Winter 2018

Two Post-Glacial Sagebrush Steppe Fire Records at the
Wildland_Urban Interface, Eastern Cascades, Washington

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TWO POST-GLACIAL SAGEBRUSH STEPPE FIRE RECORDS AT THE
WILDLAND-URBAN INTERFACE, EASTERN CASCADES, WASHINGTON

A Thesis
Presented to
The Graduate Faculty
Central Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Resource Management

by
Dusty Joel Pilkington
November 2018
We hereby approve the thesis of

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APPROVED FOR THE GRADUATE FACULTY

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Dean of Graduate Studies
Recent increases in large fires in the rapidly developing wildland-urban interface (WUI) areas of central Washington, where development intermixes with wildland fuels, contribute to federal firefighting costs exceeding of $1 billion annually. In addition, cheatgrass (*Bromus tectorum*) invasion and anthropogenic-caused warming shorten fire return intervals while lengthening fire seasons. These climatic, ecological, economic, and social factors combine with fuel accumulation resulting from historic fire suppression to threaten lives and property in the WUI. To plan for safe growth in WUI areas, long-term fire histories are needed to expand understanding of past fire regimes in an understudied ecosystem, sagebrush steppe. In this thesis, two ca. 15,000-year-old fire histories were developed from study sites in Okanogan County, Washington. Lake sediment cores were analyzed using macroscopic charcoal analysis and CharAnalysis software. Relationships between past fire, vegetation, human activities, and climatic drivers, such as the Early Holocene Warm Period, the Medieval Climate Anomaly, the Little Ice Age, and El-Niño Southern Oscillation, were considered. Results suggest that although climate influences eastern Cascades sagebrush steppe environments over millennial timescales, fuel availability represents a limiting factor over shorter intervals, with wet years allowing sagebrush and other fine fuels to proliferate, and fires occurring in subsequent dry intervals. The performance of CharAnalysis in sagebrush environments suggests that constant charcoal influx from frequent, low-severity fire events renders individual fire difficult to resolve from macroscopic charcoal records. The record analyzed here can inform decision makers in setting policies consistent with the long-term fire regime of the Methow Valley.
ACKNOWLEDGEMENTS

Many thanks to my thesis committee, Dr. Megan Walsh, Dr. Michael Pease, and Dr. Steven Hackenberger for their patience with my disorganized drafts, and their assistance in cobbling them into an organized narrative. I would also like to recognize the Kittitas Audubon Society, along with Central Washington University’s Graduate Studies and Research for their generous grants.

Special thanks to Zoe Rushton, Kevan Ferrier, Dr. Craig Revels, Hailey Duke, Sarah Jenson, Forest Beard, Megan Cline, and Kylie Ishimitsu for their generous laboratory and field assistance. I would like to acknowledge my family: my mom, my dads Eddie Pilkington and James Larson, both Dans: Hernandez and Ralph, my sisters Erica and Jessica, and my aunt Joni for coming to my thesis defense. My Utah friends for the encouragement: Tim and Jessi Done, Ty Norton, Dustin Booker, Ryan Baldwin, Justin Olson, Katie Maloney, and the Poulsen brothers. Washington friends: Lynn and Patience, Nic Crosby, Robert Moser, James Brown, Chazidy Norton and the whole clan in Spokane, along with Lucas Norton and Joseph Whisler.

Special regards to Dr. Karl Lilliquist for all the support, and to Dr. Elvin Delgado for pushing me to put together a top-notch thesis proposal. I also thank the faculty at Weber State University who helped me get to where I am: Dr. Julie Rich, Dr. Dan Bedford, and Dr. Carla Trentelman.

And most importantly, to my wife Liz. Your constant reminders that the best thesis is a completed thesis were indispensable in completing this work.
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CHAPTER I
INTRODUCTION

A recent increase in the occurrence of large, destructive wildfires in the western United States (US) is threatening lives and property in the wildland-urban interface (WUI) (Wimberly and Liu 2014). The WUI refers to lands developed with structures, such as detached single family homes, near undeveloped and fire-prone areas (Radeloff et al. 2005). In these areas, residential housing units increased by 15% in the states of Oregon, California, and Washington between the years 1990 and 2000 (Hammer et al. 2007). Rapid growth in the WUI presents challenges to fire managers, considering that fire ignitions have been shown to increase with development (Hawbaker et al. 2013, Cardille, Ventura, and Turner 2001), and fighting wildfires in WUI areas contributes significantly to federal firefighting costs, which can reach $1 billion per year (Stephens and Ruth 2005).

With the exception of the state of California (Renner, Reams, and Haines 2006), zoning regulations usually fall under the jurisdictions of local governments, and many municipalities lack regulations requiring defensible spaces between development and wildland fuels (Miller 2013). In the absence of strong regulatory frameworks, homeowners have little incentive to engage in voluntary measures to reduce risk to WUI lives and property (Reilly 2015). As a result, rapid development is occurring in areas at high risk of fire, with public firefighting expenditures strongly correlated with the number of homes near a wildfire (Miller et al. 2016). Fragmented development also
increases expenses. According to one modeling approach, efforts to protect an isolated home can add $225,000 to the cost of fighting a single fire (Scofield et al. 2015).

Factors compounding fire risk in the WUI are not limited to land use policy decisions and population growth. Fire suppression in the western US since the early 20th century has left an unwanted fuel legacy in many areas of the WUI, including the eastern Cascades of Washington (Marlon et al. 2012). Fire is a necessary component of forest communities; less intense fires consume fuel which can accumulate if left unburned (Keeton et al. 2007). However, one study shows that despite recent increases in fire activity, fire frequency remains below what would be expected with current temperature and precipitation levels in the Pacific Northwest (PNW) (Marlon et al. 2012). The authors imply that human activities such as fire suppression are to blame for this discrepancy and suggest that this “fire deficit” should not be expected to last long into the 20th century (Marlon et al. 2012). Compounding the fuel problem, cheatgrass (*Bromus tectorum*) invasions into WUI sagebrush zones in the PNW have created more continuous fuels, and have certainly increased fire risk (Bradley et al. 2006).

The intersection of residential development with legacies of historic fire suppression and invasive species became apparent during the fire seasons of 2014 and 2015. In 2014, the Carlton Complex Fire (CCF) occurred in Okanogan County, Washington. The fire burned more than 1,000 km², destroyed 300 homes, claimed one life, and set the record for the largest fire event in Washington State history (Hughes 2014). Suppression costs for this fire exceeded $60 million (McNiel 2014). The new record for a fire event lasted only a single year; the following fire season brought the Okanogan Complex Fire (OCF), which exceeded the CCF’s area burned by
approximately 20,000 hectares at a public cost of $21.54 million (InciWeb 2015). The OCF and the CCF burn perimeters are shown in Figure 1, both of which occurred near populated areas of Okanogan County.

Figure 2.1: The Carlton and Okanogan Complex burn areas. Note the nearby communities of Okanogan, Omak, Brewster, and Twisp. Tick marks indicate location in degrees latitude and longitude.

Global warming also compounds wildfire problems in the WUI and events such as the CCF and OCF are likely to become more common as human-induced warming
A number of models accounting for factors such as precipitation the year before and after a fire, slope, and vegetation types, using several emissions scenarios project up to a quadrupling of median area burned annually in the PNW by the year 2080 compared to 1916-2007 median values, with a 400% increase projected on the Columbia Plateau, and increases of up to 600% predicted in parts of Eastern Oregon and Idaho (Mote et al. 2014.; National Academies Press 2011). This is largely the result of earlier spring snowmelt in the western United States, which has led to a longer fire season (Westerling et al. 2006). The combined impact of fire suppression, climate change, and growth in the WUI means that now more than ever, knowledge of past fire frequency, magnitude, and relationships with climatic and human influences is needed.

One way to better understand current fire activity in WUI areas is through the reconstruction of charcoal-based fire histories. Charcoal-based fire histories are developed using lake sediments, and can stretch thousands of years into the past (Conedera et al. 2009). Knowledge of past fire frequency, severity, and other fire characteristics within sagebrush steppe/ponderosa pine ecotones in and around WUI communities in the eastern Cascades can assist policy makers in planning for future fire activity by identifying areas prone to fire over long-term timescales. This knowledge can allow development policies to be tailored to local, long-term fire risk. Long-term fire histories can also provide a rational basis to adopt such policies, however, no such histories are available in this area of the eastern Cascades.

Purpose and Objectives

The purpose of this study was to reconstruct the post-glacial fire history of two watersheds in the Methow Valley region of the eastern Cascades using macroscopic
charcoal analysis of lake sediment cores. The goal of this research was to better understand past relationships between fire activity, climate variability, and human activities for a relatively understudied ecological area, the sagebrush steppe/ponderosa pine ecotones of eastern Washington. Sediment cores were recovered from two study sites during the summers of 2012 and 2015; Green Lake, which sits at the north end of the valley just outside the CCF burn perimeter, and Campbell Lake, which exists in the valley’s northwest corner within the OCF burn perimeter, in order to better understand the long-term fire history in a rapidly developing area.

This research addressed the following research questions:

1) How has fire activity varied within and between the two study sites during the past ~15,000 years?
2) To what extent have climatic variability and human actions during the past ~15,000 years influenced fire activity at the two sites?
3) What do the Campbell and Green Lake records suggest about Holocene fire regimes in sagebrush steppe/ponderosa pine ecotone environments, and how do these regimes differ from those of other PNW environments?
4) How can this information be used to more effectively manage development in the WUI areas of the Methow Valley?

The specific objectives of this research were:

1) To reconstruct the fire history of the Green and Campbell lakes watersheds for the past ~15,000 years using macroscopic charcoal analysis of lake sediment cores.
   - Sediment cores were recovered from both Green and Campbell lakes and analyzed in the Paleoeocology Lab at Central Washington University. The
Green Lake sediment core was 687 cm in length and spanned ~14,700 calendar years before present (cal yr BP), and the Campbell core was 692 cm in length and spanned ~15,300 cal yr BP. The fire history for each site was performed using methods outlined in Long and Whitlock (1997) and modified by Walsh et al. (2008). The fire reconstructions were analyzed using the program CharAnalysis (Higuera et al. 2009a) to produce estimates of fire frequency and magnitude.

2) To evaluate the effects of climate variability and human actions on fire history at both study sites during the past ~15,000 years.

- Timing of fire activity was compared to known climatic and human events for each fire history. Climatic influences were inferred from published records, and included changes in summer insolation, precipitation, and relative influences of events such as the El Nino/Southern Oscillation (ENSO). Climatic events considered included glacial retreat in the Late Glacial, the Early Holocene Warm Period (EHWP), the Medieval Climate Anomaly (MCA), the Little Ice Age (LIA), and recent anthropogenic warming. Human events were inferred from archeological, ethnographic, and historic records within the Eastern Cascades and Plateau cultural regions. Historic events considered included Euro-American contact and settlement, and the advent of fire suppression policies.

3) To perform a regional comparison of fire activity at the two study sites with other fire histories from the PNW.
The fire histories from the study sites were placed into a regional context through a comparison with fire histories from similar ecozones, and a recently published regional fire summary (Walsh et al. 2015). Fire histories developed by other authors were compared with the Green and Campbell records to create a more complete Eastern Cascades fire record.

4) To provide Methow Valley policymakers with relevant information in making well informed decisions and communicating their rationales to the public.

Significance

This research is significant for several reasons. First, this study will extend our understanding of fire history in the PNW into a previously understudied ecosystem and add to the existing database of charcoal-based fire records for the PNW (Walsh et al. 2015). Walsh et al. (2015) aggregated and analyzed 34 macroscopic charcoal records spanning Washington, Oregon, and British Columbia. Of the 34 records analyzed, only four exist east of the crest of the Cascades, and only two came from sagebrush steppe or ponderosa pine environments. In addition, comparison of the records obtained to the timing of past warming events such as the MCA and shifts in ENSO variability can provide eastern Cascades land use planners with insights into future fire regimes within these ponderosa pine and sagebrush steppe environments.

Lastly, this study can help inform development policy in the WUI of the eastern Cascades. A long-term fire history can help in educating residents about fire’s natural role in the Methow Valley WUI, facilitating voluntary measures to reduce fire risk. These measures include fire conscious zoning regulations favoring clustered development, and the International WUI Code (IWUIC), which includes fuel management requirements,
building standards, participation in the Firewise program currently underway and conducted by the Okanogan Conservation District, and insurance rates intended to create incentives for fire resistant development (Miller et al. 2016; Okanogan Conservation District 2018). If WUI property owners are made aware of fire risks in their communities, they may cooperate with officials in efforts to create defensible spaces, ensure the use of fire resistant building materials, and promote home construction in clusters easily accessible to firefighting personnel (Miller et al. 2016).
CHAPTER II

LITERATURE REVIEW

Introduction to Fire in the Wildland-Urban Interface of the Eastern Cascades

Considering current and future climatic change, WUI development is likely to continue in areas projected to have radically different fire regimes than they have experienced historically. According to the Federal Register, where US government administrative regulations are posted for the public, the WUI is defined as areas where human development exists in close vicinity to wildland fuels (USFS 2001). WUI is subdivided into three categories: interface WUI, intermix WUI, and occluded WUI. Interface WUI refers to areas where a clear line exists between human development and wildland fuels, and where structure densities average more than 3 structures per km$^2$. Intermix WUI refers to areas where no clear boundary exists between human structures and wildland fuels, and where development densities are as low as one structure per 16 hectares. Occluded WUI refers to areas where development surrounds wild areas, such as open spaces and parks within urban areas (USFS 2001).

Current policies make distinctions between “natural” lighting fires and anthropogenic fires, instructing fire managers to allow certain natural blazes to burn, provided they do not threaten populated areas and do not escape pre-defined boundaries (Arno and Allison-Bunnel 2002). However, the area that can be allowed to burn without risk to lives and property decreases as the WUI expands, leading directly to increases in fire risks (Hammer et al. 2007). In the decade between 1990 and 2000, the United States added 13.6 million new housing units, with much of this growth occurring at low densities, reflecting Americans’ fondness for picturesque views and natural settings.
One geographic information system (GIS)-based study found that the WUI in the United States increased from 306,325 km$^2$ in 1970 to 465,614 km$^2$ in 2000, representing a 52% increase over that three decade period (Theobald and Romme 2007). Considering that private property concerns motivate 87% of firefighting efforts, increases in WUI area increases fire risks in populated areas, forcing firefighting resources to be allocated away from non-WUI areas. One estimate suggests a minimum annual level of funding required for fuel treatments across the entire United States WUI at $16 billion (Theobald and Romme 2007).

Fire risks in the WUI have been investigated at smaller geographic scales. Hammer et al (2007) used GIS methods to track WUI growth in the states of Washington, Oregon, and California from 1990–2000. The study used housing density data from the United States Census, land-cover classification courtesy of the National Land Cover Dataset (NLCD) for the three states to identify WUI areas in the three states, and to track their progression throughout the 90s. The WUI definitions provided in the Federal Register were used to define housing density thresholds assigning areas to intermix or interface WUI. Census blocks fitting these housing density thresholds were identified from the census data, and those near enough to land cover types such as shrublands, grasslands, or forests were classified as WUI.

The study found an increase in WUI area across the three states of interest, with development increasing WUI acreage by 11%. However, variation was found between the three states. California’s WUI grew by 8.7%, while the WUI in Oregon grew by 9.4%. Washington led the three states in WUI growth, with a 16.4% increase from 1990 to 2000. Combined, WUI in the three regions grew by 10.9%. Growth in the WUI can
exacerbate fire risk; fire ignitions have been shown to increase linearly with housing density (Hammer et al. 2007).

In the same publication, Hammer et al. (2007) performed additional mapping of Fire Regime Condition Class (FRCC). Lands within the states of Washington, Oregon, and California were aggregated into three categories according to fire return intervals (FRI), yielding three categories: 0-35 years, 35-100+ years, and 200+ years.

Table 2.1: Fire Regime Condition Classes

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<th>Condition Class</th>
<th>Attributes</th>
<th>Management Options</th>
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<td><strong>FRCC 1</strong></td>
<td>• Fire regimes in or near to historic ranges, • Low risk of key ecosystem component loss • Vegetation attributes within historic range.</td>
<td>Fire can be used to maintain conditions within historic fire regimes</td>
</tr>
<tr>
<td><strong>FRCC 2</strong></td>
<td>• Fire regimes moderately altered from historic parameters • Moderate changes in fire size, type, and severity. • Vegetation moderately altered from historic ranges.</td>
<td>Moderate levels of restoration treatments needed, including mechanical thinning and use of fire.</td>
</tr>
<tr>
<td><strong>FRCC 3</strong></td>
<td>• Fire regimes significantly altered from historic ranges • Dramatic changes in fire size, severity or landscape patterns have resulted • Vegetation attributes significantly altered from historic range</td>
<td>May need high levels of treatment to restore historic fire regimes.</td>
</tr>
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Areas within the three states of interest were classified per these categories, and as Condition 1, Condition 2, or Condition 3 according to the FRCC system. For example, a grid cell with a long return interval that had not departed far from its historical fire regime could be classified as 200+ with a condition class of 1, while an area where the historic return interval is 200+ years but has departed far from its historic fire regime would be assigned a condition class of 3 (Figure 2.1). (Hammer et al. 2007). The FRCC system as applied in the PNW is explained in Table 2.1 (Rice, Kertis, and Hawkins 2006).

