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The Role of Fire in Montane Forest Environments in the Willamette National Forest, Oregon

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THE ROLE OF FIRE IN MONTANE FOREST ENVIRONMENTS IN THE

WILLAMETTE NATIONAL FOREST, OREGON

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Tamara Cox

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ABSTRACT

THE ROLE OF FIRE IN MONTANE FOREST ENVIRONMENTS IN THE WILLAMETTE NATIONAL FOREST, OREGON

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High-resolution charcoal and pollen analyses were used to reconstruct a 16,000-year-long fire and vegetation history of the Blair Lake watershed in the Willamette National Forest of Oregon. The record shows that during the late glacial period, overall fire frequency was relatively low. *Pinus* and *Abies* were the dominant vegetation, along with *Pseudotsuga* and *Alnus*, suggesting that an open-canopy conifer forest developed soon after the area was glacier free. Fire frequency increased during the early Holocene. Warmer and drier conditions are reflected in the herbaceous vegetation, *Artemisia*, Poaceae, and Cyperaceae, suggesting that meadows or other openings were part of the forest environment at this time. Fire frequency decreased at the beginning of the middle Holocene and was relatively stable until it began increasing at ca. 6,000 cal yr BP, and the highest fire frequency for Blair Lake occurred at ca. 5,500 cal yr BP. Increases in *Tsuga heterophylla* and *Tsuga menziesii* during the middle Holocene indicate that conditions were wetter, and decreases in *Pseudotsuga* and *Alnus* suggest that the forest was more closed than earlier. Fire frequency decreased at the beginning of the late Holocene and was especially low at ca. 3,000 cal yr BP. It then increased until ca. 900 cal yr BP, before decreasing toward present. Decreases in *Pinus* and *Artemisia*, combined with increases in

Tsuga heterophylla, *Tsuga mertensiana*, and *Cupressaceae*, indicate cold, wet conditions prevailed during the late Holocene. Herbaceous pollen was higher during the late Holocene than at any other time in the record, suggesting that meadows may have been an important part of montane forest environments. Archaeological and historical data were combined with the paleoenvironmental reconstructions at Blair Lake in order to better understand the role that humans may have played in the creation and/or use of montane forests and whether human activity or climate was the major influence on past fire and vegetation history. Climate seems to have been the major driver past fire and vegetation history, but it is likely that humans contributed to the fire activity at Blair Lake, particularly during the middle and late Holocene.

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CHAPTER I

INTRODUCTION

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Montane regions of the coastal Pacific Northwest (PNW) are dominated by evergreen coniferous forests, typified by such large trees as *Pseudotsuga menziesii* (Douglas-fir), *Abies amabilis* (Pacific silver fir) *Tsuga heterophylla* (western hemlock), *Tsuga mertensiana* (mountain hemlock), *Thuja plicata* (western redcedar), and *Pinus monticola* (western white pine), as well as many others (Waring and Franklin, 1979). These forests cover many thousands of square kilometers and are essential in terms of the benefits they provide to the region (Hickman, 1976; Halpern, 1999; Loheide II et al., 2008, Stillwater Sciences, 2012). Not only are forests an important source of fresh groundwater, but they also play a critical role in preventing soil erosion, mitigating risks posed by natural disasters, providing timber and wood for fuel, serving as habitat for wildlife, and providing areas for hunting, fishing, and recreation (Price, 2003). In addition, they are also areas of generally high biodiversity that store large amounts of atmospheric carbon dioxide (McKinley et al., 2011).

Meadows are important components of these montane forest environments and serve many important ecological functions. Plant species found in these meadows, many of which are rare and/or endemic, provide forage and habitat for a wide variety of wildlife (Hickman, 1976; Halpern, 1999; Haugo and Halpern, 2007; Loheide II et al., 2008, Takaoka and Swanson, 2008; Haugo and Halpern, 2010; Stillwater Sciences, 2012). In addition, montane meadows improve water quality and increase late summer water storage (Stillwater Sciences, 2012). The mechanism by which montane meadows become established within forest ecosystems is not entirely clear, but they may result from disturbances such as fire, mass movements, snow, beaver dams, or geomorphic processes, such as topography, which may be a limiting factor in the growth or establishment of trees (Knight, 1994; Debinski et al., 2000).

In the montane ecosystems of the PNW, montane meadows make up a small portion of the otherwise forested landscape (Hickman, 1976; Halpern, 1999). In recent years, however, these relatively small, unforested areas have been threatened by the encroachment of trees (Franklin et al., 1971; Vale, 1981; Magee and Antos, 1992; Rochefort et al., 1994; Miller, 1995; Miller and Halpern, 1998; Halpern, 1999; Haugo and Halpern, 2007; Takaoka and Swanson, 2008; Haugo and Halpern, 2010). A study by Miller and Halpern (1998) suggests that several factors, such as regional changes in climate, cessation of sheep grazing, and decades of fire-suppression policies, may have allowed for these invasions. This research aims to help inform the literature on montane environments of the PNW, and more specifically, the role of fire in the creation and persistence of montane forests and meadows.

