frequent (FRI = 110 years). However, low CHAR (mean, 1.6 particles/cm^2/yr) and peak magnitude (mean, 112 particles/cm^2/episode; range 1.10 to 260 particles/cm^2/episode) suggest fires were of low severity (Figure 6a). Climate was similar to temperature and precipitation conditions reconstructed for the pre-*Populus* and post-*Populus* period (Figure 7a).

However, a brief warm and dry period occurred between 49 and 28 cal. yr BP (1901 – 1922 CE) (MTWA mean, 16ºC ± 1.4; MTCO mean, -7.8ºC ± 1.7; AE/PE mean, 0.46 ± 0.5; AnnP mean, 419 ± 43 mm) (Figure 7a). Additionally, ADI (mean, 0.44 ± 0.12) increased from the previous zone, further suggesting drier conditions.

Discussion

Physiological changes in forest productivity are dependent upon climate and the limiting factors of a particular site, such as aspect (i.e., solar radiation) (Boisvenue & Running, 2006). The distribution of aspen is dependent upon climate and other environmental conditions, such as aspect and slope (Morelli & Carr, 2011). Disturbances such as wildfire have also been shown to exert strong control on aspen regeneration (Kulakowski et al., 2004) and occurrence in contemporary landscapes (Romme et al. 1995). However, the long-term natural range of variability of aspen-climate-fire relationships and the distribution of past aspen communities is not well understood. Typically, because *Populus* pollen is poorly preserved, there have been few studies that have been able to offer insights of presettlement conditions that are necessary to fill in the knowledge gap regarding aspen-climate-fire relationships. The results of this study suggest that warmer temperatures influenced upslope migration of past aspen communities, while a frequent fire regime helped maintain aspen dominance. These results enhance our understanding about aspen-climate-fire relationships, and provide valuable information that can help land managers anticipate future changes in aspen distributions (Worrall et al., 2013).

Late Holocene Climate Variability and Fire Effects on Aspen in the Medicine Bow Mountains

Prior to the *Populus* period, the pollen-based climate reconstruction suggests decreased effective moisture and increased temperatures for ~150 years between 4300 and 4100 cal. yr BP (Figure 7b). Pollen influx data and NAP pollen ratio are indicative of an open lodgepole pine-dominated forest at Long Lake. However, an abrupt increase in *Populus* pollen influx around 4200 cal. yr BP suggests that the aspen ecotone likely began migrating upslope closer to Long Lake as a result of the drought. Sparse fuels and limited moisture likely inhibited fire activity during this warm drought.

The inferred drought centered on 4200 cal. yr BP not only affected the Long Lake catchment, but also affected Little Windy Hill Pond (elevation 2980 m a.s.l.), 8 km upslope from Long Lake. During this drought, Little Windy Hill Pond experienced a slight increase in *Picea* pollen, which suggests that the subalpine forest was also migrating upslope in response to warm and dry conditions (Minckley et al., 2012). Similar to Long Lake, Minckley et al. (2012) attribute the long fire-free period at Little Windy Hill Pond to low effective moisture.

Regional responses to the drought centered on 4200 cal. yr BP include widespread dune reactivation at the Ferris Dune Field roughly 80 km northwest of Long Lake (Stokes & Gaylord, 1993), and reduced lake levels at Upper Big Creek Lake in northern Colorado roughly 69 km southwest of Long Lake (Shuman et al., 2015). Warm and dry conditions were also recorded in a $\delta^{13}C$ and $\delta^{18}O$ isotope record from a speleothem from Minnetonka Cave on the Utah/Idaho border roughly 430 km west of Long Lake (Lundeen et al., 2013). Similarly, Booth et al. (2005) also present evidence of an abrupt and severe drought from the mid-continent of North America. Enhanced El Niño Southern Oscillation (ENSO) variability and/or more persistent La Niña conditions have been hypothesized as possible mechanisms for the drought in the mid-continent of North America ~4200 cal. yr BP (Barron & Anderson, 2011; Booth et al., 2005; Forman et al., 2001; Menking & Anderson, 2003), which potentially explains the widespread drought response recorded throughout the Rocky Mountain region.

However, immediately following the drought at ~4100 cal. yr BP, the open lodgepole pine-dominated forest at Long Lake became a closed mixed-conifer forest as demonstrated by the AP:NAP ratio (Figure 6b). Reconstructed temperature and precipitation variables suggest a change from drought-like conditions to effectively wetter-than-previous conditions, similar to conditions experienced prior to ca. 4200 cal. yr BP (Figure 7b). An abrupt change in climate indirectly influences vegetation composition and ultimately leads to an increase in fire activity because of fuel accumulation (Marlon et al., 2012). In this case, the abrupt change from warm and dry conditions to cooler and effectively wetter conditions around 4100 cal. yr BP led to an increase in biomass (i.e., fuel), and the connectivity of fuel led to more fire activity at Long Lake. This fuel connectivity is demonstrated by a fire event immediately following the abrupt change in climate at 4100 cal. yr BP (Figure 6b). Anderson (2011) documented a change from a rain-dominated precipitation pattern to a more snow-dominated pattern in the Rocky Mountains around 4100 cal. yr BP, which could explain the effectively wetter-than-previous conditions identified at Long Lake.

At the beginning of the *Populus* period around 3950 cal. yr BP, pollen-based climate reconstructions suggest continued effectively wet conditions with high annual precipitation and average temperatures (Figure 7b). Increased moisture likely led to further increases in forest productivity, indicated by the increases in *Pinus*, *Abies*, *Picea*, and NAP pollen influxes (Figure 5b). However, it is the dramatic increase in *Populus* pollen influx and the *Pinus*:*Populus* ratio that is truly unique in our record, indicating a switch from a lodgepole pine-dominated forest to a mixed forest abundant with aspen for roughly 500 years (Figure 5b). Since aspen are typically located where annual precipitation exceeds evapotranspiration and mean annual temperatures are relatively cool, the optimal climatic conditions experienced during the *Populus* period created a suitable environment for aspen establishment at Long Lake. Once established, persistent aspen populations were likely related to shorter FRIs (~110 years). Aspen regeneration can be prolific after stand-replacing fires (Brown & DeByle, 1987; Smith et al., 2011). Large peak magnitudes during the *Populus* period can be attributed to the conifer forest, which likely increased local fire severity by creating fuel ladders (Cumming, 2001). Our data are consistent with fire-supported aspen persistence at Long Lake during the *Populus* period. The timing of increased FRI at Long Lake appears to be a regional phenomenon. Higuera et al. (2014) documented an increase in the FRI (~77 years/fire) in Rocky Mountain National Park (roughly 257 km south of Long Lake) during the *Populus* period. The authors conclude that the increase in FRI was likely a result in the switch from rain-dominated precipitation to snow-dominated precipitation regimes beginning around 4100 cal. yr BP.

Immediately following the end of the *Populus* period around 3450 cal. yr BP, pollen-based climate reconstructions show a return to climatic conditions experienced prior to the drought. As a result, conditions were no longer suitable for aspen at Long Lake. *Populus* pollen influx decreased dramatically, and the *Pinus*:*Populus* ratio indicates an abrupt return to a lodgepole pine-dominated forest. FRI lengthened and fire events became more infrequent than those experienced during the *Populus* period to a more typical fire regime for lodgepole pine pine forests (~100 – 300 FRI; Knight, 1994).

Modern Climate Variability and Fire Influences on Aspen in the Medicine Bow Mountains

Over the past 550 years, the ecosystem at Long Lake has been dominated by lodgepole pine, with Engelmann spruce and subalpine fir located on more mesic areas. Climatic conditions are currently not conducive for aspen establishment at Long Lake. According to data from the USDA Forest Service Forest Inventory and Analysis (FIA) program (Gillespie, 1999), the elevation of the aspen ecotone is lower in elevation than Long Lake by roughly 200 m. However, aspen does exist in small stands close to Long Lake and at higher elevations on south-facing slopes (Figure 8). This is significant because it demonstrates that aspen can exist at higher elevations, but that its occurrence at higher elevations is likely dependent on warm temperatures characteristic of south facing slopes.

Significance of the *Populus* Period

The rapid rise to dominance, long persistence, and rapid decline of an aspen community in the Long Lake core is unusual and provides an opportunity to examine prolonged aspen stand dynamics. Local dominance of aspen normally occurs under two different general scenarios, depending upon the local climatic conditions. The first and most broad scenario is seral aspen, where aspen communities yield to spruce and fir ~80 to 150 years after the onset of aspen dominance (Mueggler, 1985; Rogers, 2002). This occurs where annual precipitation exceeds evapotranspiration and mean annual temperatures are relatively cool, commonly at higher elevations. Under this scenario, relative pollen abundance between aspen and conifer species would be expected to oscillate on centennial timescales. The other common scenario is that of so-called stable aspen, which occurs when climatic conditions are too warm and dry to support late-succession conifers, but not too warm and dry for aspen. Stable aspen are able to persist in the absence of disturbance or climate change (Kurtzel et al., 2007; Morelli & Carr, 2011) as a result of episodic aspen regeneration (Kurtzel et al., 2007; Mueller-Dombois, 1992). In some areas, sites that support stable aspen are even too dry to support the establishment of aspen by seeding. However, in the Medicine Bow Mountains, and the nearby Uinta Mountains in Utah and Wyoming, aspen is presently seral in the upper end of its elevational range and stable in the lower end (Shaw & Long, 2007). In the lower end, aspen also forms the lower tree line either transitioning to sagebrush or occurring as islands that are topo-edaphically controlled. The modern upper limit of aspen on north facing slopes in the Medicine Bow Mountains is similar to the elevation at Long Lake (Figure 8, dashed line), indicating that aspen is primarily seral in the vicinity of the lake today. Identifying which of these two states was dominant during the *Populus* period is difficult as climatic conditions could have favored stable aspen criteria, but frequent fire could have resulted in a persistent seral aspen state by resetting long-term succession patterns. However, the rapid increase and persistence of *Populus* pollen is more consistent with stable aspen in the immediate vicinity of Long Lake, and suggests that the aspen ecotone shifted upward at least 200 m at the onset of the *Populus* period, remained in that position for approximately 500 years, and retracted to approximately the modern elevational range or lower.

It may be that understanding the natural range of variability between seral and stable aspen needs to be addressed independently, as each may respond to climate differently. For example, Anderegg et al. (2013) and Worrall et al. (2013) attribute aspen mortality across much of the San Juan National Forest and southern Rocky Mountains to low soil moisture and high growing season temperatures. The mortality documented by Anderegg et al. (2013) most likely took place in stable aspen stands located at lower tree line, and Worrall et al. (2013) state that mortality took place at low elevations. Because stable aspen is typically found at lower tree line, it is expected that recent mortality would be highest among aspen populations there. However, it is not understood whether the recent mortality among aspen in the western U.S. is within the natural range of variability, or whether the recent mortality is unprecedented.

Conclusions

The aim of this study was to understand the conditions that allowed for a period of aspen dominance in the Medicine Bow Mountains between 3950 and 3450 cal. yr BP.

This paleoecological reconstruction offers valuable insight regarding the natural range of variability of aspen ecosystems. Kulakowski et al. (2013) suggest that understanding long-term aspen dynamics at finer spatial scales is necessary in order to understand how climate variability contributes to aspen mortality. While our study interpreted data from one catchment on the north slope of the Medicine Bow Mountains, our study does offer the first high-resolution aspen reconstruction for the area. The results from our study demonstrate that warming temperatures play an important role in aspen migration, while frequent fire activity maintained aspen dominance.

Future climate-fire patterns of more frequent drought and/or warmer temperatures may inhibit aspen regeneration at lower elevations (Elliot & Baker, 2004; Hanna & Kulakowski, 2012; Romme et al., 2001), and may facilitate upslope migration of aspen, if coupled with frequent and severe fires. Landhäusser et al. (2010) have already documented the expansion of aspen to higher elevations in Alberta, Canada because of disturbance and management practices, and suggest that these sites may become aspen-dominated if warming conditions persist with frequent disturbances. Because the *Populus* period is characterized by a frequent FRI with severe fires, these conditions may have aided in the persistence of stable aspen populations. While a few studies have documented the increase of aspen following fire (Kulakowski et al., 2004), this differs from Morris et al. (2012) who document an increase in *Populus* pollen in the absence of fire activity in southern Utah. Therefore, additional palaeoecological reconstructions specifically conducted near the aspen ecotone in western North America are needed in order to further improve our understanding of the natural range of variability of the climate-fire-aspen relationships that effect current management practices focused on facilitating and/or inhibiting aspen migration in the face of climate change.

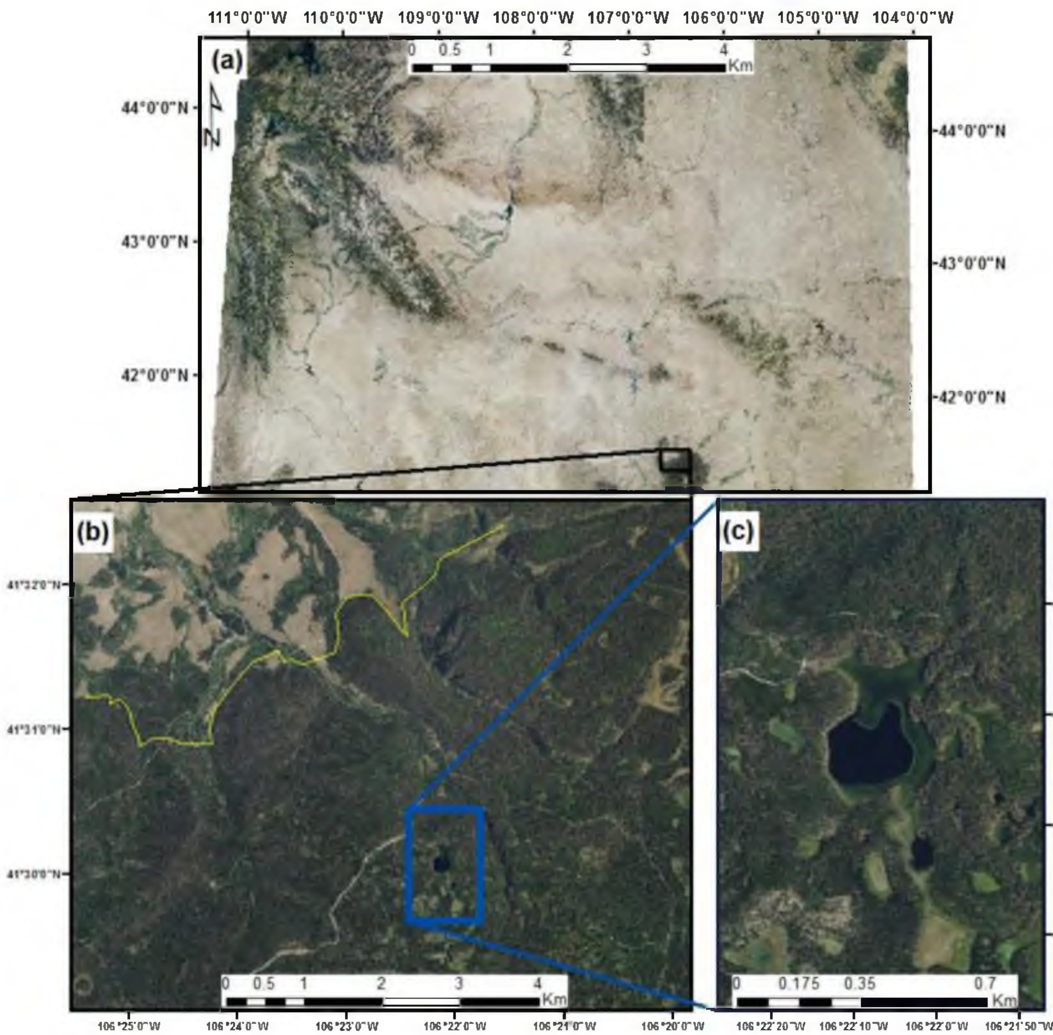


Figure 3. Long Lake, Wyoming study site. (a) Location of the study area located in the Medicine Bow Mountains within the state of Wyoming. (b) Image of the study site, Long Lake in relation to the modern aspen ecotone (yellow line), which is roughly 4 km and 200 m downslope from Long Lake. (c) Image of Long Lake, Wyoming. All images were made using 2012 NAIP imagery with a Universal Transverse Mercator Zone 13 map projection.

Table 1. Summary of age-depth relations for Long Lake, Wyoming used by Carter et al. (2013). Dates with a '*' symbol next to the individual depth indicate new dates that were used to refine the age-depth model in this study. The ^{14}C date at depth 129 cm was used to constrain the upper age of the *Populus* period. The *Populus* period is characterized as a unique vegetation transition period when a lodgepole pine-dominated forest transitioned to a mixed conifer-quaking aspen forest between 3950 and 3450 cal. yr BP.

Depth (cm)	UGAMS #	Source Material	Age (^{14}C yr BP)	Age (cal yr BP) with 2 sigma range
1		Date collected		-57
13*		Cesium peak		-10
29	3249	*Pinus contorta* needle	50 ± 35	31 - 139
49	3710	*Abies lasiocarpa* needle	845 ± 30	688 - 796
88	2772	*Pinus contorta* needle	1730 ± 35	1549 - 1714
129*	17695	pollen	3380 ± 25	3570 - 3649
156	3032	*Pinus contorta* needle	3510 ± 30	3698 - 3864
232	2774	*Pinus contorta* needle	6460 ± 45	7275 - 7435
249	3031	*Abies lasiocarpa* needle	8110 ± 50	8976 - 9152
323.5	2775	*Pinus flexilis* needle	9630 ± 50	10,774 - 11,180
449	3478	*Abies lasiocarpa* needle	10400 ± 50	11,975 - 12,386

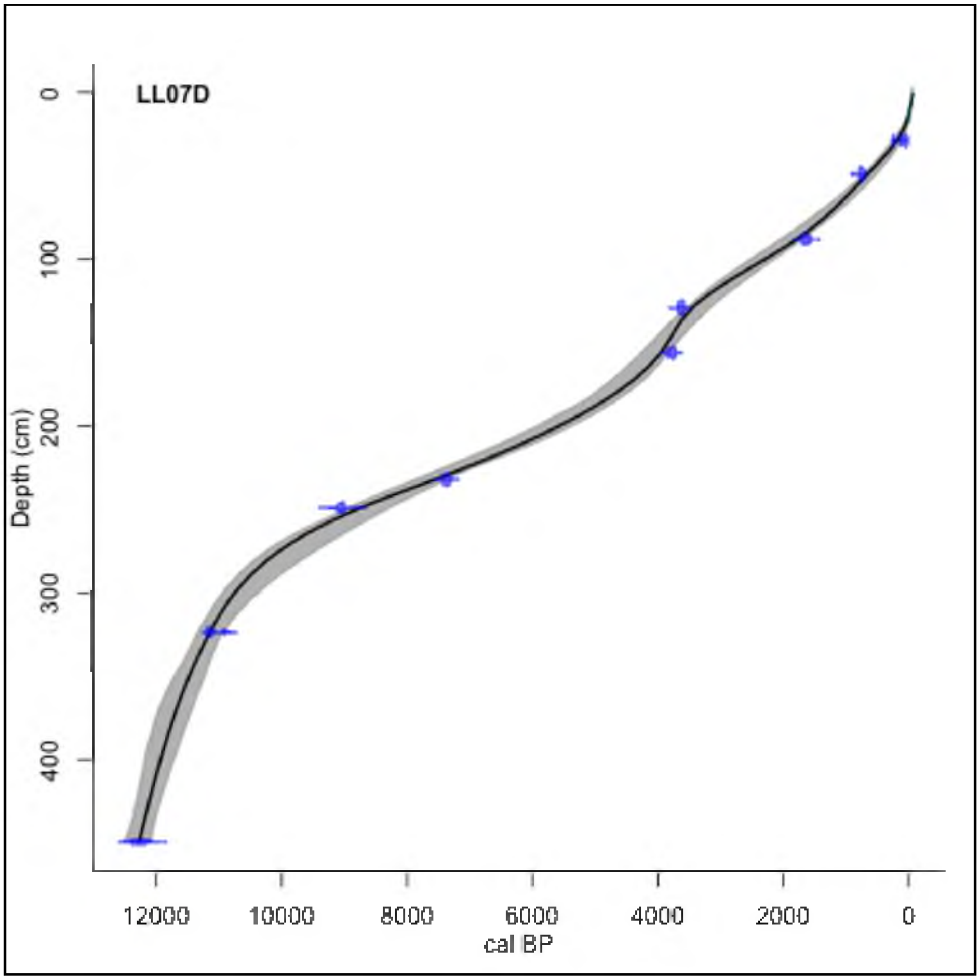


Figure 4. New age-depth model updated from Carter et al. (2013) from Long Lake, Wyoming. The age-depth model was constructed using the classical age-depth model (CLAM) with a smoothing spline and a smoothing parameter of 0.3.

Table 2. List of arboreal pollen (AP), which are tree species, and non-arboreal pollen (NAP), which are herbs and shrubs used in the AP:NAP ratio. The AP:NAP ratio was calculated using the equation $(a-b)/(a+b)$, where a represents the sum of all AP, and b represents the sum of all NAP, and was used to infer changes in canopy density through time.

Arboreal Pollen	Non-Arboreal Pollen			
Total *Pinus*	Amaranthaceae	*Cercocarpus*	Loranathaceae	Rosaceae
Abies	*Ambrosia*	*Chickory*	Malvaceae	Rubiaceae
Picea	*Amelanchier*	*Ephedra*	Onagraceae	*Salix*
Pseudotsuga	*Artemisa*	*Eriogonum*	Poaceae	*Sarcobatus*
Acer	Apiaceae	Fabaceae	Polymoniaceae	*Ribes*
Populus	Schrophulaceae	*Shepherdia*	*Thalictrum*	Liliaceae
Betula	Asteraceae	Fagaceae	Polygonaceae	*Ceanothus*
Celtis	Brassicaceae	*Juniperus*	Ranunculaceae	
	Caryophyllaceae	Lamiaceae	Rhamnaceae	

Table 3. Results from the Tukey HSD test, which was used to identify which pairs of zones exhibited significant differences based on climate variables, fire history variables, and aspen (*Populus*) pollen influx data. The six climate variables used in this study include mean temperatures of the warmest month (MTWA), mean temperature of the colder month (MTCO), annual precipitation (AnnP), growing season precipitation (GSP), the ratio of actual evapotranspiration to potential evapotranspiration (AE/PE), and annual dryness index (ADI). Two fire history variables included in this statistical analysis included charcoal accumulation (CHAR) and fire return interval (FRI). Zones analyzed in this study include LL:III 4500 - 3950 cal. yr BP; LL:IVa 3950 - 3450 cal. yr BP; LL:4b-5a 3450 - 2000 cal. yr BP; , and LL:5b 550 cal. yr BP to present.

Zones compared	Peaks	FRI	CHAR	AnnP	GSP	ADI	AE/PE	MTCO	MTWA	*Populus*
LL:III & LL:IVa	0.659	**<0.001**	**<0.001**	0.106	0.508	0.088	**<0.001**	0.195	0.453	**<0.001**
LL:IVa & LL:IVb	0.627	**<0.001**	**<0.001**	0.007	0.381	0.011	0.007	0.183	0.067	**<0.001**
LL:IVb & LL:Va	0.609	**<0.001**	0.602	0.999	0.080	0.773	0.434	0.052	0.602	0.002

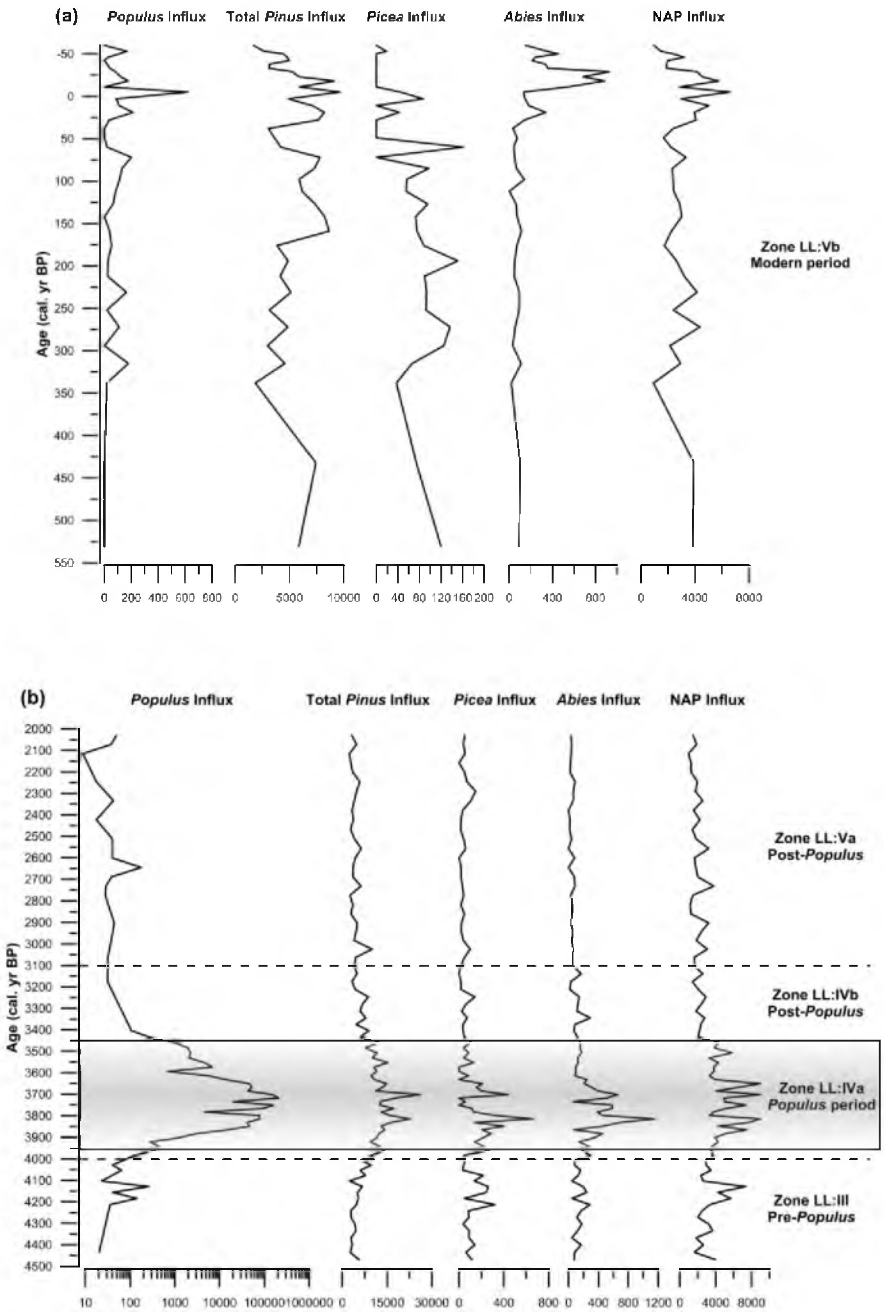


Figure 5. Pollen influx (particles cm^{-2} yr) diagram for Long Lake, Wyoming. Note the change in scale in *Populus* pollen influx between (a) the modern period, and (b) the *Populus* period, which is plotted on a logarithmic scale. The dashed lines represent the original zone boundaries that once defined the *Populus* period (Carter et al., 2013). The shaded gray scale box indicates the new *Populus* period ages used in this study.

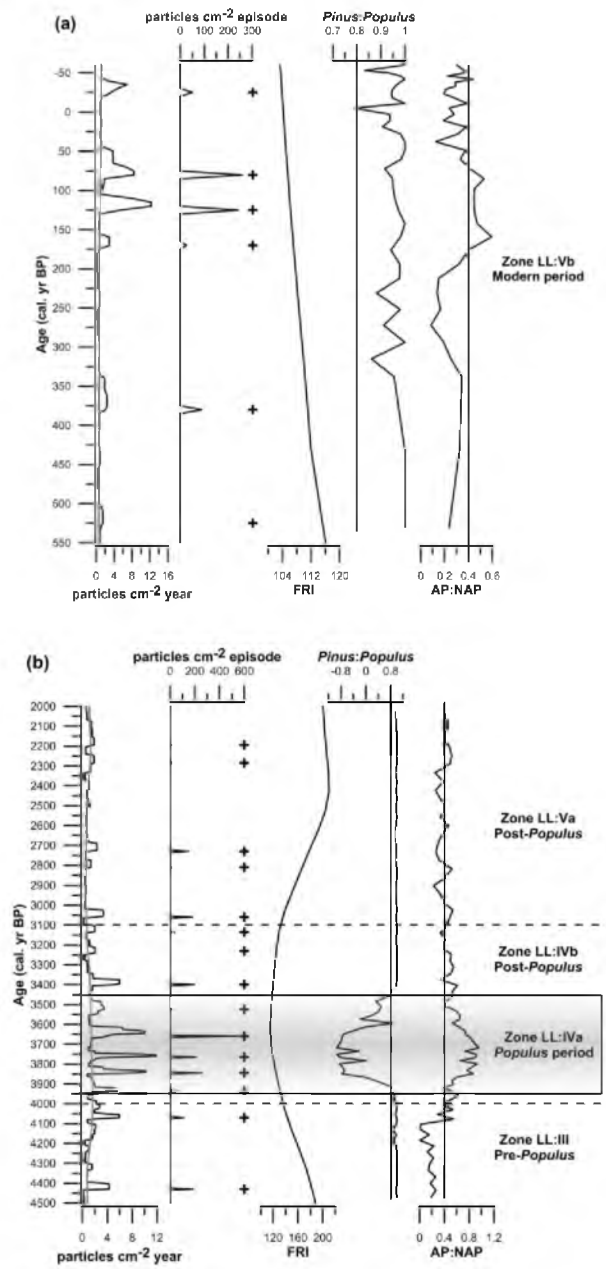


Figure 6. Fire history and pollen ratio diagram for Long Lake, Wyoming during (a) the modern period, and (b) the *Populus* period. From left to right; CHAR (particles cm^{-2} yr) (black), indicating instantaneous charcoal input into the lake from a local fire event when it exceeds the background (gray), which represents the continual input of charcoal from varying local and extra-local fire activity; Peak magnitude (particles cm^{-2} episode) represents the number of charcoal particles associated with each fire peak, which is represented by the '+' symbol; *Pinus:Populus* and AP:NAP ratios were used to compare the dominant canopy species, as well as compare the canopy to understorey. The dashed lines represent the original zone boundaries that once defined the *Populus* period (Carter et al., 2013). The shaded gray scale box indicates the new *Populus* period ages used in this study.