According the study, 1.5 million American homes exist in regions in FRCCs 2

Figure 2.1: Historic return intervals and Fire Regime Condition Classes for the states of Washington, Oregon, and California. Note the areas marked Condition Class 2 and 3 along the eastern Cascades boxed in red (Hammer et al. 2007).
and 3 (Hammer et al. 2007). Figure 2.1 shows United States FRCCs within three FRI classes derived in the states of Oregon, Washington, and California (Hammer et al. 2007). Many areas to the east of the Cascades have FRIs of less than 35 years, while much of the region falls into FRCCs 2 and 3, and are “moderately” or “significantly” altered from their historic ranges of variability (Hammer et al. 2007). Much of the area just to the east of the Cascades is in FRCCs 2 and 3 (Figure 2.1). Remote sensing research has quantified relationships between WUI and fire ignitions. Fusco et al. (2016) used MODIS satellite data to detect ignition events using removal of vegetation and replacement with darker colored ash as proxies for fire events between the years 2000 and 2012. Fires within 4 km and four days of a lightning strike were removed from analysis to limit the study to anthropogenic fire ignitions. Fire ignitions were then classified spatially, according to Omernik Level I ecoregions, and statistical tests were run. In the Marine West Coast ecoregion, human land use and infrastructure factors such as distance to agricultural land, railroads, roads, and WUI accounted for 69% of variation in fire ignitions. On its own, distance to WUI was positively associated with fire ignitions, accounting for 10% of ignition variation (Fusco et al. 2016).

More complex relationships emerge when fire and the WUI are analyzed at finer spatial scales. Syphard et al. (2007) used GIS to perform statistical regressions using variables such as population density, distance to interface WUI, distance to intermix WUI, and road density to determine their effects on both fire ignitions and area burned in California. Results showed that human activities played primary roles in driving both areas burned and ignitions. However, these relationships were not linear. Fire ignitions per square kilometer peaked at 35 to 45 people per km$^2$ but declined with higher
population densities. The data showed a similar pattern with the WUI. Counties with moderate levels of WUI cover (25-35%) had the highest numbers of fire ignitions. The study suggested that fire risk to lives and property is highest at moderate levels of development, and that clustered, high density development in WUI areas can reduce fire risk.

Fire Regimes and General Background

Forest fires involve the release of stored solar energy through oxidation of chemical bonds within biomass (Agee 1993). For the oxidation process to occur, a confluence of factors must come together. There must be sufficiently dry fuel, a supply of oxygen, and heat to break the chemical bonds within plant tissues and to induce combustion (Agee 1994; Byram 2004). This relationship can be conceptualized as a “fire triangle” where all three sides (oxygen, fuel, and heat) must be present in order for a fire to occur (Byram 2004).

Short-term weather conditions affect fire activity by modifying the supplies of oxygen, moisture content of fuel, and temperature (Agee 1993). Precipitation levels influence the odds of fuel combustion. Water can absorb large amounts of heat energy which would otherwise have ignited the fuel. Thus, wetter fuels burn less often, and require more intense fires for combustion. Precipitation provides moisture to fuels, reducing the chances of fire ignition, while dry winds will reduce moisture content while providing oxygen, increasing the chance of combustion. Elevated air temperatures further evaporate water from fuels (Agee 1993).

The majority of naturally-ignited fires occur due to lighting strikes, while sources such as sparks from rock falls and volcanic eruptions account for a small minority (Agee
Lightning strikes generally occur during convectional thunderstorms striking different areas of the United States at varying frequencies. Fires peak in the dry, warm conditions found in the PNW during late summer, when temperatures are high and moisture levels are low (Hessl, McKenzie, and Schellhaas 2004). Recent warming is extending the length of the fire season in the Western US through earlier spring snowmelt and subsequently drier fuels later in the season (Westerling et al. 2006).

Individual fires can be classified in terms of intensity as surface, understory, or crown fires (Agee 1994). Surface fires are the lowest intensity classification, with flame lengths less than 1 m, primarily consuming ground-level vegetation. Understory fire flame lengths range between 1 and 3 m. Crown fires exceed flame lengths of 3 m and represent the highest intensity fires. Fire frequency is measured as a fire return interval (FRI), measuring the number of years between fires at a particular location (Agee 1993; Hessl, McKenzie, and Schellhaas 2004). A low FRI value indicates more frequent fires. Frequency can also be expressed as fires per a unit of time, commonly given as fires episodes/1000 years (Whitlock and Bartlein 2004).

A “fire regime” refers to a generalized way of describing fire conditions within an area under investigation (Agee 1994). Fire regimes can be described in terms of severity and frequency. A low severity, high frequency regime will feature frequent surface fires, while a high severity, low frequency regime may experience infrequent crown fires (Agee 1993). A mixed severity regime lies between these extremes (Brown, Agee, and Franklin 2004).

PNW plant species have evolved a wide variety of adaptations in response to variations in fire regimes (Agee, 1994). For example, some seeds of shrub and
herbaceous species can lie dormant for years, only to open in response to fire (Agee, 1994). Fireweed (*Epilobium angustifolium*) takes advantage of gaps cleared after fires by spreading seeds over large areas after disturbance, while shade-tolerant trees such as western juniper (*Juniperus occidentalis*) depend on environments where fire is all but absent (Agee 1993). Species such as ponderosa pine (*Pinus ponderosa*) develop thick bark, insulating it against damage from frequent, low intensity fires (Agee 1993).

These differences are reflected in observed FRIs. Vegetation cover in the eastern Cascades ranges from grand fir (*Abies grandis*) and Douglas-fir (*Pseudotsuga menziesii*)-dominated mid-elevation areas, to ponderosa pine-dominated locations in the drier, low elevations. Shrub steppe lands cover the lowest elevations and much of the Columbia Plateau. Fire regimes vary between vegetation cover types (Franklin and Dyrness 1973; Agee 1993). When fires occur in mesic (moist) environments with shade tolerant tree species, they tend to be of higher intensity (Agee 1993). In contrast, ponderosa pine and sagebrush communities experience more frequent and less intense fires.

FRIs as short as 3-5 years have been documented within some ponderosa pine environments, which is the dominant tree in lower elevation forests of the eastern Cascades. FRIs in PNW ponderosa pine environments are shorter and with lower intensity than in Douglas-fir communities, which tend to inhabit more mesic (moist) sites (Agee 1994). FRIs of 16-38 years and 7-20 years were observed in stand level fire scar studies of ponderosa pine conducted near Bend, Oregon, while FRIs of 11-16 years have been observed in fire scar studies of individual trees (Agee 1994). In undisturbed ponderosa pine communities, these relatively frequent fires kill understory vegetation and contribute to an open structure with few ladder fuels to carry fires to tree crowns (Agee
Fire history studies within eastern Cascades ponderosa pine environments are sparse, but show FRIs ranging from 6.6 to 18.8 years (Everett et al. 2000; Wright and Agee 2004). Prior to settlement, sagebrush steppe stands likely burned every 60-110 years, but now burn as often as every 5 years with the introduction of cheatgrass (*Bromus tectorum*), which provides a continuous and easily burnable fuel source (Whisenant 1990). The addition of invasive species to sagebrush environments occurs while human activities make ignitions of large fires more likely.

**Pacific Northwest Climate and Linkages with Fire**

Although short-term weather cannot be ignored, climate nonetheless exerts strong influences on fire regimes on longer timescales (Syphard et al. 2007). During the glacial period and the following Holocene epoch (last ~11,000 years), summer insolation values have varied in response to the earth’s orbital configuration in relation to the sun, with these variations influencing glacial retreat and advance along with fire behavior (Whitlock, Shafer, and Marlon 2003). Summer insolation was similar to modern values at the last glacial maximum, but earth’s orbital configuration shifted such that 8% more insolation struck the earth at 45°N latitude in the summer months at approximately 11,000 cal yr BP, and approximately 8% less sunlight struck the earth at that same latitude in winter. This intense seasonality strengthened the summer high pressure system over the PNW, leading to drier, more fire prone summers (Whitlock and Bartlein 1993).

Climatic factors affecting PNW fire regimes include El Niño Southern Oscillation (ENSO), summer drought, and summer insolation (Ferguson 2001). ENSO describes a 3-7 year oscillation between warm and cool Pacific Ocean sea surface temperatures and is associated with warm, dry PNW temperatures during its warm phases.
(Ferguson 2001). Keeton, Mote, and Franklin (2007) investigated ENSO, and wildfire area burned (WFAB) at three different spatial scales using historic wildfire area burned data spanning most of the 20th century. The researchers used national forest boundaries, state boundaries, and the boundaries for the United States Department of Agriculture (USDA) Region 6. Correlations were not found at the USDA Region 6 scale between WFAB and ENSO, while only one state showed such a relationship at the state scale. Five national forests showed significant associations between WFAB and ENSO (Keeton, Mote, and Franklin 2007). Fewer relationships between wildfire area burned and warm phase ENSO were found than expected. To account for the lack of direct significant relationships between wildfire area burned and ENSO, the authors suggest several factors explaining the disparity. 20th century fire suppression may have obscured the relationship between ENSO and wildfire area burned, and ENSO can also interact indirectly with fire by drying soil and vegetation, which is shown by a significant correlation in the study between warm phase ENSO and Palmer Drought Severity Index (PDSI) (Keeton, Mote, and Franklin 2007).

Longer-term climatic events can also influence fire regimes in the PNW, and include the LIA and the MCA (Marlon et al. 2012). The LIA was a cooling event that occurred from approximately 500 to 100 cal yr BP, while the MCA refers to a warming trend observed during the middle ages, from approximately 1100 to 700 cal yr BP (Mann et al. 2009). In the PNW, the LIA event generally led to a reduction in fire activity, while warm conditions during the MCA had the opposite effect (Marlon et al. 2012). However, increases in burning occurred at the beginning and end of each event, whether the shift
involved warming or cooling temperatures. Shifts to warmer or cooler conditions can increase tree mortality, and with it, fuel availability (Marlon et al. 2012).

Modern anthropogenic warming threatens to exacerbate fire risk in the PNW through multiple mechanisms. Earlier spring snowmelt, decreased snowpack, reduced summer precipitation, and lower stream flows increase fire severity and extent by reducing fuel moisture (Mote 2006; Westerling et al. 2006; Mote et al. 2014). These reductions in fuel moisture can work to increase available fuel by stressing trees, leaving them more vulnerable to insect attack and resulting mortality (Carroll, Taylor, and Safranyik 2003; Mote et al. 2014). Incorporating reduced fuel moisture, insect attack, and other factors, models suggest a quadrupling of area burned across the entire PNW under the “moderate emissions” A1B scenario, and up to a 500% increase in area burned along the eastern Cascades assuming a 2.2° F mean temperature increase (Mote et al. 2014).

Walsh et al. (2015) examined regional scale relationships between these climatic events and fire behavior when they analyzed 34 charcoal records at sites across the PNW for shifts in fire activity throughout the Holocene, while investigating relative contributions of precipitation, elevation, and vegetation types at the various sites. Considering that local conditions influence charcoal influx rates, statistical transformations were necessary to compare the records in a meaningful manner. Z scores quantifying deviations from the means were calculated. The 34 records show shifting Z scores throughout the epoch, from 12,000 cal yr BP to the present. Biomass burning was low but increased during the early Holocene (ca. 2,000 to 8,000 cal yr BP) as summer insolation increased and vegetation recovered following the retreat of the Cordilleran Ice Sheet (Ryder, Fulton, and Clague 1991). Burning dropped during the transition to the
cooler, wetter, middle Holocene as summer insolation declined (ca. 8,000-5500 cal yr BP) and increased through the rest of the period (ca. 5500-4000 cal yr BP) as ENSO variability related drought became more common (Bartlein et al. 1998). Burning continued to increase from approximately ca. 4,000 cal yr BP until the present, likely in response to increased drought variability driven by more frequent ENSO events, except for a decline during the LIA (Walsh et al. 2015).

Humans, Fire, and Risk

Native American uses of fire were observed upon the arrival of Europeans, and are recorded in historical and ethnographic records (Scharf 2010). Prior to the arrival of settlers, Native Americans in the PNW intentionally ignited fires for various reasons, with variations between locations in burning practices. Purposes for such ignitions included herding deer for hunting, and gathering of insects, nuts, and roots (Hunn, Turner, and French 1998). Use of fire as a land management tool was prevalent in the ponderosa pine environments and along the edges of forests, but less common in the mountains than in the valleys (Agee 1993; Boyd 1999, Walsh et al. 2018). Within the Columbia Plateau, purposes for burning also included encouragement of grasses and roots used for food such as biscuitroot (*Lomatium triternatum*), bitterroot (*Lewisia rediviva*), and camas (*Camassia spp.*)(Boyd 1999). North of the Columbia Plateau in the Okanogan Highlands, Native Americans burned to facilitate the growth of plants such as tiger lily (*Lilium columbianum*), avalanche lily (*Erythronium montanum*), spring beauty (*Claytonia lanceolate*), and mountain huckleberry. At lower elevations, fire was employed to encourage blueberries (*Vaccinium spp.*), onions (*Allium spp.*), and raspberries (*Rubus spp.*) (Boyd 1999).
Although human activities have played a role in PNW fire activity since the arrival of humans to the continent, climate is thought to have remained the dominant factor controlling fire activity until the late 19th century (Marlon et al. 2012). After contact, Europeans altered PNW fire regimes through changes in land use and active fire suppression (Marlon et al. 2012). A survey of fire histories across the western United States shows an 1850-1870 increase in burning coinciding with settlement, indicating intentional fires set for land clearance along with unintentional fires ignited when locomotives generated sparks, among other causes (Marlon et al. 2012). Later in the post-contact era, settlement and land uses such as livestock grazing and logging transformed low severity, high frequency fire regimes into low frequency, high severity regimes by removing older, fire resistant trees, and removing ignition sources for frequent fires (Brown, Agee, and Franklin 2004). As a result, the general post-settlement trend in the PNW was toward a drop in fire activity (Marlon et al. 2012).

This decline continued with the rise of active forest management in the late 19th century (Agee 1993). Throughout much of the 20th century, fire was seen as the enemy of a healthy forest, and its exclusion represented a top priority for the United States forest service (Stephens and Ruth 2005). This attitude was not reconsidered until the 1960s, when research found that the policy of active suppression adversely affected wildlife, and that fire represented a necessary part of forest ecosystems (Stephens and Ruth 2005). Beyond its detrimental ecological effects, fire suppression allowed for the buildup of fuels that would have otherwise been consumed in more frequent, less intense fires, contributing to the risk of larger fires (Haugo et al. 2010). Land use activities and fire exclusion have kept the total mass burned in the PNW below what would be expected.
considering recent temperature increases, and Marlon et al. (2012) suggest that burning will eventually come into equilibrium with temperatures. This may already be occurring, as warming trends and earlier spring seasons have been shown to lead to increased wildfire activity (Westerling et al. 2006).

In recent decades, the policy of strict fire suppression has been reexamined (Agee 1993; Arno and Allison-Bunnel 2002). By the 1970s, prescribed burning had become a more common fire management tool, with the National Forest Service initiating burns across Oregon between 1971 and 1975, and Crater Lake National Park implementing fuels treatment by 1978. In the 1980s, the Clean Air Act, along with tougher regulations on particulate matter from the Environmental Protection Agency, required that effects on air quality be considered in planning fuels treatments (Agee 1993). Awareness of fire as a natural process was finally encoded into policy in the 1990s, when Forest Service rules were amended to allow for mechanical thinning and prescribed burn treatments to reduce fuel loads.

Although FRIs are longer in the post-suppression era, area burned continues to increase as fuel accumulation interacts with warming temperatures and development-related increases in ignitions (Everett et al. 2000; Syphard et al. 2007; Mote et al. 2014). The National Interagency Fire Center (NIFC) compiles national wildfire statistics. Between the years 1960 and 2014, the total number of United States wildfires decreased while the area burned increased (NIFC 2016) (Figure 2.2).
WUI growth, shortsighted fire suppression policies, and rising temperatures contribute to growth in federal fire suppression expenditures. In 1994, fire expenditures accounted for a substantial, yet relatively small 16% of the United States Forest Service budget (Miller 2013). In 2015, the agency spent well over half its funds on wildfire related expenses (USFS) (Figure 2.3). If fires are suppressed at government expense and thus rendered a nonissue from the perspective of an individual property owner, it makes little sense to factor them into home building or land use decisions (Busby, Amacher, and Haight 2013). Developers, homeowners, and insurers often fail to incorporate fire risk into building and purchase decisions since they can count on federal money spent on fire suppression activities (Busby, Amacher, and Haight 2013).
Reilly (2015) examined WUI residents’ moral hazard regarding the federal government’s wildfire expenditures. Moral hazard refers to a situation where an individual is incentivized to take on more risk than they would otherwise, if third parties such as insurers and government were willing and able to reimburse losses (The Economic Times 2018.) Reilly (2015) observes that fire suppression to protect property often exceeds the property value to the point where it would be less expensive for the government to allow property to burn and then reimburse losses, and suggests that current policies create a moral hazard by reducing incentives for fire insurers to set premiums at efficient levels.

Busby, Amacher, and Haight (2013) demonstrated this moral hazard from the perspective of an individual property owner. They investigated the effects of fire suppression on levels of hazard reduction using mathematical modeling. They showed
that inefficient levels of fire hazard reduction occurred even when fire insurance premiums were adjusted to reflect increased risk at the WUI, because homeowners still considered the government’s suppression expenditures when deciding on a level of effort when reducing fuels.

The federal government is only directly responsible for wildfire suppression on lands it controls (Reilly 2015). However, because natural forces such as fire do not respect human political boundaries, property owners on private and state lands will benefit from suppression activities on federal lands (Miller 2013). In addition, the Federal Emergency Management Agency (FEMA) operates a grant program where state land management agencies can be reimbursed for up to 75% of wildfire suppression costs incurred (Reilly 2015). From the perspective of an individual property owner in Okanogan County, Washington, the burden is disproportionately placed upon the federal government, considering the state’s lack of an income tax (WA Department of Revenue 2010), and that a mere 4% of local property taxes paid go toward fire districts (Okanogan County 2018). Thus, the individual property owner pays little to build in fire prone areas, while public money protects the artificially cheap investment.

To reduce wildfire related losses and expenditures borne at public expense, the International Code Council has produced a model code to guide governments in regulating WUI development. The International WUI Code (IWUIC) can be adopted at a jurisdiction’s discretion, and contains provisions designed to mitigate risk in WUI areas (International Code Council 2015). The code contains provisions requiring fire resistant materials be used in WUI areas classified as presenting moderate to extreme fire hazard, requires that combustible materials be stored away from structures, and that defensible
spaces be maintained between tree crowns and buildings. The code also allows building officials to require that defensible space plans be submitted along with construction plans when necessary. As of November 2016, neither Okanogan County, the City of Okanogan near Green Lake, nor the City of Winthrop near Campbell Lake have adopted the IWUIC (City of Winthrop 2014; Okanogan County 2014; City of Okanogan 2015). However, the Okanogan County Conservation District does participate in the Firewise program to educate property owners in voluntary measures to reduce their risk of loss from wildfire (Okanogan Conservation District 2018).

Fire History Methods

In this environment of land-use and fuels management challenges, knowledge of long-term fire history is crucial to policymakers and land managers. Methods for fire history reconstructions include the examination of historical archives, analysis of fire scars and tree cohorts, and macroscopic charcoal analysis performed on charcoal fragments from lake sediments (Conedera et al. 2009). Each method has advantages and limitations. Historical records are limited to the advent of record keeping and only include fires witnessed by or reported to record keepers. Fire scar analysis is performed on charred trees that survived past fires (Everett et al. 2000). The fire scar method allows inferences of fire frequency and severity at the location of a single tree and can identify individual fires, but is limited to the age of the oldest tree available in the study area (Whitlock 1992; Conedera et al. 2009). While fire scar studies can resolve individual fire events, macroscopic charcoal analysis infers fire episodes, where one or more fires occurred (Conedera et al. 2009). When performing fire scar analyses, investigators also develop chronologies of fire by cross-dating samples over large areas (Cissel, Swanson,
Macroscopic charcoal analysis involves the use of a combination of field, laboratory, and statistical methods to reconstruct fire histories stretching thousands of years into the past (Conedera et al. 2009). When fires occur, partially combusted material (charcoal) is deposited in lake sediments through several mechanisms. These mechanisms include the ejection into the air in smoke plumes and eventual deposition in lakes, primary surface runoff during a fire, and secondary surface runoff after an event. During macroscopic charcoal analysis, lake sediments are recovered from lakes, and sampled at contiguous intervals. Charcoal particles are then counted, and peaks in charcoal counts are interpreted as evidence of past fire episodes. The technique can be combined with pollen-based vegetation reconstructions to investigate relationships between vegetational shifts and fire frequency and severity. Macroscopic charcoal analysis is described in further detail in (Walsh, Whitlock, and Bartlein 2008; Conedera et al. 2009), and Chapter IV: Methods herein. Macroscopic charcoal analysis the preferred method for this study, with several advantages. First, the record obtained is not limited to the age of living trees, and can extend millennia into the past (Gavin et al. 2007; Conedera et al. 2009). Second, macroscopic charcoal analysis allows the investigator to limit analysis to larger charcoal fragments, which are produced in the watershed of interest (Whitlock and Bartlein 2004).
Agee (1994) describes in detail the various eastern Cascades vegetation groupings and their relationships with fire. The report describes plant communities in terms of climax species. A climax species refers to the plant species that would eventually come to dominate a community in the absence of disturbances such as fire. For example, two stands can currently be dominated by ponderosa pine. If the ponderosa pine would still dominate if disturbance were removed, then the community would be classified as a ponderosa pine climax community. However, if the community would transition to Douglas-fir dominance in the absence of disturbance, it is classified as a Douglas-fir climax community. A seral species refers to one that dominates a community after it outcompetes a pioneer species but prior to successional climax. Disturbances such as fire tend to maintain seral dominated communities, preventing the community from reaching the climax stage (Agee 1994). A variety of climax communities exist across the eastern Cascades region, with variation in fire regimes (Franklin and Dyrness 1973; Agee 1994). Douglas-fir climax communities cover wetter areas on the eastern flank of the Cascades and the Okanogan Highlands, ponderosa pine communities cover foothills of the Cascades and the Okanogan Highlands, and woodland communities featuring sagebrush steppe and desert scrub cover the Columbia Plateau (Franklin and Dyrness 1973; Agee 1994) (Figure 2.4).
Ponderosa Pine Communities

Ponderosa pine ranges across western North America, from Central Mexico to British Columbia (Little 1971) (Figure 2.5). The species favors sunlit locations, and is out competed by shade-tolerant species such as Douglas-fir as stands become denser (Agee 1994). In ponderosa pine-dominated communities, frequent, low intensity ground and understory fire maintains open, park-like stands by eliminating younger trees and protecting older trees from crown fires through the elimination of ladder fuels. (Agee 1994; Everett et al. 2007).
Figure 2.5: Map of ponderosa pine distribution in North America (Little 1971)
Changes in land use and the adoption of suppression policies after Euro American contact removed fire from many ponderosa pine environments, increasing FRIs (Agee, 1993; Arno and Allison-Bunnel 2002). These increases led to denser stands with increased fuel loads, and varied age structures, which are prone to encroachment from shade-tolerant tree species such as Douglas-fir (Agee 1993; Camp 1999).

The effects of these human-induced changes to ponderosa pine fire regimes are reflected in available fire histories. Everett et al. (2000) investigated tree ring fire scars, comparing FRIs within two eastern Cascades watersheds. Results showed a statistically significant increase in FRIs between the pre-suppression (AD 1850-1910) and post suppression (AD 1910-1996) periods, with substantially longer FRIs in the post suppression period.

Bork (1984) conducted a fire scar survey at three locations within the Deschutes National Forest of Central Oregon covering years from approximately AD 1300 CE to just after the beginning of the 20th century when active fire suppression began. The sites were called Pringle Butte, Cabin Lake, and Lookout Mountain. The sites varied in understory vegetation, precipitation, and elevation. Sagebrush stands bordered the study area, while climatic and human influences had allowed ponderosa pine to encroach into the sagebrush. Results showed little evidence of fire prior to AD 1400 CE, with declines in fire activity at times that varied between sites, but generally declined in the 20th century with fire suppression.
Sagebrush Steppe Communities

Sagebrush environments cover dry areas across the Western United States (Figure 2.6). Mensing, Livingston, and Barker (2006), along with Miller and Tausch (2000) summarize our understanding of fire in sagebrush (Artemisia spp.) communities. A series of years with cool, wet conditions followed by drier conditions can lead to more

Figure 2.6: Big Sagebrush extent in North America (Little 1971).
frequent fires than consistently warm, dry conditions in sagebrush steppe environments. Fires tend to be stand replacing in these areas, leaving little fuel behind after a fire. Cooler, wetter conditions allow sagebrush stands to recover. Dry intervals within wetter periods lead to fires after periods of growth.

Fire burns and kills sagebrush, leaving no record within the sagebrush stand itself (Baker 2006). Fire scar investigations at sagebrush sites thus rely on trees adjacent to sagebrush stands. These differences complicate direct comparisons between macroscopic charcoal and fire scar studies. However, general comparison of trends over time between the methods is possible.

Currently, few macroscopic charcoal investigations have been performed in eastern Cascades sagebrush steppe environments. Those available include a series of sediment cores obtained in the ponderosa pine/sagebrush steppe Five Lakes region along the Columbia River, approximately 70 km from the study area used in this research (Scharf 2010). At the location, a 1543-year charcoal record was analyzed statistically, comparing charcoal influx values to pollen counts, human population data, and oxygen isotope values. Results indicate that charcoal influx was positively influenced by human population, the abundance of pine pollen, and positive oxygen isotope values indicating warm, dry conditions from nearby Hidden Lake and Rinker Lake, while charcoal influx was negatively associated with high levels of sagebrush. Fire events were primarily controlled by drought and warm temperatures, but with human populations and pine fuel loading playing important roles. These results suggest that fuel availability often limited
fire activity throughout the period studied, with taxa that colonize after disturbances such as sagebrush negatively correlated with charcoal influx.

In contrast, Mensing, Livingston, and Barker (2006) found a positive relationship between sagebrush and fire activity. They developed a 5500-year fire history in a sagebrush steppe environment in the Newark Valley of Nevada. Pollen recovered at the site suggests a wetter local climate that at present at approximately 5000-4700 cal yr BP, coincident with a period of elevated fire activity. Dry periods coincided with declines in fire activity, while elevated precipitation levels allowed sagebrush to proliferate, providing enough fuel for more frequent fires.

Nelson and Pierce (2010) also found an association between wetter conditions, more abundant sagebrush, and elevated fire activity in another charcoal record at a sagebrush/forest ecotone site in the Wood Creek area of Southwestern Idaho, using alluvial charcoal. Several periods of elevated fire activity emerged from the analysis: 4400-4000, 2000-1400, and 650-400 cal yr BP. These periods of elevated charcoal influx coincided with wetter conditions, suggesting that fuel loading played a role in driving fire activity at the site.

One study is available from the Okanogan region. Walsh, Duke and Haydon (2018) recovered an approximately 4000-year charcoal record from Fish Lake, within the Sinlahekin Wildlife Area just to the north of the study area. The current vegetation community is a ponderosa pine/sagebrush ecotone similar to the environment at Green Lake. The sediment record recovered there showed a virtually unchanged fire regime characterized by frequent, low-severity fires from the beginning of the record (ca. 3800
cal yr BP) to ca. 1200 cal yr BP. From ca. 1200 cal yr BP to ca. 150 cal yr BP, fire activity generally increased, including during both the LIA and the MCA.

Prior to Euro-American settlement and subsequent fire suppression and exclusion, fire worked to maintain sagebrush steppe communities by excluding conifers (Miller and Heyerdahl 2008). Prior to settlement, FRIs in sagebrush steppe environments likely ranged between 60 and 100 years (Whisenant 1990). Since settlement and the resulting changes in fire management and land use, sagebrush steppe communities in the Western US have generally experienced longer FRIs. Fire scar histories have been developed using trees adjacent to sagebrush steppe environments within Yellowstone National Park showing FRIs of 32-70 years, with results for some smaller areas showing FRIs of 17-41 years, but with some other sagebrush steppe areas showing FRIs of 100 years (Whisenant 1990; Mensing, Livingston, and Barker 2006).

Although conversion to land for grazing and fire suppression increases fire return intervals, cheatgrass introduced by settlers increases a sagebrush community’s vulnerability to fire and to reduces FRIs (Whisenant 1990; Baker 2006). Easily ignited, cheatgrass creates its own habitat at the expense of sagebrush species by quickly resprouting after a fire, only to burn again within a short interval. FRIs in sagebrush steppe communities under cheatgrass invasion can be as short as 5 years.

Conclusions

The nature of fire activity in the eastern Cascades depends upon vegetation, climate, human activities, and human land use policies. In a warming climate, the dry steppes east of the Cascades are experiencing larger fires as WUI population growth, fire
suppression, and invasive species alter the landscape. All these factors are commonly observed in the study area in Okanogan County, Washington.
CHAPTER III

STUDY AREA

Setting

Geography

The study area exists in north central Washington, with the North Cascades and the Okanogan-Wenatchee National Forest to the west (Figure 3.1). Near this western edge are the unincorporated communities of Winthrop and Twisp. The Okanogan River forms the eastern boundary with the community of Omak, near Green Lake. To this south lie the towns of Okanogan, Brewster, and Pateros. The Sinlahekin Wildlife Area is just to the north.

Figure 3.1: Study area with study site locations, nearby communities, and nearby managed forest areas.
**Geology**

The Cascade Mountains have undergone numerous changes over the past 200 million years (Alt and Hyndman 1984). During this period, a stretch of basaltic oceanic crust separated the mainland of what is now North America from a land mass now known as the Okanogan micro-continent. The Okanogan micro-continent then collided with the mainland to form much of northeastern Washington. 50 million years ago, a second collision occurred as the North Cascade micro-continent met the mainland. Intense volcanism followed this collision, building the Cascades (Alt and Hyndman 1984). Formed in the North Cascades collision, and dotted with volcanoes such as Mt. St. Helens, Mt. Baker, Mt. Rainer, and Glacier Peak, the Cascades separate the basaltic rocks of Washington’s west side from granitic formations of the east. East of the Cascades, the Okanogan Highlands sit upon the remnants of the Okanogan microcontinent (Alt and Hyndman 1984).

The larger study area falls within the eastern portion of the North Cascades geologic province (Washington Department of Natural Resources 2018). At this location, metamorphic rock formations of pre-Tertiary and pre-Cretaceous origin transition to sedimentary rock formations of Paleozoic to Mesozoic origin. Both rock formations have volcanic formations interspersed. The geology as it exists today was heavily influenced by the retreat of the Okanogan Lobe of the Cordilleran Ice Sheet, carving glacial U-shaped valleys and leaving glacial lakes (Booth 1987; Washington Department of Natural Resources 2018).

Franklin and Dyrness (1973) divide the PNW in a manner that places the study area at the convergence of two geographic zones: The North Cascades and the Okanogan
Highlands. In the North Cascades, evidence of glaciation is abundant, with numerous cirques and once glaciated valleys. Dry conditions eastward of the Cascade Crest produce chestnut and brown soils with layers of volcanic ash interspersed with loess deposits. These soils are often classified as Regosols, Podzols, and Haploxerolls. In the Okanagan Highlands, slopes are more moderate and show less overall relief, with much of the province ranging between 1200 and 2400 m above sea level. Evidence that ice sheets once covered the Highlands is abundant. Glacial deposits are found throughout the province and underlying rock materials are similar to those in the North Cascades province. Highland soil patterns vary with elevation. Very low elevation areas feature soils derived from glacial outwash, while more moderate elevations feature soils sourced from glacial till. At high elevations, soils are derived from granite, are high in stone content, and often include volcanic ash.

Climate

The rain shadow (orographic) effect created by the Cascades Mountains makes the eastern PNW drier than the west side (Franklin and Dyrness 1973; Agee 1993). In this process, the Aleutian Low-pressure system drives moist air eastward from the Pacific Ocean, where it rises, cools, and precipitates as it reaches the Cascades. The now drier air parcels warm as they descend, reducing relative humidity and precipitation on the leeward side of the Cascades. Although summer drought is typical on both sides of the Cascades, with wet winters and summer moisture deficits, the inland east remains drier than the coastal west, with annual precipitation averages as low as 200 mm just to the east of the Cascades, and as high as 3000 mm just inland from the western coast (United States Geological Survey 2017). The study sites fall in a transition zone between the two
climate zones, with locations at the foot of the eastern Cascades receiving 1540-2030 mm of precipitation per year, and locations in the Okanogan Highlands receiving as little as 120 mm (United States Geological Survey 2017). Like most areas of eastern Washington, Okanogan Highland summers are dry, and most precipitation falls during the winter as snow (Franklin and Dyrness 1973).

**Biota**

Harris, Franklin, and Dyrness (1990) classify the vegetation zones of Washington according to potential climax vegetation. This system classifies vegetation zones by the vegetation that would come to dominate a location if successional processes persisted without disturbance. The study area is at a transitional location where shade and moisture-tolerant Douglas-fir (*Pseudotsuga menziesii*) zones of the High Cascades meet the meet ponderosa pine (*Pinus ponderosa*) and sagebrush (*Artemisia* spp.) zones in the Okanogan Highlands.

Ponderosa pine zones generally exist in drier sites than those featuring Douglas-fir (Harris, Franklin, and Dyrness 1990). Ponderosa pine communities prefer sites receiving between 355 and 760 mm of precipitation annually, where the growing season is short, summers are dry, and most annual precipitation falls as winter snow. Big sagebrush (*Artemisia tridentata*), the most common sagebrush species, generally occupies xeric (dry) sites receiving between 180 and 400 mm of annual precipitation, and various varieties are adapted to a wide range of elevations and soil conditions (Mozingo 1987; NRCS 2002).