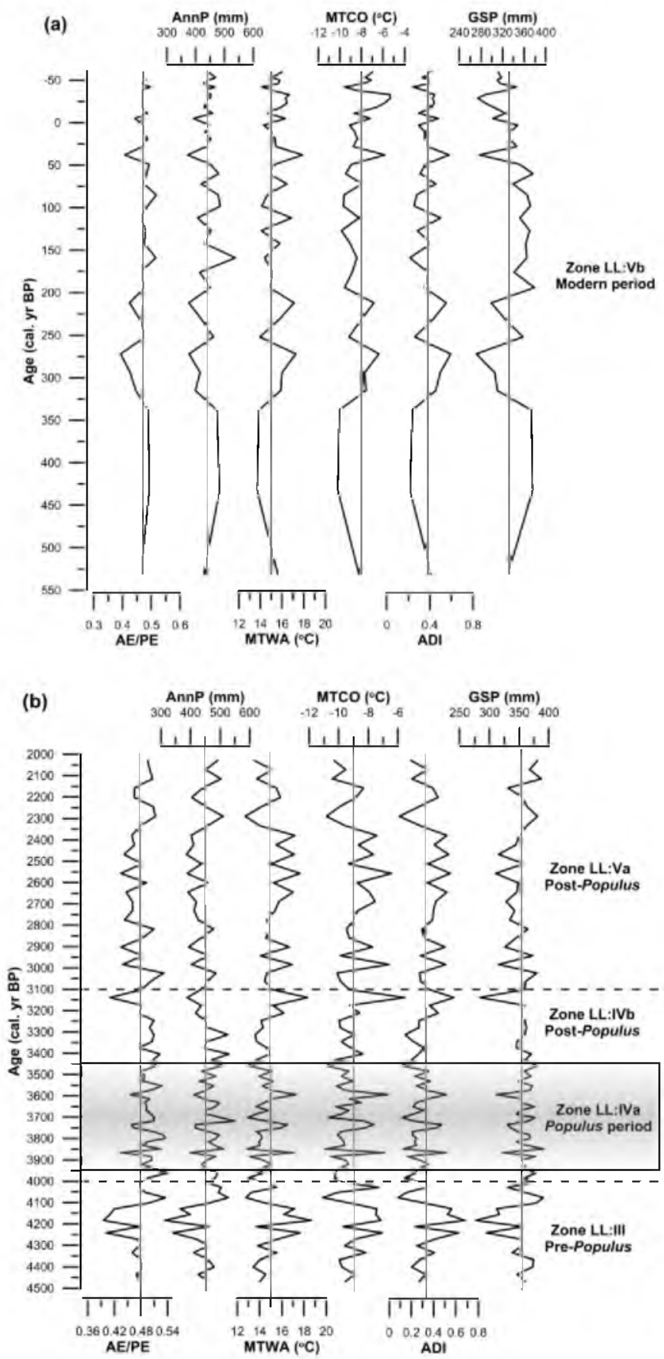


Figure 7. Reconstructed climate variables using modern pollen-climate relations from Long Lake, Wyoming for (a) the modern period, and (b) the *Populus* period. From left to right; AE/PE is the ratio of actual evapotranspiration to potential evapotranspiration; AnnP is reconstructed annual precipitation; MTWA and MTCO are the mean temperature of the warmest and coldest months; ADI is reconstructed annual dryness index (Rehfeldt et al. (2009); GSP is growing season precipitation (Worrell et al., 2013). The dashed lines represent the original zone boundaries that once defined the *Populus* period (Carter *et al.*, 2013). The shaded gray scale box indicates the new *Populus* period ages used in this study.

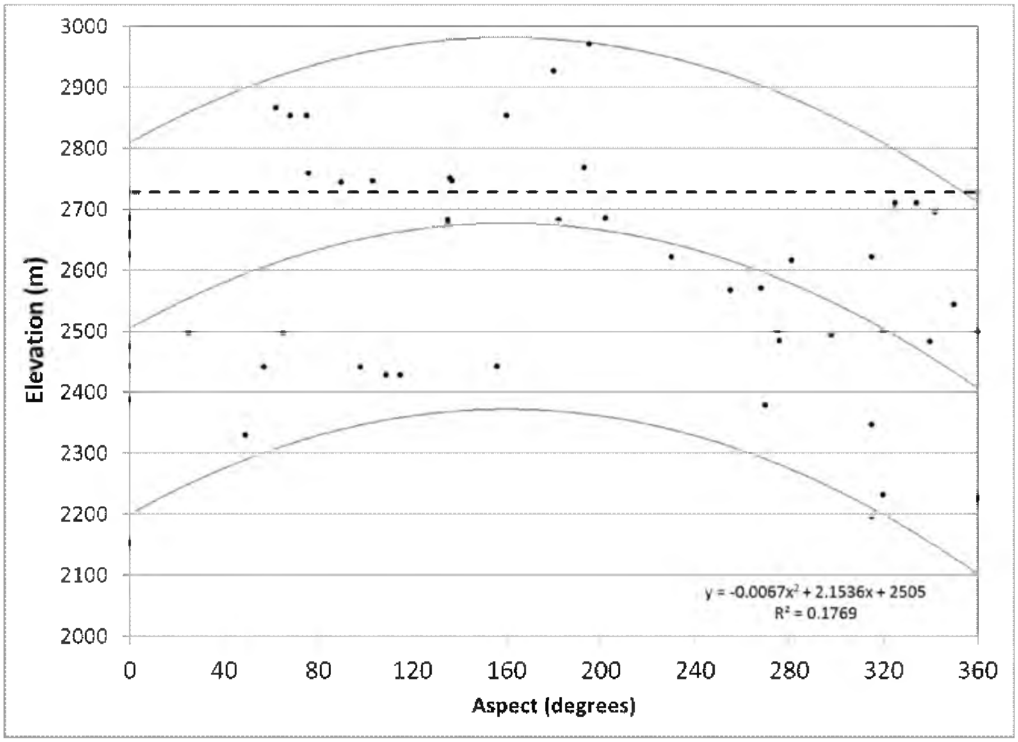


Figure 8. Diagram showing the relationship between quaking aspen, aspect, and elevation (m) on the north slope of the Medicine Bow Range, southeastern Wyoming. The black dots represent the elevation of all USDA Forest Service Forest Inventory and Analysis (FIA) plots with aspen present on site. The horizontal dashed line indicates the elevation of the study site, Long Lake. The polynomial fit is for the middle arched line, representing the mean elevation of aspen (intercept 2502 m) located near Long Lake. The upper and lower arched lines represent ± 300 m from the mean. The figure shows that the modern upper limit of aspen on north facing slopes in the Medicine Bow Mountains is similar to the elevation at Long Lake. However, aspen does exist in small stands close to Long Lake and at higher elevations on south-facing slopes.

CHAPTER 3

HYDROCLIMATE VARIABLITY AND FIRE-VEGETATION RESPONSES OVER THE PAST 1,300 YEARS AT FISH LAKE, SOUTH CENTRAL UTAH, USA.

Introduction

The Intermountain West (IW) region of the western United States (US) encompasses both the Great Basin and the Colorado Plateau provinces, and is characterized as a topographically and climatically complex region (Wise, 2012). Precipitation in the IW is reliant on two major moisture patterns; winter frontal systems originating from the Pacific, and summer precipitation from summer seasonal convectional systems with moisture sourced from the North American Monsoon (NAM) (Mock, 1996; Shinker, 2010). Additionally, the El Niño-Southern Oscillation (ENSO), which is a winter precipitation phenomenon, also influences winter moisture delivery in the IW (Wise, 2010). Typically, ENSO creates a north-to-south ‘seesaw’ of precipitation variability as seen by anomalously wet conditions in the desert southwest-southern Rocky Mountains and anomalously dry conditions in the Pacific Northwest-northern Rocky Mountains during El Niño years, and vice versa during La Niña years (Wise, 2010). However, at the fulcrum is a ‘dipole transition zone’ (DTZ) centered between 40^{o} and 42^{o} - 45^{o} north latitude (Dettinger et al., 1998; Shinker, 2010; Wise, 2010), which is currently centered over the IW, meaning the IW is within in the weak-to-no ENSO correlation zone. The DTZ has been documented to shift either north or south on decadal timescales (Westerling & Swetnam, 2003), and the position of the dipole has been shown to be transient, holding constant over space for the past three decades (DeRose et al., 2013). The ENSO cycle has been known to influence wildfire occurrence in the western US (Westerling & Swetnam, 2003), but the latitudinal position of the DTZ within the Intermountain West may also influence wildfire dynamics.

Fire frequency has increased in the Great Basin portion of the IW since the 1980s as a result of invasive species (Balch et al., 2013), land use and land management practices (Littell et al., 2009), and an increase in summer temperatures and dryness. However, it is unclear as to how fire activity has responded to the recent, 21st-century climate change on the Colorado Plateau region of the IW (Dennison et al., 2014). Currently, climate change is hypothesized to increase the vulnerability of forest systems to mortality (van Mantgem et al., 2009) due to increased wildfire activity (Dennison et al. 2014) and drought occurrence (Breshears et al., 2005). Wildfires in the western U.S. are strongly linked to the length of the fire season and warming temperatures (Westerling et al. 2006). Over the past 100 years, temperatures have increased 0.5^{o}C to 1.5^{o}C in the IW, and are projected to increase 2^{o} to 5^{o}C by the end of the century (Chambers and Pellant, 2008). Warming temperatures in the future will likely continue to lengthen the fire season. Therefore, understanding how sensitive vegetation composition and wildfire activity are to changing climate is a major concern for managing ecosystem sustainability in the IW.

Vegetation composition has changed over the past 150 years in many forested regions of the IW as a result of grazing, logging, and modern land management practices (Belsky & Blumenthal, 1997). For example, ecosystem stability in the Great Basin is currently under threat because of the introduction of annual grasses, such as cheatgrass (*Bromus tectorum*), which has come to dominate many low-elevation vegetation types in the IW (Weltz et al., 2014). The invasion of cheatgrass into higher elevations has increased fine fuels (i.e., fuel connectivity), thus increasing the risk of high-severity stand-replacing fires in the IW (Romme et al., 2009). The introduction of domestic livestock in the mid-1850s seriously degraded many high-elevation landscapes of the IW (Ellison, 1954; Billings, 1990; D'Antonio & Vitousek, 1992). Also at higher elevations in the IW, woody (i.e., more trees) infilling is occurring as a result of land management legacies, such as grazing and/or fire suppression, and settlement-era harvesting (Morris et al., 2015), which have changed the ecology the landscape (Brunelle et al., 2014).

Here, we present a 1,300-year sedimentary record of fire and vegetation history from Fish Lake, south-central Utah, based on macroscopic charcoal and pollen in order to understand the sensitivity of the greater Fish Lake region to changes in climate and moisture variability. Fish Lake is located in the IW on the Great Basin/Colorado Plateau boundary, and on ENSO DTZ, making it an ideal setting to study long-term changes in the hydroclimatic variability and the possible impacts on vegetation composition and wildfire activity. The objectives of this study are; 1) provide insight into the ecological responses to latitudinal shifts in the DTZ in the IW; 2) determine how fire and vegetation have changed over the past 1,300 years; and 3) examine the potential ecological impacts of prehistoric and recent anthropological influences.

Material and Methods

Study Site

Fish Lake (38° 32' N, 111° 43' W; elevation 2700 m) is a large natural graben-filled mountain lake located in south-central Utah. Fish Lake is surrounded by the Mytoge Mountain Range to the southwest and the Fish Lake Hightop Plateau to the northeast (Figure 9). Fish Lake has a high lake area to watershed ratio with the lake basin comprising ~20% of the watershed (Utah Division of Water Quality, unpublished report). The watershed is approximately 73.8 km^2 with a surface area of approximately 8.6 x 1.8 km and average water depth of ~27 m (Marchetti et al., 2011).

Climate interpolations from the surrounding Fish Lake region were determined by selecting Parameter-elevation Relationships on Independent Slopes Model (PRISM) pixels (Daly, 2008) using WestMap Climate Analysis data between 1895 and 2015 CE. PRISM pixels were centered on Fish Lake, UT (38.5°N, -111.71°W), and indicate January and July precipitation averaged 83 mm and 43 mm, respectively, while temperature has averaged -8°C and 12°C (Figure 10).

Contemporary vegetation occurrence at Fish Lake is strongly controlled by aspect and elevation (proxies for moisture availability), where overstory tree species Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) are dominant on the north-facing slope of the Mytoge Mountains, and quaking aspen (*Populus tremuloides*), Rocky Mountain juniper (*Juniperus scopulorum*), and curlleaf mountain mahogany (*Cercocarpus* spp.) typically dominate south-facing slopes. Dominant understory vegetation includes many herbs in the sunflower family (Asteraceae), grass family (Poaceae), Rose family (Rosaceae), and buttercup family (Ranunculaceae). Aquatic and riparian vegetation includes sedges (Cyperaceae), horsetails (*Equisetum* sp.), watermilfoil (*Myriophyllum* sp.), and willow (*Salix* sp.).

Core Collection

In February 2014, a 49.5 cm freeze core (FLFC2_17_14) was taken from near the deepest point of Fish Lake using a Freeze Corer device. Sediments were transported back to the Records of Environment and Disturbance (RED) Lab at the University of Utah and kept frozen at -18°C.

Hydroclimate Reconstruction

To document the geographical complexity in seasonal precipitation for the region, we analyzed data from the SNOTEL sites closest to Fish Lake. Interpolations from Black Flat SNOTEL station (site ID 348; 38° 68'N, 111° 6'W; 2884 m), which is ~16 km northeast of Fish Lake, provide continuous precipitation and temperature records since 1987, and indicates average January and July precipitation and temperature to be 42 mm and 50 mm and -5.8°C and 13.7°C, respectively. Conversely, interpolations from Donkey Reservoir SNOTEL station (site ID 452; 38° 13' N, 111° 29' W; elevation 2987 m), which is ~41.4 km southeast and provide a continuous record since 1986, and indicates average January and July precipitation and temperature to be 36 mm and 54 mm, and -6.9°C and 13.6°C (Figure 9). The average July precipitation is suggestive of a bi-modal precipitation regime south of Fish Lake.

To evaluate the relationship between modern ENSO events near Fish Lake, we collected continuous instrumental precipitation data from Richfield, Utah, the closest town to Fish Lake. Richfield is located ~41 km northwest and ~1000 m lower in elevation than Fish Lake. We also interrogated precipitation data from the three nearest SNOTEL sites but excluded the Fish Lake SNOTEL site since this site is limited to five years of precipitation data. We standardized the precipitation data from Richfield, Utah and the SNOTEL data and compared them to standardized Nino 3.4 anomalous sea surface temperatures (SST).

To examine the influence of seasonal moisture changes on fire regimes and vegetation at Fish Lake, we created a ratio using pollen taxa that are indicative of winter precipitation (*Picea* + *Abies*) and summer precipitation (*Juniperus* + *Quercus*) (Thompson et al., 1999). We then overlaid our winter:summer precipitation ratio over a reconstructed winter precipitation ($\delta^{13}C$) record from a speleothem from Minnetonka Cave (Lundeen et al., 2013). Minnetonka Cave is currently in the present day ENSO DTZ and serves as a useful record to compare with the Fish Lake to determine how moisture availability has changed and how this may have impacted ecosystems located in the IW.

Climate Reconstruction

Modern temperature and precipitation data (1895 – 2013 CE) were obtained using Westmap prism climate data centered on the Fish Lake pixel (38.5° N, -111.7° W) (Figure 9). A tree-ring reconstructed Palmer Drought Severity Index (PDSI) (Cook et al., 2004) was used to examine moisture anomalies for the region using the average of grid points 86, 87, 102, and 103 with a 27-year moving average. Instrumental (1895 – 2010 CE) and reconstructed (1951 – 1300 CE) PDSI data were obtained online via NOAA's National Climatic Data Center.

Charcoal Analysis

Macroscopic charcoal was used in order to determine the fire history from Fish Lake. Samples were processed at contiguous 0.5 cm intervals with 5-cm^3 of sediment using standard methods (Long et al., 1998) and were sieved through 125 and 250 μm wire mesh sieves as charcoal particles larger than 125 μm do not travel far from their source and represent local fire activity within the catchment (Clark et al. 1988; Gardner & Whitlock, 2001). Total charcoal counts were converted to charcoal concentration (particles/cm^3) and then transformed into charcoal accumulation (CHAR; particles/cm^2/yr). A transformed charcoal time-series was determined using CharAnalysis (Higuera et al., 2009; Huerta et al., 2009) binned into 15-year intervals. The time-series is comprised of a slow moving background component, that represents continual charcoal input into the lake basin from regional sources (CHAR), and a peaks component, that represents a pulse of charcoal into the lake basin (i.e., a local fire within the watershed). The background component was smoothed using a 100-year moving window, while the peak frequency was smoothed using a 300-year window. The fire history will be presented as CHAR, fire episodes, and peak magnitude, the latter representing the numerical number of charcoal particles produced above the background component.

Pollen Analysis

Pollen analysis was conducted at contiguous one-cm intervals throughout the core to provide a high-resolution vegetation history from Fish Lake. Single 1-cm^3 samples were processed using standard acid-base rinse methods (Faegri et al., 1989). *Lycopodium* tablets were placed in with each sample and were used as an exotic tracer. A minimum of

300 terrestrial pollen grains or *Lycopodium* was counted per sample using light microscopy at 500X magnification. The pollen record from Fish Lake was described in terms of summed influx and ratios, but pollen percentages were standardized for visual purposes. Pollen influx (grains/cm^2/year) was summed into six different groups (conifers, herbs, shrubs, deciduous trees, riparian species, and aquatic species) in order to provide information about changes in pollen abundance, while standardized pollen percentages allow for vegetation transition comparisons throughout the record. Pollen ratios allow for comparison between a single taxon to another single taxon, or to a group of taxa. Pollen ratios were calculated using the formula $(a-b)/(a+b)$ (Maher, 1963, 1972). Ratio data are presented in standard units (SU), where higher (lower) values indicate greater (lesser) abundance of a particular taxa or taxon.

Results

Chronology

Age-depth relationships were determined using a nearly contiguous ^{210}Pb series of the top 15 centimeters, and two ^{14}C AMS dates (Figure 11) (Table 4). ^{210}Pb was conducted on a separate core (B14) that was extracted ~10 m northwest from FLFC2_17_14 by Mark Abbott at the University of Pittsburgh. We justify the use of the ^{210}Pb series from the top of the B14 core because the B14 and FLFC2_17_14 were collected from ~10 m apart with no change in water depth between the two sites. Therefore, sedimentation rates are likely the same in both cores. AMS dates were converted to calendar years before present (0 cal yr BP = 1950 CE) using CALIB 11.1

(Stuvier et al., 1998). The CLAM software for classical age-depth modeling (Blaauw et al., 2010) was used with a smoothing spline to create the age model.

Hydroclimate

The long-term winter:summer precipitation ratio averaged 1.0 (Figure 12). Prior-to and during the MCA, the winter:summer ratio averaged 0.56. During the LIA, the winter:summer ratio averaged -0.56. During the modern period, the winter:summer ratio averaged -0.19.

The reconstructed $\delta^{13}C$ record from a speleothem from Minnetonka Cave (Lundeen et al., 2013) has a long-term average of -5.39 ‰ between 7 and 743 cal yr BP, and a long-term average of -4.73‰ (Figure 12). A growth hiatus occurred between 1800 and 740 cal yr BP, outlined as a black box (see Figure 12). After the growth hiatus, between 600 and 740 cal yr BP, the reconstructed $\delta^{13}C$ averaged -5.91‰. However, around 600 cal yr BP, $\delta^{13}C$ values increase and remain relatively high between 220 and 600 cal yr BP (average, -5.02‰). Modern $\delta^{13}C$ values average -5.26‰.

The Moy record documents ENSO events/century (Figure 13). Prior to the MCA, at the beginning of the record ~1300 cal yr BP, ENSO frequency was high reaching a peak of 30 events/century. Between 1000 and 1200 cal yr BP, ENSO frequency was low (<10 events/century). During the mid-MCA, ENSO frequency increased to nearly 30 events/century until the end of the MCA ~800 cal yr BP. After 800 cal yr BP until modern, ENSO frequency has declined.

Climate Reconstruction

Reconstructed temperatures between modern and 1,300 years ago from the Colorado Plateau suggest a long-term mean of 15.2°C (Salzer & Kipfmueller, 2009) (Figure 13). However, prior to the MCA, temperatures averaged near the long-term average (15.2°C). Temperatures during the MCA between 850 and 1050 cal yr BP averaged warmer than the long-term mean (15.3°C). Between the MCA and LIA from 500 and 850 cal yr BP and into the LIA between 100 and 500 cal yr BP, temperatures averaged slightly cooler than the long-term mean (15.2°C). During the modern period between present and 100 cal yr BP, temperatures averaged warmer than the long-term mean (15.5°C), with the period between 1940 and 1996 CE being the warmest period over the past 1,300 years averaging 16.1°C.

Charcoal Analysis

Prior to the Medieval Climate Anomaly (MCA) between 1,150 and 1,300 cal yr BP two fire events (1182 and 1257 cal yr BP) occurred with a fire frequency of roughly 3.9 fire events per 300 years (Figure 11). Peak magnitudes averaged 1.6 particles/cm^2/episode, while CHAR averaged 0.35 particles/cm^2/yr (Figure 13).

During the MCA between 800 and 1,150 cal yr BP, three fire events occurred (927 cal yr BP; 1017 cal yr BP; and 1092 cal yr BP) with a fire frequency of 2.8 fire events per 300 years. Peak magnitudes from these three fires averaged 8 particles/cm^2/episode. CHAR was high averaging 0.55 particles/cm^2/yr.

Between the MCA and Little Ice Age (LIA) (500 and 800 cal yr BP), only one fire event occurred at 672 cal yr BP with a low 0.7 particles/cm^2/episode. CHAR was low averaging 0.4 particles/cm^2/yr, while fire frequency averaged one fire event per 300 years.

During the LIA between 100 and 500 cal yr BP, only one fire event occurred at 402 cal yr BP with a peak magnitude of one particle/cm^2/episode. Fire frequency averaged one fire event per 300 years during the LIA. CHAR significantly decreased during the LIA averaging 0.18 particles/cm^2/yr.

During the modern period between present and 100 cal yr BP, two fire events occurred; the first in 1893 with a peak magnitude of 19 particles/cm^2/episode; the second fire occurred 2014 with a peak magnitude of 4.4 particles/cm^2/episode. CHAR increased during the modern period averaging 0.6 particles/cm^2/yr. Fire frequency averaged 2.5 fires per 300 years during the modern period.

Pollen Analysis

Because the modern period averaged an order of magnitude more pollen grains than the rest of the record, summed pollen influx have been split into the modern period, which encompasses modern to 100 cal yr BP (Figure 14), and the late Holocene period, which encompasses the rest of the record between 100 and 1,300 cal yr BP (Figure 14). Additionally, pollen percentages were standardized in order better visualize changes in vegetation composition through time (Figure 15)

Prior to the MCA, conifers averaged 18,163 grains/cm^2/year, herbs averaged 4,213 grains/cm^2/year, shrubs averaged 13,662 grains/cm^2/year, deciduous species averaged 1,036 grains/cm^2/year, riparian species averaged 179 grains/cm^2/year, and aquatic species averaged 332 grains/cm^2/year (Figure 14).

During the MCA, conifer pollen influx decreased slightly from the previous period and averaged 13,325 grains/cm^2/year. The summed herbs, shrubs, and riparian pollen influx all increased from the previous period averaging 4,513, 15,756, and 265 grains/cm^2/year, respectively. Deciduous pollen influx decreased averaging 877 grains/cm^2/year, while the summed aquatic pollen influx remained relatively the same, averaging 378 grains/cm^2/year.

Between the MCA and the LIA, all six summed pollen influx groups decreased when compared to the MCA. Conifers averaged 9,817 grains/cm^2/year, herbs averaged 3,971 grains/cm^2/year, shrubs averaged 11,984 grains/cm^2/year, deciduous pollen influx averaged 657 grains/cm^2/year, riparian pollen influx averaged 260 grains/cm^2/year, and the summed aquatic pollen influx averaged 191 grains/cm^2/year.

The decreasing trend continued into the LIA with conifers averaging 4,212 grains/cm^2/year, shrubs averaging 1,293 grains/cm^2/year, shrubs averaging 4,847 grains/cm^2/year, deciduous averaging 403 grains/cm^2/year, and riparian averaging 50 grains/cm^2/year. However, the summed aquatic pollen influx increased slightly from the previous period averaging 211 grains/cm^2/year.

During the modern period, all six summed pollen influxes increased dramatically. Conifers averaged 32,687 grains/cm^2/year, herbs averaged 6,114 grains/cm^2/year, shrubs averaged 20,224 grains/cm^2/year, deciduous species averaged 2,346 grains/cm^2/year, riparian species averaged 231 grains/cm^2/year, and aquatic species averaged 1,865 grains/cm^2/year (Figure 14).

Discussion

Recent ecological and disturbance changes in the IW can be attributed to recent climate change and land management practices since Euro-American settlement. However, the latitudinal position of the ENSO DTZ also influences ecological and disturbances regimes in the IW. Because the IW lies within the ENSO DTZ, it is an ideal location to examine changes in the position of the DTZ and its influence on vegetation composition and wildfire activity over time. The objectives of this study are; 1) provide insight into the ecological responses to latitudinal shifts in the DTZ in the IW; 2) analyze how fire and vegetation have changed over the past 1,300 years; and 3) examine the potential ecological impacts of prehistoric and recent anthropological influences.

Hydroclimate across Utah over the Past 1,300 Years

The MCA is characterized as a warm and dry climate anomaly (Mann et al., 2009). However, prior-to and during the MCA between 1,300 and 800 cal yr BP, winters are interpreted to be either too cold and/or too wet to support speleothem growth in the Bear River Range (Lundeen et al., 2013). Decreased ENSO frequency at the beginning of the MCA suggests more La-Niña-like conditions (Mann et al. 2009; Moy et al., 2002; Trouet et al. 2009), which would result in decreased winter precipitation in the southern IW and western U.S., and increased winter precipitation in the Pacific Northwest and northern Rocky Mountains where Minnetonka Cave is more closely located. Steinman et al. (2012) and Lundeen et al. (2013) both suggest increased winter precipitation in the Pacific Northwest and Utah/Idaho border at this time, further supporting the hypothesis of consistent La-Niña-like conditions observed north of the ENSO DTZ (i.e., winter precipitation in the Pacific Northwest). However, high winter precipitation ratios from Fish Lake suggest increased winter precipitation south of the present day DTZ. Because Minnetonka Cave is within the present day ENSO DTZ and Fish Lake is located slightly south of the transition zone, we expect these two records to capture opposite winter precipitation signals. Therefore, in order for the two sites to both record increased winter precipitation during the MCA, we hypothesize that the ENSO DTZ may have been positioned further south than the modern 40° N boundary and that Fish Lake was responding to the same precipitation patterns that northern Utah experienced. Other paleoenvironmental proxy records south of Fish Lake also suggest increased winter snowpack during the MCA (Morris et al., 2013). Therefore, we suggest that the ENSO DTZ was likely nonstationary and influenced the winter hydroclimate variability at Fish Lake during the MCA. Our interpretation from Fish Lake agrees with the overall reconstructed climate of the western U.S., which indicates multidecadal precipitation variability (Nelson and Pierce, 2010; Stine, 1998). Both the winter:summer precipitation ratio and the reconstructed $\delta^{13}C$ appear to be in agreement after the MCA, which show a switch in seasonal moisture dominated by winter precipitation to a summer wet precipitation regime (Figure 12).

After the MCA, reconstructed temperatures from the Colorado Plateau show high variability in magnitude (Figure 13). However, during the LIA between 100 and 500 cal yr BP, reconstructed temperatures were consistently below the long-term average. This agrees with the characterization that the LIA was a cool climate anomaly (Mann et al., 2009). During the LIA, the winter:summer precipitation ratio at Fish Lake diverges from the $\delta^{13}C$ record from Minnetonka Cave, which we interpret as a northward migration of the ENSO dipole closer to its modern position of 40° N (Figure 12). Again, decreased ENSO frequency would suggest more La-Niña-like conditions during the LIA (Mann et al. 2009; Moy et al., 2002), which would result in dry winters in the southern IW and southwest U.S. and wet winters in the northern Rocky Mountains. High $\delta^{13}C$ values at Minnetonka Cave indicate more winter precipitation north of Fish Lake, which is supported by the summer precipitation ratios indicating decreased winter precipitation at Fish Lake.

The winter:summer precipitation ratio and $\delta^{13}C$ winter precipitation reconstruction appear to be in agreement during the modern period between 0 (1950 CE) and 100 cal yr BP (1850 CE), with both suggesting decreased winter precipitation (Figure 12). Gillies et al. (2012) have also documented a decrease in snow since 1950 CE throughout the state of Utah. The $\delta^{18}O$ demonstrates that winter temperatures were consistently above the long-term average, and were the warmest of the entire record in the modern period. The reconstructed PDSI record also shows increased summer precipitation, which supports the interpretation of low winter precipitation. Again, because the $\delta^{13}C$ record and winter:summer precipitation ratio data are in agreement, we suggest a more southerly position of the ENSO DTZ between 0 (1950 CE) and 100 cal yr BP. Unfortunately, the $\delta^{13}C$ reconstruction ends at 1950 CE, so we are not able to compare our winter:summer precipitation ratio to it for the most recent period. However, our winter:summer precipitation ratio has been highly variable after 1950, with instrumental data documenting above average summer precipitation, and near average winter precipitation during the most recent modern period (since 1950 CE).

The ENSO DTZ is currently positioned north of Fish Lake between 40° – 43° N (Dettinger et al., 1998; Shinker, 2010; Wise, 2010). Therefore, Fish Lake should have no significant relationship with El Niño. Analyzing the relationship between anomalous SST's in the western Pacific and winter precipitation from the Fish Lake region, there appears to be no significant relationship with either El Niño or La Niña events at Fish Lake and Donkey Reservoir (r=0.01 and r=0.0) (Figure 16), while the Black Flats and Box Springs sites appear to have a significant relationship between precipitation and El Niño events (r=0.39 and r=0.36). There appears to be a slight relationship between 'Mega El Niño' and 'Mega La Niña' events, which we defined as El Niño and La Niña events with anomalous SST above or below 1.5°C at all four sites. This suggests that in order to have a regional signal, ENSO events need to be anomalously wet or dry. The lack of any ENSO relationship at Richfield could be a result of elevational differences between Richfield and Fish Lake, Utah. Conversely, regional precipitation and temperature data from these SNOTEL sites demonstrate the heterogeneity in precipitation throughout this area, with the site north and west of Fish Lake receiving slightly more winter moisture than the Fish Lake site and southern site (Figure 9). Therefore, we suggest that the DTZ may actually be positioned further south than the hypothesized 40°N boundary and may include Fish Lake within the boundary, which could explain the complexity in precipitation variability from the area.

Fire-climate Linkages during the MCA and LIA

Fire activity at Fish Lake has fluctuated over the past 1,300 years as a result of changes in temperature and moisture availability. For example, fire activity at Fish Lake during the MCA was frequent as a result of a combination of above average temperatures on the Colorado Plateau (Salzer & Kipfmuller, 2005), and strong swings between pluvials and droughts with extended periods in summer (JJA) drought conditions. Relatively high CHAR at Fish Lake during the MCA is in agreement with Morris et al. (2015) who also document an increase in charcoal accumulation and a more frequent fire regime during the MCA and Late Holocene from Emerald Lake (3200 m), located on the Wasatch Plateau. Likewise, Marlon et al. (2009) and Calder et al. (2015) also documented widespread burning in the western U.S. and Rocky Mountain region, which they attributed to increased temperatures during the MCA. Conversely, Purple Lake (3200 m), which is located south of Fish Lake on the Aquarius Plateau (2500 m), and Plan B Pond, which is located near Minnetonka Cave on the Utah/Idaho border, both experienced decreased CHAR and a nonexistent fire regime during the MCA because of increased winter snowpack (Lundeen & Brunelle, 2016; Morris et al., 2013).

Even though our winter:summer precipitation ratio indicates wetter winters during the MCA at Fish Lake, one possible explanation as to why Fish Lake and likely the Wasatch Plateau (Morris et al., 2013) experienced an increase in fire activity during the MCA is a result of increased fine fuel production. Increased fine fuel production is the result of previous winter season moisture and may increase the area burned in an area (Westerling et al., 2003). Even though the Fish Lake area is near the modern NAM region, convective thunderstorms were likely frequent and likely provided dry lightning; this could explain the frequent fire regime experienced during the MCA.

Alternatively, the frequent fire regime could have been amplified by anthropogenic activity during the MCA. The Colorado Plateau and Great Basin were home to numerous prehistoric societies over the past ~12,000 years. Specifically, there is evidence of the Fremont prehistoric society at Fish Lake. The Fremont were a nomadic group who foraged and farmed across central and northern Utah between 500 and 2000 years ago (Madsen & Simms, 1998; Massimino & Metcalfe, 1999). Radiocarbon dates of charcoal from an archeological site (Mickey's Place) on the north end of Fish Lake document Fremont occupation at 800 cal yr BP and 1150 cal yr BP (Janetski, 1995). It has been hypothesized that the Fremont likely foraged and fished in the Fish Lake basin during the summer months (Janetski, 1995). The frequent but low-to-mid severity fire regime experienced at Fish Lake during the MCA may have been amplified by human occupation on the landscape during the summer months as they were likely burning for land maintenance and agricultural purposes (Morris, 2010).

Beginning mid-MCA and continuing until the modern period, fire frequency and the overall CHAR production decreased at Fish Lake. The decrease in CHAR follows the regional decline in CHAR values from western US (Marlon et al. 2009), which Marlon et al. (2009) attribute to either a reduction in vegetation productivity and/or reduced fire weather during the LIA. Additionally, Calder et al. (2015) also suggest decreased burning mid-MCA in the Rocky Mountains was a result of reduced fuels. Calder et al. (2015) suggest that the ~80% in area burned during the first half of the MCA ultimately changed the postfire stand composition, which could have limited the ignition and/or spread of fires during the mid-MCA. Even though PDSI values show abundant effective moisture beginning post MCA, which would have led to increased fine fuel production, temperatures were consistently below the long-term average on the Colorado Plateau between the MCA and LIA suggesting that temperatures were likely too cool for fire spread at Fish Lake. Similarly, fire activity at Plan B Pond was nonexistent after the MCA and into the LIA, which Lundeen and Brunelle (2016) suggest was either higher-than-average snowpack or cooler spring temperatures. Purple Lake on the Aquarius Plateau also experienced reduced fire activity at this time as a result of increased winter snowpack (Morris et al., 2013). Therefore, cooler temperatures and/or wetter conditions likely reduced the conditions conducive for wildfire activity both at Fish Lake and throughout the region. Additionally, it is hypothesized that the Fremont population declined beginning around 800 cal yr BP (Massimino & Metcalfe, 1999), which could also explain the decreasing trend in fire activity at Fish Lake.

Vegetation-climate Linkages during the MCA and LIA

During the MCA, two unique periods centered around 800 and 1150 cal yr BP both show exceptionally high values of all summed pollen influx, which we hypothesize to be an ecological response to increased precipitation. Knight et al. (2010) and Lundeen and Brunelle (2016) both document pronounced wet conditions around 900 cal yr BP in northern Utah, further indicating increased effective moisture at this time, which is indicated by the winter:summer precipitation ratio. Additionally, because the MCA likely experienced more La-Niña-like conditions (Mann et al. 2009; Moy et al., 2002), re-circulated NAM moisture could have contributed to the increased vegetation productivity during these two unique periods (Figure 14). However, these two unique time periods also align with the radiocarbon dates that document Fremont occupation at Fish Lake. Therefore, these periods of increased summed pollen influx could also be a result of anthropogenic burning for agricultural purposes. Wild plants utilized by indigenous people of the southwest and likely the Fremont group were plants from the Amaranthaceae and Poaceae families (Morris, 2010), which were abundant during the MCA (Figure 15).

Similar to the fire history already discussed, summed pollen influx from all vegetation groups shows a decreasing trend beginning around 800 cal yr BP and continued until 1980 CE. High standardized pollen percentages of *Artemisia* and *Ambrosia* demonstrate that the period of time between the MCA and LIA was a transitional phase in vegetation composition because *Artemisia* typically occurs in areas with intermediate precipitation but typically cold temperatures, while *Ambrosia* typically occurs in moisture limited areas (Minckley et al., 2008). Using a tree-ring reconstruction of mean annual temperature from northern Arizona, Salzer (2000) demonstrated that the 13th century was characterized by extremely cold conditions, which agrees with our pollen reconstruction of cooler conditions, and with the overall interpretation that the LIA was cooler. Therefore, cooler climatic conditions likely reduced overall vegetation productivity. However, towards the latter half of the LIA, vegetation composition began to change from low-lying herbs and shrubs to more tree species (Figure 15). This is likely a result of changes in moisture availability, with increased winter and summer precipitation.

Fire-climate Linkages during the Modern Period

Fire activity in the modern period between present and 100 cal yr BP is unique when compared to the last 1,300 years. Since 1984 CE, Dennison et al. (2014) have demonstrated an increase in both fire occurrence and fire severity across much of the western U.S., especially in the Great Basin as a result of invasive grasses (Balch et al. 2013). At Fish Lake, CHAR values have increased dramatically in agreement with the reported increased regional burning documented by Dennison et al. (2014). In addition, the largest peak magnitude fire event also occurred in the modern period.

Similar to Fish Lake, Plan B Pond, Emerald Lake and Purple Lake all document an increase in CHAR and fire frequency during the modern period (Lundeen & Brunelle, 2016; Morris et al. 2013; Morris et al., 2015). Reconstructed temperatures from the Colorado Plateau suggest the modern period was the warmest period over the past 1,300 years (Salzer & Kipfmueller, 2005), with the period between 1940 and 1996 being a full degree Celsius warmer than the long-term average. Lundeen et al. (2013) also document above average winter temperatures during the modern period (Figure 12). Averaged June, July, and August temperatures using Westmap PRISM data centered on Fish Lake (Figure 10) further demonstrates that summer temperatures have steadily increased since the 1950s, which has resulted in a longer fire season. This is important because Westerling et al. (2006) have demonstrated the link between fire activity and the length of the fire season across the western U.S. and thus, increased fire activity seen at Fish Lake and regionally is likely a result of changes in the modern climate, specifically warming temperatures and a lengthening of the fire season. While we have documented how sensitive Fish Lake has been to climate change, the potential change in wildfire activity at Fish Lake is a major concern for this area and all forested ecosystems in the IW.

Vegetation-climate Linkages during the Modern Period

Vegetation composition at Fish Lake is also unique during the modern period between present and 100 cal yr BP because the ecosystem has been dominated by tree species (Figure 14). This could be explained by anthropogenic influences as the Euro-American settlement in Utah began in the mid-1800s, which brought logging, understory vegetation removal, and grazing to the Fish Lake area as early as the late 1880s. As a result, standardized pollen percentages demonstrate that tree species, such as *Pinus*, *Juniperus*, *Picea*, and *Pseudotsuga* are more prevalent than understory herbs and shrubs. The increase in tree species could be a result of understory removal by humans, or by the introduction of sheep and cattle roughly 150-200 years ago, which favor palatable species such as grasses, herbs, and shrubs (Cole et al., 1997).

However, the influence of climate on vegetation composition at Fish Lake likely extends into the historic record. Summed pollen influx has steadily increased throughout the modern period, especially after 1980 CE (Figure 14). If we examine averaged seasonal precipitation and temperature data centered on Fish Lake (Figure 10), we see that both winter and summer temperatures have been well above average beginning the in the 1980s, and that summer precipitation has also increased since 1980 CE. Salzar and Kipfmueller (2005) also document the general increase in annual precipitation in their tree-ring calibration from northern Arizona. As a result, vegetation productivity across all vegetation groups has increased since this time (Figure 14). Conversely, the most recent increase in pollen influx could also be an artifact of lack of compression in the sediment core, thus potentially giving a false representation of the past 30 years of vegetation composition in the basin.

Increased temperatures during the modern period may offer an analog of how we would expect the vegetation composition to respond during the MCA when temperatures were also warmer than the long-term average. While pollen influx has increased for all vegetation types during the modern period, the standardized pollen percentages demonstrate vegetation composition is drastically different due to anthropogenic influences. This is of concern because the change in vegetation composition may be increasing the potential fire severity at Fish Lake. While subalpine forests typically burn infrequently and at higher severities (McKenzie et al., 2004), which is the type of forested ecosystem currently present at Fish Lake, the recent increase in tree species along with the increase in all summed pollen influx groups suggest greater fuel connectivity and greater fire severity threat because of the amount of fuel loading on the modern landscape.

Conclusion

According to the Fish Lake record, the ecosystem at Fish Lake has been sensitive to changes in moisture over the past 1,300 years, likely as a result of changes in the position of the DTZ. During the MCA and shortly after, the precipitation was similar to that experienced in northern Utah, suggesting that the DTZ may have been more southerly positioned. However, antiphasing between the winter:summer precipitation at Fish Lake and the $\delta^{13}C$ record from Minnetonka Cave suggests a more modern-like position in the DTZ. Between 1950 and 100 cal yr BP, the two records appear to be in agreement suggesting a southerly position of the DTZ. Since 1950, SNOTEL data suggest a mixed relationship with ENSO, demonstrating the complexity in precipitation availability in the area. However, we hypothesize that the DTZ may actually be positioned further south than the hypothesized 40°N boundary and may include Fish Lake within the boundary, which could explain the complexity in precipitation variability from the area. This study suggests that the spatial specificity of moisture has changed as a result of small shifts in the position of the ENSO DTZ.

Fire activity has been largely influenced by changes in climate, including both temperature and moisture availability. During the MCA, fire frequency was high at Fish Lake, which contradicts both Plan B Pond and Purple Lake. Radiocarbon dates document Fremont occupation at Fish Lake and human activity may have amplified the increased frequency of fire during the MCA. The decreasing trend in CHAR and fire activity at Fish Lake agrees with the regional decline in wildfire activity after the MCA until the modern period as a result of cooler temperatures and/or wetter conditions. The fire regime in the modern period is unique in that the largest peak magnitude fire event occurred. Increased CHAR at Fish Lake is likely a result of increased burning both locally and regionally as a result of increased temperatures during the modern period.

Vegetation composition has changed at Fish Lake as a result in changes in climate. During the MCA, vegetation consisted of low-lying herbs and shrubs, and warm adapted species as a result of above average summer temperatures. However, increased pollen influx during the MCA suggests precipitation was sufficient despite the consistent negative PDSI values. Pollen influx values show a decreasing trend after the MCA until the modern period, which is largely attributed to cooler temperatures. Since Euro-American settlement, vegetation composition has been dominated by more tree species and is likely a result of anthropogenic influences, as well as increased winter and summer precipitation. However, the increase in tree species combined with warming summer temperatures and a lengthening of the fire season is of concern because the ecosystem at Fish Lake has not experienced this combination of vegetation composition and climate over the past 1,300 years.

Ultimately, Fish Lake has demonstrated that it has been sensitive to changes in moisture over the past 1,300 years. It is likely that climate phenomena, such as ENSO, have influenced the changes we have seen at Fish Lake, but more research is needed from the area in order to understand the spatial patterns of seasonal moisture through time in this region. Additionally, a longer temporal record from Fish Lake is needed in order to investigate the DTZ and seasonal moisture influences on wildfire activity and vegetation composition prior to 1,300 years ago. Understanding how this sensitive site has responded to past climatic phenomena will offer insight of more informative and descriptive interpretations of the spatial specificity of seasonal moisture at Fish Lake.

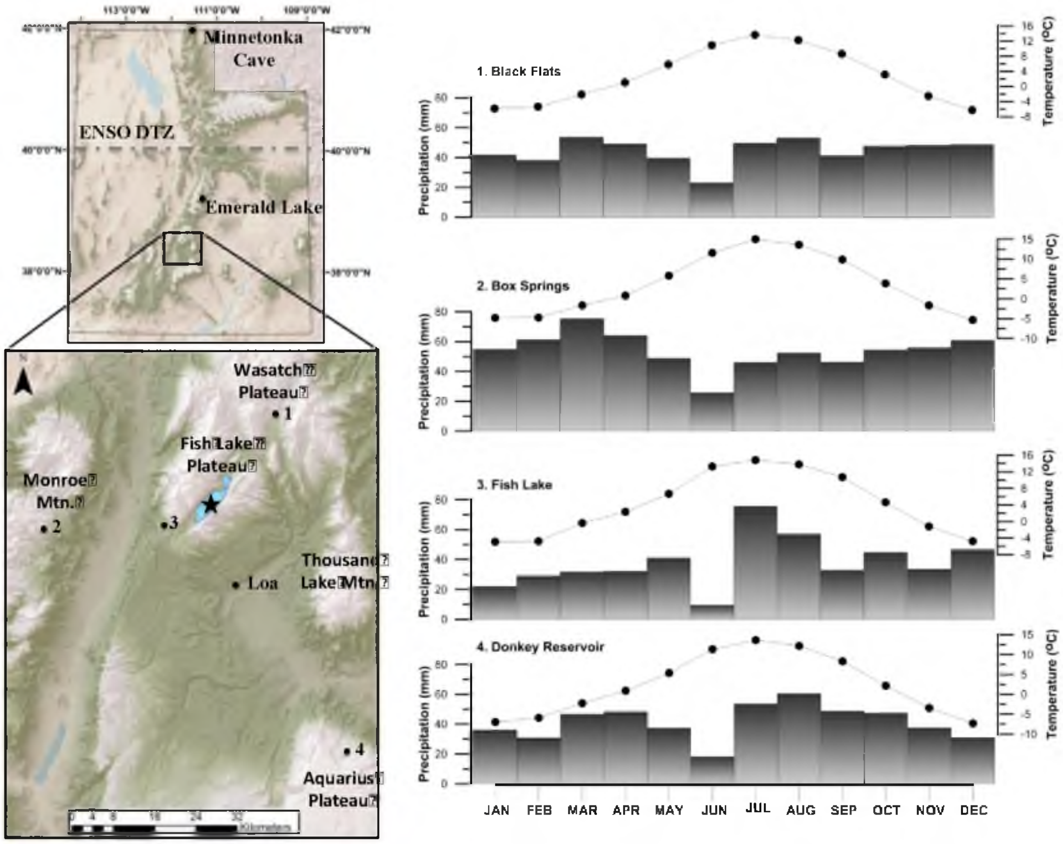


Figure 9. Fish Lake location map, located in south-central Utah (black star). 1. Black Flats SNOTEL site (site ID348, elevation 2884 m); 2. Box Springs SNOTEL site (site ID364, elevation 2995 m); 3. Fish Lake SNOTEL site (site ID1149, elevation 2681 m); 4. Donkey Reservoir SNOTEL site (site ID452, elevation 2987 m).

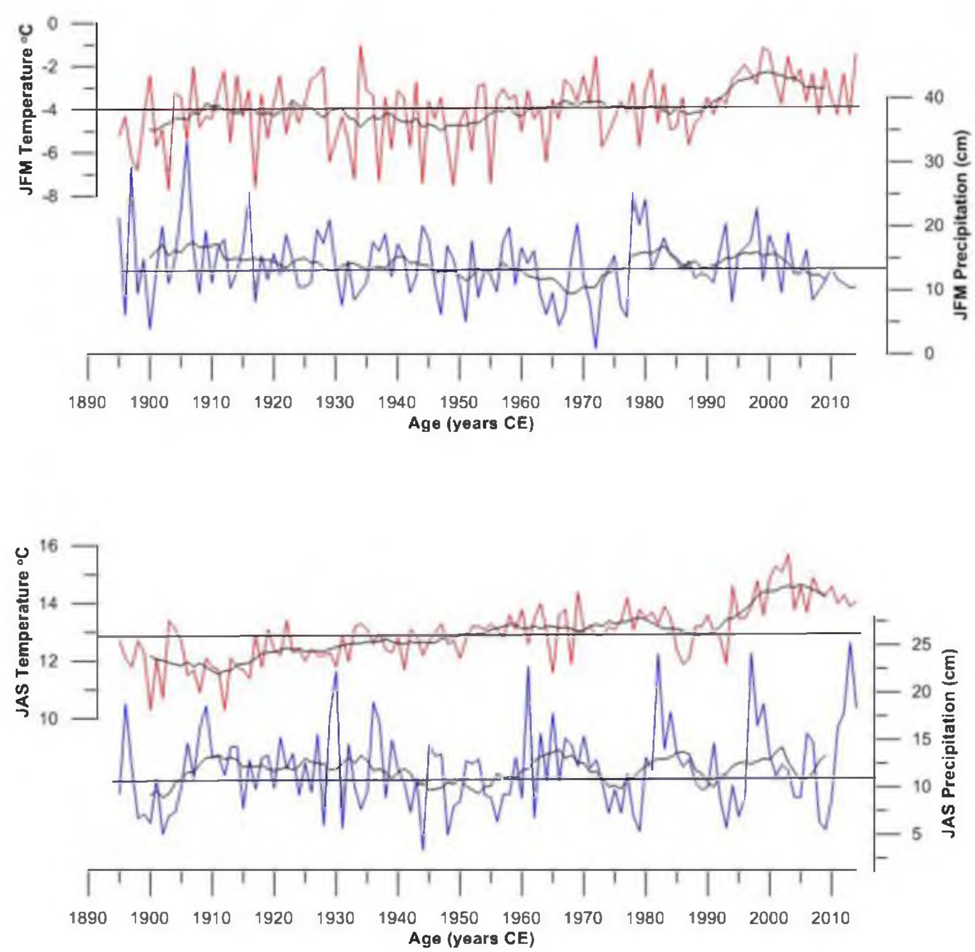


Figure 10. Westmap PRISM climate data for the pixel centered on 38.5N, -111.7 W (Fish Lake, Utah).

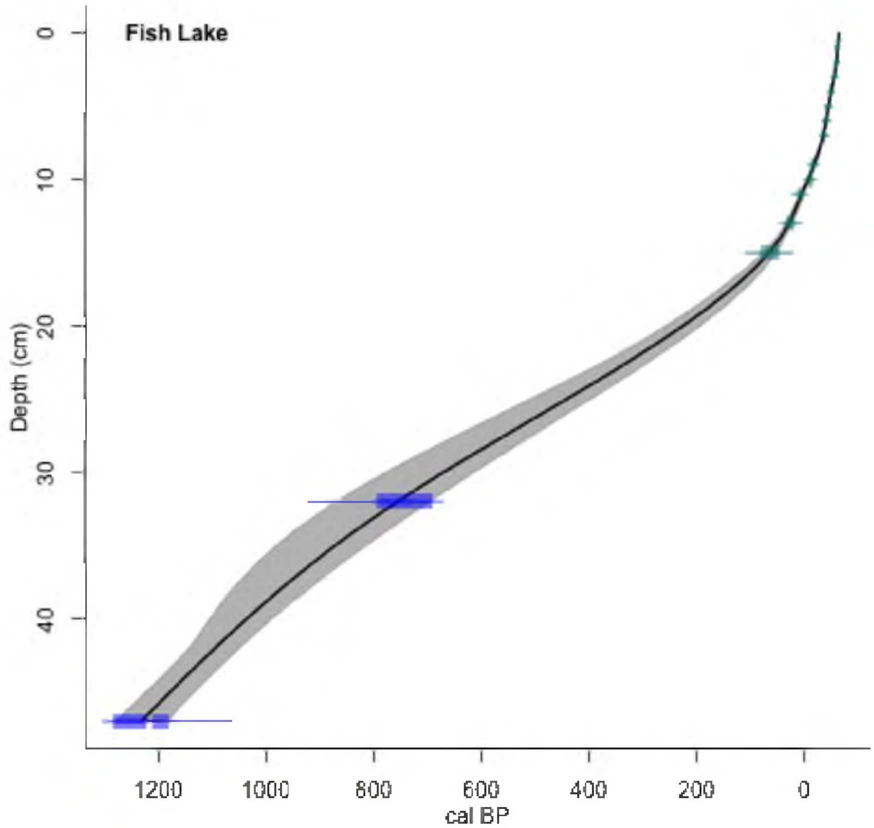


Figure 11. Fish Lake age-depth model based on 13 ^{210}Pb dates for the top 14 cm and two ^{14}C AMS dates. The age-depth model was constructed using the classical age-depth model (CLAM) with a smoothing spline. Gray shading indicates range of error at the 95% confidence interval.

Table 4. Summary of age-depth relations for Fish Lake, Utah.

Depth (cm)	Source Material	Age (^{14}C yr BP)	Age (cal yr BP) with 2 sigma range	Assigned ^{210}Pb Age (yr C.E.)	Assigned age (cal yr BP)
0	Gyttja			2013 ± 1.1	-63
0.5	Gyttja			2011 ± 1.1	-61
1	Gyttja			2009 ± 1.2	-59
2	Gyttja			2005 ± 1.3	-55
3	Gyttja			1999 ± 1.4	-49
4	Gyttja			1994 ± 1.5	-44
5	Gyttja			1990 ± 1.7	-40
6	Gyttja			1986 ± 1.8	-36
7	Gyttja			1966 ± 2.2	-16
9	Gyttja			1960 ± 2.5	-10
10	Gyttja			1941 ± 3.2	9
12	Gyttja			1924 ± 4.4	26
14	Gyttja			1884 ± 9.1	66
32	Pollen	848 ± 26	691 - 796		773
47	Pollen	1290 ± 25	1221 - 1284		1246

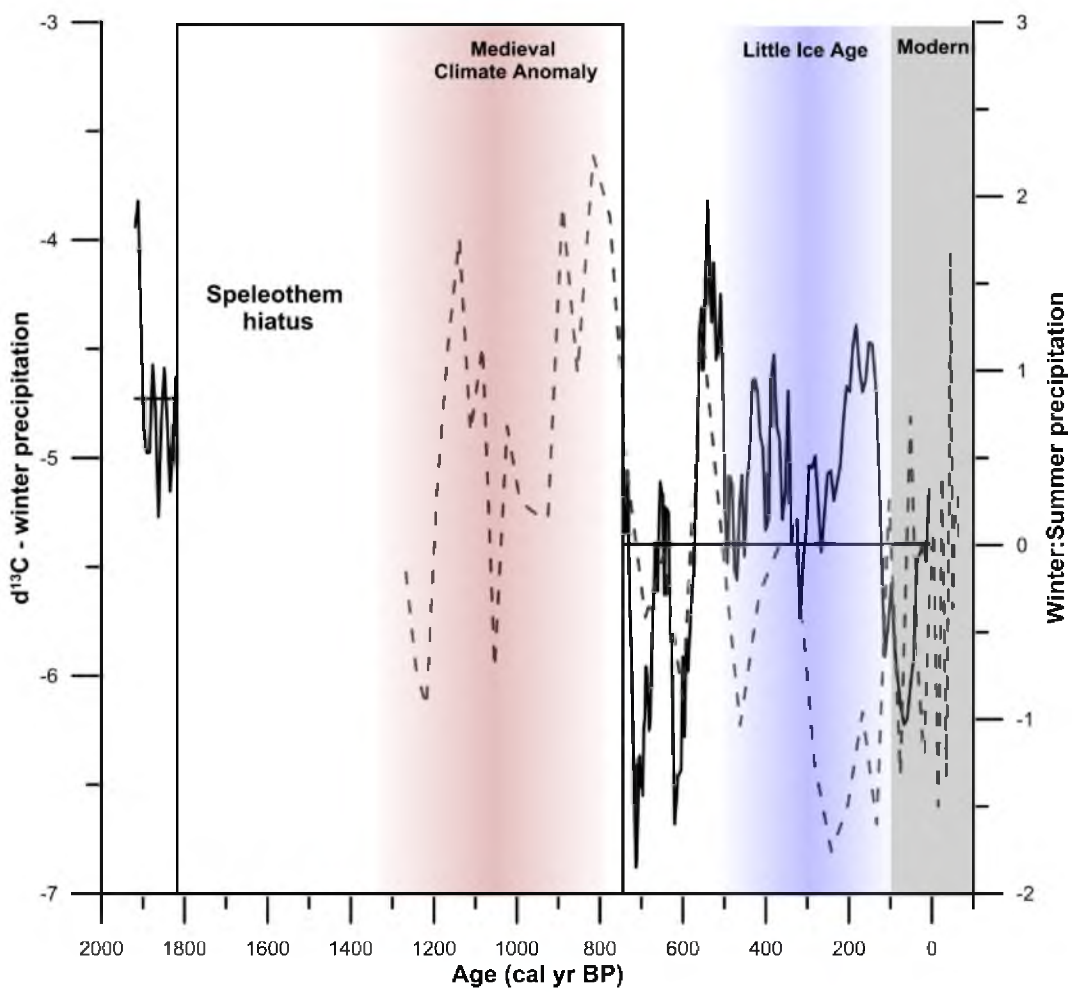


Figure 12. Winter:summer precipitation ratio from Fish Lake. Calculated using taxa indicative of winter conditions (*Picea* + *Abies*) and summer conditions (*Juniperus* + *Quercus*) (dashed line) compared to $\delta^{13}C$ values from a speleothem record from Minnetonka Cave, Idaho (Lundeen et al., 2013). Red vertical shading indicates the Medieval Climate Anomaly. Blue vertical shading indicates the Little Ice Age. Gray vertical shading indicates the modern period (post 1850 CE).

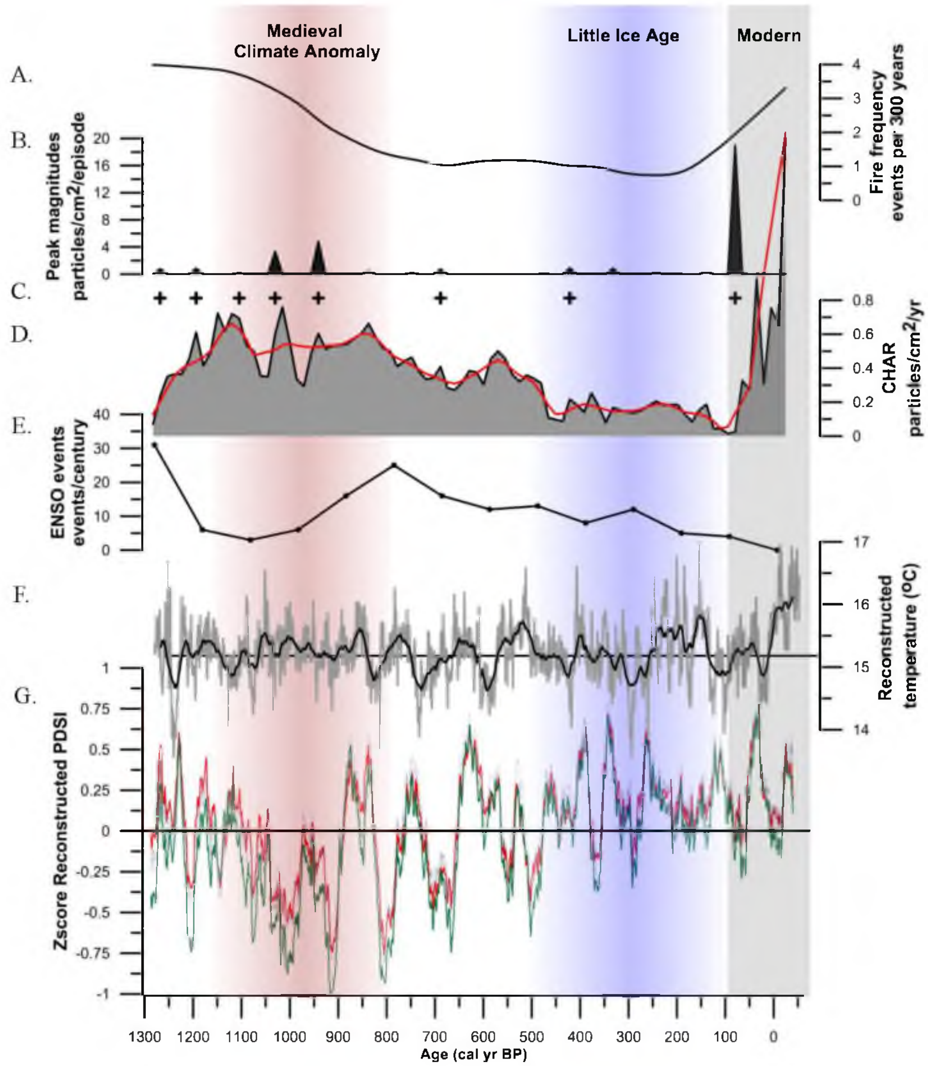


Figure 13. Reconstructed fire record from Fish Lake, Utah compared to the reconstructed ENSO record, and averaged reconstructed PDSI record. A) Reconstructed fire frequency (number of fires per 300 years) from Fish Lake. B) Peak magnitude (particles/cm^2/episode) is the number of charcoal particles associated with each fire episode (C.), which is represented by the '+' symbol. D) CHAR (particles/cm^2/yr; shaded gray line) and BCHAR (red line). BCHAR represents the continual input of charcoal from regional fires, while CHAR indicates instantaneous input of charcoal into the Fish Lake basin. When CHAR surpasses BCHAR, it represents a local fire within the Fish Lake basin. E) Reconstructed ENSO events (events/century)(Moy et al., 2002). F) Reconstructed temperatures from the Colorado Plateau (Salzar & Kifmueller, 2009). G) Reconstructed PDSI using the average of grid points 86 (red line), 87 (black line), 102 (electric blue), and 103 (forest green) with a 20-year moving average. Red vertical shading indicates the Medieval Climate Anomaly. Blue vertical shading indicates the Little Ice Age. Gray vertical shading indicates the modern period (post 1850 CE).