The Okanogan ecoregion is home to 205 species of birds, 50 species of fish, and 87 mammal species (National Geographic Society 2018). Okanogan bird species include
various grouse, such as sharp tailed grouse (*Tympanuchus phasianellus*), greater sage grouse (*Centrocercus urophasianus*), and the greater and lesser prairie chickens (*Tympanachus cupido* and *Tympanachus pallidinctus*) (Connelly 2010). Mammal species include beaver (*Castor canadensis*), black bear (*Ursus americanus*), white tailed deer (*Odocoileus virginianus*), and mule deer (*Odocoileus hemionus*). Bighorn sheep (*Ovis canadensis*) inhabit upland sites (Nature Mapping Foundation 2018).

**Human Habitation and History**

The study area exists at the boundary between the northern and southern portions of the Columbia Plateau. The Columbia Plateau covers a large area including the Okanogan Highlands and straddles the border between the United States and Canada (Ames et al. 1998; Pokotylo and Mitchell 1998). The Plateau can be divided into two physiographic regions: The Northern and Southern Plateaus (Ames et al. 1998; Pokotylo and Mitchell 1998). The Northern Plateau extends as far northward to central British Columbia, and southward to the area surrounding the modern-day town of Twisp (Pokotylo and Mitchell 1998, Google Earth). The Coast Range marks the Northern Plateau’s western border, while the Columbia Mountains mark its eastern flank (Pokotylo and Mitchell 1998) The Northern Plateau’s topography varies, with low relief areas interspersed with highlands up to 2500 m in elevation, all falling within the Fraser River watershed (Figure 3.2) (Pokotylo and Mitchell 1998).
Pokotylo and Mitchell (1998) divided the Northern Plateau’s Okanogan Valley prehistory into four phases; The Okanogan, the Indian Dan, the Chiliwist, and the Cassimer Bar phase. Dates for the Okanogan phase are difficult to constrain, but it is estimated to cover the end of the Pleistocene to approximately 6000 years before present (BP). Evidence for this phase is limited to small assemblages of leaf shaped and stemmed points, flake tools, and mussel shells. The Indian Dan phase lasted from ca. 6000-3000 years BP. Site assemblages in this phase show additional complexity relative to the Okanogan phase, with the appearance of milling stones, ovens, pestles, along with bones of fish and land mammals. The Chilwist phase covers ca. 3000-900 years BP. Pit houses
appear during this period, and mussel shells grow in number in comparison with the previous phases. Lastly, the Cassimer Bar phase lasted from ca. 900 years BP to Euro-American contact. Cultural materials found include milling stones and bone harpoon heads. Ornamented items are more common in the northern half of the valley. This complexity has been interpreted as evidence of a more stable population in the Northern Valley than in the Southern (Pokotylo and Mitchell 1998). Both the study sites sit to the south and west of the Okanogan River at the southern tip of the South Okanogan Valley sites (Figure 3.3).

Figure 3.3: Southern Okanogan Plateau with study sites (Pokotylo and Mitchell 1998).
Ames et al. (1988) give an overview of the Southern Plateau’s prehistory. This account divides the Southern Plateau into three provinces for analysis of the PNW’s early peoples: The Southwest, the Southeast, and the South Central. As they describe the divisions, Green and Campbell Lakes are located on the Northern edge of the Southern Plateau. The authors divide the early peoples temporally as well as spatially. These divisions include the Paleo Indian Period (Period IA) (ca. 11,500-11,000 years BP), which is subdivided into a second period from ca. 11,000-6350 BP (Period IB). Period II lasted from ca. 6350-3850 years BP, and Period III ran from ca. 3850-230 years BP (Ames et al. 1988). One intact site has been found that demonstrates human occupation on the Southern Plateau during period IA. During IB, the record shows high seasonal mobility, no evidence of food storage, and low population densities (Ames 1988). During period II, pit houses appear in the record. Finally, Period III shows the development of longhouses and advances in fishing technology (Ames et al. 1988).

No cultural artifacts have been identified on the South-Central Plateau prior to Period IB (Ames et al. 1988). Native American dwellings from Period IB have been unearthed at Wells Reservoir to the southwest of the Green Lake study site. Period II is characterized by increases in population, a shift toward greater sedentism and more diverse faunal assemblages at excavated sites. Wells Reservoir is represented in the record spanning this period, just as in Period IB. During Period III, pit houses increase in number, and signs of increasingly sedentary lifestyles appear (Ames et al. 1988).

Baker (1990) explores groups speaking various Okanogan dialects and areas they inhabited, with a focus on three dialect groups among the Okanogan: the Northern, the Southern, and the Similkameen, each named for the drainage basin the group occupied.
Okanogan groups inhabited the study area, and were known to burn vegetation. The Southern Okanogan were no exception, burning to encourage plants such as avalanche lily (*Erythronium grandiflorum*), spring beauty (*Claytonia lanceolate*) and tiger lily (*Lilium columbianum*) (Boyd 1999). Other managed plants included wild onions (*Allium* spp.), blueberries (*Vaccinium* spp.), and raspberries (*Rubus* spp.).

Euro-American influence in the region appears in the historical record during the late 17th century when the Hudson’s Bay Company developed a fur trapping and trading network covering the PNW and extending as far north as Saskatchewan (Wilson 1990). However, over 100 years would pass before the fur trapping industry expanded to what is now Okanogan County. Fur trading companies constructed a succession of forts at the confluence of the Okanogan and Columbia Rivers, starting with Fort Okanogan in AD 1811 (Wilson 1990). Just prior the fort’s construction, smallpox accompanied the fur trappers, leading to a regional indigenous population crash (Hunn 1999). Mining communities preceded homesteaders, beginning in the mid-19th century (Wilson 1990). Washington Territory was established in AD 1853, a first step toward settlement of the inland Okanogan. The Yakama treaties negotiated from AD 1854 to 1855 provided the next step toward dispossessing the Okanogan people and clearing the way for settlement and subsequent land use changes, including the clearing of forest land and the introduction of livestock (Hunn 1999). Okanogan County was officially organized in AD 1888 (Wilson 1990). Settlement related to changes in land use practices led to drops in overall PNW fire activity (Marlon et al. 2012), and there is little reason to believe that Okanogan County offered an exception to this trend. Active management came later with the establishment of the Forest Service in AD 1905 (Arno and Allison-Bunnel 2002).
East of the Cascades, a mix of management practices gave way to the policy of total fire exclusion in the year AD 1928 (Agee 1993).

Study Sites

Green Lake

Geography and Geology

Green Lake (48°26’47” N, 119°37’45” W, 476 m a.s.l) sits at the northern edge of the Southern Plateau, at the foot of the Okanagan Highlands (Figure 3.4). It is located approximately eight km northeast of the town of Omak (Figure 3.5). The Sinlahekin Wildlife Area exists four km to the northeast of the lake, and the Okanogan-Wenatchee National Forest is 20 km to the west. The lake sits upon the Okanogan Metamorphic core complex, a formation consisting of layers of gneiss and granite with the Okanogan Valley
and Omak Lake fault systems on its western side (Wolff, McKay, and Norman 2011). Green Lake likely formed in a depression left when the Okanogan Lobe of the Cordilleran Ice sheet retreated at the end of the last ice age (Booth 1987; Clark et al. 2009).

**Figure 3.5: General vicinity of Green Lake**

**Hydrology**

The watershed surrounding Green Lake is shown in Figure 3.6. According to calculations performed within the ArcGIS software environment, Green Lake’s watershed covers 190 km² and has a drainage density of 1.87 linear km of streams per km of area (Figure 3.6). An unnamed stream flows into the lake from the northwest, and another unnamed stream travels from Green Lake to Little Green Lake just to the south. Little Green Lake connects the unnamed stream and Green Lake to Salmon Creek, which flows southeast toward Omak (United States Geologic Survey 2018).
Figure 3.6: Elevation map of the Green Lake watershed.

Climate

At Green Lake, the average minimum monthly temperature occurs in December.

Figure 3.7: Green Lake temperature and precipitation 30-year monthly averages based upon Oregon State University’s PRISM climate data.
(-3.7°C) (Figure 3.7), while the average maximum monthly temperature is shared between the months of July and August (20.6 °C), and the average annual precipitation total is 352.15 mm (PRISM 2015). On average, Green Lake’s wettest month is December, with 54.06 mm of precipitation, and its driest is September, with 13.64 mm of precipitation.

**Biota**

An informal vegetation survey was conducted at Green Lake in summer 2015 to determine the dominate plant communities. Ponderosa pine dominates the small forest community growing in the immediate area surrounding the lake, likely due to higher moisture availability compared to the surrounding sagebrush steppe. A few Douglas-fir trees are mixed in, along with serviceberry (*Amelanchier* spp.), and Rocky Mountain maple (*Acer glabrum douglasii*). Other tree species include blue elderberry (*Sambucus cerulea*), bitter cherry (*Prunus emarginata*), sumac (*Rhus* spp), and cottonwood (*Populus trichocarpa*). Willow (*Salix* spp.) and red osier dogwood (*Cornus sericea*) grow along the shoreline of the lake. Sagebrush (*Artemisia* spp.) dominates the understory, along with other shrubs including Cascade grape (*Mahonia aquifolium*), snowberry (*Symphoricarpos* spp.), antelope bitterbrush (*Purshia tridentata*), rabbit brush (*Chrysothamnus nauseosus*), and wax currant (*Ribes cereum*). Herbaceous understory species include lupine (*Lupinus* spp.), yarrow (*Achillea millefolium*), arrow leaf balsam root (*Balsamorhiza sagittata*), nightshade (*Solanaceae*), brown-eyed susan (*Rudbeckia hirta*), as well as numerous sedges (*Cyperaceae*) and grasses (*Poaceae*). Aquatic plant species found along the shoreline of Green Lake include scouring rush (*Equisetum hyemale*) and great bulrush (*Schoenoplectus tabernaemontani*). Several invasive plants inhabit the Green Lake area, including mullein (*Verbascum* spp.), diffuse
knapweed (*Centaurea diffusa*), Canada thistle (*Cirsium arvense*) and sweet white clover (*Melilotus albus*).

**Campbell Lake**

**Geography and Geology**

Campbell Lake’s position is almost due west of Green Lake (48°26'32" N, 120°4'1" W at an elevation of 877 m a.s.l.) (Figures 3.8-9). Campbell Lake sits at the northern edge of the glacially carved Pipestone Canyon (Barksdale 1975). The Pipestone formation consists of granitic, volcanic-clast, chert conglomerate rock, and course to fine sandstones mixed with shale and siltstone (Barksdale 1975). Like Green Lake, Campbell Lake likely formed in a depression left after the Okanogan Lobe’s retreat and eventual collapse shortly after the Last Glacial Maximum (Booth 1987; Clark et al. 2009).

![Campbell Lake Study Site](image_url)

**Figure 3.8:** Aerial view of the Campbell Lake study site
Figure 3.9: Elevation map of the Campbell Lake watershed
Figure 3.10: General Campbell Lake area.

**Hydrology**

Pipestone Canyon and Campbell Lake fall within a HUC Level 12 watershed (Figure 3.7). The watershed covers 281 km$^2$ and has a drainage density of 1.28 km per square kilometer according to calculations performed within the ArcGIS 10.3 software package. An unnamed stream flows into Campbell Lake from the north. To the northeast of the lake, Bowen Creek connects to the unnamed stream. Another unnamed stream flows out of the lake from its southern edge and connects to Beaver Creek at the bottom of the Pipestone formation (United States Geologic Survey n.d.).
Climate

At Campbell Lake, the average minimum monthly temperature is 1.2°C, while the average maximum monthly temperature is 13.1°C, and the average annual precipitation total is 513.36 mm (PRISM 2015). On average, Campbell Lake’s wettest month is December with 86.13 mm of precipitation, and its driest is April with 24.95 mm of precipitation. December temperatures average -4.3 °C and the average July temperature is 26.26 °C (Figure 3.1).

![Campbell Lake, WA Temperature and Precipitation](image)

Figure 3.11: Campbell Lake climate information. Source: Oregon State University’s PRISM program.

Biota

Campbell Lake sits at the convergence of the Douglas-fir, ponderosa pine, and steppe climax zones (Harris, Franklin, and Dyrness 1990). Their report describes a natural landscape dominated by sagebrush, but with scattered Douglas-fir and ponderosa pine. An informal vegetation survey was conducted at Campbell Lake in October 2015.
The 2014 Carlton Complex fire burned the area around the lake and killed many native plants in the vicinity. With the landscape cleared, invasive species such as Canada thistle, diffuse knapweed, and various non-native grasses have invaded the site. A few native trees exist at the site, such as ponderosa pine, aspen (*Populus tremuloides*), elderberry, willow, and cottonwood. Shrub species growing in the vicinity include sagebrush, serviceberry, and elderberry. Herbaceous and aquatic species include cattail (*Typha* spp.), great bulrush, sedges, yarrow, and plants belonging to the *Lomatium* genus.
CHAPTER IV

METHODS

Field Methods

At both study sites, a coring platform was assembled and anchored near the center of the lake to extract a sediment core (Figure 4.1A). A Bolivia piston corer was used to extract a short core at each site, which captured the sediment-water interface (Figures 4.1B and C). The sediment from these cores was sampled vertically in the field into whirl-pak bags at 1 cm intervals. The long cores were obtained using a Livingstone piston corer, and individual drive lengths were wrapped in plastic wrap and aluminum foil, encased in split PVC lengths, and transported to Central Washington University’s Paleoecology Lab where they were kept under refrigeration for later analysis (Figure 4.1D).

Figure 4.1: (A) Coring platform assembled at Campbell Lake, (B) Livingstone piston corer (photo credit: D. Gavin), (C) recovered sediment core, and charcoal counting microscope in the CWU Paleoecology Lab (D).
Green Lake was cored in July of 2012 and 2015, at water depths of 808 and 859 cm, respectively. During the 2012 excursion, the Mazama tephra proved impenetrable, and coring ceased after five drives. In total, a 443-cm long core was recovered from Green Lake in 2012, along with a 66 cm short core. During a second excursion to Green Lake in July of 2015, cores lengths were recovered from the top of the sediment and discarded until the Mazama tephra was reached. Once past the tephra, similar procedures were used to recover sediment to add to the 2012 record. In the 2015 Green Lake excursion, a 562-cm long core was recovered for a total recovery of 1005 cm.

Campbell Lake was cored in October 2015 at a water depth of 600 cm. Similar procedures to those performed at Green Lake were used at Campbell Lake, but Campbell Lake required a single excursion. At Campbell, 680 cm of sediment were recovered, along with an 87 cm short core.

Laboratory Methods

**Chronology and Lithology**

Each core was split in half and described using a Munsell Color Chart. Macrofossils such as twigs and seeds found within the sediment were recovered for radiocarbon dating. Bulk sediment was also sampled for additional radiocarbon dates. Loss-on-ignition (LOI) analysis was performed in order to determine the lithological content of the sediment cores. LOI is used to calculate the organic and carbonate content of the record and interpret relationships between vegetation/lake productivity and fire activity (Heiri, Lotter, and Lemcke 2001; Walsh, Whitlock, and Bartlein 2008). At every 5 cm, a 1 cm³ sample was taken and placed in a weighed ceramic crucible. Each sample was then dried at 90°C for at least 24 hours. The samples were then heated at 550°C for
2 hours to burn off all organic content and weighed afterward. The post ignition weight was subtracted from the dry weight prior to ignition, and divided by the dry weight prior to ignition with the following formula:

\[
W_b - \frac{W_a}{W_b}
\]

Where:

\( W_b = \) sample weight prior to ignition
\( W_a = \) sample weight after ignition

The remaining sediment was again burned at 900°C for 2 hours and weighed to calculate the carbonate content of each sample. Carbonate content was calculated using the following formula:

\[
\left(\frac{W_{bc} - W_{ac}}{W_{bc}} \times 1.36\right) \times 100
\]

Where:

\( W_{bc} = \) sample weight prior to 900 °C burn
\( W_{ba} = \) sample weight after

In addition to LOI, the magnetic susceptibility of the long cores was measured. Drives were run through a Sapphire Instruments magnetic coil at 1 cm intervals in order to obtain magnetic readings. Magnetic susceptibility readings quantify sediment responses to magnetic fields and can provide evidence of past erosional and volcanic events within a lake’s watershed (Dearing and Flower 1982; Sandgren and Snowball 2002).

An age-depth model was developed from each site to estimate the amount of time each sediment sample represents. The Mount Saint Helens W (MSH-W) and Mazama tephra layers provide temporal points known with a reasonable degree of certainty.
Macrofossils and bulk sediment were sampled from each core for Accelerator Mass Spectrometry (AMS) radiocarbon dating. The Green Lake short core was connected by plotting the charcoal counts on a graph and identifying areas of similar values. The Campbell Lake cores were connected through identification of the MSH-W tephra in both cores and connecting at that point. The known dates of ash layers and any radiocarbon dates were used to develop an age-depth model by fitting a cubic smoothing spline best fit polynomial curve to the estimated dates. From these models, the annual rate of deposition for each centimeter of sediment was approximated (cm of sediment /year) (Cwynar 1987).

Macroscopic Charcoal Analysis

For the Green Lake record, charcoal samples were taken at 1 cm intervals to a depth of 1350 cm and at 0.5 cm intervals below that depth. The Campbell Lake record was sampled at 1 cm intervals throughout the entire length of the core. Two cubic centimeters (cc) were taken at each interval and soaked in a 5% solution of sodium hexametaphosphate solution for > 24 hours. Each sample was then soaked in approximately 5 mL of commercial bleach solution for approximately 3 hours to remove pigments from unburned organic material, leaving charcoal unbleached and visible under a stereomicroscope.

Samples were sieved to separate charcoal size classes; > 250 µm in diameter and those between 125 and 250 µm. Sieved samples were transferred to scored petri dishes designed to fit under a 10-40x stereomicroscope. All charcoal fragments in the dishes were counted under the microscope, and categorized as either woody or herbaceous using methods consistent with those used in Walsh, Whitlock, and Bartlein (2008).
particles with visible stomata are presumed to represent understory vegetation such as grasses and forbs and were classified as herbaceous, while all other charcoal particles were classified as woody (Figure 4.2).

Figure 4.2: Woody (A) and herbaceous (B) charcoal fragments. Photo: Walsh, Whitlock, and Bartlein 2008)

Data Analysis

Charcoal counts were converted to charcoal concentrations by dividing the total amount of charcoal in each sample by the sample volume. Charcoal concentration values were entered into CharAnalysis software along with ages of the depths in the cores and from that charcoal influx values (CHAR; particles/cm$^3$/year) were calculated (Higuera et al. 2007). Campbell Lake CHAR values were interpolated to constant 20-year time steps, and Green Lake values were interpolated to constant 14-year time steps. The data were not log transformed for either core. CharAnalysis software separates charcoal counts into
“background” and “peak” values. Background values refer to low frequency trends in the interpolated CHAR, while peak values refer to high-frequency trends after the background component is removed. The program tests each peak above the background level via a Gaussian mixture model. Values above the 95th percentile were identified as peak values. Values with a $\geq 5\%$ chance of coming from the same Poisson distribution as peaks during the previous 75 years were displayed on the output but not considered in the analysis.

Signal to noise index (SNI) measures the departure of peaks from the background values. SNI is sensitive to the smoothing window used in CharAnalysis software and quantifies the effectiveness of CharAnalysis in separating background and peak CHAR values and is defined as a ratio of the peak. Sensitivity analysis of Green Lake charcoal showed the highest SNI when a 600-year smoothing window was applied. The same protocol was employed for Campbell Lake charcoal counts. The best SNI for Campbell Lake was obtained using a 500-year smoothing window. After software analysis, results were graphed and assessed.
CHAPTER V

RESULTS

Green Lake

Chronology and Lithology

A short core and long core were recovered from Green Lake in 2012. The short core (GL12A) was 66 cm in length and included the sediment-water interface (Figure 5.1). The long core (GL12B) was recovered in six drives and measured a total length of 443.5 cm. Each “drive” refers to a single penetration of the corer, recovering approximately one meter of sediment. No short core was taken in 2015, but the six drives...
of the long core (GL15A) measured a total length of 562 cm. When combined, the sediments recovered from both GL12B and GL15A measured 1005.5 cm. However, GL15A drives 4 and 5 consisted primarily of inorganic clay and other eroded material (likely from the ice sheet) and would have yielded little information on fire history, so they were not analyzed. Green Lake sediments were thus sampled for charcoal and loss-on-ignition only through drive 4 in the GL15A core. The top 11 cm of the GL12A short core was combined with the selected drives from cores GL12B and GL15A to create one continuous record (hereafter referred to as GL15B). In total, the sampled portion of the GL15B core, with the tephra layers removed (because these are assumed to be instantaneous events), measured 687 cm, with a median resolution of 13.57 yr/cm (Figure 5.1).

The Green Lake age-depth model for core GL15B was developed using radiocarbon dates along with well-dated tephra layers. One macrofossil and four bulk sediment samples were collected and sent to DirectAMS radiocarbon services in Bothell, WA. Radiocarbon dates for the five samples were calibrated to calendar years using the Calib14 version 7.1 online calibration package (Stuiver, Reimer, and Reimer 2017). The Calib program provides a probability distribution for each sample’s radiocarbon age. When the calibrated median date coincided with the peak in the probability distribution, the date was selected and rounded to the nearest decade. When the radiocarbon age did not coincide with a peak in the probability distribution, the closest adjacent highest peak was selected and rounded to the nearest decade. The accepted dates of the Mazama and Mount Saint Helens W (MSH-W) tephra layers were combined with five AMS radiocarbon dates and the coring year, which was assigned to the top of the core, for a
total of eight points in order to make the age-depth model (Table 5.1). A constrained cubic smoothing spline was used to fit the age model, which suggests a basal date of ca. 14,670 cal yr BP (Figure 5.2).

Table 5.1: Age determinations for Green Lake core GL15B.

<table>
<thead>
<tr>
<th>Depth Below Mud Surface (cm)</th>
<th>Source Material</th>
<th>Lab Number</th>
<th>Age(^{14}\text{C yr BP})^{a}</th>
<th>Age (cal yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>MSH – W Tephra</td>
<td>N/A</td>
<td>N/A</td>
<td>470 cal yr BP</td>
</tr>
<tr>
<td>140</td>
<td>Bark Fragment</td>
<td>D-AMS 002840</td>
<td>1421 +/- 28</td>
<td>1310 cal yr BP</td>
</tr>
<tr>
<td>242</td>
<td>Seed</td>
<td>D-AMS 012605</td>
<td>2969 +/- 34</td>
<td>3130 cal yr BP</td>
</tr>
<tr>
<td>313</td>
<td>Twig</td>
<td></td>
<td>3964 +/- 29</td>
<td>4420 cal yr BP</td>
</tr>
<tr>
<td>420</td>
<td>Mazama Tephra</td>
<td>N/A</td>
<td>N/A</td>
<td>7627 cal yr BP</td>
</tr>
<tr>
<td>493.5</td>
<td>Bulk Sediment</td>
<td>8930</td>
<td>8930 +/- 39</td>
<td>10050 cal yr BP</td>
</tr>
<tr>
<td>586.5</td>
<td>Bulk Sediment</td>
<td>10397</td>
<td>10397 +/- 47</td>
<td>12270 cal yr BP</td>
</tr>
</tbody>
</table>

\(^{a}\text{C age calculations were conducted at Direct AMS, Seattle, Washington.}\)

\(^{b}\text{Known age of MSH-W Tephra (Mullineax 1974)}\)

\(^{c}\text{Known age of Mazama Tephra (Zdanowicz 1999)}\)

\(^{d}\text{Calendar ages with 2 sigma age ranges calculated using Calib 7.1 (Stuiver, Reimer and Reimer 2017).}\)

Overall, the sedimentation rate of the GL15B record varied little, and predominantly only within the last 1000 years (Figures 5.2 and 5.3). The average sedimentation rate for the entire core was 0.053 cm/yr. Average sedimentation rate during the Late Glacial (ca. 14,670-12,000 cal yr BP; 687-574 cm) was 0.039 cm/yr. Early Holocene (ca. 12,000-8,000 cal yr BP; 574-431 cm) rates were similar to those in the Late Glacial, with an average of 0.036 cm/yr.
Figure 5.2: Green Lake (GL15B) age-depth model. See Table 5.1 for age determinations used. The slope of the line indicates the sedimentation rate of the record.

Rates remained low through the middle Holocene (ca. 8,000-4,000 cal yr BP; 431-293 cm) with an average of 0.035 cm/yr. During the late Holocene (ca. 4000 cal yr BP to present; 292-0 cm) the average sedimentation rate increased to 0.087 cm/yr.

The lithology of the record revealed a general pattern of banded gyttia with ostracod shells and shell fragments throughout (Figure 5.1). Gyttia colors identified included very dark gray, brown and yellow shades. Tephra layers were identified at 81 cm (MSH-W) and 420 cm (Mazama) below the mud surface.
Charcoal Concentrations, Loss-on-Ignition, and Magnetic Susceptibility

The average charcoal concentration was 9.09 particles/cm$^3$ for the full GL15B record, but values varied between the time periods (Figure 5.4). The Late Glacial concentration averaged 1.36 particles/cm$^3$. On average, herbaceous charcoal accounted for 30.4% of the total charcoal concentration in this period. During the early Holocene charcoal concentrations increased and averaged 2.78 particles/cm$^3$, with an herbaceous contribution of 62.1%. During the middle Holocene, charcoal concentrations averaged 6.42 particles/cm$^3$, and 67% of charcoal particles were herbaceous. Late Holocene
charcoal concentrations were highest, averaging 22.58 particles/cm$^3$. Herbaceous charcoal concentrations during this period were 43.7%.

Loss-on-ignition analysis of the GL15B record revealed relatively low levels of organic content and high levels of carbonate content throughout (Figure 5.4). The maximum organic content value was 67.88%, with a minimum organic content of 1.66%. The average organic content value of the record was 11.16%. Organic content values were particularly low in the early part of the record. Late Glacial values show an average organic content of 4.56%. Values increased during the early Holocene, indicating Green Lake became more productive at that time, with an average organic content of 8.1%. Organic content continued to increase from the middle Holocene through the late Holocene. Middle Holocene organic content averaged 12.24%, while productivity was highest during the Late Holocene, with an average organic content of 15.88%.

Carbonate values reflected the CaCO$_3$ containing ostracod shells which were ubiquitous throughout Green Lake record, with an average carbonate content of 32.0% for the GL15B record. However, low carbonate values appeared in the record, with a minimum of 1.77%, while the maximum carbonate content was 52.67%. Despite wide swings on shorter timescales, average carbonate values varied little between Holocene time periods, except for the middle Holocene. Late Glacial, early Holocene, and late Holocene carbonate values were 39.72%, 39.97%, and 36.72%, respectively. The average carbonate value during the middle Holocene was 15.84%.

Green Lake magnetic susceptibility values showed evidence of allochthonous inputs (i.e., material originating from outside the lake) early on, but were low for much of the record (Figure 5.4). The average value for the entire record was $1.4893 \times 10^{-8}$.
electromagnetic units (emu). The average susceptibility value during the Late Glacial was $2.99651 \times 10^{-7}$ emu while susceptibility values averaged $7.6711 \times 10^{-8}$ emu during the early Holocene. Susceptibility values did show peaks during the middle Holocene, and susceptibility values averaged $2.8943 \times 10^{-8}$ emu. Late Holocene magnetic values averaged $2.89685 \times 10^{-8}$ emu. Peaks appear around the time of the Mazama eruption at 7627 cal yr BP, and values were highest toward the beginning of the record during the Late Glacial period when a large amount of presumably glacial material was washed into the lake.

Figure 5.4: Green Lake (GL15B) herbaceous (green) and woody (black) charcoal concentration (left), loss-on-ignition (middle) with organics (orange) and carbonates (blue), and magnetic susceptibility values (right) plotted against depth (black) (cm). Note: the magnetic susceptibility curve includes the additional two drives from core GL15A that were not analyzed for charcoal.
CharAnalysis

Late Glacial Period (ca. 14,670 to 12,000 cal yr BP)

During the Late Glacial, CHAR values were low, averaging 0.06 particles/cm²/yr (Table 5.2; Figure 5.5). Average fire frequency was low at 4.4 episodes/1000 yr in comparison to the average of 5.07 episodes/1000 yr for the overall record. Fire return intervals (FRIs) were long at an average of 173 years, but still shorter than the average for the entire record of 193 years. Fire frequency steadily increased from 0.47 episodes/1000 yr at ca. 14,670 cal yr BP until leveling off at ca. 13,080 cal yr BP; then values hovered around 6.14 episodes/1000 yr for the rest of the period. FRIs were long toward the early part of the record, with the earliest return interval at 272 years. FRIs

Table 5.2: Summary of charcoal data for GL15B.

<table>
<thead>
<tr>
<th>Zone: Age cal yr BP</th>
<th>Charcoal Concentration (particles/cm³)</th>
<th>CHAR (particles/cm²/yr)</th>
<th>Fire Frequency (episodes/1000/yr)</th>
<th>Mean Fire Episode Return Interval (years)</th>
<th>Peak Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Glacial: Pre-12,000</td>
<td>1.36</td>
<td>0.06</td>
<td>4.4</td>
<td>173</td>
<td>1.44</td>
</tr>
<tr>
<td>Early Holocene 12,000 - 8,000</td>
<td>2.78</td>
<td>0.01</td>
<td>4.5</td>
<td>215</td>
<td>3.32</td>
</tr>
<tr>
<td>Middle Holocene 8,000 - 4,000</td>
<td>6.42</td>
<td>0.22</td>
<td>3.78</td>
<td>244</td>
<td>2.91</td>
</tr>
<tr>
<td>Late Holocene 4,000-Present</td>
<td>22.58</td>
<td>1.62</td>
<td>7.38</td>
<td>129</td>
<td>14.67</td>
</tr>
</tbody>
</table>
Figure 5.5: Green Lake (GL15B) Signal to noise index (dashed orange line), fire episode peak magnitude (charcoal particles/peak; horizontal black line), fire episode frequency (episodes/1000 yr; blue line), and charcoal influx (CHAR; particles/cm²/yr; black curve) with significant peaks (black plus signs) plotted against age (cal yr BP).

**Early Holocene Period (ca. 12,000 to 8,000 cal yr BP)**

During the early Holocene period, the average CHAR value was .01 particles/cm²/yr. On average, 4.5 episodes/1000 yr occurred during the period. The average FRI was 215 years, which is higher than the average for the entire Green Lake record. The earliest value for episodes/1000 yr was 6.2, dropping to below 4 episodes/1000 yr at ca. 10,970 cal yr BP. After that, episodes/1000 yr increased again, reaching 4.62 at ca. 10,260 cal yr BP. Fire frequency again dropped below 4
episodes/1000 yr at ca. 9,840 cal yr BP, and remained below that level until ca. 8,770 cal yr BP. Values then increased throughout the rest of the period and reached 5.9 episodes/1000 yr at ca. 8000 cal yr BP.

FRIs were shorter at the start of the period, beginning at 154 years, and increased to 248 years by ca. 10,940 cal yr BP. From that point, FRIs decreased until ca. 10,100 cal yr BP when they reached 199 years and increased again, reaching 272 years at ca. 9,430 cal yr BP. From that time, FRIs decreased reaching 153 years at the end of the period. During the period, 18 significant peaks were detected, with all peaks averaging a magnitude of 3.32 particles/episode.

**Middle Holocene Period (ca. 8,000 to 4,000 cal yr BP)**

During the middle Holocene, the average CHAR value was 0.22 particles/cm²/yr. On average, the record shows 3.78 episodes/1000 yr during the period. The average fire return interval was 244 years. The earliest value for episodes/1000 years during the period was 5.9. Fire episode frequency dropped after that, reaching 3.13 episodes/1000 yr at ca. 6,880 cal yr BP. Fire frequency then increased, reaching 3.68 episodes/1000 yr at ca. 5,710 cal yr BP. Fire frequency then decreased to 2.27 episodes/1000 yr, the minimum value for the period. From this minimum, fire frequency again increased, reaching 6.78 episodes/1000 yr by ca. 4,010 cal yr BP. From the date, CHAR values stayed above 0 and below 0.4 particles/cm²/yr until reaching 0.86 particles/cm²/yr at ca. 4,980 cal yr BP. Values hovered between 0.15 and 0.62 particles/cm²/yr until a maximum value of 1.19 was reached at ca. 4,290 cal yr BP. From that time, CHAR values trend downward, reaching 0.26 particles/cm²/yr at the end of the period.
The earliest value FRI for the period was 153 years. FRI values then increased, reaching 288 years at ca. 6,730 cal yr BP. FRI then decreased until reaching 216 years at ca. 6140 cal yr BP. After that time, FRIs increased, reaching a maximum for the period at 318 years at ca. 5,130 cal yr BP. After the maximum, FRIs decreased until the end of the period, reaching 113 years at ca. 4,010 cal yr BP. During the period, 15 significant peaks were recorded with an average magnitude of 2.91 particles/episode.

**Late Holocene Period (ca. 4,000 to -62 cal yr BP)**

The average CHAR value was 1.62 particles/cm²/yr. CHAR values began the period at a low level, less than 1 particle/cm²/yr. reaching 5.27 particles/cm²/yr at ca. 2010 cal yr BP. CHAR values declined from that point, reaching 0.47 particles/cm²/yr at ca. 540 cal yr BP. From there, CHAR values increased dramatically, reaching 7.7 particles/cm²/yr prior to crashing again, dropping to 1.5 particles/cm²/yr at ca. -50 cal yr BP. On average for the period, 7.38 episodes/1000 yr occurred. The earliest recorded value for episodes/1000 yr during the period is 6.88. From there, fire frequency increased, reaching 8.35 episodes/1000 yr at ca. 3550 cal yr BP. From that time, fire frequency decreased again, reaching 6.32 episodes/1000 yr at ca. 2640 cal yr BP. Another increasing trend followed, with fire frequency reaching 7.85 fires/1000 yr at ca. 1870 cal yr BP. A decreasing trend followed, reaching a minimum value of 5.89 fires/1000 yr at ca. 1030 cal yr BP. From that time, fire frequency increased, reaching 8.76 fires/1000 yr at -62 cal yr BP.