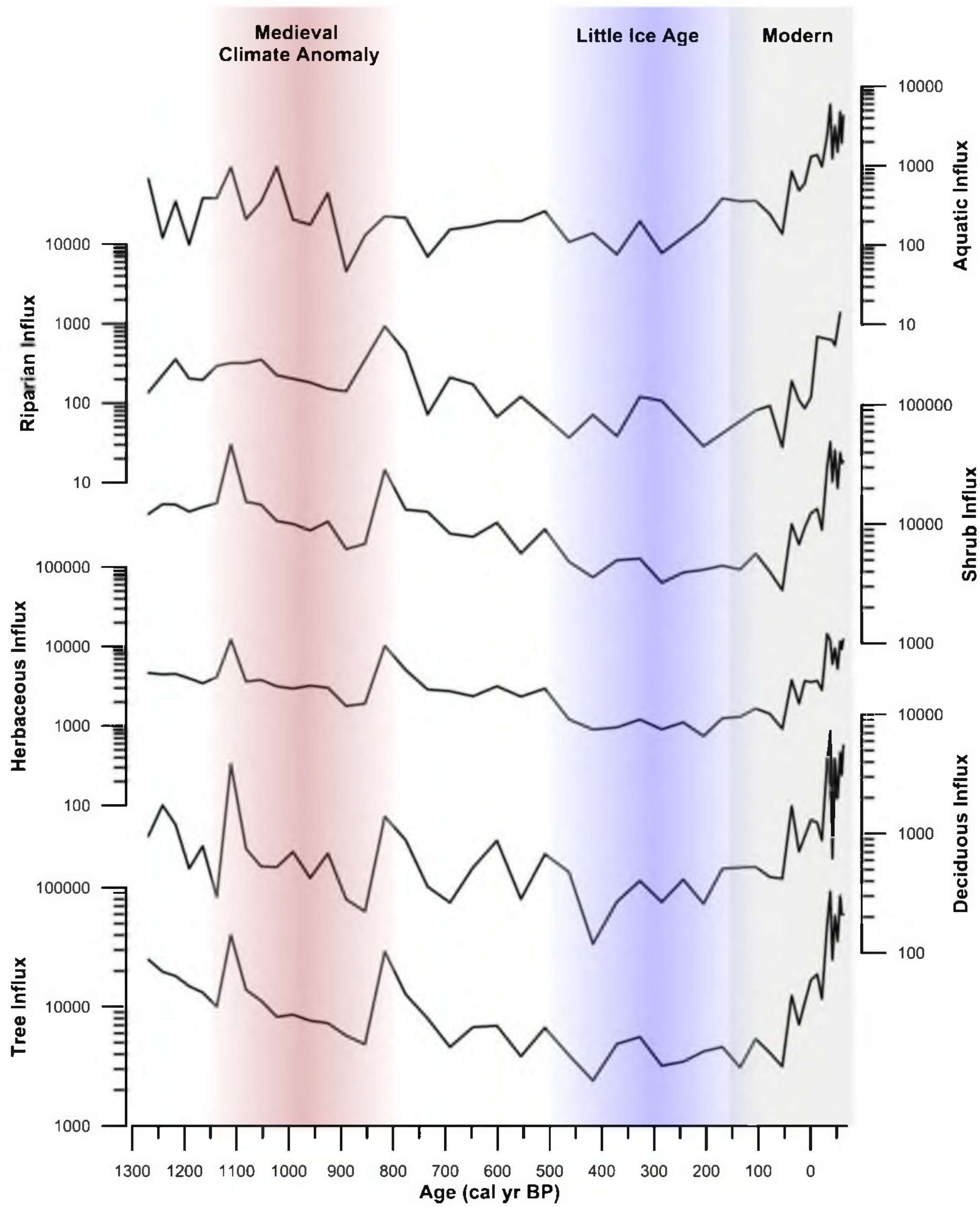


Figure 14. Summed pollen influx data (particles/cm^2/yr) for the main vegetation types found at Fish Lake, Utah.

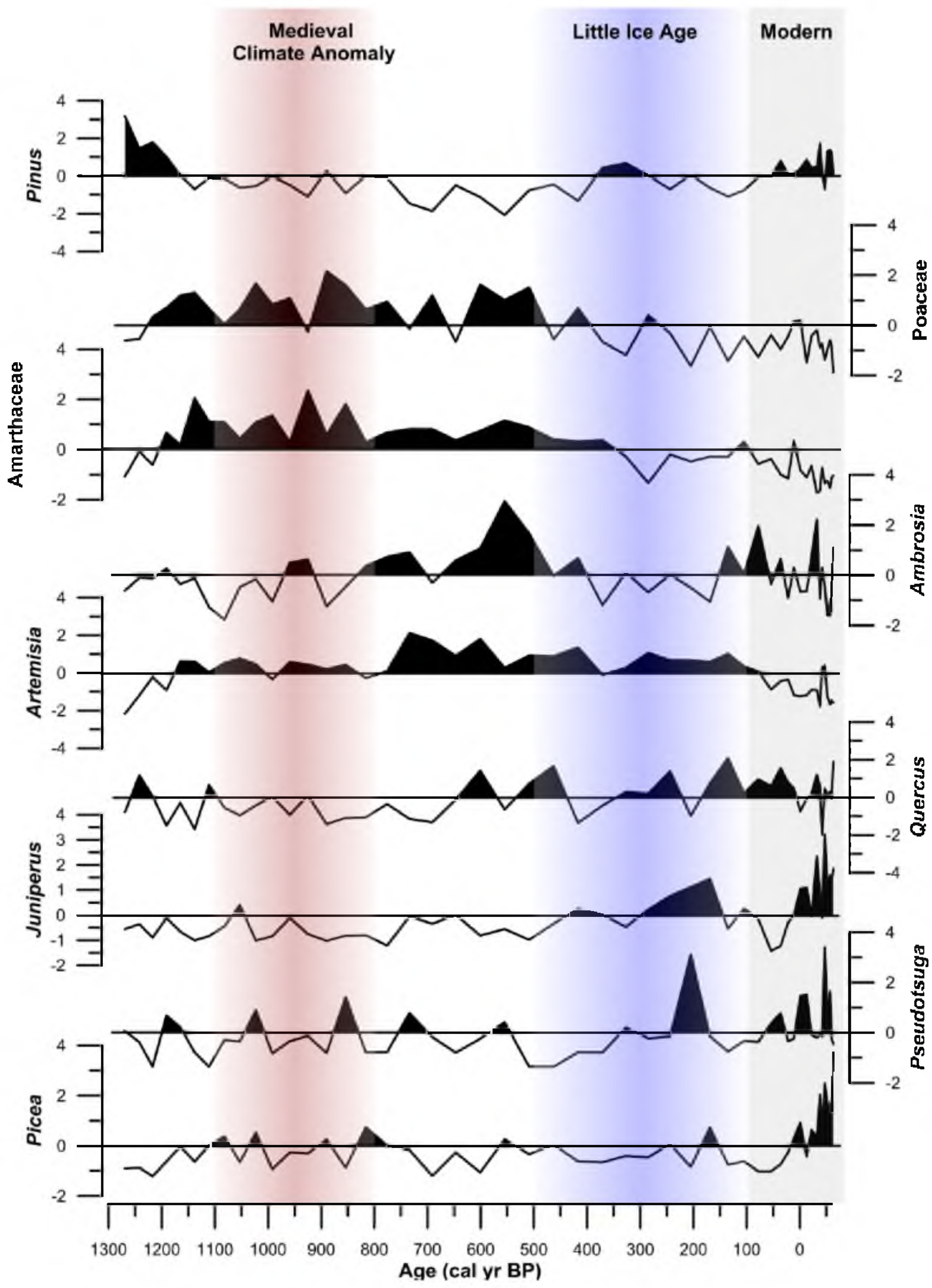


Figure 15. Standardized Fish Lake pollen percentages as Z-scores. Red vertical shading indicates the Medieval Climate Anomaly. Blue vertical shading indicates the Little Ice Age. Gray vertical shading indicates the modern period (post 1850 CE).

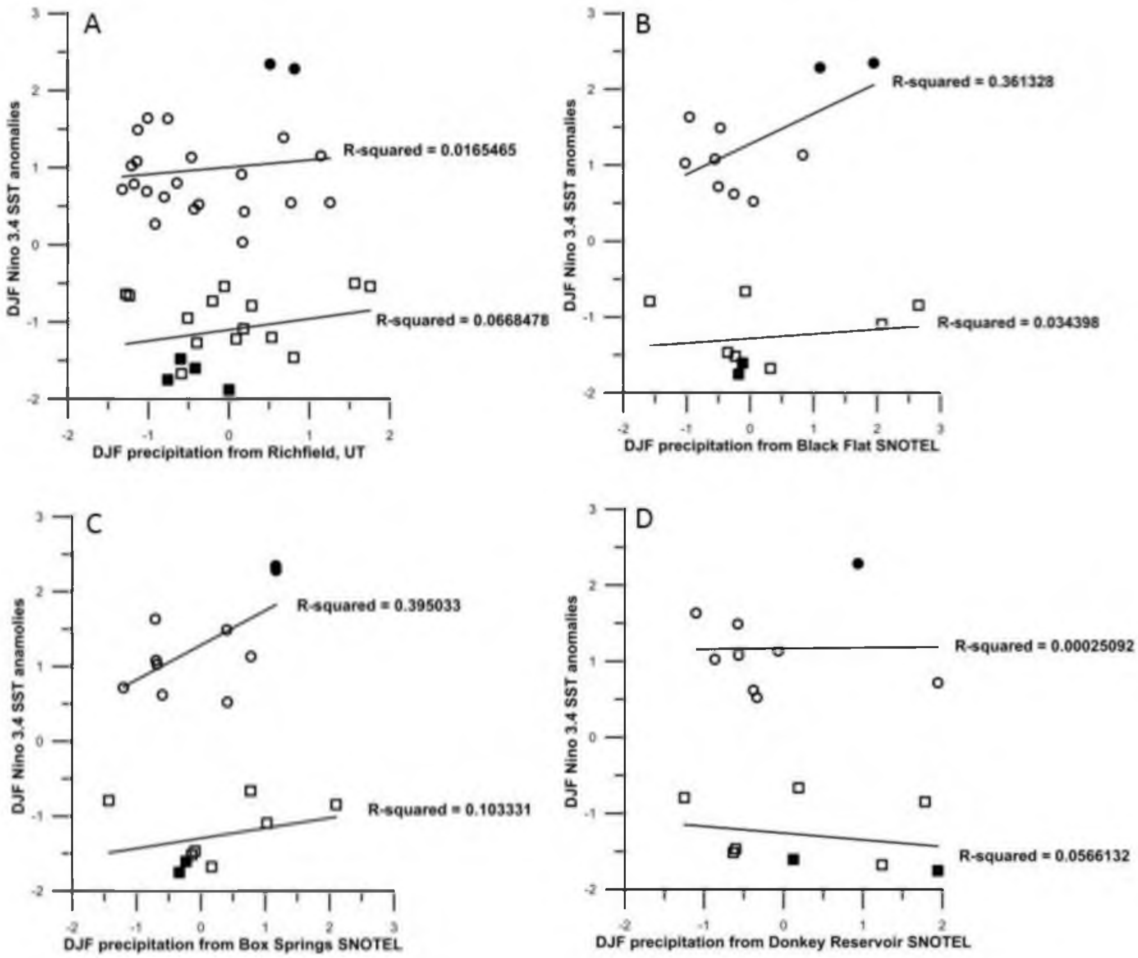


Figure 16. Line graphs showing the relationship between sea surface anomalies for the Niño 3.4 region of the Pacific Ocean, and meteorological data from the Fish Lake, and surrounding area. A) The relationship between DJF Niño 3.4 seas surface anomalies and winter precipitation from Richfield, UT precipitation. Closed circles (1983 and 1998) are considered "Mega El Nino" events and clearly show higher precipitation at Richfield, with increased SST's. Open circles are all El Niño events and show no relationship. Open triangles are La Niña events and show no relationship. Open squares are the 4 "Mega La Niña" events and show decreased precipitation with cooler SST's at Richfield, UT. B) The relationship between DJF Niño 3.4 sea surface anomalies and winter precipitation from the Black Flat SNOTEL site located north of Fish Lake. C) The relationship between DJF 3.4 Niño sea surface anomalies and winter precipitation from the Box Spring SNOTEL site located directly west of Fish Lake. D) The relationship between DJF Niño 3.4 sea surface anomalies and winter precipitation from the Donkey Reservoir SNOTEL site located further south and experiences a bimodal precipitation regime and shows the lowest amount of correlation among ENSO and precipitation during El Niño and La Niña years. These figures show that near the DTZ, there is a high degree of precipitation variability at present and that there is no clear relationship with the present day ENSO DTZ and precipitation.

CHAPTER 4

DRIVERS OF FIRE FREQUENCY IN THE UINTA MOUNTAINS, UTAH, USA

Introduction

Fire is a considered a 'keystone' disturbance because of its ecological role in many forested ecosystems across the western United States (US) (Keane et al., 2002). For example, fire releases nutrients, influences stand composition, reduces biomass, and increases biodiversity (Agee 1993; Crutzen & Goldammer 1993; Keane et al., 2002; Mutch 1994). Recent fire frequency in the western US has been linked to the length of the summer season, which is increasing with recent warming temperatures (Westerling et al., 2006). Globally, average temperatures have risen almost one degree Celsius since 1880 CE, with the 30-year period between 1983 and 2012 CE likely the warmest 30-year period of the last 1,400 years (IPCC, 2014). Dennison et al. (2014) have documented an increase in the number of large wildfires (larger than 405 hectares; >1,000 acres), as well as an increase in the area burned across many ecoregions of the western US since 1984 CE. However, the Wyoming Basin and Colorado Plateau had too few large fires to analyze trends (Dennison et al., 2014).

The Uinta Mountains are located between the Wyoming Basin and Colorado Plateau in northeastern Utah. The Uinta Mountains are a unique east-west trending mountain range centered on 40°N latitude. Between 1984 and present, 13 large fires (>405 hectares) burned a total of 53,094 hectares (131,198 acres) in the Uinta Mountains. Analysis of these 13 large fires demonstrates two unique subdivisions of the Uinta Mountains fire regime: 1) the east versus west half, and 2) the north versus south slope (Table 5). First, the majority of the burning occurred on the eastern half of the range, while the least amount of burning occurred on the western half (Figure 17) (Table 5). Additionally, most of the burning occurred on the south slope of the Uinta Mountains, while the north slope experienced the least amount of burning. These patterns of less (more) burning on the northwest (southeast) slope is likely related to the dominant seasonal precipitation patterns expressed in different regions of the Uinta Mountains, which include winter wet/summer dry (herein referred to as winter wet) and winter dry/summer wet (herein referred to as summer wet) (Whitlock & Bartlein, 1993). Precipitation on both slopes of the Uinta Mountains is dominated by winter moisture brought in from the jet stream from the Pacific Ocean. However, precipitation on the southeast slope has an additional component of summer moisture derived from the summer monsoon system from the Gulfs' of California and Mexico (Shaw & Long, 2007), which attributes to the summer/wet precipitation regime. Munroe (2006) document a prominent rain shadow effect in the Uinta Mountains, with a ~400 mm difference between the western and eastern flanks of the mountain range. Additionally, MacDonald and Tingstad (2007) analyzed climagraphs from Vernal, Utah located on the eastern side of the Uinta Mountains, and from Heber, Utah located on the western side of the Uinta Mountains and demonstrated that precipitation during the summer months (June, July, and August) contributes ~23% of the total annual precipitation at Vernal, and only ~17% at Heber, thus documenting the decrease in the relative importance of the summer monsoon sourced precipitation northwest of the heart of the monsoon boundary. If we analyze wildfire trends from the winter wet versus summer wet regions, we see that more fires burned on the southeastern side (i.e., the summer wet region) of the Uinta Mountains since 1984 CE (Table 5).

MacDonald and Tingstand (2007) propose that synchronous arid periods in the Uinta Mountains, such as in 1988 CE are a result of a lack of winter precipitation. Coincidentally, large fires were synchronous throughout the Uinta Mountains on both the north and south slope in 1988 CE. Examination of North American Regional Reanalysis (NARR) climate data from the Uinta Mountains during 1988 CE documents slightly lower-than-average winter precipitation (December through March) rates, lower-than-average summer precipitation (June through September) rates (Figure 18), and anomalously warm summer temperatures (Figure 19). Therefore, it was likely the combination of reduced winter and summer precipitation coupled with warmer temperatures that led to widespread fire activity in the Uinta Mountains in 1988 CE, not solely reduced winter precipitation.

Whitlock et al. (1995) suggest that the boundary between the winter wet and summer wet precipitation regime has remained fixed throughout the Holocene. However, Barron et al. (2012) suggest otherwise: that the true monsoonal boundary has been non-stationary through time and that the position has shifted both in terms of latitude and longitude throughout the Holocene. Therefore, changing fire regimes in the Uinta

Mountains may reflect changes in the boundary between winter wet and summer wet precipitation regimes through time. Additionally, other climatic variables, such as insolation and site characteristics, such as topography and fuel type, also influence fire activity on longer time-scales (Courtney Mustaphi & Pisaric, 2013). Therefore, it is important to understand how both changes in precipitation regimes and insolation influence wildfire activity over time and space. In addition, it is important to understand how site characteristics, such as fuel type influence wildfire activity over time (Courtney Mustaphi & Pisaric, 2013). The purpose of this study is to determine the primary mechanism controlling fire activity in the Uinta Mountains throughout the Holocene. Specifically, the objectives of this study are 1) to determine whether changes in fire regimes from the Uinta Mountains were linked to changes in winter wet and summer wet regime; and 2) determine the role of site characteristics on fire activity in the Uinta Mountains.

Materials and Methods

Study Site

Salamander Pond (40^{o} 54' 6.8"N, 110^{o} 37' 11.3" W) (Figure 20) is located on the north slope of the Uinta Mountains within an oval shaped meadow complex along with four other small ponds, surrounded by a steep ridge to the west and a Pinedale aged moraine to the east of the meadow in the East Fork of Blacks Fork Canyon. The meadow complex is located at an elevation of 3079 m in a depressed glacial amphitheater that was likely associated with the Blacks Fork piedmont glacier (Figure 21), which was the longest (length) known glacier on the north slope forming a terminal moraine near Interstate 80, ~38 miles north of the mountain range (Hansen, 2005).

Interpolations from the nearest SNOTEL site, which is the Steel Creek Park site (ID #790; 40°55'N, 110°30'W; elevation 3,109 m), have a continuous 29-year record of temperature and precipitation data. Interpolated January and July temperature average -8°C and 12°C, while January and July precipitation average 61 and 51 mm. Mean annual precipitation is approximately 733 mm/year (Figure 22).

The modern montane forest is influenced by aspect, with Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) found on the east facing steep ridge to the west of the pond, and lodgepole pine (*Pinus contorta* Douglas ex Loudon) on more xeric soils to the east. However, during the late 2000s, a severe mountain pine beetle (*Dendroctonus ponderosae*) outbreak occurred on the north slope of the Uinta Mountains, killing ~90% of the lodgepole pine in some stands. Salamander Pond was affected by this most recent mountain pine beetle outbreak (Figure 23). The nearest quaking aspen stand (*Populus tremuloides* Michx.) is located ~0.5 km from the pond. Dominant understory vegetation was comprised of whortleberry (*Vaccinium scoparium* Leiberg ex. Coville), dogwood (*Cornus* sp.), elephant head (*Pedicularis groenlandica* Retz.), gentian (*Gentian* sp.), kinnikinnick (*Arctostaphalus* sp.), Indian hellebore (*Veratrum viride* Aiton), thimbleberry (*Rubus* sp.), and other herbs in the mustard famly (Brassicaceae), carrot family (Apiaceae), sunflower family (Asteraceae), and rose family (Roaeaceae). The meadow complex is comprised of sedges (Cyperaceae) close to the ponds' edge and grasses (Poaceae) further away from the pond.

Fieldwork

In August 2012, a 53.5 cm short core (SP12A) was collected using a Klein corer. In August 2013, two long cores, one 170 cm (SP13B) and one 152.5 cm (SP13D), were collected using a Livingstone corer. All three cores were collected from an anchored platform in 4.2 m of water. The short core was subsampled at 1 cm intervals in the field, whereas the long cores were described in the field and then wrapped in plastic wrap and aluminum foil and subsampled at the Records of Environment and Disturbance (RED) Lab at the University of Utah. All three cores are currently being stored in the RED Lab.

Chronology and Lithology

Age-depth relationships were determined using eight AMS ^{14}C dates, one from the short core, and seven from the long core (Table 6). The AMS date from the short core and the uppermost AMS date from the long core, as well as the aligning charcoal peaks from both cores, were used to align the two cores together to create one composite long core. Based on this analysis, there was 5 cm of overlap between the short core and the two long cores. Therefore, the composite record from this study used the top 26 cm from the short core, with the long core beginning at depth 27 cm through 195 cm. A combination of SP13D and SP13B were used in this analysis for several reasons; 1) SP13D was used between depths 27 – 152 cm, because this core contained better visual identification of important whitish clay layers; and 2) the long core SP13B was used between depths 152 – 195 cm, because this core captured a longer record.

AMS dates were converted to calendar years before present (cal yr BP; 0 = 1950 CE) using CALIB 11.1 (Stuvier et al., 1998). The age-depth model used the classical age-depth modeling CLAM software (Blaauw et al., 2010). However, there was an apparent age reversal in the ^{14}C AMS dates (Table 6). Therefore, we used the best-fit model to determine which AMS date to neglect from analysis based on the sedimentation rates (see Table 2). The final age-depth model used a smoothing spline (type=4) to create the age chronology (Figure 24). The interpolated basal age of Salamander Pond is 9,650 cal yr BP.

The uppermost sediments of SP13A contained the mud/water interface, which consisted of a flocculent mixture of mud and water. The remaining 26 cm of SP13A consisted of brown organic gyttja. Both SP13B and SP13D cores were mostly comprised of organic brown/dark brown gyttja. Several white and pinkish colored layers were visible at depths 80.5-82.5 cm, 136-138 cm, 147-149 cm, 180-181 cm, 185-185.5 cm, and 191-192 cm. Several charcoal layers were also visible at depths 44-45 cm, and an 8 cm thick charcoal layer between 169 and 177 cm (Figure 25). We hypothesize the 8 cm thick layer may have been a burnt branch that fell into the basin (see Discussion). Additionally, the ^{14}C AMS date that was rejected for this study occurred at the top of the 8 cm thick charcoal layer and likely represents sediment mixing from this fire episode (Table 6).

Magnetic Susceptibility and Loss-on-Ignition

Magnetic susceptibility was used to determine allochthonous input into the pond basin (i.e., erosional events) (Thompson et al. 1975) (Figure 25). Magnetic susceptibility was analyzed contiguously at one cm intervals using a Bartington MS2B cup sensor for the short core, and a Bartington MS2C coil core logging sensor for the composite long core. Both cores were measured in SI units.

Loss-on-Ignition (LOI) was used to determine lake productivity (% organic) and meltwater/groundwater fluxes (% carbonate) (Dean, 1974) (Figure 25). LOI was analyzed contiguous at 1 cm intervals for the entire short core, and at 4 cm intervals for the entire composite long core. Samples were dried at 550°C and 900°C to determine organic content and carbonate content of the soils.

Charcoal Analysis

Macroscopic charcoal was analyzed to reconstruct the fire history from Salamander Pond. Sediments were analyzed contiguously at 1 cm intervals using 5 cm^3 of sediment. Sediments were placed in a solution of the disaggregate sodium hexametaphosphate. Sediments were then rinsed through both 125 µm and 250 µm wire sieves. Charcoal particles > 125 µm do not travel far from their fire source, and typically represent a local fire episode with the catchment area (Clark, 1988; Whitlock and Larson, 2001). Particles of charcoal were identified and counted using a dissecting scope at 40X magnification. Total charcoal counts were then converted to concentration (particles/cm^3) and then into charcoal accumulation rates (CHAR; particles/cm^2/yr). Fire events and a transformed charcoal time series were identified using the peak detection software program, CharAnalysis (Higuera et al., 2009; Huerta et al., 2009). The time series is comprised of a slow moving background (BCHAR), which indicates the continual input of charcoal from regional fire episodes, and a peaks component (CHAR), which indicates the rapid input of charcoal from a fire episode within the catchment. To determine the BCHAR, the background component used a Lowess smoother robust to outliers, smoothed at a 500-year window. The peaks component was smoothed using a 1000-year window, and was tested for significance using a Gaussian distribution (>95th percentile). Peak detection used a window width that maximized the signal-to-noise index (SNI > 3) (Kelly et al., 2011). The fire history will be presented as BCHAR and CHAR, fire peaks, peak magnitude, which is the number of charcoal particles associated with each fire episode, and the fire return interval, which is the average number of years per fire peak (Figure 25).

To analyze the long-term trend in fire across the north slope versus the south slope of the Uinta Mountains, we reanalyzed two charcoal records, Heller Gulch (Turney, 2014), and Reader Fen (Koll, 2012), both located on the south slope, and compared them to the charcoal record from Salamander Pond. Charcoal data from these two sites were treated similarly to Salamander Pond dataset in CharAnalysis (Figure 26).

Pollen Analysis

Pollen preserved in lake sediments was analyzed to reconstruct the vegetation history at Salamander Pond. Pollen analysis was conducted contiguously at 1 cm intervals throughout the short core, and at 4 cm intervals, or ~165 year resolution throughout the long composite core. Additionally, pollen analysis was analyzed contiguously for other time periods of interest, specifically between depths 76-85 cm, which is on either side of the visually identified clay layer identified at depths 80.5-82.5 cm. Samples were processed using standard acid-base rinse methods (Faegri et al., 1989). *Lycopodium* tablets were placed in each sample at the beginning of the acid-base method, as an exotic tracer. A minimum of 300 terrestrial pollen grains or *Lycopodium* was counted per sample using light microscopy at 500X magnification. Pollen grains were identified to the lowest taxonomic rank possible using reference slides and published pollen keys (Kapp et al. 2000). In this study, Latin names (e.g. *Picea*) will be used when discussing specific pollen taxa, while common names (e.g. Engelmann spruce) will be used when discussing the environment. Total *Pinus* consists of sum of *Pinus* undifferentiated, *P.* haploxylon-type (also known as white pines) and *P.* diploxylon-type (also known as yellow pines). Pine grains without distal members were identified as *P.* undifferentiated. Based on the modern phytogeography, *P.* haploxylon-type could represent limber pine (*P. flexilis*) or pinyon pine (*P. edulis*), while *P.* dipoloxylon-type likely represents lodgepole pine, which is a dominant conifer species in the Uinta Mountains (Shaw & Long, 2007). There are currently no haploxylon-types within the Salamander Pond watershed. However, limber pine is found on the north slope of the Uinta Mountains, outside of the Salamander Pond watershed. Therefore, *P.* haploxylon-type pine grains likely indicate long distance transport, at least during the modern period. Pollen counts were converted to pollen percentages based on the abundance of each pollen type relative to the total sum of terrestrial pollen and are used to visually identify long-term trends in vegetation composition through time (Figure 27). Pollen counts were also converted to pollen influx (PAR; particles/cm^2/yr), which is the actual rate of pollen accumulation over time (Figure 28a & 28b). Finally, pollen ratios were calculated using pollen influx data and allow for the comparison between two types of pollen taxon or a group of pollen taxa. Based on modern phytogeography of lodgepole pine (*Pinus*), Engelmann spruce (*Picea*), and sagebrush (*Artemisia*) and their climate envelopes identified by Thompson et al. (1999)(Figure 29), ratios of annual precipitation (*Artemisia*:*Pinus*), summer temperature (*Artemisia*:*Picea*), and winter temperature

(*Picea*:*Pinus*) were calculated using the formula (*a*-*b*)/(*a*+*b*) (Maher, 1963, 1972) and are presented in standard units (SU) (Figure 30).

Results

Zone 1: Early Holocene 9,700 to 7,500 cal yr BP

In the earliest part of the record, magnetic susceptibility was the highest of the entire record averaging 6 SI units, 3 SI units higher than the long-term average. Relatively high magnetic susceptibility indicates increased erosional input from the surrounding meadow complex into the Salamander Pond basin during this zone. Total organics were the lowest of the entire record averaging 17%, compared to the long-term average of 28% (Figure 25). Total carbonates were relatively high (average 3%) compared to the long-term average of 2.6 (Figure 25). A total of five fire episodes occurred with an average CHAR of 17.6 particles/cm^2/yr. The average signal-to-noise index (SNI) for the early Holocene was 67. Large peak magnitude fire episodes characterize this zone with a mean of 5,836 particles/cm^2/episode. The largest peak magnitude event occurred during this zone with a peak magnitude of 23,555 (Figure 25, red line). If we exclude this fire episode, the remaining 3 fire episodes have a mean peak magnitude of 1,406 particles/cm^2/episode. Fire frequency was infrequent during this zone, with a mean of 2.6 fires/1000 years (Figure 25).

In the early Holocene, total PAR was relatively low averaging 5,469 grains/cm^2/yr with relatively high NAP pollen influx values (2,010 grains/cm^2/yr) (Figure 28b). AP pollen influx averaged 3,458 grains/cm^2/yr and suggests an open forested environment. *Picea* pollen and total *Pinus* pollen were the dominant canopy species averaging 9% (average influx 305 grains/cm^2/yr) and 13% (average influx 2,993 grains/cm^2/yr). *Abies* and *Pseudotsuga* were minimal averaging 1% (average influx 38 grains/cm^2/yr) and 2% (average influx 81 grains/cm^2/yr). Total herbs and shrubs were high averaging 13% and 45% (Figure 27), with *Artemisia* comprising 24% (average influx 813 grains/cm^2/yr) and Amaranthaceae comprising 13% (average influx 448 grains/cm^2/yr) of the total shrub category. Poaceae was the highest of the entire record during the early Holocene, averaging 5% (average influx 151 grains/cm^2/yr). Total aquatic pollen averaged 7% (average influx 246 grains/cm^2/yr) with Cyperaceae (average influx 202 grains/cm^2/yr) comprising the majority of the aquatic category (6%). Total riparian pollen was very low averaging 2% and 42 grains/cm^2/yr.

Zone 2: Transitional Period 7,500 to 6,500 cal yr BP

During the early-to-mid Holocene, magnetic susceptibility slightly decreased from the previous zone averaging 5 SI units, but is still higher than the long-term average of 3 SI units. Total organics increased from the previous zone averaging 20% (Figure 25), but was still below the long-term average of 28%. Carbonates remained the same as the previous zone averaging 3%. Additionally, two fire episodes during this zone with a mean CHAR of 2 particles/cm^2/yr and an average SNI of 35. Peak magnitudes for these two fire episodes were 3,813 and 798 particles/cm^2/episode, with a mean of 2,306 particles/cm^2/episode. Fire frequency was low, averaging 2.1 fires/1000 years (Figure 25).