The average FRI for the late Holocene was 129 years. At the beginning of the late Holocene, the FRI was 113 years. This value then increased to 117 years at ca. 3,830 cal yr BP. FRIs decreased from that point, until ca. 3,420 cal yr BP, when the value reached
108 years. FRIs increased after ca. 3,420 cal yr BP, reaching 152 years at ca. 2,720 cal yr BP. FRIs fell again until ca. 1,940 cal yr BP, reaching 122 years. FRIs increased from that time, reaching 169 years at ca. 1,030 cal yr BP. FRIs dropped from there to the end of the record, reaching 66 years at -62 cal yr BP. During the period, 30 significant fire episodes were recorded, with an average peak magnitude of 14.67 particles/peak.

Recent History: AD 1450 to 2012

During this period from AD 1450 to 2012, the average charcoal influx value was 3.56 particles/cm²/yr, while the average herbaceous influx value was 1.53 particles/cm²/year (Figure 5.6). The Green Lake record showed an influx value of 1.59 particles/cm²/year at the time of the MSH-W eruption, AD 1480 (470 cal yr BP). From that point, influx values increased, reaching 6.71 particles/cm²/year at ca. AD 1560 (380 cal yr BP). From that time, influx values decreased to reach 1.53 particles/cm²/year at ca. AD 1680 (260 cal yr BP). Influx values increased from that point, reaching 7.91 particles/cm²/year at ca. AD 1720 (220 cal yr BP). Influx values reached a high for the period of 10.20 particles/cm²/year at ca. AD 1800 (150 cal yr BP), then began a general pattern of decline to reach 0.19 particles/cm²/year at ca. AD 2010 (~60 cal yr BP).

On average, herbaceous charcoal accounted for 41% of charcoal influx during this period. The proportion of herbaceous charcoal was 83% at AD 1480 (470 cal yr BP). Herbaceous charcoal content followed a general pattern of decline from that time, reaching 10.1% at ca. AD 1720 (230 cal yr BP). Values increased again, reaching 80% ca. AD 1790 (160 cal yr BP). Herbaceous content trended down from that time, reaching 33% ca. 2010 (~60 cal yr BP).
Figure 5.6: Recent history at Green Lake, AD 1480 to AD 2012. Herbaceous (green) and total (black) charcoal concentrations (particles/cm²/year) plotted against age (cal yr BP and yr AD).

Campbell Lake

Chronology and Lithology

A short core and a long core were recovered from Campbell Lake in 2015. The Campbell Lake short core (CBL15A) was 87 cm in length and included the sediment-water interface (Figure 5.7). The long core (CBL15B) was recovered in nine drives and measured 767 cm. Using the MSH-W tephra layer present in both cores, the top 46 cm of core CBL15A was combined with core CBL15B, hereafter referred to as core CBL15C. After removing the two tephra layers, the combined CBL15C core spanned 692 cm in
length. The core showed a pattern of clearly banded layers dark to light gray gyttja with intermixed yellow and sandy layers. Tephra layers were found at 81 (MSH-W) and 526 cm (Mazama O).

Figure 5.7: Examples of CBL15B drives. Clockwise from right: CBL15B drive 4, CBL15B drive 5, CBL15B drive 6, CBL15B drive 8.

The age-depth model for the CBL15C record was developed using 5 AMS $^{14}$C dates derived from bulk sediment, along with accepted dates of the Mazama and MSH-W tephra layers and the coring year, which was assigned to the top of the core, for a total of eight points (Table 5.2). Radiocarbon dates were calibrated using the same methods described above. A constrained cubic smoothing spline was used to fit the age model, which suggests a basal date of 15,270 cal yr BP, with a median resolution of 20.28 yr/cm (Table 5.3, Figure 5.8).
Table 5.3: Age determinations for Campbell Lake core CBL15C.

<table>
<thead>
<tr>
<th>Depth Below Mud Surface (cm)</th>
<th>Source Material</th>
<th>Lab Number</th>
<th>Age($^{14}$C yr BP)$^a$</th>
<th>Age (cal yr BP)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>MSH – W Tephra</td>
<td>N/A</td>
<td>N/A</td>
<td>470 (300-470)$^c$</td>
</tr>
<tr>
<td>195</td>
<td>Bulk Sediment</td>
<td>D-AMS 01596</td>
<td>2707 +/- 61</td>
<td>2770 (2744-2944)</td>
</tr>
<tr>
<td>289</td>
<td>Bulk Sediment</td>
<td>D-AMS 015965</td>
<td>4146 +/- 63</td>
<td>4680 (4521-4838)</td>
</tr>
<tr>
<td>381</td>
<td>Bulk Sediment</td>
<td>D-AMS 015966</td>
<td>6058 +/- 68</td>
<td>6920 (6747-7031)</td>
</tr>
<tr>
<td>526</td>
<td>Mazama Tephra</td>
<td>N/A</td>
<td>N/A</td>
<td>7627 (7577-7777)$^d$</td>
</tr>
<tr>
<td>594</td>
<td>Bulk Sediment</td>
<td>D-AMS 016760</td>
<td>10283 +/- 40</td>
<td>12060 (11924-12187)</td>
</tr>
<tr>
<td>679</td>
<td>Bulk Sediment</td>
<td>D-AMS 016761</td>
<td>12837 +/- 44</td>
<td>15270 (15139-15532)</td>
</tr>
</tbody>
</table>

$^a$ Age calculations were conducted at Direct AMS, Seattle, Washington.

$^b$ Known age of MSH-W Tephra (Mullineax 1974)

$^c$ Known age of Mazama Tephra (Zdanowicz 1999)

$^d$ Calendar ages with 2 sigma age ranges calculated using Calib 7.1 (Stuiver, Reimer and Reimer 2017)

Sedimentation rates varied throughout the core, with an average sedimentation rate of 0.094 yr/cm (Figures 5.8 and 5.9). During the Late Glacial (ca. 15,270 -12,000 cal yr BP; 693-593 cm) the average sedimentation rate was 0.026 yr/cm. During the early Holocene (ca. 12,000-8,000 cal yr BP; 592-538 cm) the sedimentation rate increased to average .014 yr/cm. The sedimentation rate changed little from the early Holocene to the middle Holocene (ca. 8,000-4,000 cal yr BP; 538-257 cm), staying at 0.14 yr/cm. Late Holocene (ca. 4,000 cal yr BP to present; 256-0 cm) sedimentation rates averaged 0.085 yr/cm.
Figure 5.8: Campbell Lake (CBL15C) age-depth model. See Table 5.2 for age determinations used. The slope of the line indicates the sedimentation rate of the record.
Charcoal Concentration, Loss-on-Ignition and Magnetic Susceptibility

Charcoal concentrations remained low for much of the core, staying below 1 particle/cm³ for much of the late Glacial (average: 0.18 particles/cm³) and early Holocene (average: 0.13 particles/cm³) (Figure 5.10). Concentrations increased slightly in the middle Holocene, averaging 0.71 particles/cm³. Concentrations reached their highest levels in the late Holocene, averaging 4.37 particles/cm³. The average organic content for the entire Campbell Lake core was 8.0% (Figure 5.10). Organic content values remained below 10.2% at Campbell Lake for most of the core. The highest peak of 34.1% appears at 276 cm (ca. 4,376 cal yr BP).
Organic content then reached 2.47% at 215 cm (ca. 3,149 cal yr BP). Organic content increased from that point, reaching 27.7% at the top of the core. Late Glacial organic content averaged 6.2%, while the early Holocene organic content averaged 6.45%. Middle Holocene organic content averaged 5.6% and the average organic content in the late Holocene was 11.4%.

The average carbonate content for the entire core was 4.07%. Carbonate content ranged between 0.34% and 2.42% from the bottom of the core until a depth of 579 cm.
(ca. 11,020 cal yr BP), where carbonate content reached 1.92% (Figure 5.10). Above 579 cm, carbonate content declined, reaching 0.18% at 440 cm (ca. 7,210 cal yr BP).

Carbonate content reached a maximum value of 2.73% at 255 cm (ca. 3,940 cal yr BP). Carbonate content quickly dropped to 0.011% at a depth of 250 cm (ca. 3,840 cal yr BP). Carbonate content then reached 2.28% at 197 cm (ca. 2,790 cal yr BP), and the lowest carbonate content for the core was reached at a depth of 713 cm (ca. 1,000 cal yr BP).

Values trend upward until ca. 260 cal yr BP, where they reached 1.44% before dropping to 0.44% at the top of the core. Late Glacial carbonate values averaged 2.2% and early Holocene carbonate values averaged 6.44%. Middle Holocene carbonate values averaged 2.78%, while late Holocene carbonate content averaged 6.3%.

Campbell Lake magnetic susceptibility values show evidence of allochthonous inputs throughout, with the first major peak at 550 cm (ca. 8,650 cal yr BP). Values declined from that point, until a depth of 467 cm (ca. 7,300 cal yr BP), where susceptibility increased, reaching another peak at 315 cm (ca. 5,340 cal yr BP). Values dropped until a depth of 261 cm (ca. 4,060 cal yr BP) and then increased to a maximum for the core at 223 cm (ca. 3,310 cal yr BP). Values then follow a trend of decline until the top of the core. Susceptibility values were elevated coincident with the Mazama and MSH-W events. However, values were also elevated through much of the Campbell Lake core. None of the other peaks in magnetic susceptibility coincided with clearly discernable ash layers. This could be an indication frequent in wash events such as landslides.

The average magnetitic susceptibility value for the entire core was $4.06 \times 10^{-7}$ emu. Late Glacial magnetic susceptibility values averaged $3.71 \times 10^{-7}$ emu. Middle
Holocene values averaged $4.73 \times 10^{-7}$ emu and early Holocene values averaged $2.94 \times 10^{-7}$ emu. The average value during the late Holocene was $2.87 \times 10^{-7}$ emu.

CharAnalysis

**Late Glacial Period (ca. 15,270 to 12,000 cal yr BP)**

During this period, evidence of fire was all but non-existent. The average charcoal concentration was 0.18 particles/cm$^3$ while the average CHAR value was 0.003 particles/cm$^2$/yr. Fire frequency was low throughout the period, with an average fire frequency of 0.27 episodes/1000 yr. One significant peak suggests a single fire episode at ca. 12,860 cal yr BP, with a magnitude of 5.97 particles. Due to the infrequent nature of

Figure 5.11: Cambpell Lake signal-to-noise index (dashed red line), fire episode peak magnitude (charcoal particles/episode; black line), fire episode frequency (fire episodes/1000 years; blue line), and CHAR horizontal black lines (particles/cm2/yr) with significant peaks (black crosses) plotted against age (cal yr BP).
fire during the period, CharAnalysis did not calculate FRIs for the Late Glacial period (Figure 5.11).

**Early Holocene (12,000 to 8,000 cal yr BP)**
The Campbell Lake core suggests little evidence of fire during this period. During the early Holocene, the average charcoal concentration was 0.13 particles/cm$^3$, while the average CHAR value was 0.002 particles/cm$^2$/yr. On average, 0.03 episodes/1000 years occurred. No significant peaks occurred during the period. Like the Late Glacial period, CharAnalysis did not calculate FRIs for the Early Holocene.

**Middle Holocene (ca. 8,000 to 4,000 cal yr BP)**
In this period, the average charcoal concentration was 0.71 particles/cm$^2$, while CHAR values averaged 0.05 particles/cm$^3$/yr. CHAR values were low for the first half of the period, remaining below 1 particle/cm$^3$/yr until ca 5850 cal yr BP, when values reached 2.76 particles/cm$^3$/yr. CHAR values declined again, to reach 1.2 particles cm$^3$/yr. Values then stayed below 1 particle/cm$^3$/yr for the rest of the period. Fire frequency was lowest at the beginning of the period, but steadily increased, reaching 4.22 episodes/1000 yr at ca. 6,900 cal yr BP. From that time, fire frequency declined to 0.75 episodes/1000 yr at ca. 5,900 cal yr BP. Frequency increased again to 2.52 episodes/1000 yr at ca. 4,940 cal yr BP. Frequency dropped from there to the end of the period, reaching 0.44 episodes/1000 yr at ca. 4,020 cal yr BP. Eight significant peaks were identified in this period, with an average peak magnitude of 6.33 particles/episode. The average FRI was 249.0 years.
Late Holocene (4,000 cal yr BP to -65 cal yr BP)

During this period, the average charcoal concentration was 4.37 particles/cm², while the CHAR values averaged 0.2 particles/cm³/year. CHAR values were low to begin the period, staying below 0.75 particles/cm³/yr until ca. 1770 cal yr BP, when they reached 2.76 particles/cm³/yr. After that high value, CHAR remained below 2.78 particles/cm³/yr until ca 550 cal yr BP, when the value was 1.2 particles/cm³/yr. Values from there were below 1 particle/cm³/yr to the top of the core. Fire frequency was low at the beginning of the period, with a low value of 0.011 episodes/1,000 yr at ca. 3,660 cal yr BP. Frequency increased from that time, reaching a high value of 4.81 episodes/1,000 yr at ca. 2,300 cal yr BP. Fire frequency decreased afterward, reaching 2.622 episodes/1,000 yr at ca. 1,140 cal yr BP. Fire frequency increased after that, reaching 4.17 episodes/1,000 yr at -65 cal yr BP. Eleven fire episodes were recorded during the period, with an average peak magnitude of 25.81 particles/episode (Table 5.4).

Table 5.4: Summary of charcoal data for Campbell Lake.

<table>
<thead>
<tr>
<th>Zone: Age cal yr BP</th>
<th>Charcoal Concentration (particles/cm³)</th>
<th>CHAR (particles/cm²/yr)</th>
<th>Fire Frequency (episodes/1000/yr)</th>
<th>Mean Fire Return Interval (years)</th>
<th>Average Peak Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Glacial: Pre-12,000</td>
<td>0.18</td>
<td>0.003</td>
<td>0.27</td>
<td>N/A</td>
<td>5.97</td>
</tr>
<tr>
<td>Early Holocene 12,000 -8,000</td>
<td>0.13</td>
<td>0.002</td>
<td>0.03</td>
<td>N/A</td>
<td>No significant peaks</td>
</tr>
<tr>
<td>Middle Holocene 8,000-4,000</td>
<td>0.71</td>
<td>0.22</td>
<td>1.33</td>
<td>249</td>
<td>50.66</td>
</tr>
<tr>
<td>Late Holocene 4,000-Present</td>
<td>4.37</td>
<td>0.23</td>
<td>2.7</td>
<td>274</td>
<td>25.81</td>
</tr>
</tbody>
</table>
Recent History: AD 1450 to 2015

During the most recent period, the average charcoal influx was 0.70 particles/cm\(^2\)/year, the average herbaceous influx was 0.34 particles/cm\(^2\)/year, and the overall portion of herbaceous charcoal contribution was 41\%. Charcoal influx was 0.84 particles/cm\(^2\)/year in ca. 1480 AD (470 cal yr BP). From that point, influx values varied between 0.05 particles/cm\(^2\)/year and 1.54 particles/cm\(^2\)/year until ca. AD 1620 (330 cal yr BP), when an upward trend began, reaching 2.05 particles/cm\(^2\)/year by ca. AD 1740 (210 cal yr BP). From there, influx values crash, reaching 0.08 particles/cm\(^2\)/year by ca. AD 1760 (190 cal yr BP). Influx values increased again, reaching 1.93 particles/cm\(^2\)/year in AD 1800 (150 cal yr BP). Influx values dropped from that point, reaching zero by ca. AD 1870 (80 cal yr BP). An increasing trend followed, reaching 1.72 particles/cm\(^2\)/year by ca. AD 1920 (30 cal yr BP). Influx values decreased from ca. AD 1920 to reach 0.10 particles/cm\(^2\)/year by ca. AD 1970 (-20 cal yr BP). Influx remained below 0.5 particles/cm\(^2\)/year until ca. AD 2000, when influx increased to 2.02 particles/cm\(^2\)/year.

Early in the period, herbaceous charcoal accounted for the majority of charcoal influx. In AD 1480 (470 cal yr BP), 94\% of charcoal influx was herbaceous. Herbaceous contributions dropped from there, reaching zero at several points prior to AD 1780 AD (170 cal yr BP). Shortly after that, the herbaceous contribution reached 100\% by ca. AD 1830 (120 cal yr BP). The herbaceous contribution dropped from that point and remained below 80\% until AD ca. 1980 (-30 cal yr BP), when it reached 100\%. Herbaceous charcoal concentration variability increased after that, with values ranging between 0 and 100\% until the top of the core, and 50\% of charcoal fragments were herbaceous in AD 2015 (-65 cal yr BP) (Figure 5.12).
Figure 5.12: Recent fire history at Campbell Lake. Herbaceous (green) and total (black) charcoal influx (particles cm$^2$/yr) plotted against age (cal yr BP and yr AD).