During the transitional period, total PAR increased from the previous zone averaging 10,355 grains/cm^2/yr (Figure 28b). Total AP increased drastically from the previous zone averaging 8,720 grains/cm^2/yr, while total NAP decreased from the previous zone averaging 1,635 grains/cm^2/yr. *Picea* and *Pseudotsuga* pollen percentages averages remained the same as the previous zone (Figure 27), yet pollen influxes increased averaging 413 grains/cm^2/yr and 91 grains/cm^2/yr (Figure 28b). However, total *Pinus* and *Abies* pollen increased from the previous zone averaging 26% (average influx 8,039 grains/cm^2/yr) and 2% (average influx 118 grains/cm^2/yr). Both total shrubs and herbs decreased during this zone averaging 26% and 8%, with *Artemisia* and Amaranthaceae contributing 13% (average influx 632 grains/cm^2/yr) and 8% (average influx 372 grains/cm^2/yr) of the total shrub category. Poaceae decreased from the previous zone averaging 3% and 135 grains/cm^2/yr. Total aquatic pollen increased from the previous zone averaging 9% and 472 grains/cm^2/yr, with Cyperaceae comprising 8% and 407 grains/cm^2/yr) of the total aquatic category.

Zone 3: Mid-Holocene 6,500 to 4,750 cal yr BP

Magnetic susceptibility continued to decrease averaging 3 SI units throughout the mid-Holocene. Total organic content increased to an average of 21%, but was still below the long-term average of 28% (Figure 25). Total carbonates only increased slightly from the previous zone averaging 3.3%, which was still higher than the long-term average of 2.6%. During the mid-Holocene, a total of 9 fire episodes occurred with a mean CHAR of 3 particles/cm^2/yr with an average SNI of 18. Peak magnitudes were generally low during this zone, with a range of 0.05 to 141 particles/cm^2/episode and a mean of 42 particles/cm^2/episode. Fire frequency increased from the previous zone but was still relatively infrequent averaging 2.5 fires/1000 years (Figure 25).

Biomass productivity was the highest of the record during the mid-Holocene with an average PAR of 11,902 grains/cm^2/yr. AP pollen influx increased from the previous zone averaging of 10,434 grains/cm^2/yr, while NAP pollen influx decreased slightly from the previous zone averaging 1,475 grains/cm^2/yr (Figure 28b). Total *Pinus* pollen continued to increase from the previous zone averaging 34% and 10,110 grains/cm^2/yr. Along with the increase in total *Pinus* pollen was the abrupt appearance of dwarf mistletoe (*Arceuthobium*) averaging 11 grains/cm^2/yr, the highest of the entire record. All other taxa and categories experienced a decreasing trend during the mid-Holocene. *Picea*, *Abies*, and *Pseudotsuga* averaged 8% (average influx 176 grains/cm^2/yr), 1% (average influx 51 grains/cm^2/yr), and 1% (average influx 42 grains/cm^2/yr), respectively. Total shrubs, herbs, and aquatics all decreased averaging 19%, 6%, and 3%. *Artemisia* decreased to 10% (average influx 597 grains/cm^2/yr) and Amaranthaceae decreased to 5% (average influx 268 grains/cm^2/yr) of the total shrub category. Poaceae decreased slightly averaging 2% (average influx 129 grains/cm^2/yr). Cyperaceae decreased to 3% (average influx 154 grains/cm^2/yr) of the total aquatic category.

Zone 4: Late Holocene Drought 4,750 to 4,100 cal yr BP

During the late Holocene drought, magnetic susceptibility averaged 2 SI units, below the long-term average. Total organic content remained the same as the previous zone averaging 20%, while total carbonate content increased slightly averaging 3.5%. Two fire events occurred during the drought period with a mean CHAR of 0.5 particles/cm^2/yr with an average SNI of 9. Peak magnitudes for these two fire episodes were 0.2 and 6 particles/cm^2/episode, with a mean of 3.1 particles/cm^2/episode. Fire frequency increased from the previous period averaging 3 fires/1000 years (Figure 25).

During the late Holocene drought, total PAR decreased dramatically from the previous zone averaging 3,911 grains/cm^2/yr. Total AP was reduced significantly from the previous zone averaging 3,149 grains/cm^2/yr, while total NAP averaged 762 grains/cm^2/yr (Figure 28b). Total *Pinus* pollen slightly decreased during the late Holocene drought averaging 33% and 2,957 grains/cm^2/yr. *Pseudotsuga* influx pollen remained the same as the previous zone with an average of 23 grains/cm^2/yr. At the peak of the drought around 4,450 cal yr BP, total *Pinus* pollen declined to 30% (average influx 199 grains/cm^2/yr). *Abies* (average influx 41 grains/cm^2/yr) and *Picea* (average influx 82 grains/cm^2/yr) pollen both increased to 1% during the drought period (Figure 27). The late Holocene saw the increase of *Populus* pollen averaging 1% (average influx 20 grains/cm^2/yr). Total shrub, herb, and aquatic pollen percentages remained the same as the previous zone. Aquatic pollen influx decreased to the lowest of the entire record averaging 72 grains/cm^2/yr. Poaceae pollen increased slightly from the previous zone averaging 3% and 89 grains/cm^2/yr.

Zone 5: Late Holocene 4,100 to 450 cal yr BP

During the late Holocene, magnetic susceptibility continued to have a decreasing trend averaging 1 SI unit. Total organic content increased from the previous drought period averaging 29%, higher than the long-term average. Total carbonates decreased slightly averaging 3.5%. Additionally, a total of 9 fire episodes occurred with a mean CHAR of 1.9 particles/cm^2/yr with an average SNI of 12. Peak magnitudes averaged 368 particles/cm^2/episode, but ranged between 1 and 2891 particles/cm^2/episode. Fire frequency continued to increase from the previous zone, with a mean of 4 fires/1000 years (Figure 25).

After the late Holocene drought, biomass productivity increased from the previous zone with an average PAR of 7,200 grains/cm^2/yr. Both AP and NAP pollen influxes recovered from the late-Holocene drought and averaged 6,132 and 1,067 grains/cm^2/yr during the late Holocene period (Figure 28b). Total *Pinus* and *Picea* pollen percentages remained the same as the previous zone, while their influx increased averaging 5,894 and 99 grains/cm^2/yr, respectively. *Abies* and *Pseudotsuga* pollen both decreased averaging 1% (average influx 30 grains/cm^2/yr) and <1% (average influx 10 grains/cm^2/yr). *Populus* pollen influx decreased from the previous zone averaging 10 grains/cm^2/yr. Total shrub pollen increased slightly from the previous drought period averaging 19% (Figure 27). Poaceae pollen percentages remained the same as the previous zone, while Poaceae pollen influx increased averaging 115 grains/cm^2/yr. Total aquatic pollen decreased slightly averaging 2% and 91 grains/cm^2/yr), being mostly comprised of Cyperaceae pollen with an average pollen influx of 82 grains/cm^2/yr (Figure 28b).

Zone 6: Modern 450 cal yr BP to Present

During the modern period, magnetic susceptibility was low averaging the same as the previous zone (one SI unit). However, total organic content increased to the highest value of the entire record averaging 40%, while total carbonate content decreased to the lowest value of the entire record averaging 1% (Figure 25). Three fire events have occurred during the most recent portion of the record with an average SNI of 8, which is statistically significant for peak analysis (Kelly et al., 2011). CHAR averaged 2 particle/cm^2/yr, while peak magnitudes averaged 156 particles/cm^2/episode. Fire frequency was the highest of the entire record with an average of 5 fires/1000 years.

During the modern period, total PAR increased to the highest of the entire record averaging 73,674 grains/cm^2/yr, with AP comprising the majority of the total PAR (mean, 71,488 grains/cm^2/yr) (Figure 28a). NAP increased to the highest of the entire record averaging 2,185 grains/cm^2/yr. Total *Pinus* pollen averaged 40% and 70,860 grains/cm^2/yr, and reached a peak of 45% and 147,603 grains/cm^2/yr in the 1970s, which was the highest of the entire record. Modern *Picea* pollen averaged 2% with pollen influx averaging values similar to those during the early Holocene (345 grains/cm^2/yr). Modern *Abies* pollen averaged 1% and 151 grains/cm^2/yr. *Pseudotsuga* pollen averaged <1% and 5 grains/cm^2/yr, which is consistent with the modern phytogeography of this canopy species (Shaw and Long, 2007). Total shrub pollen averaged 13% during the modern zone, with *Artemisia* comprising 8% and 1,074 grains/cm^2/yr of the total shrub category. Amaranthaceae comprised 3% and 336 grains/cm^2/yr of the total shrub pollen category. *Quercus* pollen influx decreased to 0 grains/cm^2/yr, which is consistent with the modern phytogeography of this species (Shaw and Long, 2007). Total herb pollen percentages have averaged 7% (Figure 27). Poaceae pollen averaged 2% and 218 grains/cm^2/yr during the modern period. Total aquatic pollen averaged relatively low percentages (2%). However, total aquatic influx increased dramatically from the previous two zones with an average of 271 grains/cm^2/yr, with Cyperaceae comprising nearly the entire total aquatic category (250 grains/cm^2/yr) (Figure 28a).

Discussion

The Uinta Mountains have a unique precipitation regime that varies both from the north to south, and east to west. Winter wet conditions primarily occur on the northwestern slope of the range, while summer wet conditions primarily occur on the southeastern slope. The influence of these moisture patterns likely influences both fire regimes and vegetation composition in the Uinta Mountains. The objectives of this study are to determine whether changes in fire regimes from the Uinta Mountains are linked to changes in winter wet and summer wet precipitation boundary, as well as determine the role of site characteristics on fire activity in the Uinta Mountains.

Holocene Fire, Vegetation and Climate Linkages in the Uinta Mountains

Early Holocene (9,700 to 7,500 cal yr BP)

In the early Holocene, the fire regime at Salamander Pond was characterized by an infrequent but high severity fire regime, as indicated by the high peak magnitudes (Figure 25), which is consistent with the low fuel load of spruce parkland present at this time (Figure 26). Infrequent fires are typical for Engelmann spruce and subalpine fir (*Abies lasiocarpa*) forests, as conditions are likely too wet to burn in those forest types (Bradley et al., 1992; Shaw & Long, 2007). However, within the Engelmann spruce and subalpine fir forest zone, fuel accumulation is common during the fire-free periods, thus resulting in high-severity, stand-replacing fire episodes when conditions are conducive for burning (Shaw & Long, 2007). Large peak magnitudes suggest fuel accumulation and stand replacing events (Figure 25). Additionally, a 7 cm thick charcoal layer was evident during this portion of the core suggesting that either, 1) the surrounding forest had burned in a stand-replacing crown fire and that a high abundance of charcoal was washed into the pond basin and preserved, or 2) a charred log located near the ponds' edge fell into the lake, which contributed to the thick layer of charcoal.

The basal age of Salamander Pond suggests that remnant Black Forks piedmont glacial ice did not melt until after 10,000 cal yr BP. Deglaciation in the Henrys Fork Canyon, two canyons south of the East Fork of Blacks Fork canyon occurred prior to 10,000 cal yr BP (Monroe, 2003). High abundances of *Picea* and *Artemisia* pollen percentages at Salamander Pond suggest an-open spruce-sagebrush parkland immediately after deglaciation (Figure 27). Similarly, sites HF98-1 and HF98-2 also documented an-open spruce-sagebrush parkland during the early Holocene (Monroe, 2003).

Paleoclimate simulations suggest greater-than-present summer insolation directly affected summer temperatures, which were simulated to be warmer-than-present (Kutzbach et al., 1998). The *Artemisia:Pinus* ratio agrees with the interpretation that the early Holocene experienced warmer-than-present summer temperatures (Figure 30). Paleoclimate models also suggest that the early Holocene experienced an enhanced subtropical high off the coast of the Pacific northwest, and a deeper-than-modern low in the southwestern region of the US, which likely enhanced onshore flow of monsoonal moisture (Bartlein et al., 1998). Whitlock and Bartlein (1993) suggest that regions currently in the winter wet (summer wet) precipitation boundary were drier (wetter) than at present as a result of a strengthening of the two precipitation regimes, and that the boundary between the two precipitation regimes likely hasn't shifted spatially through time. However, pollen ratios from Salamander Pond indicate increased annual precipitation ~9,000 cal yr BP (Figures 30), suggesting that the precipitation boundary had shifted, allowing Salamander Pond (a modern winter wet site) to experience wetter, not drier conditions during the early Holocene. High abundances of Cyperaceae pollen (Figure 27 and 28b) further support wetter conditions. Additionally, pollen ratios from Salamander Pond also suggest cooler-than-modern winter temperatures (Figure 30).

Both Douglas-fir and gamble oak pollen were present during the early Holocene, but at very low percentages (~5% each). Fall (1992) suggests that *Pseudotsuga* has a very localized pollen source area. While Douglas-fir has a similar annual precipitation climate space as Engelmann spruce, Douglas-fir cannot tolerate cold winter temperatures, which were colder-than-modern during the early Holocene (Kutzbach et al., 1998) and therefore was not very abundant at Salamander Pond. As for gamble oak, it is a drought tolerant species (Abrams, 1990), suggesting that conditions were likely too wet for the species on the north slope of the Uinta Mountains during the early Holocene. Shaw and Long (2007) have documented the modern absence of Douglas-fir and gamble oak from the northwestern Uinta Mountains. However, Douglas-fir becomes more abundant further east, while the closest gamble oak populations are found in the Wasatch Mountain Range to the west. Shaw and Long (2007) also document the coincident occurrence of more abundant Douglas-fir in the eastern Uinta Mountains with the summer wet precipitation regime at present. Our interpretation agrees with the interpretation that conditions were too cold and too wet for both species in the early Holocene.

Fire activity on the south slope at both Reader Fen and Heller Gulch experienced a general decreasing trend in fire frequency during the early Holocene. However, at ~8,500 cal yr BP, fire frequency increased at both sites (Figure 26). While all sites in the

Uinta Mountains experienced a generally infrequent fire regime during the early Holocene, the difference in severity could have been a result of fuel connectivity as indicated by relatively low peak magnitudes and CHAR values (Figure 26). Koll (2012) suggests that the landscape at Reader Fen consisted of an open spruce-parkland and fen meadow complex, while Turney (2014) documents an open spruce parkland at Heller Gulch. Additionally, Lundeen and Brunelle (2016) suggest that decreased fire frequency at Plan B pond, located on the Utah/Idaho border, was a result of higher-than-average winter snowpacks. In general, the regional records indicate increased effective moisture, which could explain the infrequent fire regime at Salamander Pond.

Transitional Period (7,500 to 6,500 cal yr BP)

The transitional period was a period when vegetation composition transitioned from an open spruce parkland to a lodgepole pine forest. Two fire episodes occurred during the transition period at Salamander Pond; one at the beginning of the transition period, and one at the end of the transition period. The first fire episode could have facilitated the development of a lodgepole pine forest, which is documented by the increase in *Pinus* pollen and decrease in *Picea* pollen. This transitional period was also experienced throughout the entire Uinta Mountain range, both on the north and south slopes but at varying times (Koll, 2012; Louderback et al., 2015; Monroe, 2003; Turner, 2014). Louderback et al. (2015) suggest that the change to a lodgepole-dominated forest was climatically driven. Kutzback et al. (1998) suggest summer temperatures had cooled slightly since the early Holocene, but were roughly 1 - 2°C warmer-than-present during the transitional period, while winter temperatures had warmed to near modern temperatures as a result of increasing winter insolation. Pollen ratios from Salamander Pond support cooler-than-previous summer temperatures and warmer-than-previous winter temperatures (Figure 30). Currently, modern winter (January) temperatures average -7^{o}C, which is near the winter temperature limit for Engelmann spruce (Figure 29f), but is within the climate space of lodgepole pine (Thompson et al., 1999).

Increased fire frequency at Plan B pond around 7,100 cal yr BP is indicative of reduced winter snowpacks, because of a lengthening of the fire season (Lundeen & Brunelle, 2016). The fire frequency at Salamander Pond also begins to increase towards more frequent ~7,000 cal yr BP. The more frequent fire regime could be associated with reduced winter snowpack in the winter wet precipitation regime, despite the *Artemisia*:*Picea* pollen ratio indicating increased annual precipitation (Figure 30). While increased fire frequency was also documented at Reader Fen, low CHAR and peak magnitudes continue to suggest fuel, not changes in the summer wet precipitation regime was a limiting factor on the southeast slope of the Uinta Mountains. Peak magnitudes were relatively high during the transitional period at Heller Gulch (Figure 26), suggesting more fuel connectivity at this site. Additionally, because Heller Gulch is located more closely to the boundary between the winter wet/summer wet precipitation regime, the variable fire frequency suggests changes in precipitation influenced the fire activity at this site. Similar to Salamander Pond, Louderback et al. (2015) also do not correlate any peak in charcoal abundance with the transition of an open spruce-parkland to a lodgepole pine-dominated forest at Marsh Bog located downslope from Salamander Pond.

Mid-Holocene (6,500 to 4,750 cal yr BP)

At the onset of the mid-Holocene period, large peak magnitude fire events occurred at both Salamander Pond and Heller Gulch (Figure 26). Around 6,500 cal yr BP, annual precipitation declines rapidly at Salamander Pond (Figure 30). Lundeen and Brunelle (2016) document less winter precipitation and warmer spring temperatures during the mid-Holocene suggesting that sites in the winter wet precipitation regime were more arid than previous. High severity fires occur under extreme conditions when fuels accumulate (Lotan et al., 1985), which suggests that the lack of fires at both Salamander Pond and Heller Gulch between ~7,000 and ~6,500 cal yr BP led to fuel accumulation. When extremely dry conditions occurred around 6,500 cal yr BP, a high severity fire occurred at both sites.

After 6,500 cal yr BP, the fire regime at Salamander switched from a high-severity regime to a low-severity regime, while Reader Fen switched from a low-severity regime to a relatively high-severity regime (Figure 26). Strength of the two precipitation regimes were attenuating due to a weakening of both the subtropical high off the coast of the Pacific northwest, and the thermal low in the southwestern region of the US (Bartlein et al., 1998). As a result, Whitlock and Bartlein (1993) suggest that regions currently in the winter wet (summer wet) precipitation boundary became wetter (drier) than present as a result of the weakening of the two precipitation regimes. Brunelle et al. (2005) hypothesized that fire frequency would decrease in areas located in the present day winter wet regions as a result of wetter conditions. Therefore, it would then be expected that summer wet regions would experience an increase in fire frequency. While the fire frequency at Reader Fen was the most frequent of the entire record, fire frequency averaged ~3 fires/1000 years or ~300 years per fire which is relatively infrequent. Additionally, while peak magnitudes do increase at Reader Fen during the mid-Holocene, the number of charcoal particles is significantly lower than both Salamander Pond and Heller Gulch, which is suggestive of lower fuel connectivity. Koll (2012) attribute the more frequent fire regime to increased monsoonal moisture (i.e., summer wet conditions). However, high abundances of Amaranthaceae and *Sarcobatus* suggest dry conditions at lower elevations (Koll, 2012). Amaranthaceae is typically found where moisture is relatively limited (Minkley et al., 2008), which could be attributed to decreased winter precipitation experienced during the mid-Holocene.

Fuels were relatively consistent at Salamander Pond, Heller Gulch and Reader Fen, which were characterized by the development of the modern stable lodgepole pine forest (Figure 31). Kutzbach et al. (1998) suggest summer temperatures were still ~1 to 2^{o}C warmer-than-present, and that winter precipitation was near modern as a result of increasing winter insolation. Warmer-than-present summer temperatures and near modern precipitation is documented in the pollen ratios from Salamander Pond (Figure 30). However, according to the *Artemisia*:*Picea* ratio from Salamander Pond, an abrupt switch in annual precipitation occurred ~6,500 cal yr BP and conditions became drier-than-previous (Figure 30). At Salamander Pond, *Picea* pollen was reduced significantly as a result of warmer winter temperatures and decreased annual precipitation (Figure 28b). Relatively low *Artemisia* and Amaranthaceae pollen percentages also suggest treeline was lower as a result of reduced summer temperatures (Figure 27).

Coincident to the decline in annual precipitation is a switch to the most frequent fire regime at both Salamander Pond and Plan B pond (Figure 26). Additionally, total

NAP was relatively high during the mid-Holocene at Salamander Pond, which suggests high fuel connectivity among the stable lodgepole pine forest. However, low peak magnitudes at Salamander Pond suggest fires were less severe than the previous two zones. Fire regimes in lodgepole pine forests vary from low-severity to stand-replacing crown fires (see Lotan et al., 1985), but are generally characterized by an infrequent and high-severity fire regime. However, Arno (1980) documented a more frequent historic fire regime than previously realized (Lotan et al., 1985). Frequent fires clear seeds and seedlings from shade-tolerant species, such as Engelmann spruce, which would replace lodgepole pine during long fire-free periods (Lotan et al., 1985). The frequent fire regime experienced at Salamander Pond could explain the stability of the lodgepole pine forest during the mid-Holocene. Reduced winter snowpack during the mid-Holocene (Lundeen & Brunelle, 2016), coupled with reduced annual precipitation recorded at Salamander Pond (Figure 30), along with high fuel connectively led to the frequent fire regime on the north slope of the Uinta Mountains. However, we hypothesize that conditions were likely too dry for stand-replacing fire events that are typical in lodgepole pine forests.

Late Holocene Drought (4,750 to 4,100 cal yr BP)

Fire frequency declined at Salamander Pond during the late Holocene drought period as a result of exceptionally dry conditions, as indicated by the lowest total PAR values of the entire record suggesting decreased biomass productivity of both AP and NAP species (Figure 28b). Decreased NAP pollen influx suggests less fuel connectivity, which would have inhibited fire spread at Salamander Pond during the late Holocene drought, which explains the return to an infrequent fire regime.

The late Holocene drought, centered on 4,500 cal yr BP, was identified by a 2 cm thick clay layer, which indicates a dry lake basin. An abrupt decline in both total organics and total carbonates during the late Holocene drought further suggests decreased biomass productivity and increased aeolian dust deposition (Figure 25). During the late Holocene drought, vegetation composition was highly variable, with *Pinus*, *Artemisia*, Amaranthaceae, and Poaceae pollen percentages oscillating during this time (Figure 27).

Coincidentally, the ecological response to the late Holocene drought recorded at Salamander Pond is strikingly similar to the ecological response recorded at Long Lake, Wyoming (Carter et al., 2013; Carter et al., *in review*). Carter et al. (*in review*) document how warmer temperatures directly influenced the upslope migration of an aspen ecotone, which was evidenced by the increase and anomalously high abundance of *Populus* pollen at Long Lake, Wyoming. However, the increase in *Populus* pollen lagged the drought by roughly 150 years. Similarly, *Populus* pollen appears for the first time at Salamander Pond shortly after the late Holocene drought and suggests that the local aspen stands were likely migrating upslope in response to warmer-than-previous temperatures. However, aspen is currently present downslope of Salamander Pond in small stands. The actual aspen ecotone is roughly ~5.5 km downslope from Salamander Pond, which differs from Long Lake in that the aspen ecotone is only ~200 m downslope from Long Lake. Therefore, this is indicative of local expansion of small aspen stands and not the entire aspen ecotone during the late Holocene drought.

Lundeen et al. (2013) document drought-like conditions in Minnetonka Cave beginning around 4,400 cal yr BP. Additionally, Lundeen and Brunelle (2016) document a switch from more winterpack to less winter snowpack and warmer spring temperatures

~4,400 cal yr BP. Similarly, Purple Lake, located on the Aquarius Plateau in southern Utah, also document the upslope migration of treeline ~4,400 cal yr BP in response to dry conditions. The drought recorded in the sedimentary record at Salamander Pond is roughly 300 years prior-to the drought centered on 4,200 cal yr BP that occurred in the Great Plains region (Booth et al., 2005). However, AMS ^{14}C dating above and below the 2 cm clay layer confirms that this drought was centered on 4,500 cal yr BP (Table 6). This suggests that the period between 4,500 and 4,100 cal yr BP was a period of persistent drought-like conditions throughout the western region and Great Plains region of the US.

Despite the relatively close proximity of Heller Gulch and Reader Fen to Salamander Pond, no drastic changes occurred in the pollen or charcoal records. Fire frequency slightly declines at Reader Fen, which could be attributed to drier conditions. But because Heller Gulch experienced a slight increase in fire frequency during the late Holocene drought, this suggests that local factors may have been more influential to the fire activity on the south slope than the actual drought.

Late Holocene (4,100 to 450 cal yr BP)

Fire frequency was generally infrequent during the late Holocene at Salamander Pond, except around ~2,000 cal yr BP when fire frequency increased slightly (Figure 26). The fire frequency from Plan B and Heller Gulch is strikingly similar to that of Salamander Pond, both documenting decreased fire frequency until ~2,000 cal yr BP (Lundeen & Brunelle, 2016; Turney, 2014). The change in fire frequency at Salamander Pond and Heller Gulch cannot be explained by changes in fuel, as the surrounding landscape was still dominated by a stable lodgepole pine forest. Warmer winter temperatures and decreased annual precipitation can be attributed to the continued dominance of lodgepole pine at both sites (Figure 30). At Salamander Pond, high abundances of *Juniperus* pollen (most likely *J. scopulorum* based on the modern phytogeography of Rocky Mountain juniper) also suggest dry conditions, but more moisture than the previous drought period. Relatively low *Artemisia* and Amaranthaceae pollen suggest treeline was lower as a result of reduced summer temperatures (Figure 27). The continued presence of *Populus* pollen likely suggests expansion of the local aspen stands during the late Holocene period as a result of consistently dry conditions (Figure 27). Therefore, the changes in fire frequency at Salamander Pond must be explained by changes in climate.

Lundeen and Brunelle (2016) suggest that increased winter snowpack caused the decrease in fire frequency between 4,400 and 2,000 cal yr BP, while reduced winter snowpack and warmer spring temperatures likely caused the increase in fire frequency between 2,000 and 450 cal yr BP. While the record from Salamander pond suggests less annual moisture during the late Holocene (Figure 30), if we take into consideration Lundeen and Brunelle's (2016) interpretation of changes in winter precipitation, the near identical fire frequencies between Salamander pond, Heller Gulch, and Plan B pond suggests that winter precipitation was the primary control of fire frequency during the late Holocene. Additionally, wet conditions are inferred from Reader Fen (Figure 31), which would have led to greater fuel connectivity. A slight increase in CHAR values, as well as the highest peak magnitude events occur ~2,000 cal yr BP at Reader Fen, which support the greater fuel connectivity, and is suggestive of greater amounts of woody biomass on the landscape (Figure 26).

Modern (450 cal yr BP to present)

Fire frequency during the modern period saw a general increase towards more frequent fire activity at Salamander Pond, Plan B Pond, and Reader Fen during the modern period. Over the past 450 years, vegetation composition has remained relatively stable, with lodgepole pine dominating the canopy at Salamander Pond, which can be attributed to cooler-than the previous summer temperatures and warmer-than-previous winter temperatures (Figure 30). Additionally, a general decreasing trend in *Artemisia* and Amaranthaceae pollen suggest decreased summer temperatures and increased annual precipitation (Figure 30) on the north slope of the Uinta Mountains.

However, ~100 cal yr BP (1850 CE), total *Pinus*, *Abies*, and *Picea* pollen influxes (which mostly comprise the AP PAR) increased, along with a slight increase in *Artemisia* pollen influx and total NAP pollen influx at Salamander Pond (Figure 28a). This can be attributed to tie-hack logging. In the late 1860s, Euro-American settlement and related activities, including logging for the construction of the transcontinental railroad, began affecting the composition and structure of forests of the western US (Thybony et al., 1985). Substantial changes occurred along the corridor of the transcontinental railroad where construction and maintenance of the railroad created a high dependence on timber. The primary trees that were hewn into railroad ties were lodgepole pine. The Uinta Mountains happen to be within the corridor of the transcontinental railroad. Evidence of old tie-hack logging cabins are ~0.5 m downslope from Salamander Pond and suggests the East Fork of Blacks Fork canyon was logged between the 1860s and early 1900s. The increase in total *Pinus* percentages (Figure 27) and total *Pinus* pollen influx (Figure 28a) is counter-intuitive, as one would suspect the decrease in *Pinus* pollen with the removal of lodgepole pine. However, lodgepole pine is considered an aggressive seral species that establishes itself on disturbed soils, either burned by wildfire or cleared by logging (Lotan et al., 1985). The opening of the canopy also allowed for shade-tolerant species, such as Engelmann spruce and subalpine fir to increase near Salamander Pond. The increase in total NAP pollen influx further suggests an opening of the canopy (Figure 28a).

Koll (2012) document a decrease in peak magnitudes (Figure 26), and suggest a less severe fire regime at Reader Fen as a result of cool and wet conditions, and a peat-producing fen on the south slope of the Uinta Mountains We also suggest that the decrease in peak magnitudes at Reader Fen is indicative of less fuel connectivity. The modern record at Heller Gulch was washed away in a catastrophic dam failure in the early 1900s (Turney, 2014). However, Turney (2014) analyzed sediments from Larvae Lake, ~18 km northeast of Heller Gulch to remedy the lack of historical data. The charcoal record from Larvae Lake, while only 600 years long, also documents a relatively frequent fire regime on the south slope of the Uinta Mountains for the modern period. Lundeen and Brunelle (2016) suggest that lower than average snowpacks and warmer springs explains the increase in fire frequency at Plan B Pond. The record from Salamander Pond suggests cooler and wetter conditions, but this could be an artifact of local site factors, such as topography (Courtney Mustaphi & Pisaric, 2013) playing a more important role in vegetation composition. Additionally, the modern climate is influenced by numerous climatic variations that operate on different time scales

(Dettinger et al., 2000; Gray et al., 2003). These climatic variations likely have played an important role in the position of the winter wet, summer wet precipitation boundary on shorter time scales than what paleoenvironmental records are capable of reconstructing. While we expect fire regimes to return to an infrequent fire regime at Salamander pond with the abrupt increase in annual moisture, we hypothesize that site characteristics, rapid climatic fluctuations and/or a lengthening of the summer season due to anthropogenic caused climate change is altering the natural fire regime on the north slope of the Uinta Mountains.

Conclusions

The paleoecological record from Salamander Pond was compared to the nearest charcoal records from the south slope of the Uinta Mountains and northern Wasatch Mountain Range to determine whether changes in fire regimes from the Uinta Mountains were linked to changes in winter wet/summer wet regime, as well as to determine whether site characteristics, such a fuel type played a more important role in fire activity in the Uinta Mountains. This study suggests that wildfire activity occurred independently than changes in vegetation composition. However, the development of the lodgepole pine across the Uinta Mountains played an important role in maintaining the species stability, with frequent fires removing shade-tolerant species from the understory and allowing the dominance of lodgepole pine regardless of changes in the position of the winter wet/summer wet precipitation regime. The two charcoal records located furthest west (Plan B Pond and Salamander Pond) in the winter wet precipitation regime suggests winter precipitation and the length of the summer season have controlled fire frequency.

Decreased winter precipitation leads to early snowmelt (i.e., longer summer season), which has been correlated with the most recent increase in fire activity (Westerling et al., 2006). Therefore, the position of the winter wet precipitation boundary appears to have influenced the fire regime on the northwest slope of the Uinta Mountains throughout the Holocene. The two charcoal records located furthest east (i.e., Heller Gulch and Reader Fen) in the summer wet precipitation regime appears to be fuel limited throughout the Holocene, suggesting that site characteristics played a more important role in the fire regime on the south slope of the Uinta Mountains. Vegetation across the region appears to be linked with changes in both winter and summer temperature, which has been directly influenced by changes in insolation throughout the Holocene.

Currently, there are only three Holocene length fire records from the Uinta Mountains. In order to fully understand how the position of the winter wet/summer wet precipitation regime, as well as local site characteristics influenced wildfire activity from the Uinta Mountains, more paleoenvironmental research is needed from the area.

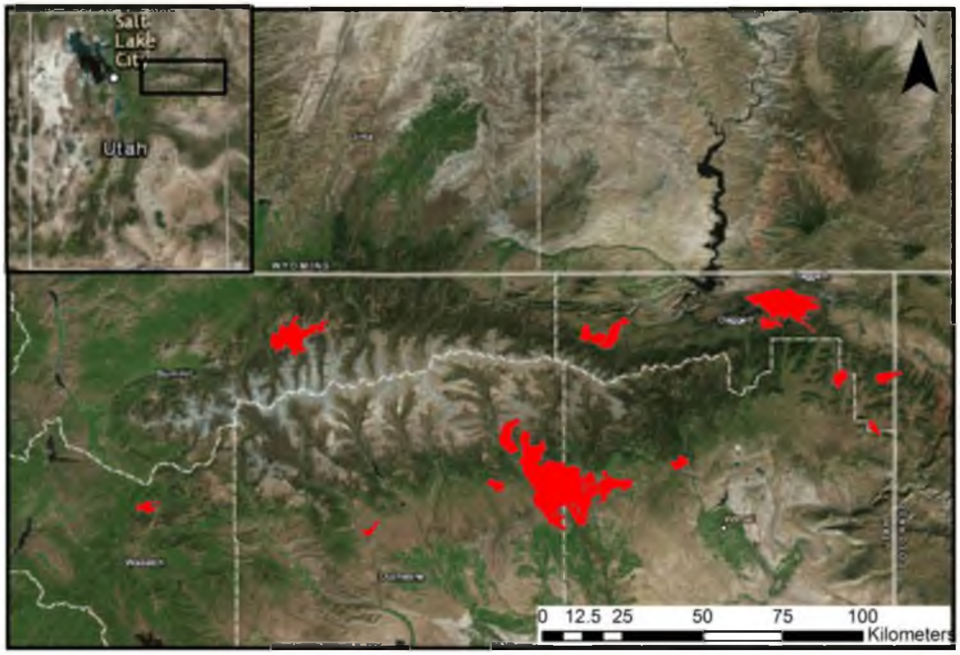


Figure 17. Large fires (>405 hectares) that have burned in the Uinta Mountains since 1984. Data are from the Monitoring Trends in Burned Severity (MTBS), shown in red.

Table 5. Total acreage burned in the Uinta Mountains between 1984-2015. Data are from the Monitoring Trends in Burned Severity (MTBS)

	North Slope	**Year**	**South Slope**	**Year**
Name of fire & hectares burned	Garden Valley Complex 5,765 ha	2002	Still Water 586 ha	2000
	Sheep Creek WFU 1,671 ha	2005	South Hollow 936 ha	2001
	Weyman 2,072 ha	1985	North Neola 2,102 ha	2005
	Green River 779 ha	1988	Neola North 18,983 ha	2007
	Mustang 8,339 ha	2002	Whiterocks 7,643 ha	1988
			Johnstarr 848 ha	1999
			Dry Fork II 912 ha	2000
			Uinta Canyon 2,458 ha	1989
Total hectares burned	18,626 ha		34,468 ha	

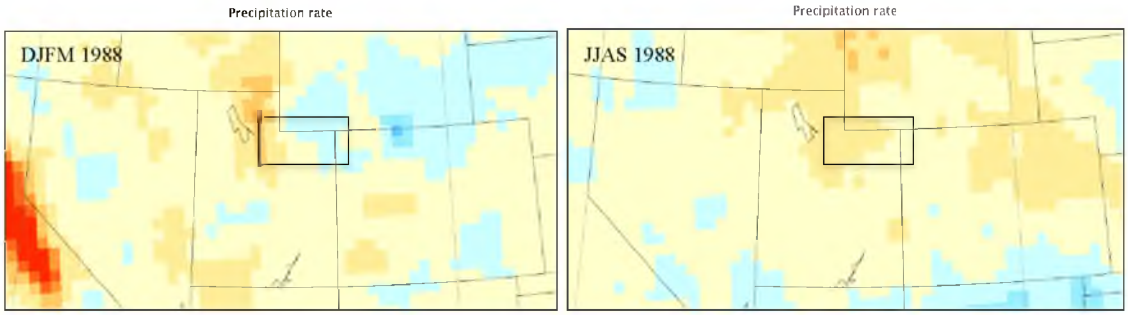


Figure 18. Anomalous winter (December through March) and summer precipitation (June through September) rates for 1988. Data collected from the North American Regional Reanalysis dataset. The black box indicates where the Uinta Mountains are located.

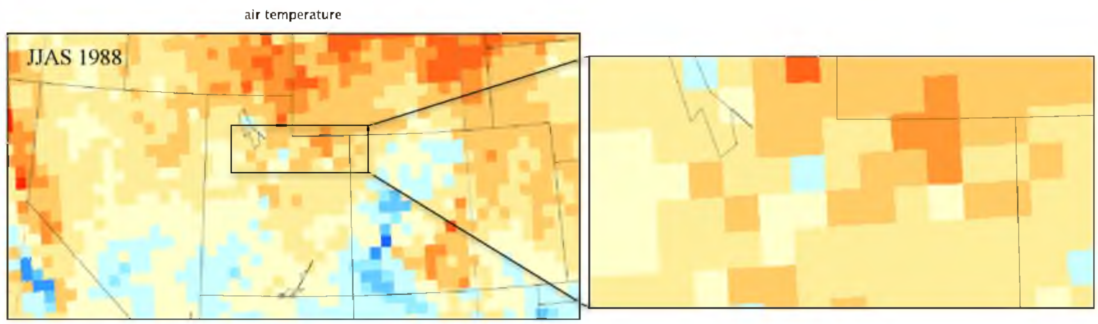


Figure 19. Anomalous summer (June through September) temperatures for 1988. Data collected from the North American Regional Reanalysis dataset. The black box indicates where the Uinta Mountains are located.

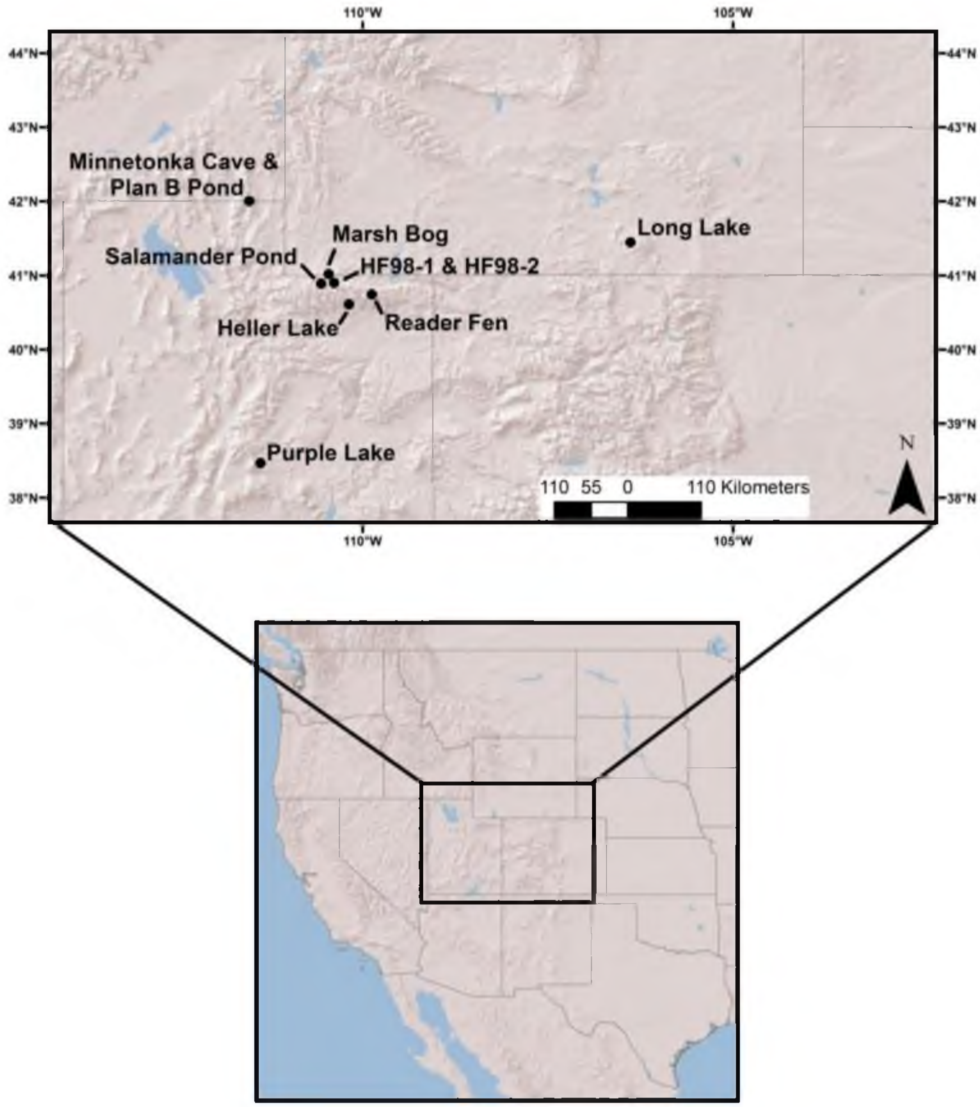


Figure 20. Site map of Salamander Pond (40° 54' 6.8"N, 110° 37' 11.3" W), Uinta Mountains, northeastern Utah in comparison to regional sites discussed in the text; Plan B Pond (Lundeen and Brunelle, 2015), Minnetonka Cave (Lundeen et al., 2013), Long Lake (Carter et al., 2013), Heller Gulch (Turner, 2014), Reader Fen (Koll, 2012), and Purple Lake (Morris et al., 2013).

Figure 21. Aerial photography taken by Vachel A. Kraklow from an airplane that documents the glacial ice amphitheater surrounding Salamander pond.

Table 6. Age-depth relation from Salamander Pond. The AMS with the '*' symbol indicates the ^{14}C date we did not include in the age-depth model likely due to sediment mixing associated with a charcoal layer.

Sample ID	UGAMS#	Depth (cm)	$\delta^{13}C$ corrected Radiocarbon Age (YBP)
SP12A	12052	53-54	1700 ± 20
SP13D_B	16121	40-45	1340 ± 25
SP13D_B	19876	73-74	3584 ± 23
SP13D_B	16977	83-84	4315 ± 30
SP13D_B	16122	119-120	5460 ± 25
SP13D_B*	16978	166-167	8155 ± 35
SP13D_B	16979	177-178	7970 ± 33
SP13D_B	16123	194-195	8715 ± 30

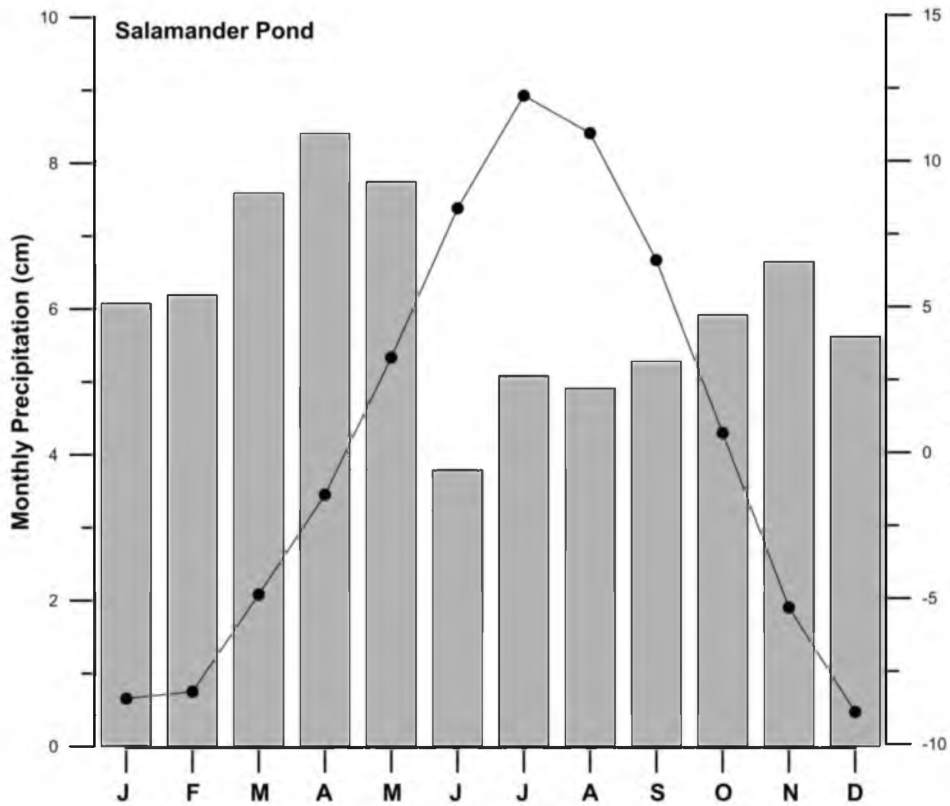


Figure 22. Climagraph for precipitation (histogram) and temperature (line plot) data from the nearest SNOTEL site (Steel Creek Park; Site ID #790) from Salamander Pond. Instrumental data from the Steel Creek Park site has a continuous record of temperature and precipitation beginning in 1978.

Figure. 23. Photograph taken from Salamander Pond in August 2013 by Charlie Hastings documenting the most recent mountain pine beetle outbreak.

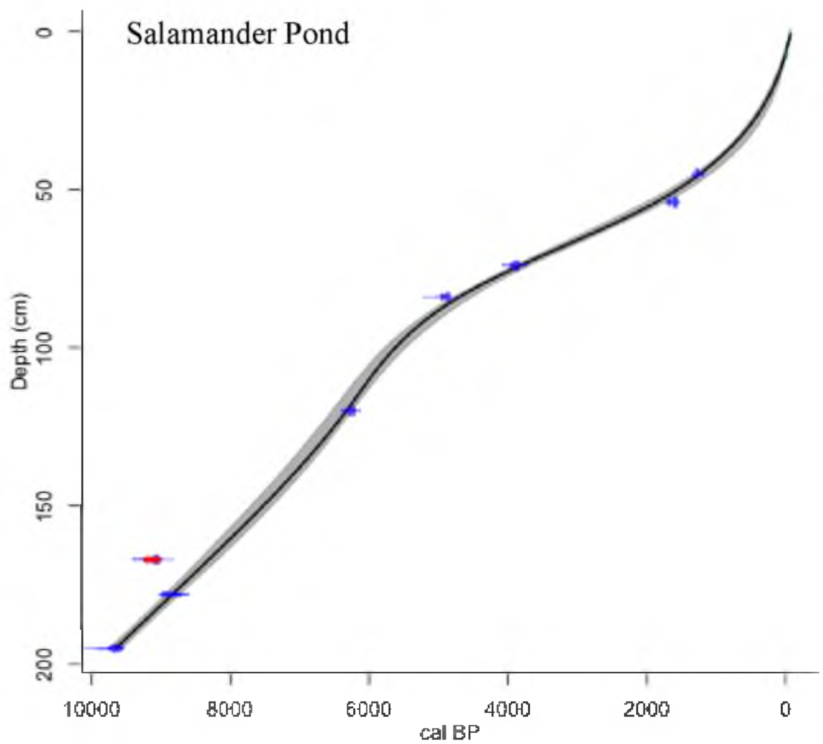


Figure 24. Salamander Pond age-depth model. The age-depth model was constructed using the classical age-depth model (CLAM) with a smoothing spline. Gray shading indicates range of error at the 95% confidence interval.

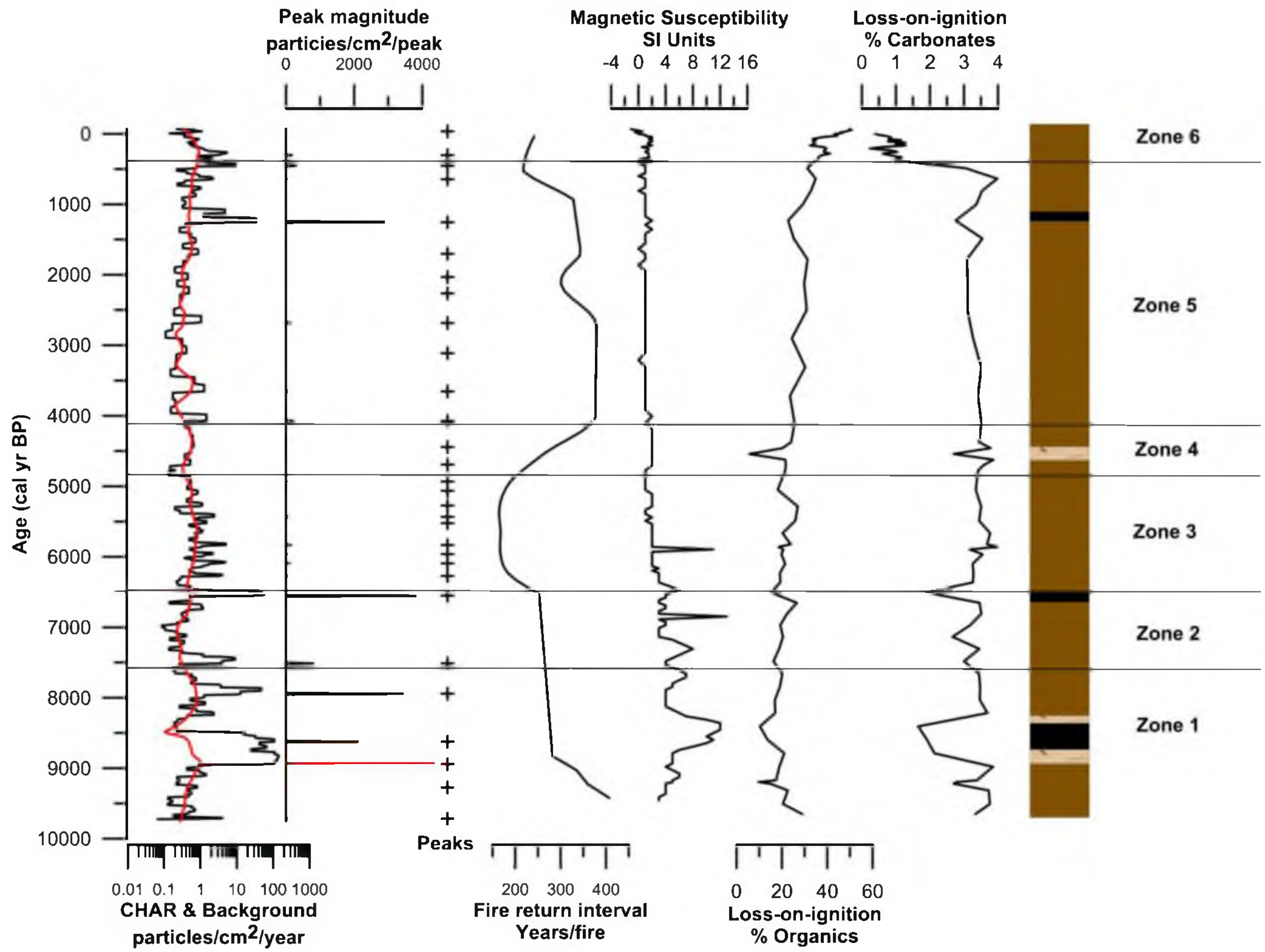


Figure 25. Fire history, magnetic susceptibility, and loss-on-ignition from Salamander Pond.

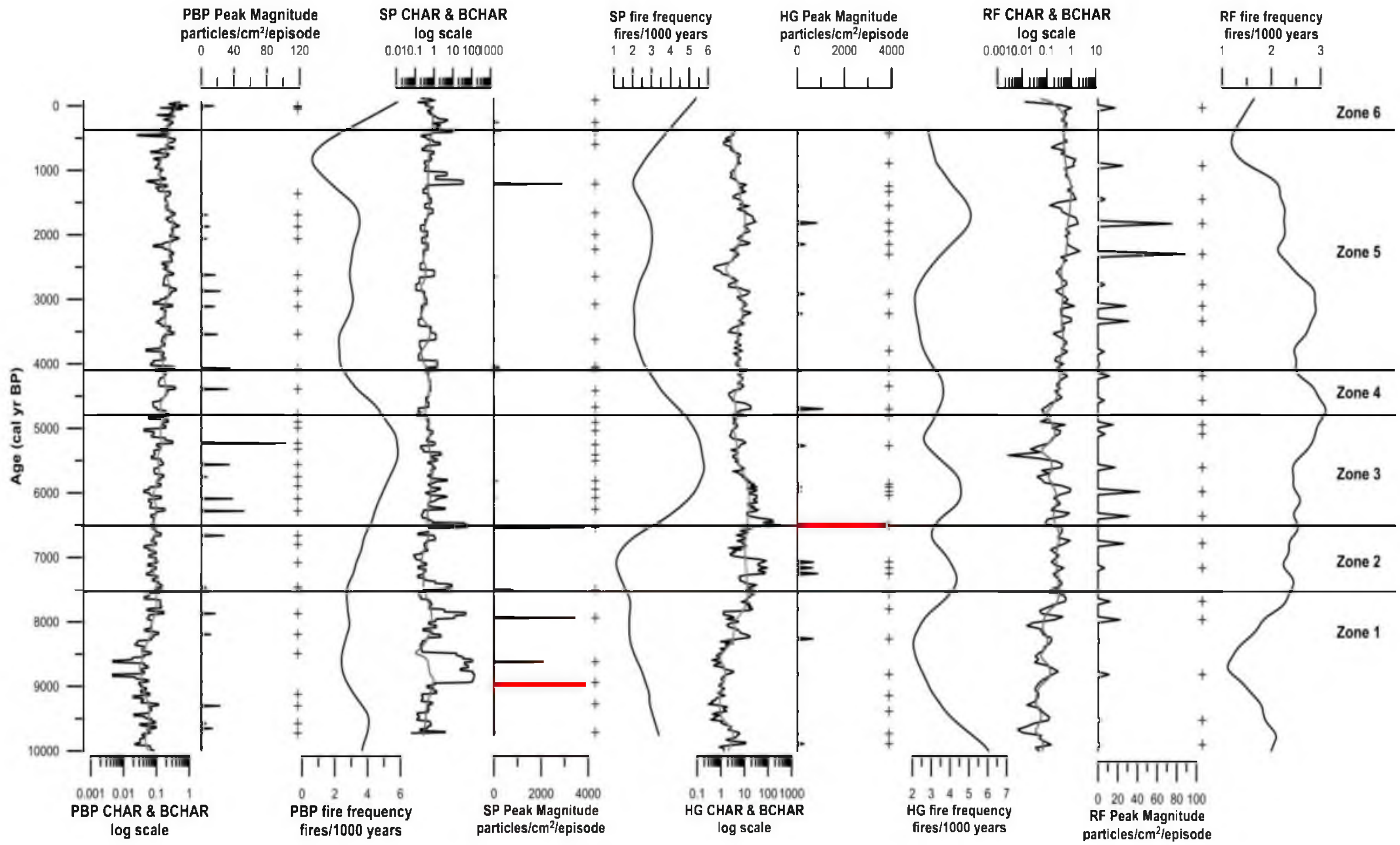


Figure 26. Fire history from regional sites, starting with the furthest west site Plan B Pond (PBP) (Lundeen & Brunelle, 2015), Salamander Pond (SP; this study), Heller Gulch (HG) (Turner, 2014; Turner et al., *in review*), and Reader Fen (RF) (Koll, 2012), which is the furthest east site. Each site has CHAR and BCHAR (gray line) plotted on a log scale, followed by peak magnitudes (charcoal particles/cm^2/episode), fire episodes indicated by the '+' symbol, and finally fire frequency (the number of fires per 1,000 years). Red solid lines on the SP and HG peak magnitudes indicate peak magnitudes greater than 4,000 particles/cm^2/episode.

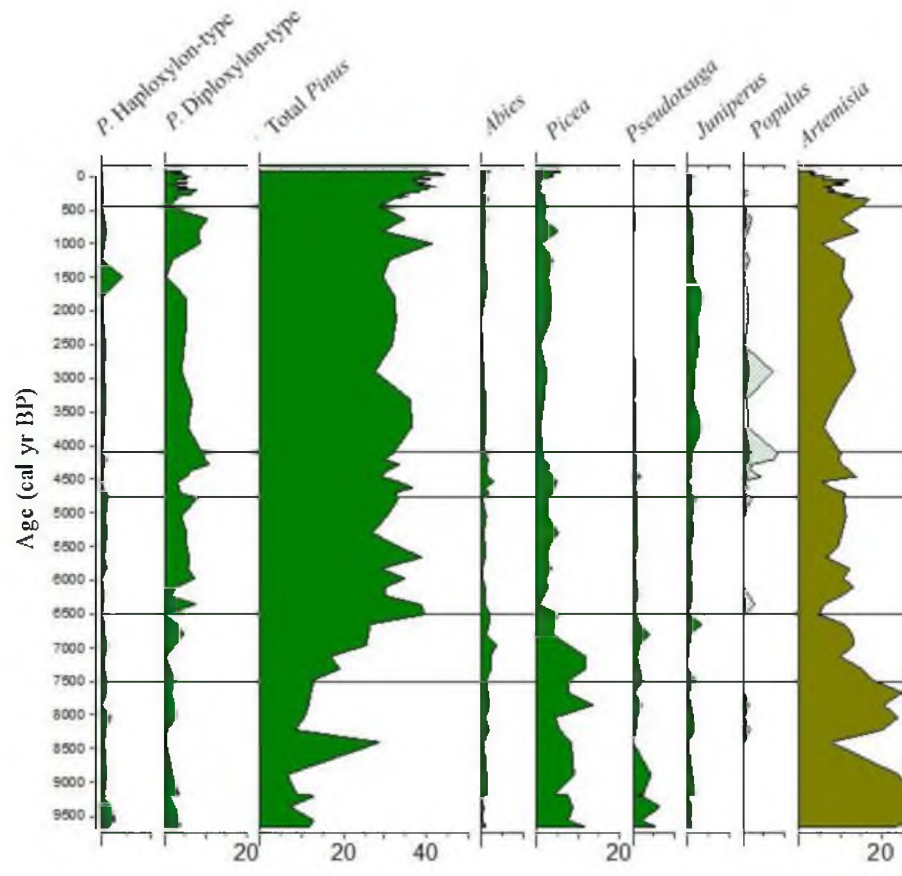
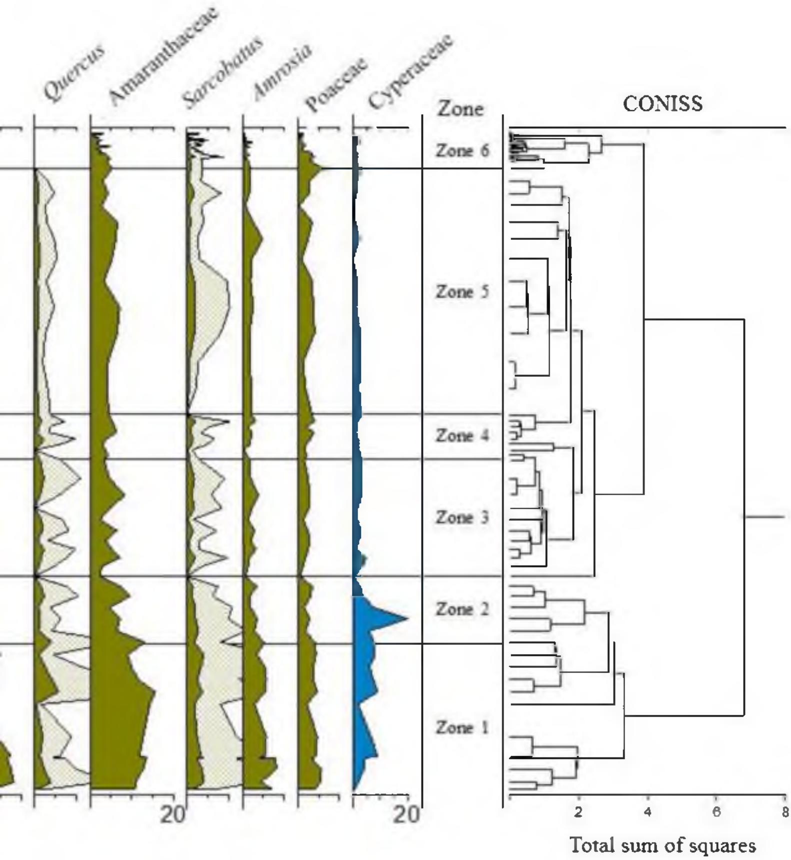


Figure 27. Pollen percentage diagram for Salamander Pond, Utah


Quercus
Amaranthaceae
Sarcobatus
Amrosia
Poaceae
Cyperaceae
Zone
CONISS
Zone 6
Zone 5
Zone 4
Zone 3
Zone 2
Zone 1
20
20
2
4
6
8
Total sum of squares

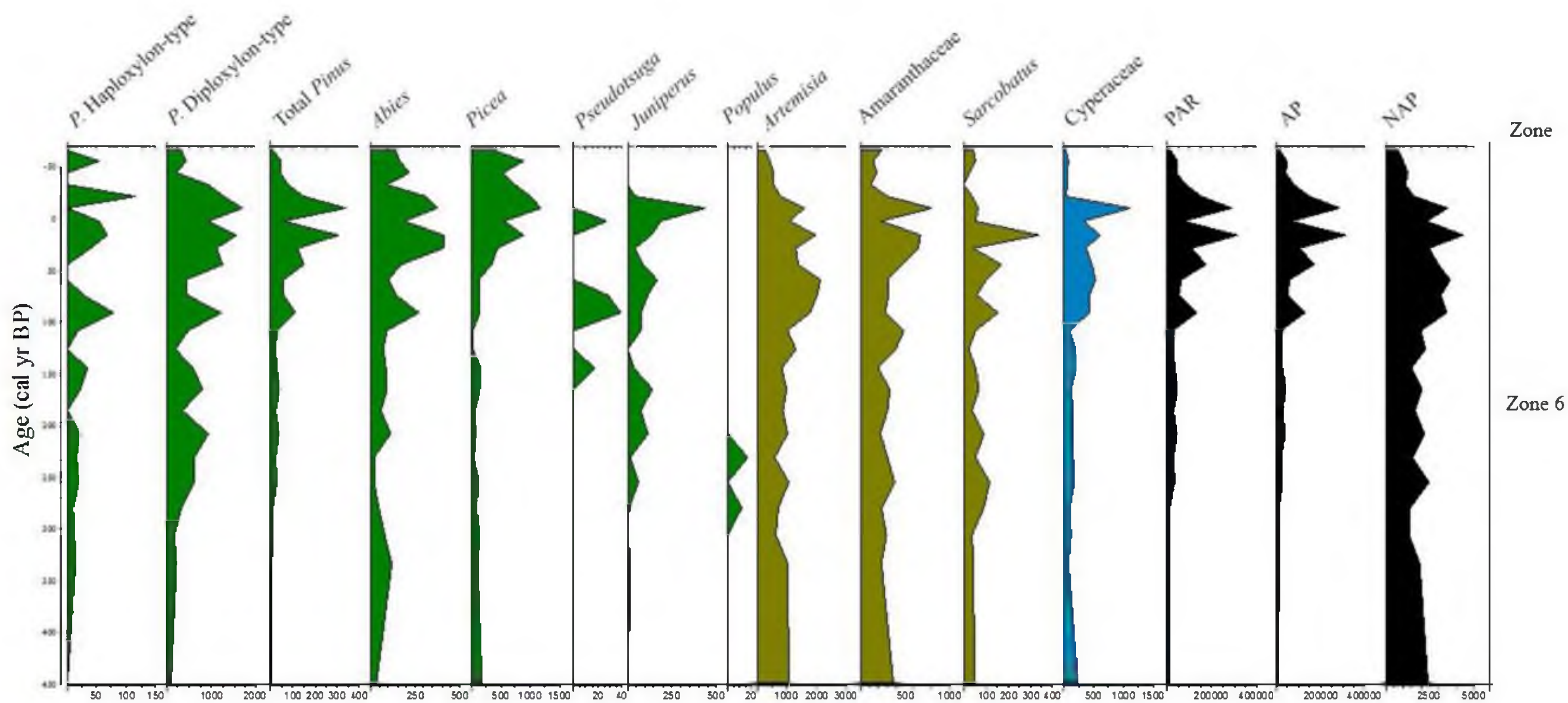


Figure 28a. Modern pollen influx diagram for Salamander Pond.