CharAnalysis Performance

In MCA studies, an SNI ratio of 3 or higher is generally considered an indication of well resolved peaks suggesting fire episodes (Kelly et al. 2011; Haydon 2018).

CharAnalysis results at both lakes show SNIs well above the desired 3.0 threshold during much of the post-glacial period (Kelly et al. 2011; Haydon 2018). The SNI at Green Lake was 4.15 for the entire record, while the Cambell Lake record shows at SNI of 4.97. While the software had an easier time separating charcoal peaks from the background charcoal at Campbell Lake, it may have struggled to identify fire events when overall charcoal influx was relatively low, such as during the Late Glacial when only a single charcoal peak was identified, and SNI fell below the threshold at several points. SNI also dropped below 3.0 during much of the early Holocene, when no fire events were identified. The software performed well during the first half of the middle Holocene, but
SNI dropped below 3.0 around ca. 6,000 cal yr BP, and again in the first part of the late Holocene.

In contrast, Green Lake’s SNI was lower on average for the entire record, but more consistently stayed above the threshold, dropping below 3.0 for approximately 900 years during the middle Holocene, and for a few brief time periods during the late Holocene. SNI tended to be higher during the Late Glacial and early Holocene, when low fuel loads likely did not allow for frequent fires, making fire episodes easier to separate from the background. During much of the middle and late Holocene, SNI stayed above the threshold, but was lower than in the Late Glacial and early Holocene. This suggests more frequent fire episodes during the second half of the Holocene at Green Lake, which may have overwhelmed the program’s ability to detect discrete fire episodes. Therefore, fire events may be more frequent within the Green Lake watershed than this analysis would suggest.
CHAPTER VI

DISCUSSION

Green Lake

*Late Glacial Period (ca. 14,670 – 12,000 cal yr BP)*

The paleoenvironmental reconstruction from Green Lake extends back to ca. 14,670 cal yr BP. High magnetic susceptibility values near the bottom of the record, the earliest interpolated date in the age-depth model, and a reconstruction of the retreat of the

Figure 6.1: Summary of Green and Campbell Lake fire frequencies and peak magnitudes. Top: July Insolation anomaly compared to present day values (blue line) and ENSO episode frequency (red). Middle Top: Z scores of 34 charcoal records compiled by Walsh et al. (2015) with 95 % standard error ranges. Middle Bottom: Green Lake Fire frequency (purple) and peak magnitude (red). Bottom: Campbell Lake fire episode frequency (purple) and peak magnitude (red).
Okanogan Lobe of the Cordilleran ice sheet (Booth 1987) suggest that the lake formed soon after the region became ice free, ca. 16,000-15,000 cal yr BP. During the Late Glacial, Green Lake fire activity increased considerably within two millennia of the ice sheet’s retreat, with the first significant fire episode detected at ca. 13,460 cal yr BP. After that point, fire episodes remained relatively infrequent, reaching 6 episodes/1000 yr by the end of the period. Increased fire activity during the Late Glacial likely occurred as summer insolation increased and the ice sheet retreated in response (Bartlein et al. 1998) (Figure 6.1 B, E).

Pollen data are not currently available for comparison with this portion of the Green Lake record. Nearby Doheney Lake, Mud Lake, and Bonaparte Meadows reconstructions all have basal dates younger than the earliest dates in the Green Lake record (Mack, Rutter, and Valostro 1979; Haydon 2018). However, macrofossil data show that sagebrush was well established in the PNW by ca. 14,000 cal yr BP (Bartlein et al. 1998). It is likely that although conditions were cool and dry, they nonetheless allowed sagebrush and grasses to quickly colonize the site after the ice sheet’s retreat and the carving of Green Lake, providing sufficient fuel for fires (Booth 1987; Bartlein et al. 1998). Green Lake fires at the time were likely low-severity ground fires, indicated by the small peak episode magnitudes averaging 2.2 particles/episode, and herbaceous charcoal values averaging 70%.

**Early Holocene (ca. 12,000 – 8,000 cal yr BP)**

The early Holocene saw the onset of the Early Holocene Warm Period (EHWP). Despite the resulting increases in summer insolation and warmer temperatures during the early
Holocene (Walker and Pellatt 2008), average fire frequency did not increase much relative to the Late Glacial period. Green Lake’s fire frequency started at just over 6 episodes/1000 yr at ca. 12,000 cal yr BP and hovered between 3 and 6 episodes/1000 yr until ca. 8,000 cal yr BP, with an average 4.5 episodes/1000 yr for the period. However, charcoal concentrations more than doubled relative to the Late Glacial average of 1.36 particles/cm³ to 2.78 particles/cm³. On average, herbaceous charcoal accounted for 62% of charcoal particles during the period, suggesting low-severity and infrequent ground fires (Figure 6.1B).

The pollen record at Mud Lake (Mack, Rutter, and Valostro 1979) shows a mixed ponderosa pine, sagebrush, and sedge community from ca. 12,000-10,000 cal yr BP. Ratios of arboreal to non-arboreal pollen tended toward non-arboreal pollen during this time, suggesting that even though temperatures were several degrees warmer than at present (Walker and Pellatt 2008), trees were likely still sparse on the landscape. As a result, fuel limitations probably suppressed fire activity at the Green Lake site at this time. In the second half of the early Holocene, sagebrush became dominant in the Mud Lake record, while fire frequency increased at Green Lake along with the herbaceous contribution to the charcoal influx, averaging ~70% from ca. 10,000 to 8,000 cal yr BP. The Doheny Lake pollen record shows pine values at their lowest in the record during the early Holocene period, with sagebrush and grasses well represented (Haydon 2018). Like Green Lake, charcoal at Doheney was primarily herbaceous (74%). The two sagebrush environments likely experienced similarly low-severity fire events (Figure 6.1A, B, E).

The elevated charcoal influx at Green Lake during the early Holocene could indicate human use of fire near the site, although it is just as likely that lightning ignited
the fires observed in the reconstruction. Archeological records specific to the Northern Okanogan Plateau are not well developed for the early Holocene (Pokotylo and Mitchell 1998), making it difficult to infer human influences on the landscape. However, studies of sites just to the southwest of Green Lake show evidence of some dwellings appearing during the period between ca. 11,000 and 6,350 yr BP (Pokotylo and Mitchell 1998). Fire has been documented as a tool to clear dwelling sites (Kimmerer and Lake 2001), providing some evidence that frequent, low-intensity human activities contributed to the increase in charcoal concentrations relative to the Late Glacial, and the increased fire episode frequency observed toward the second half of the early Holocene.

*Middle Holocene (ca. 8,000 – 4,000 cal yr BP)*

Green Lake fire episode frequency decreased in the middle Holocene, averaging 3.78 episodes/1000 yr. At the start of the period, fire frequency was at approximately 6 episodes/1000 yr but declined to just above 3 episodes/1000 yr by ca. 7,000 cal yr BP, reaching just over 6 episodes/1000 yr by the end of the period. Charcoal concentrations averaged 6.42 particles/cm³, while charcoal influx values averaged 0.22 particles/cm²/yr. Charcoal influx values began the period at 0.21 particles/cm²/yr, and followed an increasing trend over the period, reaching 1.2 particles/cm²/yr by ca. 4,290 cal yr BP.

The Doheny Lake pollen record shows an increase in pine contribution and a coincident decrease in sagebrush during this period. Douglas-fir/larch are also first noted at the site at this time. At Mud Lake and Bonaparte Meadows, the pine and sagebrush communities were well established by the beginning of the middle Holocene. The shift toward sagebrush environments mixed with some moisture and shade-tolerant species
suggests that the Green Lake watershed was no exception to the cool, wet conditions of the middle Holocene.

Reduced fire frequency in the middle Holocene suggests that reduced summer insolation and cooler, wetter conditions drove fire activity at Green Lake during the middle Holocene (Bartlein et al. 1998) (Figure 6.1B). However, charcoal concentrations (avg. 6.22 particles/cm$^3$) and influx values (avg. 0.22 particles/cm$^2$/yr) were elevated during the period compared to earlier; however, the middle Holocene SNI dropped below three for much of the period. This discrepancy between calculated fire episode frequency, charcoal concentration and influx values, along with reduced SNI suggests that fires may have been more frequent during the middle Holocene than this analysis suggests. Constant influx of charcoal from frequent fires may render the “peaks” component difficult to separate from the “background” component of the charcoal signal.

Mechanisms explored by Mensing, Livingston, and Barker (2006) could explain the discrepancy between calculated fire frequency and elevated charcoal influx values at the Green and Doheney sites during the middle Holocene (Figure 6.1 A, B). A sediment charcoal record from Newark Valley, Nevada, stretching to ca. 5,500 cal yr BP shows a relationship between cooler, wetter, periods and elevated fire activity relative to dry periods where fire activity was suppressed. Wet periods allow sagebrush to proliferate, and dry intervals within those wet periods provide sufficient dead fuel for fires to burn. Sagebrush growth is inhibited during extended dry periods, reducing fuel loads. The elevated charcoal influx and concentrations observed during the period could represent low severity fire events that were too frequent for CharAnalysis to easily resolve.
Human influence at Green Lake cannot be discounted as a reason for the increasing trend in charcoal values of the middle Holocene. Evidence of moderately sedentary Okanogan Valley habitation exists as far back as ca. 6,000 yr BP (Pokotylo and Mitchell 1998). The archeological record shows a shift toward a sedentary foraging lifestyle among Native American groups present in the Southern Plateau at ca. 5,200 cal yr BP (Chatters and Prentiss 2005). This shift occurred during the same general time frame as an increase at Green Lake toward the end of the middle Holocene. Fire has been documented as tool to clear village areas, and could have facilitated the increased sedentism (Kimmerer and Lake 2001).

*Late Holocene (ca. 4,000 cal yr BP – Present)*

Overall, fire activity at Green Lake was at its highest during the late Holocene, as increased ENSO variability, land use changes, and vegetational shifts likely drove fire activity in the watershed (Figure 6.1B). Other published records describe similar dynamics across the PNW (Marlon et al. 2012; Walsh et al. 2015). ENSO variability provided additional dead fuel and frequent drought conditions to allow more frequent fire events than temperature and precipitation trends would suggest (Moy et al. 2002). Land use changes occurred after Euro-American contact, by way of an indigenous population crash and land conversion to agricultural and grazing uses (Marlon et al. 2012).

At the beginning of the period, nearly 7 episodes/1000 yr occurred. From that time, Green Lake fire frequency varied between 6 and 8 fires until just after the start of the MCA at ca. 1100 cal yr BP, when fire frequency dropped back to approximately 6 episodes/1000 yr (Mann et al. 2009). Charcoal influx at Green Lake did not decrease with
the end of the MCA or with the onset of the LIA. Rather, Green Lake charcoal influx trended upward, reaching 7.7 particles/cm$^2$/yr at ca. 120 cal yr BP.

Like during the middle Holocene, high late Holocene charcoal influx values (avg. 1.62 particles/cm$^2$/yr) and low SNI may indicate that fires were more frequent than the CharAnalysis calculated frequency would suggest. The SNI dropped below three at several points during the late Holocene. It is likely that like during the middle Holocene, frequent, low-severity fires rendered discreet episodes difficult for CharAnalysis to resolve. At nearby Fish Lake, a site situated in a dry ecotone environment in the Sinlahekin Wildlife Area, low SNI values and consistently high charcoal influx prevented the use of CharAnalysis (Walsh, Duke, and Haydon 2018).

The Fish Lake record stretches to just after the transition to the late Holocene (Figure 6.2). Pollen analyzed from site shows a relatively unchanging plant community dominated by pine mixed with various understory species including sagebrush. The charcoal record from Fish Lake features high levels of herbaceous charcoal, suggesting frequent, low-severity fires helped maintained the ponderosa pine community. The Doheney Lake pollen record shows that sagebrush declined at the site during the late Holocene, suggesting a shift to a community more similar to the dry forest seen today (Haydon 2018). The Doheney fire regime remained one of low severity fires despite this shift (Figure 6.1A, Figure 6.2) (Haydon 2018). At Newark Valley, the late Holocene pollen record shows shifts between an environment dominated by sagebrush and one dominated by desert scrub (Mensing, Livingston, and Barker 2006).
Figure 6.2: Total (black) and herbaceous (green) charcoal influx values over the past 4000 cal yr BP at Green, Campbell, Fish, and Doheney lakes.
Vegetation reconstructions at Mud Lake and Bonaparte Meadows show trends toward reduced levels of sagebrush and increased levels of pine and sedge during the late Holocene, likely in response to progressively cooler, wetter conditions (Walker and Pellatt 2008). If similar processes occurred at nearby Green Lake, the immediate community progressed toward a seral stage consisting of ponderosa pine and sedges near the water, but with fire clearing herbaceous vegetation to maintain a “park like” community as discussed in several sources (Agee 1993, 1994; Arno and Allison-Bunnel 2002). Elevated levels of woody charcoal in Green Lake late Holocene sediments relative to the rest of the record (56%) support this interpretation. The Fish Lake record also shows frequent, low-severity fires maintaining the community, but Green Lake fires were likely of higher severity (Walsh, Duke and Haydon 2018). Newark Valley fires were infrequent during this period and showed a general pattern of decline (Mensing, Livingston, and Barker 2006).

During the MCA and LIA, the Green, Fish, and Doheney records show some coherence, which may provide some insight into vegetation/fire dynamics in dry sagebrush environments (Figure 6.2). The records do not show steep increases in charcoal influx with the onset of the MCA and dry, warm conditions (Haydon 2018; Walsh, Duke, and Haydon 2018). Instead, charcoal influx increased during the LIA.

It seems likely that during the late Holocene that human use of fire influenced Green Lake fire activity, at least prior to settlement. Cooling conditions from ca. 4,200 cal yr BP influenced a shift to a collector based subsistence strategy, featuring storage of resources and seasonal mobility (Chatters and Prentiss 2005). This more mobile strategy could have reduced the need to burn vegetation in the Green Lake watershed.
Nonetheless, some incentive for burning likely remained. For example, the Okanogan peoples were known to harvest at least eight different varieties of saskatoon berry plants depending on local availability (Baker 1990). Burning may have encouraged berry growth for future years as part of this collector strategy, which grow in the Green Lake watershed today and range across the PNW (Little 1976).

Later in the record, fire activity at Green Lake likely reflects both a smallpox driven indigenous population crash and internment on reservations. Estimates suggest an Okanogan population of ca. 12,000 prior to Euro-American contact (Baker 1990) (Figure 6.2). Smallpox had likely reached the area by AD 1775. Revised figures show a population of 4,361 Okanogan by the time of the Lewis and Clark expedition in AD 1805-06, and further demographic work shows an Okanagan population of 2,610 in AD 1838 (Boyd 1998). The population continued to decline after the establishment of reservations, with an AD 1890 census counting 2,417. The declining trend in Okanagan population roughly coincides with a decline in charcoal influx values. At ca. 200 cal yr BP (AD 1750) the charcoal influx was 4.76 charcoal particles/cm$^2$/yr. Influx values remained steady for 80 years, only to jump to 7.7 particles/cm$^2$/yr around 120 cal yr BP (AD 1830). From that time, influx values steeply decline, reaching 1.97 particles/cm$^2$/yr around the turn of the century, which is prior to active fire suppression (Agee 1994). Euro American land management changes likely influenced this decline in Green Lake fire activity along with declines in the Okanogan population (Marlon et al. 2012).
Campbell Lake

Late Glacial Period (ca. 15,270 – 12,000 cal yr BP)

Dates for the Campbell Lake core extend nearly 16,000 cal yr BP, suggesting that the lake formed early in the Okanogan Lobe’s retreat and eventual disintegration (Booth 1987). Little evidence of fire exists in the Campbell core during the Late Glacial period, with only one significant charcoal peak recorded during the period. This lack of evidence for fire relative to Green Lake likely reflects the cold temperatures and low insolation values present at the time (Booth 1987; Bartlein et al. 1998) (Figure 6.1C).

With only a single significant peak at 12,860 cal yr BP, little evidence of fire appears at Campbell Lake during this period. Insignificant peaks (12) were shown in the record, however. This suggests that any fires that did occur were of low enough severity or sufficiently far from the lake to be obscured by background component of the charcoal signal. Fuel limitation likely suppressed fire activity at the site as vegetation was slow to recover after the glacial retreat.

Early Holocene (ca. 12,000 – 8,000 cal yr BP)

Fire activity did not increase at Campbell Lake with warming temperatures and increasing summer insolation during the early Holocene (Figure 6.1C). This paucity of fire activity likely reflects low fuel availability at the site. Although increasing summer insolation allowed ice sheets to retreat even further, and grasslands were replaced by woodlands and tree communities at other sites in the region (Booth 1987; Mack, Rutter, and Valostro 1979, Mack; Walsh, Whitlock, and Bartlein 2008; Walsh et al. 2015), few trees likely grew in the Campbell Lake watershed at the time (Figure 6.1C). Although the sagebrush and pine community was established early in the period at nearby Mud Lake
and Bonaparte Meadows (Mack, Rutter, and Valostro 1979), vegetation within the Campbell Lake watershed was likely not much different than that at the site today (prior to the CCF in 2014), which includes few trees. No significant fire episodes were determined, and charcoal influx rates remained below 0.01 particles/cm²/yr for most of the early Holocene. Much like during the Late Glacial Period, any fires that did occur were likely of too low of severity to be detected by CharAnalysis (Conedera et al. 2009; Higuera et al. 2009; Kelly et al. 2011; Haydon 2018).