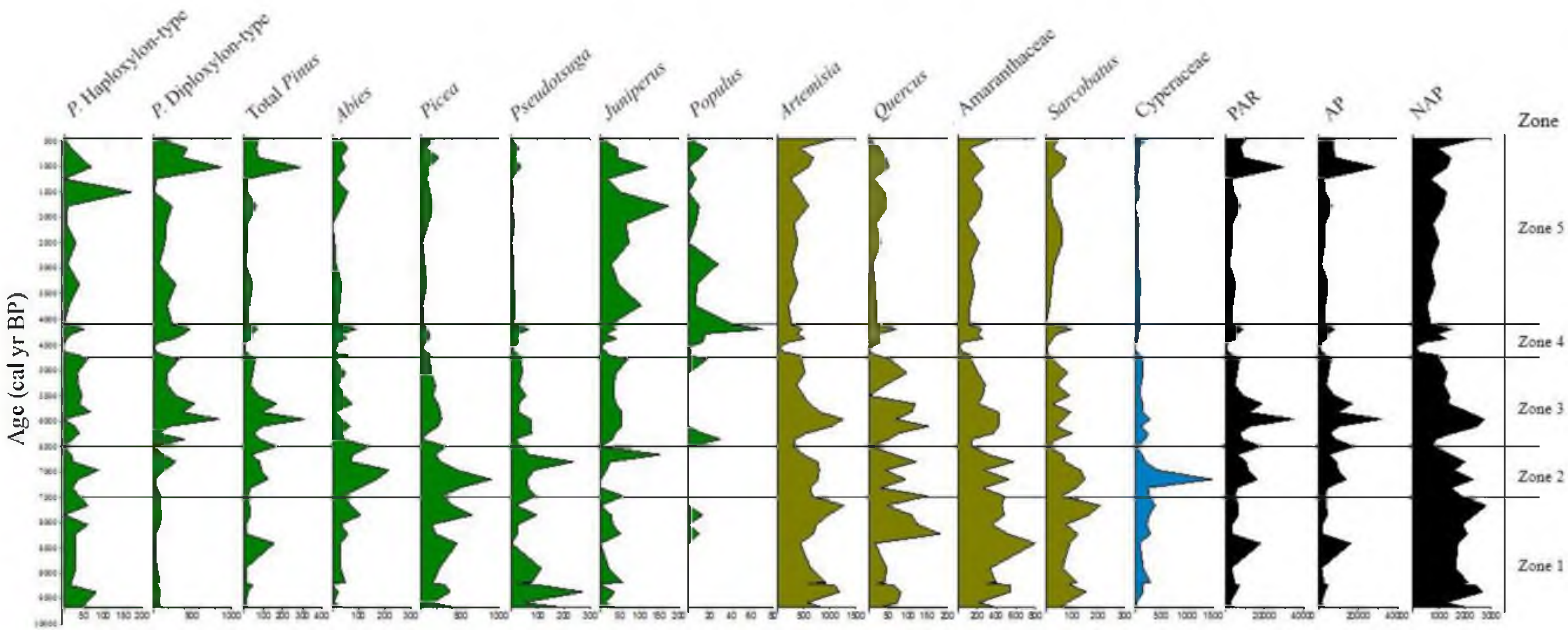


Figure 28b. Holocene pollen influx diagram for Salamander Pond.

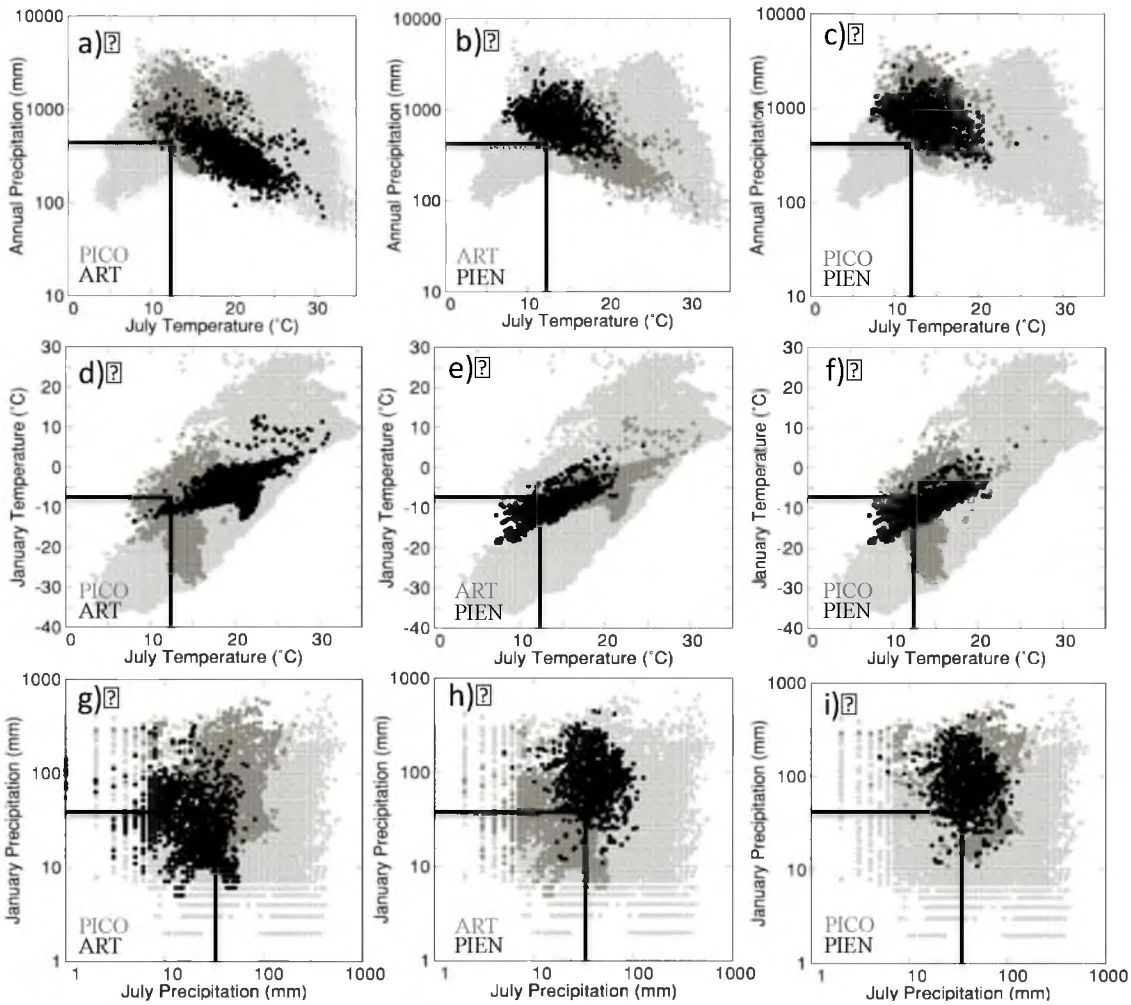


Figure 29. Modern climate envelopes for sagebrush (*Artemisia tridentata*), lodgepole pine (*Pinus contorta*), and Engelmann spruce (*Picea engelmannii*). Black lines indicate modern precipitation and temperature values using PRISM and SNOTEL data.

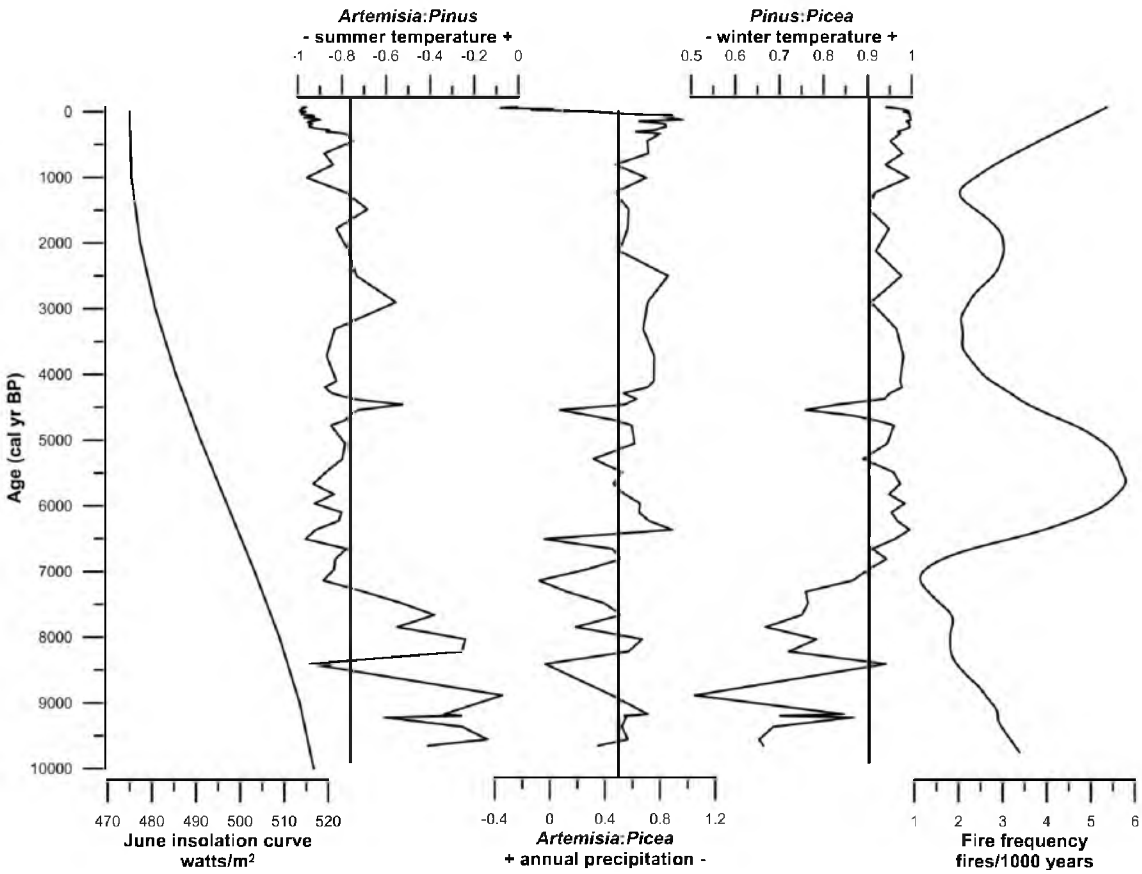


Figure 30. Pollen ratio data for Holocene summer and winter temperature, and annual precipitation compared to June summer insolation (watts/m^2) and fire frequency (the number of fires per 1,000 years) from Salamander Pond.

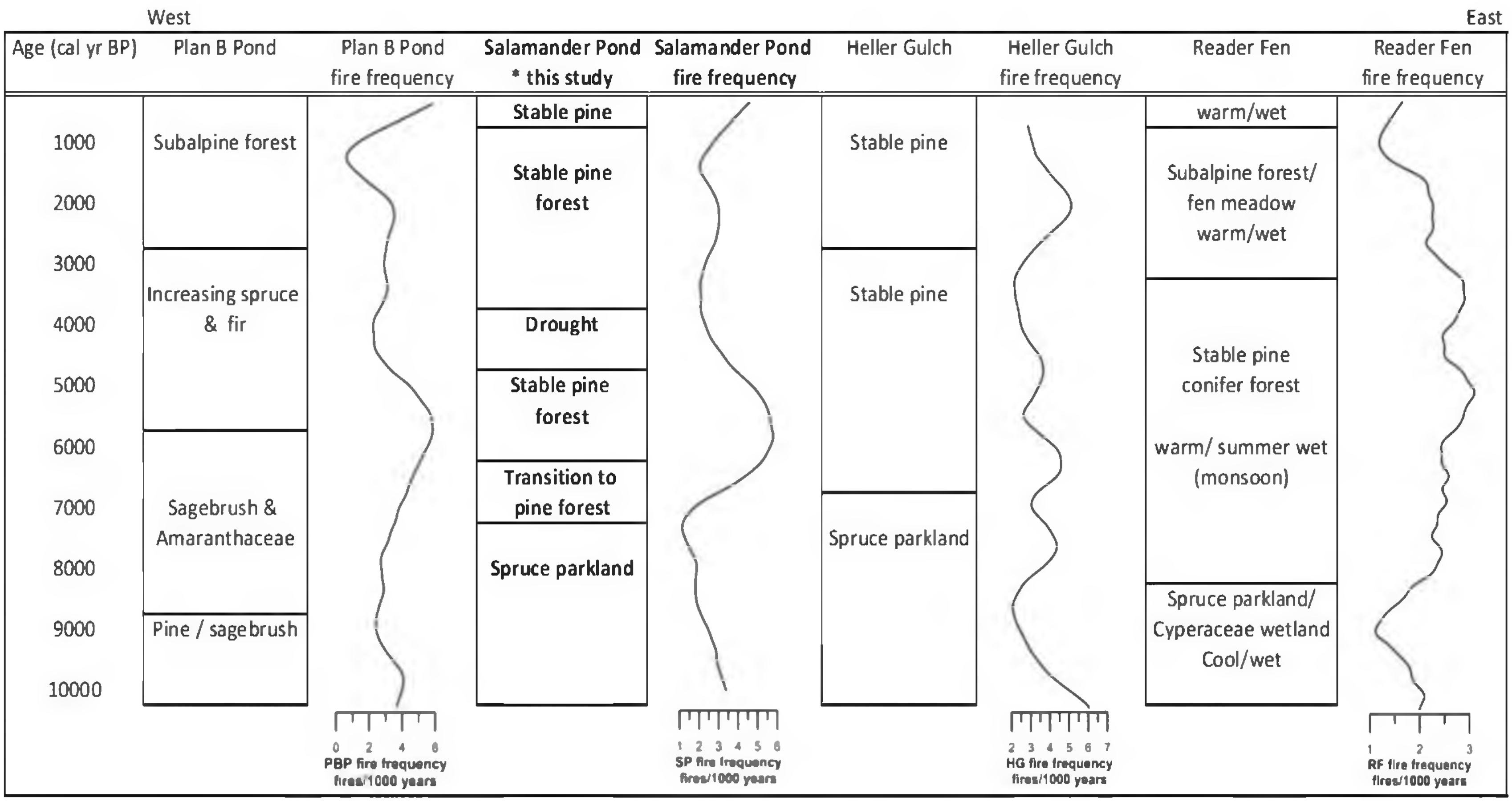


Figure 31. Regional vegetation and fire frequency diagram.

CHAPTER 5

SUMMARY OF THE ROLE OF CLIMATE VARIABILITY AND DISTURBANCES ON FOREST ECOLOGY IN THE INTERMOUNTAIN WEST

Summary

The primary research objective for this dissertation research was to determine how changes in climate on centennial-to-millennial timescales influenced vegetation composition and wildfire regimes in subalpine and montane-forested ecosystems from the Intermountain West region of the western US. The goal of this research was to provide managers with long-term information regarding the natural range of variability of climate change, of vegetation history, and of wildfire frequency that could then be applied to current and future management practices and conservation strategies that would facilitate ecosystem health. This dissertation applied a paleoecological approach, which used sedimentary proxies such as charcoal and pollen as records of past ecological changes. Paleoecological reconstructions are helpful to land managers because they provide valuable information about past ecological responses and how future ecosystems may respond with future changes in forest disturbance regimes (Millar et al., 2007).

Research from this dissertation focused on three primary research questions and hypotheses. The first research objective and working hypotheses from Chapter 2 were:

1. Determine the role of climate and wildfire on quaking aspen (*Populus tremuloides*) communities from a site in southeastern Wyoming.
    a. $Hypothesis_1$: Warmer temperatures will exert primary control over aspen pollen production.
    b. $Hypothesis_2$: Wildfire activity will exert primary control over aspen pollen production.

Chapter 2, "Climate variability and fire effects on quaking aspen in the central Rocky Mountains, USA," investigated the conditions that allowed for a period of aspen dominance in the Medicine Bow Mountains between 3950 and 3450 cal. yr BP coined the *Populus* period (Carter et al., 2013; Carter et al., *in review*). Using a modern pollen-climate analog as a proxy for reconstructing changes in temperature and precipitation, the data from this particular research suggest that increased temperatures centered ~4,200 cal yr BP was the primary mechanism that caused upslope migration of the stable quaking aspen ecotone. Currently, the modern aspen ecotone is located ~200 m downslope from Long Lake. If we apply a basic environmental lapse rate of $1^{o}C/100$ m, an increase of ~$1^{o}C$ would facilitate upslope migration of the aspen ecotone. Therefore, we can say that the original hypothesis (1) is true. Paleo-quaking aspen stands appear to be more sensitive to increased temperatures of ~$1^{o}C$. The results from this study also demonstrate that a more frequent fire regime helped to maintain aspen dominance for roughly 500 years. However, once fire frequency decreased to a fire regime typical of a lodgepole pine forest, aspen was no longer able to persist in the Long Lake watershed. This suggests that with future warming temperatures, quaking aspen stands may migrate upslope to more suitable climatic conditions. Additionally, future climate change will likely bring more frequent fire activity, which may also help facilitate the species expansion upslope.

The second research objective and working hypotheses from Chapter 3 were:

2. Determine whether the position of the El Niño Southern Oscillation dipole transition zone influences vegetation and wildfire activity in south central Utah.
    a. $Hypothesis_1$: The position of the dipole transition zone is non-stationary through time, and affects vegetation composition and wildfire frequency in south central Utah.
    b. $Hypothesis_2$: The position of the dipole transition zone is stationary through time, and does not affect vegetation composition and wildfire frequency in south central Utah.

Chapter 3, "Hydroclimate variability and fire-vegetation responses over the past 1,300 years at Fish Lake, south central Utah," investigated the ecological responses to changes in climate and moisture availability. Because Fish Lake is near the present day ENSO dipole transition zone (DTZ), this study investigated whether the position of the DTZ has shifted spatially and temporally, and whether changes in the geographic position has influenced the ecosystem at Fish Lake. In order to determine changes in the position of the ENSO DTZ, a pollen ratio was created that consisted of pollen taxa that are indicative of both winter and summer precipitation. The winter:summer precipitation ratio was then compared to a reconstructed winter precipitation record from a speleothem from Minnetonka Cave located on the Utah/Idaho border. From this comparison, we were able to suggest that the first working hypothesis is true; the position of the DTZ has been nonstationary both temporally and spatially throughout the state of Utah, and that the ecosystem at Fish Lake is sensitive to both small- and large-scale fluctuations in climate and moisture availability. During the Medieval Climate Anomaly (MCA), reconstructed temperatures were consistently warmer-than-present. Winter precipitation was more abundant at both Fish Lake and Minnetonka Cave, suggesting either a more southerly-than-modern or more easterly-than-modern position of the DTZ. Therefore, abundant winter moisture led to an increase in fine fuels on the landscape, while warmer temperatures led to more a more frequent fire regime. However, during the Little Ice Age (LIA), the winter:summer precipitation ratio diverged from the reconstructed winter precipitation record from Minnetonka Cave, suggesting a more current-like position of the DTZ and possibly less winter precipitation at Fish Lake. Reconstructed temperatures were cooler-than-modern during the LIA, which influenced the fire regime by creating an infrequent fire regime. As a result of an infrequent fire regime, vegetation composition was comprised primarily of trees, but because fuel connectivity was low, coupled with cooler temperatures, fires were of low severity. However, during the modern period, temperatures have increased to temperatures similar to the MCA. Additionally, the 20th century has experienced above average precipitation when compared to the past 1,300 years. Therefore, we would expect an increase in fine fuels and fire frequency at Fish Lake, similar to during the MCA. However, modern grazing of cattle and sheep has reduced herbs (i.e., fine fuels) in the Fish Lake basin, which has left the ecosystem to be comprised of mainly woody biomass (i.e., trees). The increase in woody biomass coupled with recent warming temperatures has led to an increase in fire severity on the landscape, suggesting that the Fish Lake basin is experiencing a novel state compared to the past 1,300 years.

Finally, the last research objective and working hypotheses from Chapter 4 were:

3. Determine the dominant controls of wildfire regimes on the north slope versus the south slope of the Uinta Mountains, Utah.
    a. $Hypothesis_1$: Fire regimes on the north slope are more responsive to changes in winter moisture, while fire regimes on the south slope are more responsive to changes in summer moisture.
    b. $Hypothesis_2$: Fire regimes on the north slope are not responsive to changes in climate, but rather respond to changes in vegetation composition (i.e., fuels).

Chapter 4, "Climate-fire-vegetation linkages from the north slope of the Uinta Mountains," investigated the large-scale drivers of fire activity in the Uinta Mountains. Currently, different regions of the Uinta Mountains are influenced by different moisture patterns, with the northwest region experiencing more winter precipitation, and the southeast region experiencing more summer precipitation. Therefore, these regions can be classified as either a winter wet or summer wet precipitation regime. Therefore, we hypothesize that the fire regime for each region of the Uinta Mountains is influenced by changes in seasonal moisture. By comparing the fire frequency record from Salamander Pond, located on the north slope to Heller Gulch and Reader Fen located on the south slope, as well as Plan B Pond located in the Bear River Range, the results from this research demonstrate that the fire frequencies from each region are influenced by different variables. Currently, the most recent increase in fire activity has been correlated to the earlier onset of winter snowmelt (i.e., a longer summer season) (Westerling et al., 2006). If we analyze the length of the summer season beyond the modern era, we see that changes in winter and/or annual precipitation and the length of the summer season have been the prominent control of wildfire from the sites located furthest west (Plan B Pond and Salamander Pond) in the present-day winter wet precipitation regime. However, according to the two charcoal records located furthest east (i.e., Heller Gulch and Reader Fen) in the present day summer wet precipitation regime, fire frequency appears to fuel limited throughout the Holocene, suggesting that site characteristics played a more important role in the fire regime on the south slope of the Uinta Mountains. Vegetation across the region appears to be linked with changes in both winter and summer temperature, which has been directly influenced by changes in insolation throughout the Holocene. Therefore, we can say that the original hypothesis (1) is both true and false; the most important variable influencing the fire regime on the north slope of the Uinta Mountains is changes in winter and/or annual precipitation (Hypothesis = true). However, changes in moisture availability were difficult to interpret from the two sites on the south slope, as these two sites were mostly fuel limited throughout the Holocene (Hypothesis = false). It is yet to be determined whether the fuel limitations were a result of changes in summer precipitation or changes in fuel moisture.

Regional Synthesis and Land Management Applications

The concept ‘natural range of variability’ is an important phrase in ecosystem management and conservation because it proves baseline context about the full spectrum of changes that an ecosystem has experienced in the past. In this dissertation, the research analyzed the natural range of variability of three separate variables: the natural range of climate variability, of vegetation change, and of wildfire frequency. This dissertation has demonstrated that the Intermountain West has experienced both gradual changes in climate, and abrupt climatic changes, revealing that there is a wide natural range of climatic variability that has influenced ecosystems through out the Holocene in the Intermountain West. The gradual changes in climate variability influenced vegetation composition and fire regimes on different temporal scales. On centennial-to-millennial timescales, changes in insolation appear to be the primary driver of gradual changes in vegetation, which subsequently influenced the fire regime. For example, during the early Holocene, Salamander Pond experienced a gradual change in forest composition from an open spruce parkland to a lodgepole pine-dominated forest as a result of increased summer temperatures that resulted from summer insolation. Subsequently, wildfire frequency was infrequent at Salamander Pond as a result of the vegetation composition (i.e., an open-spruce parkland) during the early Holocene, despite the length of the summer season being conducive for wildfire occurrence. However, since the mid-1980s, the length of the summer season has been increasing as a result of warmer spring and summer temperatures (Westerling et al. 2006), yet the modern ecosystem is composed of lodgepole pine. The increase in temperatures coupled with a lodgepole pine, which is more conducive for wildfire suggests that conditions are much more favorable for frequency wildfire activity in the Uinta Mountains at modern.

On shorter timescales (i.e., centennial) abrupt changes in climate have caused short term reorganization of vegetation composition, which ultimately affected biomass (i.e., fuels) availability temporarily. The most dramatic example of this reorganization of vegetation composition that was detected from this research were the ecological impacts recorded in the sedimentary records from Long Lake, WY and Salamander Pond, UT in association with the drought that occurred ~4,200 cal yr BP. Booth et al. (2005) presented both biological and physical evidence from the across the Great Plains region that supports the notion of large spatial extent that was affected by a drought that occurred around 4,200 cal yr BP. The site located furthest west that Booth et al. (2005) discuss that recorded an ecological response to the drought was from the Ferris Dune Field, located ~80 km northwest of Long Lake. Here, we present evidence from the north slope of the Uinta Mountains located farther west than the Ferris Dune Field, which suggests that this drought had a much larger spatial extent than once thought. This is significant because droughts are projected to intensify in the future under warmer temperatures (IPCC, 2014.

Similar to Salamander Pond, changes in vegetation composition and fire frequency have occurred at Fish Lake on shorter timescales as a result of recent climatic phenomena. For example, when temperatures increased during the Medieval Climate Anomaly ~900 cal yr BP, wildfires became more frequent as conditions were more conducive for burning because of the dominance of grasses and other fine fuels. However, the current landscape at Fish Lake is dominated by more tree species than fine fuels. The difference in vegetation composition is concerning because temperatures are similar to those experienced during the Medieval Climate Anomaly, suggesting that the fire regime is experiencing a 'novel' state; that the severity of wildfires in the Fish Lake area is greater because of the vegetation composition.

As we look towards the future, the information gained from this dissertation regarding the natural range of climate variability and the different timescales that climate variability influences vegetation composition and wildfires in the Intermountain West is beneficial for ecosystem management and conservation for several reasons; 1) the Intermountain West has experienced droughts were more severe and longer in duration droughts than the droughts that have occurred in the 20th century. However, as demonstrated by this dissertation, the spatial extent of past of historic droughts, specifically the drought centered around 4,200 cal yr BP was much larger than once thought, impacting portions of the interior western US.; and 2) Wildfire frequency in the Intermountain West is heavily impacted by climate, which influences the vegetation composition (i.e., fuels). Understanding both the spatial and temporal footprint of past droughts is important for many conservationists and land managers because of the potential outcomes for many natural resources, such as water availability and ecosystems. Therefore, ecosystem management should consider the dominant vegetation type that is currently in place, but also the potential conversion of ecosystems as biomes begin to shift in latitude or elevation as a result of warming temperatures and address the potential implications that climate will have on subsequently changing the natural fire regime of an ecosystem.

Future Research

While sedimentary records record ecological changes within an ecosystem, these sedimentary proxies that are preserved fail to record large-scale synoptic mechanism that may have caused the ecological changes recorded. Therefore, my future research will consist of trying to piece together potential climatic mechanism and synoptic processes that could have caused the wide range in ecological responses in order to understand how large-scale climatic mechanism influence local-scale ecological change. To begin with, I will investigate the ecological responses recorded at both Long Lake and Salamander Pond in response to the drought centered on 4,200 cal yr BP. One way to investigate potential climate mechanism and synoptic processes associated with drought is to use a modern climate analog technique (Mock & Shinker, 2013). The modern climate analog technique relies on the principle of uniformitarianism and assumes that modern synoptic and dynamic climate processes operated similarly in the past as they do today. The modern analog technique is an effective way to identify climate mechanism associated with past environmental changes since in the sedimentary record (Edwards et al., 2001; Mock & Brunelle-Daines, 1999; Shinker et al., 2006; Shinker, 2014). The modern climate analog is simply a conceptual model that uses modern extremes (e.g., drought) as analogs of past events to identify possible synoptic and dynamic patterns that may have caused extremes in the past in order to explain historic paleoclimate variability (Edwards et al., 2001; Shinker, 2014). Applying the modern analog approach to the paleoenvironmental approach will be beneficial because it can provide climate models of more informative ecological responses to past climate variability, which can then be integrated into future climate models regarding potential ecological changes to future climate change. This information is valuable to ecosystem management because land mangers could use this information to implement conservation targets or that would help maintain ecosystem health and function in the upcoming decades.

Additionally, the research conducted from this dissertation provides a foundation for my future research program. Because the Intermountain West is characterized as a climatologically complex region, it is the ideal location to study how changes in climate and moisture patterns influence ecosystems spatially and temporally. Knowing the natural range of climate variability and its impacts on ecosystems from this region has provided me the toolset to begin looking at the region on a much larger spatial scale in order to provide ecosystem managers with more beneficial information regarding ecological responses to climate variability.

For my future research program, I will continue to pursue collecting sedimentary records from across the Intermountain West to fill in the knowledge gap from this region. Currently, only a handful of paleoenvironmental reconstructions exist from the region, which makes it difficult to interpret how both gradual and abrupt changes in climate influence ecosystems from the region. However, in the future, I think it's beneficial to incorporate more proxies than what this dissertation used. Proxies such as isotope analysis, grain-size, X-ray fluorescence (XRF), and dendroclimatology would greatly improve our understanding of the linkages among climate-vegetation-disturbances. Additionally, I think it is important to continue working with land management agencies and conservationists in order to provide baseline knowledge that will benefit their policies that maintain ecosystem function.

Future research questions in my research program include, 1) How have climate variability and fire regimes affected other paleo-quaking aspen stands in the Intermountain West?; 2) How have large-scale changes influenced changes in moisture patterns in the Intermountain West?; 3) How have changes in moisture patterns influenced vegetation composition and disturbance regimes on longer-timescales in the Intermountain West?

REFERENCES

Abrams, M.D. (1990). Adaptations and responses of drought in *Quercus* species of North America. *Tree Physiology*, *7*, 222-238.

Agee, J.K. (1993). *Fire ecology of Pacific Northwest forests*. Washington DC: Island Press.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, N., Mcdowell, M., Vennetier, T., … Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, *259*, 660-684.

Anderegg, L.D.L., Anderegg, W.R.L., Abatzoglou, J., Hausladen, A.M., & Berry, J.A. (2013a). Drought characteristics' role in widespread aspen forest mortality across Colorado, USA. *Global Change Biology*, *19*, 1526-1537.

Anderegg, W.R.L., Plavcová, L., Anderegg, L.D.L., Hacke, U.G., Berry, J.A., & Field, C.B. (2013b). Drought's legacy: Multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased future risk. *Global Change Biology*, *19*, 1188-1196.

Anderson, L. (2011). Holocene record of precipitation seasonality from lake calcite ^{18}O in the central Rocky Mountains, United States. *Geology*, *39*, 211-214.

Anderson, L. (2012). Rocky Mountain hydroclimate: Holocene variability and the role of insolation, ENSO, and the North American Monsoon. *Global and Planetary Change*, *92*, 198-208.

Arno, S.F. (1980). Forest fire history in the Northern Rockies. *Journal of Forestry*, *78*(8), 460-465.

Balch, J.K., Bradley, B.A., D'Antonio, C.M., & Gomez-Dans, J. (2013). Introduced annual grass increases regional fire activity across the arid western USA (1980-2009). *Global Change Biology*, *19*, 173-183.

Barron, J.A., & Anderson, L. (2011). Enhanced Late Holocene ENSO/PDO expression along the margins of the eastern North Pacific. *Quaternary International*, *235*(1-2), 3-12.

Barron, J.A., Metcalfe, S.E., & Addison, J.A. (2012). Response of the North American monsoon to regional changes in ocean surface temperature. *Paleoceanography*, *27*, 1-17.

Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., … Whitlock, C. (1998). Paleoclimate simulations for North America over the past 21,000 years: Features of the simulation climate and comparisons with paleoenvironmental data. *Quaternary Science Reviews*, *17*, 549-585.

Bartos, D.L., & Mueggler, W.F. (1981). Early succession in Aspen communities following fire in western Wyoming. *Journal of Range Management*, *34*(4), 315-318.

Belsky, A.J., & Blumenthal, D.M. (1997). Effects of livestock grazing on stand dynamics and soils in upland forests of the Interior West. *Conservation Biology*, *11*(2), 315-327.

Billings, W.D. (1990). *Bromus tectorum*, a biotic cause of ecosystem impoverishment in the Great Basin. In G.M. Woodell (Ed.), *The Earth in transition: Patterns and processes of biotic impoverishment* (pp. 301-322). Cambridge, MA: Cambridge University Press.

Blaauw, M. (2010). Methods and code for 'classical' age-modeling of radiocarbon sequences. *Quaternary Geochronology*, *5*, 512–518.

Boisvenue, C., & Running, S.W. (2006). Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century. *Global Change Biology*, *12*, 862-882.

Booth, R.K., Jackson, S.T., Forman, S.L., Kutzbach, J.E., Bettis, III, E.A., Kreig, J., & Wright, D.K. (2005). A severe centennial-scale drought in the mid-continental North America 4200 years ago and apparent global linkages. *The Holocene*, *15*(3), 321-328.

Bradley, A.F., Noste, N.V., & Fischer, W.C. (1992). Fire ecology of forests and woodlands in Utah. Ogden, Utah: USDA Forest Service, Intermountain Research Station, General Technical Report INT-287, 128 pp.

Breshears, D.D., & Barnes, F.J. (1999). Interrelationships between plant functional types and soil moisture heterogeneity for semiarid landscapes within the grassland/forest continuum: A unified conceptual model. *Landscape Ecology*, *14*, 465–478.

Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., … Meyer, C.W., (2005). Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences*, *102*, 15144–15148.

Brigham Young University Digital Collections. http://contentdm.lib.byu.edu/cdm/search/Collection/GEA/searchterm/fish/field/all/mode/all/conn/and/order/title/ad/asc. Accessed December 13, 2015.

Brown, J.K., & Debyle, N.V. (1987). Fire damage, morality, and suckering in aspen. *Canadian Journal of Forest Research*, *17*, 1100-1109.

Brunelle, A., Whitlock, C., Bartlein, P., & Kipfmueller, K. (2005). Holocene fire and vegetation along environmental gradients in the Northern Rocky Mountains. *Quaternary Science Reviews*, *24*, 2281-2300.

Brunelle, A., Minckley, T.A., Delgadillo, J., & Blisset, S. (2014). A long-term perspective on woody plant encroachment in the desert southwest, New Mexico, USA. *Journal of Vegetation Science*, *25*, 829-838.

Calder, W.J., Parker, D., Stopka, C.J., Jiménez-Moreno, G., & Shuman, B.N. (2015). Medieval warming initiated exceptionally large wildfire outbreaks in the Rocky Mountains. *Proceedings of the National Academy of Science*, *112*(43), 13261-13266.

Carter, V.A., Brunelle, A., Minckley, T.A., Dennison, P.E., & Power, M.J. (2013). Regionalization of fire regimes in the Central Rocky Mountains, USA. *Quaternary Research*, *80*, 406-416.

Carter, V.A., Brunelle, A., Minckley, T.A., Shaw, J.D., DeRose, R.J., & Brewer, S. (*in review*). Climate variability and fire effects on quaking aspen in the central Rocky Mountains, USA. *Journal of Biogeography*.

Chambers, J.C., & Pellant, M. (2008). Climate change impacts on Northwestern and Intermountain United States rangelands. *Rangelandsi*, *30*(3), 29-33.

Clark, J.S. (1998). Particle motion and the theory of stratigraphic charcoal analysis: Source area, transportation, deposition and sampling. *Quaternary Research*, *30*, 81-91.

Cole, K.L., Henderson, N., & Shafer, D.S. (1997). Holocene vegetation and historic grazing impacts at Capital Reef National Park reconstructed using packrat middens. *Great Basin Naturalist*, *57*(4), 315-326.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., & Stahle, D.W. (2003). Long-term aridity changes in the western United States. *Science*, *306*, 1015-1018.

Courtney Mustaphi, C.J., & Pisaric, M.F.J. (2013). Varying influences of climate and aspect as controls of montane forest fire regimes during the late Holocene, south-eastern British Columbia, Canada. *Journal of Biogeography*, *40*, 1983-1996.

Cruzten, P.J., & Goldammer, J.G. (1993). *Fire in the environment: The ecological, atmospheric and climatic importance of vegetation fires*. New York: John Wiley and Sons.

D'Antonio, C.M., & Vitousek, P.M. (1992). Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology, Evolution, and Systematics*, *23*, 63-87.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., … Wotton, M. (2001). Climate change and forest disturbances. *BioScience*, *50*, 723–734.

Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., … Pasteris, P.P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology*, *28*, 2031-2064.

Dean Jr., W.E. (1974). Determination of carbonate and organic matter in calcareous sediments by loss on ignition: Comparison to other methods. *Journal of Sedimentary Petrology, 44*, 242-248.

Dennison, P.E., Brunelle, A., & Carter, V.A. (2010). Assessing canopy mortality during a mountain pine beetle outbreak using GeoEye-1 high spatial resolution satellite data. *Remote Sensing of Environment*, *114***,** 2431-2435.

Dennison, P.E., Brewer, S.C., Arnold, J.D., & Moritz, M.A. (2014). Large wildfire trends in the western United States, 1984 – 2011. *Geophysical Research Letters*, *41*(8), 2928 – 2933.

DeRose, R.J., Wang, S.Y., & Shaw, J.D. (2013). Feasibility of high-density climate reconstruction based on Forest Inventory and Analysis (FIA) collected tree-ring data. *Journal of Hydrometerology*, *14*, 375-381.

Dettinger, M.D., Cayan, D., Diaz, H., & Meko, D. (1998). North–south precipitation in western North America on interannual-to-decadal timescales. *Journal of Climate*, *11*, 3095–3111.

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*, 189-202.

Elliott, G.P., & Baker, W.L. (2004). Quaking Aspen (Populus tremuloides Michx.) at treeline: A century of change in the San Juan Mountains, Colorado, USA. *Journal of Biogeography*, *31*(5), 733-745.

Ellison, L. (1954). Subalpine vegetation of the Wasatch Plateau, Utah. *Utah Ecological Monograph*, *24*, 89–184.

Faegri, K., Kaland, P.E., & Kzywinski, K. (1989). *Textbook of pollen analysis*. New York: Wiley.

Fall, P.L. (1992). Pollen accumulation in a montane region of Colorado, USA: A comparison of moss polsters, atmospheric traps, and natural basins. *Review of Palaeobotany and Palynology*, *72*, 169-197.

Forman, S., Oglesby, R., & Webb, R.S. (2001). Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: Megadroughts and climate links. *Global and Planetary Change*, *29*, 1-29.

Gardner, J.J., & Whitlock, C. (2001). Charcoal accumulation following a recent fire in the Cascade Range, northwest USA and its relevance for fire-history studies. *The Holocene*, *11*, 541-549.

Gillespie, A.J.R. (1999). Overview of the annual inventory system established by FIA. *Journal of Forestry*, *97*(12), 16-20.

Gillies, R.R., Wang, S.-Y., & Booth, M.R. (2012). Observational and synoptic analyses of the winter precipitation regime change over Utah. *Journal of Climate*, *25*, 4679–4698.

Gray, S.T., Betancourt, J.L., Fastie, C.L., & Jackson, S.T. (2003). Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains. *Geophysical Research Letters*, *30*, 1-4.

Grimm, E. (1987). CONISS: A fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences, 13*(1), 13–35.

Harris, I., Jones, P.D., Osborn, T.J., & Lister, D.H. (2014). Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. International *Journal of Climatology*, *34*, 623–642.

Hanna, P., & Kulakowski, D. (2012). The influences of climate on aspen dieback. *Forest Ecology and Management*, *274*, 91-98.

Hansen, W.R. (2005). *The geologic story of the Uinta Mountains* (2nd ed.) Guilford, CT: The Intermountain Natural History Association and the Globe Pequot Press.

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*, *7*, 201–219.

Higuera, P.E., Briles, C.E., & Whitlock, C. (2014). Fire-regime complacency and sensitivity to centennial-through millennial-scale climate change in Rocky Mountain subalpine forests, Colorado, USA. *Journal of Ecology*, *102*(6), 1429-1441.

Hogg, E.H., Brandt, J.P., & Michaelin, M. (2008). Impacts of regional drought on the productivity, dieback, and biomass of Canadian aspen forests. *Canadian Journal of Forest Research*, *38*, 1373-1384.

Huerta, M., Whitlock, C., & Yale, J. (2009). Holocene vegetation–fire–climate linkages in northern Yellowstone National Park, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *271*, 170–181.

Intergovernmental Panel on Climate Change. (2014). Climate Change 2014: Synthesis Report. Core Writing Team, R.K. Pachauri & L.A. Meyer (Eds.), *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1-112). Geneva, Switzerland: IPCC.

Janetski, J.C. (1995). Archaeology and the Native American history of Fish Lake, Central Utah. BYU Museum of Peoples and Cultures Occasional Paper No. 16.

Jones, J.R., & DeByle, N.V. (1985). Fire. In N.V. DeByle & R.P. Winokur (Eds.), *Aspen: Ecology and management in the western United States* (pp. 77-81). Fort Collins, CO: USDA Forest Service Rocky Mountain Forest and Range Experiment Station.

Kashian, D.M., Romme, R.H., & Regan, C.M. (2007). Reconciling divergent interpretations of quaking aspen decline on the Northern Colorado Front Range. *Ecological Applications*, *17*(5), 1296-1311.

Kay, C.E. (1997). Is aspen doomed? *Journal of Forestry*, *95*, 4-11.

Keane, R., Ryan, K., Veblen, T., Allen, C., Logan, J., & Hawkes, B. (2002). Cascading effects of fire exclusion in Rocky Mountain ecosystems: A literature review. General Technical Report RMRS-GTR-91. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station, 1-24.

Keane, R.E., Hessburg, P.F., Landres, P.B., & Swanson, F.J. (2009). The use of historical range of variability (HRV) in landscape management. *Forest Ecology and Management*, *258*, 1025-1037.

Kelly, R.F., Higuera, P.E., Barrett, C.M., & Hu, F.S. (2011). A signal-to-noise index to quantify the potential for peak detection in sediment-charcoal records. *Quaternary Research*, *75*, 11-17.

Knight, D. (1994). *Mountains and plains*. New Haven, CT: Yale University Press.

Knight, T.A., Meko, D.M., & Baisan, C.H. (2010). A bimillennial-length tree-ring reconstruction of precipitation for the Tavaputs Plateau, Northeastern Utah. *Quaternary Research*, *73*, 107-117.

Koll, B. (2012). *Long-term vegetation, climate, and fire history in the eastern Uinta Mountains, Utah, U.S.A.* (Master's thesis). University of Utah, Salt Lake City, Utah, USA.

Kulakowski, D., Veblen, T.T., & Drinkwater, S. (2004). The persistence of Quaking Aspen (*Populus Tremuloides*) in the Grand Mesa Area, Colorado. *Ecological Applications*, *14*(5), 1603-1614.

Kulakowski, D., Kay, M.W., & Kashian, D.M. (2013). Long-term aspen cover change in the western US. *Forest Ecology and Management*, *299*, 52-59.

Kutzbach, J., Gallimore, R., Harrison, S., Behling, P., Selin, R., & Laarif, F. (1998). Climate and biome simulations for the past 21,000 years. *Quaternary Science Reviews*, *17*, 473-506.

Kurzel, B.P., Veblen, T.T., & Kulakowski, D. (2007). A typology of stand structure and dynamics of Quaking aspen in northwestern Colorado. *Forest Ecology and Management*, *252*, 176-190.

Landhäusser, S.M., Deshaies, D., & Lieffers, V.J. (2010). Disturbance facilitates rapid range expansion of aspen into higher elevations of the Rocky Mountains under a warming climate. *Journal of Biogeography*, *37*, 68-76.

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

Little, Jr., E.L. (1991). Atlas of United States Trees, vol. 1. Conifers and Important Hardwoods. US Department of Agriculture. Miscellaneous Publication 1146. Digitized 1999 by US Geological Survey. http://esp.cr.usgs.gov/data/little/.

Long, C.J., Whitlock, C., Bartlein, P.J., & Millspaugh, S.H. (1998). A 9000-year fire history from the Oregon Coast Range, based on high-resolution charcoal study. *Canadian Journal of Forestry Research, 28*, 774-787.

Lotan, J., Brown, J., & Neuenschwander, L. (1985). Role of fire in lodgepole pine forests. In D. Baumgartner, R.G. Krebill, J.T. Arnott, & G.F. Weetman (Eds.), *Lodgepole pine the species and its management* (pp. 133-152). Pullman, WA: Washington State University.

Louderback, L.A., Rhode, D., Madsen, D.B., & Metcalf, M. (2015). Rapid vegetation shifts in the Uinta Mountains (Utah and Wyoming, USA) during the Late Pleistocene and Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *438*, 327-343.

Luckman, B., & Kavanagh, T. (2000). Impact of climate fluctuations on mountain environments in the Canadian Rockies. *Ambio*, *29*, 371-380.

Lundeen, Z., Brunelle, A., Burns, S.J., & Polyak, V. (2013). A speleothem record of Holocene paleoclimate from the northern Wasatch Mountains, southeast Idaho, USA. *Quaternary International*, *310*, 83-95.

Lundeen, Z., & Brunelle, A. (2016). A 14,000-year record of fire, climate, and vegetation from the Bear River Range, southeast Idaho, USA. *The Holocene*, *26*(6), 833-842.

MacDonald, G.M., & Tingstad, A.H. (2007). Recent and multicentennial precipitation variability and drought occurrence in the Uinta Mountains Region, Utah. *Arctic, Antarctic, and Alpine Research*, *39*(40), 549-555.

Madsen, D.B., & Simms, S.R. (1998). The Fremont Complex: A behavioral perspective. *Journal of World Prehistory*, *12*(3), 255-336.

Maher, L.J. (1963). Pollen analyses of surface sediments from the southern San Juan Mountains, Colorado. *Geological Society of America Bulletin*, *74*, 1485–1504.

Maher, L.J. (1972). Absolute pollen diagram of for Redrock Lake, Boulder County, Colorado. *Quaternary Research*, *2*, 531–553.

Mann, M.E., Bradley, R.S., & Hughes, M.K., (1999). Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters*, *26*, 759-762.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., … Ni, F. (2009). Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, *326*, 1256-1260.

Marchetti, D.W., Harris, M.S., Bailey, C.M., Cerling, T.E., & Bergman, S. (2011). Timing of glaciation and last glacial maximum paleoclimate estimates from the Fish Lake Plateau, Utah. *Quaternary Research*, *75*, 183-195.

Marlon, J.R., Bartlein, P.J., Walsh, M.K., Harrison, S.P., Brown, K.J., Edwards, M.E., … Field, C.B. (2009). Wildfire response to abrupt climate change in North America. *Proceedings of the National Academy of Science*, *106*(8), 2519-2524.

Marlon, J.F., Bartlein, P.J., Gavin, D.G., Long, C.J., Anderson, R.S., Briles, C.E., … Walsh, M.K. (2012). Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Scienices*, *109*(9), E535–E543.

Massimino, J., & Metcalfe, D. (1999). New form for the formative. *Utah Archeology*, *1999*, 1-16.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., … Steig, E.J. (2004). Holocene climate variability. *Quaternary Research*, *62*, 243-255.

McDowell, N.G., Beerling, D.J., Breshears, D.D., Fisher, R.A., Raffa, K.F., & Stitt, M. (2011). The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in Ecology and Evolution*, *10*, 523-532.

McKenzie, D., Gedalof, Z., Peterson, D.L., & Mote, P. (2004). Climate change, wildfire, and conservation. *Conservation Biology*, *18*(4), 890-902.

Melgoza, G., Nowak, R.S., & Tausch, R.J. (1990). Soil water exploitation after fire: competition between Bromus tectorum (cheatgrass) and two native species. *Oecologia*, *83*, 7-13.

Menking, K.M., & Anderson, R.V. (2003). Contributions of La Nina and El Nino to middle Holocene drought and late Holocene moisture in the American Southwest. *Geology*, *31*, 937-940.

Millar, C.I., Stephenson, N.L., & Stephens, S.L. (2007). Climate change and forests of the future: Managing in the face of uncertainty. *Ecological Applications*, *17*(8), 2145-2151.

Minckley, T.A. (2003). *Holocene environmental history of the northwestern Great Basin and the analysis of modern analogues in western North America*. (Unpublished doctoral dissertation). University of Oregon, Eugene Oregon.

Minckley, T.A., Whitlock, C., & Bartlein, P.J. (2007). Vegetation, fire, and climate history of the northwestern Great Basin during the last 14,000 years. *Quaternary Science Reviews*, *26*, 2167-2184.

Minckley, T.A., Bartlein, P.J., Whitlock, C., Shuman, B.N., Williams, J.W., & Davis, O.K. (2008). Associations among modern pollen, vegetation, and climate in western North America. *Quaternary Science Reviews*, *27*, 1962-1991.

Mock, C. (1996). Climatic controls and spatial variations of precipitation in the western United States. *Journal of Climate*, *9*, 1111-1125.

Mock, C.J., & Brunelle-Daines, A.R. (1999). A modern analogue of western United States summer paleoclimate at 6,000 years Before Present. *The Holocene*, *9*, 541-545.

Mock, C.J., & Shinker, J.J. (2013). Modern analog approaches in paleoclimatology. In S.A. Elias (Ed.), *The encyclopedia of quaternary science* (vol. 3, pp. 102-112). Amsterdam, The Netherlands: Elsevier.

Monroe, J. (2003). Holocene timberline and palaeoclimate of the northern Uinta Montains, northeastern Utah USA. *The Holocene*, *13*(2), 175-185.

Monroe, J.S. (2006). Investigating the spatial distribution of summit flats in the Uinta Mountains of northeastern Utah, USA. *Geomorphology*, *75*, 437-449.

Morris, S.R. (2010). *After the Fremont: Fire and vegetation history of prehistoric abandonment and historic occupation of Range Creek Canyon* (Master's thesis). University of Utah, Salt Lake City, Utah, USA.

Morris, J.M., Brunelle, A., Munson, A.S., Spencer, J., & Power, M.J. (2013). Holocene vegetation and fire reconstructions from the Aquarius Plateau, Utah, USA. *Quaternary International*, *310*, 111-123.

Morris, J.L., DeRose, R.J., Brunelle, & Andrea R. (2015). Long-term landscape changes in a subalpine spruce-fir forest in central Utah, USA. *Forest Ecosystems*, *2*(35), 1-12.

Moy, C.M., Seltzer, G.O., Rodbell, D.T., & Anderson, D.M. (2002). Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, *420*, 162-165.

Mueggler, W.F. (1989). Age distribution and reproduction of intermountain aspen stands. *Western Journal of Applied Forestry*, *4*, 41-45.

Mueller-Dombois, D. (1992). A global perspective on forest decline. *Environmental Toxicology and Chemistry*, *11*, 1069-1076.

Mutch, R.W. (1994). Fighting fire with prescribed fire: a return to ecosystem health. *Journal of Forestry*, *92*(11), 31-36.

Nelson, N.A., & Pierce, J. (2010). Late Holocene relationships among fire, climate, and vegetation in rangeland ecosystems of southwestern Idaho. *The Holocene*, *20*, 1179-1194.

Overpeck, J.T., Webb III, T., & Prentice, I.C. (1985). Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogs. *Quaternary Research, 23*, 87-108.

Perala, D.A. (1990). *Populus tremuloides* Michx. Silvics of North America. In R.M. Burns & B.H. Honkala (Eds.), *Hardwoods Agriculture Handbook 654* (vol. 2, pp. 555-569). Washington, D.C: United States Department of Agriculture.

Rehfeldt, G.E., Ferguson, D.E., & Crookston, N.L. (2009). Aspen, climate, and sudden aspen decline in western USA. *Forest Ecology and Management*, *258*, 2352-2364.

Rogers, P.C., Eisenberg, C., & St. Clair, S.B. (2013). Resilience in Quaking Aspen: Recent advances and future needs. *Forest Ecology and Management*, *299*, 1-5.

Romme, W.H., Floyd-Hanna, L., Hanna, D.D., & Bartlett, E. (2001). Aspen's ecological role in the West. In W.D. Sheppard, D. Binkley, D.L. Bartos, T.J. Stohlgren, & L.G. Eskew (Eds.), *Sustaining Aspen in western landscapes* (pp. 243-259). Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station.

Salzar, M.W. (2000). *Dendroclimatology in the San Francisco peaks region of northern Arizona, USA*. (Doctoral Dissertation). The University of Arizona, Tuscon.

Shaw, J.D., & Long, J.N. (2007). Forest ecology and biogeography of the Uinta Mountains, U.S.A. *Arctic, Antarctic, and Alpine Research*, *39*(4), 614-628.

Salzer, M.W., & Kipfmueller, K.F. (2005). Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau, USA. *Climatic Change*, *70*, 465-487.

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

Schoennagel, T., Veblen, T.T., & Romme, W.H. (2004). The interaction of fire, fuels, and climate across Rocky Mountain Forests. *BioScience*, *54*(7), 661-676.

Shinker, J.J., Bartlein, P.J., & Shuman, B. (2006). Synoptic and dynamic climate controls of North American mid-continental aridity. *Quaternary Science Reviews*, *25*, 1401-1417.

Shinker, J.J. (2010). Visualizing spatial heterogeneity of western U.S. climate variability. *Earth Interactions*, *14*(10), 1-15.

Shinker, J.J. (2014) Climatic controls of hydrologic extremes in south-interior intermountain west of Colorado, U.S.A. *Rocky Mountain Geology*, *49*(1), 51-60.

Shinneman, D.J., Baker, W.L., Roger, P.C., & Kulakowski, D. (2013). Fire regimes of quaking aspen in the Mountain West. *Forest Ecology and Management*, *299*, 22-34.

Shuman, B.N., Pribyl, P., & Buettner, J. (2015). Hydrologic changes in Colorado during the mid-Holocene and Younger Dryas. *Quaternary Research*, *84*, 187-199.

Smith, J., Laven, R., & Omi, P. (1993). Microplot sampling of fire behavior on *Populus tremuloides* stands in north-central Colorado. *International Journal of Wildland Fire*, *3*, 85-94.

Steinman, B.A., Abbott, M.B., Mann, M.E., Stansell, N.D., & Finney, B.P. (2012). 1,500 year quantitative reconstruction of winter precipitation in the Pacific Northwest. *Proceedings of the National Academy of Science*, *109*(29), 11619-11623.

Stine, S. (1998). Medieval climatic anomaly in the Americas. In: Issar, A.S. and Brown, N., editors, *Water, Environment and Society in Times of Climatic Change*. Kluwer, pp. 43-67.

Stokes, S., & Gaylord, D.R. (1993). Optical dating of Holocene dune sands in the Ferris Dune Field, Wyoming. *Quaternary Research*, *39*, 274–281.

Stuvier, M., Reimer, P.J., & Braziunas, T.F. (1998). High-precision radiocarbon age calibration terrestrial and marine samples. *Radiocarbon*, *40*(3), 1127–1151.

Suding, K.N., & Hobbs, R.J. (2009). Threshold models in restoration and conservation: A developing framework. *Trends in Ecology and Evolution*, *24*, 271– 279.

Thompson, R., Battarbee, R.W., O'Sullivan, P.E., & Oldfield, R. (1975). Magnetic susceptibility of lake sediments. *Limnology and Oceanography*, *20*(5), 687-698.

Thompson, R.S., Anderson, K.H., & Bartlein, P.J. (1999). Atlas of relations between climatic parameters and distribution of important trees and shrubs in North America. Online publication. http://pubs.usgs.gov/pp/p1650-b/.

Thybony, S., Rosenberg, R.G., & Rosenberg, E.M. (1985). *The Medicine Bows: Wyoming's mountain country*. Cadwell, ID: Caxton Press

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., & Frank, D.C. (2009). Persistant positive north atlantic oscillation mode dominated the Medieval Climate Anomaly. *Science*, *324*, 78-80.

Turney, L. (2014). *Holocene climate, vegetation, and fire linkages in the Uinta Mountains, Utah* (Master's thesis). University of Utah, Salt Lake City, Utah.

van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fule, P.Z., … Veblen, T.T. (2009). Widespread increase of tree mortality rates in the western United States. *Science*, *323*, 521-524.

Weltz, M.A., Spaeth, K., Taylor, M.H., Rollins, K., Pierson, F., Jolley, L., … Rossi, C. (2014). Cheatgrass invasion and woody species encroachment in the Great Basin: Benefits of conservation. *Journal of Soil and Water Conservation*, *69*(2), 39-44.

Westerling, A.L., Gershunov, A., Brown, T.J., Cayan, D.R., & Dettinger, M.D. (2003). Climate and wildfire in the western United States. *American Meteorological Society*, *84*(5), 595-604.

Westerling, A.L., & Swetnam, T. (2003). Interannual to decadal drought and wildfire in the western United States. *EOS*, *84*(9), 545-560.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., & Swetnam, T.W. (2006) Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, *313*, 940–943.

Whitlock, C., & Bartlein, P.J. (1993). Spatial variations of Holocene climate change in the Yellowstone region. *Quaternary Research*, *39*, 231-238.

Whitlock, C., & Larsen, C.P.S. (2001). Charcoal as a fire proxy. In J.P. Smol, H.J.B. Birks, & W.M. Last (Eds.), *Tracking Environmental Change Using Lake Sediments* (vol. 3, pp. 75-97). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Whitmore, J., Gajewski, K., Sawada, M., Williams, J.W., Shuman, B., Bartlein, P.J., … Brubaker, L. (2005). Modern pollen data from North America and Greenland for multi-scale paleoenvironmental applications. *Quaternary Science Reviews*, *24*, 1828-1848.

Williams, J.W., Shuman, B., Bartlein, P.J., Whitmore, J., Gajewski, K., Sawada, M., … Davis, O. (2006). An Atlas of Pollen-Climate-Vegetation Relationships for the United States and Canada. AASP Contribution Series 43. Dallas, TX: American Association of Stratagraphic Palynologists Foundation, 239.

Williams, J.W., & Shuman, B. (2008). Obtaining accurate and precise environmental reconstructions from the modern analog technique and North American surface pollen dataset. *Quaternary Science Reviews*, *27*, 669-687.

Williams, P., Allen, C., Macalady, A., Griffin, D., Woodhouse, C.A., Meko, D.M., … McDowell, N.G. (2012). Temperature as a potential driver of regional forest drought stress and tree mortality. *Nature Climate Change*, *3*, 292–297.

Wise, E.K. (2010). Spatiotemporal variability of the precipitation dipole transition zone in the western United States. *Geophysical Research Letters*, *37*, L07706.

Wise, E.K. (2012). Hydroclimatology of the US Intermountain West. *Progress in Physical Geography*, *36*(4), 458-479.

Worrall, J.J., Egeland, L., Eager, T., Mask, R.A., Johnson, E.W., Kemp, P.A., & Sheppard, W.D. (2008). Rapid mortality of *Populus tremuloides* in southwestern Colorado, USA. *Forest Ecology and Management*, *255*, 686-696.

Worrall, J.J., Marchetti, S.B., Egeland, L., Mask, R.A., Eager, T., & Howell, B. (2010). Effects and etiology of sudden aspen decline in southwestern Colorado, USA. *Forest Ecology and Management*, *260*, 638-648.

Worrall, J.J., Rehfeldt, G.E., Hamann, A., Hogg, E.H., Marchetti, S.B., Michaelian, M., & Gray, L.K. (2013). Recent declines of *Populus tremuloides* in North America linked to climate. *Forest Ecology and Management*, *299*, 35-51.