With the scant evidence of fire at Campbell Lake during the period, few inferences can be made in regard to human influence on the fire regime. If it is assumed that use of fire by Okanogan peoples occurred (Kimmerer and Lake 2001), then perhaps the lack of fire activity could indicate that the Campbell Lake watershed was not commonly used or travelled. However, it seems more likely that the fuel limitation at the site inhibited fire.

**Middle Holocene (ca. 8,000 – 4,000 cal yr BP)**

Fire finally appeared in the Campbell Lake record in the middle Holocene, as cool, wet conditions overall (Bartlein et al. 1998; Walker and Pellatt 2008) allowed sagebrush fuel to accumulate and greater ENSO variability (Moy et al. 2002) dried fuels during drought intervals (Nelson et al. 2011). Starting with the beginning of the middle Holocene, significant peaks appeared, and fire frequency increased. Overall, the period was marked by temperature and precipitation anomalies cooler and wetter relative to today in the PNW (Bartlein, Hostetler, and Alder 2014). By ca. 8,100 cal yr BP, the Mud Lake and Bonaparte Meadows vegetation had shifted to include higher proportions of sagebrush (Mack, Rutter, and Valostro 1979). The cool, wet conditions likely allowed
sagebrush to proliferate at Campbell Lake, providing sufficient fuel for combustion during warmer and drier intervals within the middle Holocene period (Baker 2006; Mensing, Livingston, and Barker 2006), consistent with other sagebrush environments such as those in the Fish Lake, Doheney Lake, and Green Lake environments.

Effects of indigenous burning at Campbell Lake are not clearly evident. The dominant model for Native American subsistence during the early part of the period was one of high mobility foraging, with a shift toward less mobile subsistence strategies beginning ca. 5,200 yr BP on the Southern Plateau (Chatters and Prentiss 2005). Pit houses appeared in the Northern Plateau’s Okanogan Valley even earlier, by ca. 5,950 yr BP (Pokotylo and Mitchell 1998). However, although two significant peaks were recorded after ca. 5,200 cal yr BP, the trend in fire frequency moved toward a decline, ending the period at less than 1 episode/1000 years. Although humans were in the area by this time, it is not likely that they burned much vegetation in the Campbell Lake watershed.

Late Holocene (ca. 4,000 cal yr BP – Present)

During the late Holocene, ENSO variability and drought likely represented the primary driver of Campbell Lake fire activity as fire activity increased (Moy et al. 2002; Nelson et al. 2011). However, short term climatic events such as the LIA and MCA affected Campbell Lake fire activity. Human influences such as Native American burning, Euro-American settlement and subsequent land use shifts also seemingly affected Campbell Lake fire activity. A fire frequency curve was calculated, with an average of 2.7 fire events/1000 years. However, CharAnalysis struggled to resolve individual fire events in the record, much like at the Green, Doheney, and Fish Lake sites.
Late Holocene charcoal influx values averaged 0.23 particles/cm²/yr, virtually unchanged relative to the early Holocene. Like the middle Holocene, Campbell Lake SNI fell below three at several points during the period. The fire frequency curve likely underestimated fire events in the Campbell Lake record. Fire activity responded to the MCA and LIA (1,000-700 cal yr BP; and 550-250 cal yr BP; Mann et al. 2009) in similar fashion to fire activity at the Fish, Doheney, and Green Lake sites, with little response to the MCA, and elevated charcoal influx during the LIA (Figure 6.2).

The Campbell Lake record shows little evidence that human activities influenced fire within the Campbell Lake watershed in recent centuries. Charcoal influx was at 1.2 particles/cm²/yr at ca. 550 cal yr BP. Charcoal influx varied but did not crash from that time to the present. Charcoal influx rates were higher on average relative to the other time periods in the record, but this likely reflected ENSO variability providing additional dry and dead fuel (Moy et al. 2002). Vegetation around Campbell was likely the nearly treeless landscape seen today, with fires limited by fuel availability.

Synthesis of Green and Campbell Lakes and Regional Comparison

Green Lake fire activity quickly responded to warming temperatures during the Late Glacial period as the Okanogan Lobe retreated (Booth 1987). During the first half of the early Holocene (12,000- 10,000 cal yr BP), fire frequency at Green Lake declined from its Late Glacial maximum, while the transformed z scores for the PNW were increasing. From approximately 10,000 cal yr BP to the present, trends in Green Lake fire frequency show overall agreement with trends in the PNW. Z scores show a short-lived
decrease, followed by a moderate increase until the transition from the early to mid-Holocene at ca. 8000 cal yr BP (Figure 6.1).

In contrast, little evidence of fire was detected at Campbell Lake until ca. 12,860 cal yr BP, and no fire episodes were detected at Campbell Lake during the early Holocene. Campbell influx rates remained low throughout the period. Both study sites occupy similar longitudes, suggesting local conditions as an explanation. This contrast is likely related to fuel availability. Campbell Lake sits at twice the elevation as Green Lake. It is possible that the higher elevation led to somewhat cooler local conditions at Campbell Lake, inhibiting vegetation loads during the Late Glacial. Fire regimes at both sites resemble the fuel limited conditions common to American Southwest sites (Nelson and Pierce 2010). Local conditions likely played roles in driving differences between the two lakes.

PNW biomass burning responded to warmer conditions in the Early Holocene with increases in fire activity at multiple sites across the region (Walsh et al. 2015). In contrast, the Campbell Lake record shows little evidence of fire during the period, suggesting that fire was controlled by local conditions. Fuel availability likely inhibited fire activity at Campbell during the early Holocene. Charcoal influx at Green Lake increased somewhat but remained steady relative to the values of the Late Glacial period.

It is possible that Campbell Lake did respond to the warming conditions of the early Holocene, but with fire size or severity too low, or too frequent, to be detected as significant peaks (Kelly et al. 2011). In contrast, Green Lake charcoal influx during the period suggests more frequent fires during the early Holocene. These differences between
the two records suggest that fuel was a limiting factor at both Campbell Lake and Green Lake during the early Holocene, with more fuel available at Green Lake.

In the broader PNW, middle Holocene fire activity was suppressed as cool, wet conditions prevailed as summer insolation was reduced and forest canopies closed in response to cooler, wetter conditions, and reaches a minimum for the period at ca. 5,500 cal yr BP (Marlon, Bartlein, and Whitlock 2006; Walsh et al. 2015). The record shows that fire activity was reduced at Green lake during the period. In contrast, the middle Holocene triggered the arrival of fire to the watershed at Campbell Lake. These differences suggest that by the middle Holocene, sufficient fuel had finally accumulated at the higher elevation Campbell Lake site to facilitate combustion, while sufficient fuel had already been present at Green Lake since the Late Glacial. Fuel appears to be dominant limiting factor in fire activity at Green and Campbell Lakes. However, low Green Lake SNI values during the middle Holocene suggest that fires may have been more frequent than CharAnalysis was able to resolve.

During most of the late Holocene, the fire activity was elevated relative to previous periods in the broader PNW (Walsh et al. 2015). High fire activity during the period was likely related to frequent ENSO events, human influences such as intentionally set fires, and much later, invasive species such as cheatgrass increasing fuel loads (Baker 2006; Marlon et al. 2012). Both the Green and Campbell Lake sites show increases in charcoal influx relative to the middle Holocene.

At both sites, charcoal influx showed little response to the MCA with elevated influx during the LIA. The LIA did not bring a reduction in fire at either site, while warmer conditions did not bring increases in fire during the MCA. At Green Lake,
charcoal influx increased during both the MCA and LIA prior to steeply dropping at ca. 120 cal yr BP, around the time of Okanogan County’s settlement, but prior the onset of widespread fire suppression (Agee 1994; Marlon et al. 2012, Wilson 1990). The Green record shows declines in fire activity resulting from Native population declines and subsequent Euro-American settlement and land use changes. The Campbell Lake record suggests that human influence was not strong in the surrounding watershed, with no such declining trend.
CHAPTER VII
CONCLUSIONS

Four research questions were formulated regarding the long-term fire history in the Methow Valley. Those research questions were:

1) How has fire activity varied within and between the two study sites during the past ~15,000 years?

At Green Lake, fire activity quickly responded to the collapse of the Okanogan Lobe of the Cordilleran Ice sheet, with the earliest fire event in the record detected at ca. 14,060 cal yr BP, as vegetation colonized the site (Booth 1987). In contrast, little evidence of Campbell Lake fire was detected during the Late Glacial, suggesting that the site was slow to revegetate after the Okanogan Lobe’s retreat.

During the early Holocene, moderately frequent and low-severity fires burned at Green Lake while the Campbell Lake record shows little evidence of fire during the period. Severity was likely too low at Campbell Lake for CharAnalysis to resolve any fires that did occur (Higuera et al. 2009; Kelly et al. 2011).

The middle Holocene record shows that the cool, wet conditions brought fuel to the Campbell Lake watershed and allowed fires to burn, while fire frequency calculations suggest these same conditions somewhat inhibited fire activity at Green Lake. However, charcoal influx values increased at Green Lake relative to the early Holocene, while SNI values decreased. It is possible that just like at Campbell Lake, the cool, wet conditions of the middle Holocene brought more frequent fires to the Green Lake watershed by
allowing sagebrush fuel to grow, but the fire events were to close together in time for CharAnalysis to identify them.

During the late Holocene, Green Lake fire frequency and peak magnitudes were highest, suggesting more frequent, and closer or more intense fires as the site came to resemble the ponderosa pine and sagebrush ecotone seen today. Charcoal influx did not increase at the site during the MCA but was elevated during the LIA. Charcoal influx declined from mid AD 1800s to until AD 2012, when the first Green Lake excursion was undertaken. Although trends in charcoal influx were similar during the late Holocene at Green Lake, they were elevated at Campbell Lake. No human activity related drop was seen in recent centuries, and the watershed remained fuel-limited.

2) To what extent have climatic variability and human actions during the past ~15,000 years influenced fire activity at the two sites?

Green Lake formed shortly after the retreat of the Okanogan Lobe of the Cordilleran Ice sheet, which was caused by increased summer insolation values and atmospheric CO₂ concentrations (Whitlock 1992; Whitlock et al. 2011). Green Lake fire activity quickly responded to the warming conditions with fire episodes occurring as early as ca. 14,060 cal yr BP. Fires episodes occurred with moderate frequency, however, peak magnitudes (avg. 1.44 particles/episode) were low during the period, suggesting either low-severity or small fires, or events distant from the lake (Higuera et al. 2009). Fires continued to burn at similar frequency during the early Holocene as summer insolation and CO₂ concentrations continued to increase and the warming conditions allowed enough fuel for combustion. Green Lake fire activity declined during the middle Holocene as summer
insolation values dropped and cooler, wetter conditions prevailed. During the late Holocene, ENSO variability likely allowed for higher fire episode frequency relative to the middle Holocene, despite falling summer insolation levels and generally cooler and wetter conditions (Moy et al. 2002; Bartlein et al. 1998). Increases in peak magnitude and the proportion of woody charcoal fragments suggest a shift toward a higher severity regime relative to the middle Holocene, with sagebrush likely acting as ladder fuels to burn ponderosa pines. The MCA did not affect any major changes to fire activity at Green Lake; however, fire activity was highest of the entire record (in terms of charcoal influx) during the LIA.

At Campbell Lake, fire activity was delayed in its response to the ice sheet collapse, with little evidence of burning during both the late Glacial and early Holocene. Abundant evidence of fire does not appear in the record until the middle Holocene, when cooler, wetter conditions prevailed (Walker and Pellatt 2008). Like Green Lake, more frequent fires burned at Campbell Lake during the late Holocene, when greater ENSO variability likely provided dry fuel during more frequent drought episodes (Nelson et al. 2011). Also, like Green Lake, Campbell Lake fire activity did not strongly respond to the warm, dry conditions of the MCA, but was elevated during the LIA.

Archeological studies show evidence of human occupation on the Okanogan Plateau as early as ca. 11,500 years BP, coinciding with a general increase in fire activity during the early Holocene at Green Lake (Ames et al. 1998; Pokotylo and Mitchell 1998). During the middle Holocene, evidence of increasing sedentism and likely increased human population density appeared in the Plateau record by ca. 6,350 years BP, during a period of reduced overall fire activity relative to the early Holocene at Green Lake and
the arrival of fire to the watershed at Campbell Lake (Ames et al. 1998). During the late Holocene, both sites showed elevated fire frequency. The human and climatic signals are difficult to separate, but it is possible that human burning kept fire activity at both sites elevated during the LIA when climatic influence would have favored a decline. Late Holocene fire activity was elevated at both lakes relative to the middle Holocene, and remained elevated at Green Lake until the 19th century, when Euro-American settlement and subsequent land use changes, followed by fire suppression in the 20th century, reduced charcoal influx until the recent CCF in 2014. The Campbell Lake record does not show this settlement related decline.

3) What do the Campbell and Green Lake records suggest about Holocene fire regimes in ponderosa pine/sagebrush ecotone environments, and how do these regimes differ from those of other PNW environments?

Overall, the two records suggest fire regimes near both lakes are fuel-limited. In addition, these environments differ from low-frequency, high-severity fire regimes such as those observed west of the Cascades in terms of frequency, severity, and responses to periods of elevated drought variability. While the warming, drying conditions of the early Holocene led an increase in fire activity across the PNW, Green Lake fire activity dropped somewhat, and Campbell Lake shows little evidence of fire during the period. The conditions likely inhibited fire in these environments by inhibiting sagebrush growth. Some investigations have shown a relationship between cool, wet conditions and elevated fire activity in sagebrush environments (Baker 2006; Mensing, Livingston, and Barker 2006). Cool, wet periods allow fuel loads to increase as sagebrush proliferates, and drier
intervals within those periods allow the additional fuel to burn. This mechanism may be more likely than human influence in driving fire activity at Campbell Lake during the LIA, considering that a similar pattern is observed at Doheney and Fish lakes, both within sagebrush environments. At Green Lake, it seems more likely that humans had some influence on fire in Green Lake watershed, with elevated charcoal influx over the LIA, and a drop in influx when the indigenous population declined.

4) How can this information be used to more effectively manage development in the WUI areas of the Eastern Cascades?

The records at both Green and Campbell lakes suggest fuel-limited environments during the post-glacial period. So in order to decrease fire activity in these landscapes today, fuels must be removed. Given what was observed in the two records, the recent anthropogenic-caused warming trend might be expected to reduce fire activity in the Campbell and Green Lake watersheds by limiting the growth of sagebrush (Baker 2006). However, human alterations to these watersheds including the introduction of cheatgrass, fuel accumulation due fire suppression (primarily in ponderosa pine-dominated environments), and WUI development, will likely counteract this effect. New fuels have also been added in the form of structures, Douglas-fir trees have encroached into formerly ponderosa pine-dominated forests (Haeuser 2014), and cheatgrass has created continuous and connected fuel loads on the landscape (Radeloff et al. 2005; Baker 2006; Hammer et al. 2007). These conditions can lead to larger fires than would have otherwise occurred in areas with people and property at risk, such as the record setting CCF and OCF.
Development adds additional fuel to the already fire prone environment of the Methow Valley WUI in sagebrush/ponderosa pine ecotones where fuel is a limiting factor. Experiments and modeling analyses suggest that well planned development can mitigate WUI fire risk by creating breaks between fuels and ignition sources while making structures more resistant when a fire occurs (Cohen 2002; Colburn 2008; Scofield et al. 2015). To protect the public interest in the WUI areas, the National Fire Protection Association (2013) has released a list of recommendations. These recommendations include:

1) Building code standards:

The NFPA lists possible provisions for adoption into local codes dealing with new building construction. Design standards include, but are not limited to, fire-resistant roofs and requirements for sprinklers within larger structures.

2) Land Use standards:

The NFPA also encourages reduction of WUI risk by promoting adoption of land use codes. Standards include the use of natural features as fire breaks, and homeowner association maintained defensible space requirements. New subdivisions or Planned Unit Developments can be required to cluster development in low-hazard areas of a site.

Jurisdictions within Okanogan County have adopted these measures or ones like them to varying degrees. However, in the face of warming temperatures, and development pressures, these regulatory measures may be insufficient. To supplement existing codes, the International Code Council provides the IWUIC, which includes many of the above provisions. Adoption of the IWUIC, continued promotion of Firewise
construction and management on a voluntary basis, and promotion of subdivisions clustered in areas of reduced fire hazard may mitigate fire risk in the Okanogan County WUI.

The results of this study will be submitted for publication in the peer-reviewed scientific literature. In addition, the information contained here will be offered to Methow Valley decision makers such as land managers, land use planners, and fire district personnel to inform wildfire planning decisions. It is hoped that dissemination of this work will assist in safely living with fire in the Methow Valley.
REFERENCES CITED