Fire is the primary disturbance in many forests of the PNW, and fire regimes in these forests vary (Agee, 1993; Whitlock et al., 2003). In wet forests found at higher elevations, summers are short, and moisture levels high, making fires rare occurrences. When fires do occur in these forests, high stand densities and large fuel accumulations often produce stand-replacing events (Agee, 1993). In drier interior forests found at lower elevations and in rain shadow locations, frequent, low-intensity fires were common in the past, but many years of fire suppression have allowed fuels to build up, often resulting in stand-replacing fires normally found in wetter forests at higher elevations (Mote et al., 2003). Less is known about fire activity in mixed, mid-elevation forests, however, it is these areas that are currently under threat by changing climatic regimes and increasing human activities (Bartlein et al., 2008).

It is well documented that the frequency of large fires in the western United States has increased over the last several decades (Flannigan et al., 2000; Whitlock et al., 2003; Westerling et al., 2006; Gavin et al., 2007), and since the 1980s, many mid-elevation forests have experienced an increase in the frequency and duration of wildfires, as well as longer fire seasons (Westerling et al., 2006; Bartlein et al., 2008). On shorter timescales, synoptic weather conditions determine whether fires ignite and spread (Whitlock et al., 2003), while on longer timescales, climatic variability plays a major role in influencing fire frequency, severity, and extent by shaping forest structure and composition as a result of changes in temperature and precipitation (Mote et al., 2003). During the twentieth century, average temperatures in the PNW have risen 0.8°C, and climate models predict even higher temperatures to come (Mote et al., 2003; Whitlock et al., 2003; Westerling et al., 2006). These changes are likely to result in warmer, drier conditions and increased fire activity, stemming from increases in both natural and human ignitions.

Little is known about past relationships between fire, vegetation, and climate in mid-elevation montane forests and meadows in the western Cascades, and even less is known about the role that humans may have played in the creation and/or use of these environments. However, by better understanding how fire, vegetation, and climate interacted in the past, we may be in a better position to predict how these relationships may change in the future. When examined together, paleoenvironmental reconstructions based on charcoal and pollen analysis, as well as climate records, historical documents, and archaeological evidence can provide important information about these montane forests and meadows and the role of human-environmental interactions.

Purpose

The purpose of this study was to reconstruct the fire and vegetation history at one study site in the western Cascade Mountains of Oregon, Blair Lake, using macroscopic charcoal and pollen analysis of a lake sediment core. Blair Lake exists within a mid-elevation montane forest in the Willamette National Forest of Oregon. The goal of this research was to better understand past interactions between fire, vegetation, climate, and humans in the montane forest surrounding Blair Lake during the past ~16,000 years. These relationships were analyzed by comparing fire and vegetation records, developed in this study, to regional fire and vegetation records by researching past climatic trends in the PNW, and by evaluating historical and archaeological records of human activities in and around the Willamette National Forest. The specific research questions addressed through this research include:

(1) How has the fire and vegetation history of the Blair Lake watershed changed during the past ~16,000 years?

(2) What role has climate variability played in influencing the fire and vegetation history of the Blair Lake watershed during the post-glacial period?

(3) How were montane forest environments important to humans, and in what ways did humans possibly modify or at least utilize these environments to maximize the benefits they provide?

Given the research questions above, the specific objectives of this thesis research are:

(1) To reconstruct the post-glacial fire and vegetation history of the Blair Lake watershed.

A sediment core was obtained from Blair Lake in the summer of 2012, and analyses of the data revealed details of the lake and the watershed's history over the past ~16,000 years. Five radiocarbon dates and the presence of the Mount Mazama O tephra were used to construct an age-depth model for the core, which assigned calendar dates to each depth of the core. Loss-on-ignition and magnetic susceptibility tests were conducted to describe the core's lithology, as well as the organic and carbonate content of the core. Charcoal and pollen analyses were performed in order to reconstruct the fire and vegetation history of the watershed, respectively.

(2) To evaluate the post-glacial fire and vegetation history of the Blair Lake watershed within the context of the known regional climatic variations.

Local and regional climatic records from the western Cascades and the Pacific Northwest as a whole were analyzed in order to determine the influence that past climate variability had on the paleoenvironmental history of the Blair Lake watershed during the post-glacial period. In addition, the fire and vegetation data from Blair Lake were compared to similar data sets from the PNW in order to situate the changes seen at Blair Lake within the context of the wider, regional fire and vegetation history. This allowed for a better understanding of the local versus regional influences on the paleoenvironmental history of the site.

(3) To explore possible human-environment interactions at Blair Lake, and more generally in the montane forests of the Willamette National Forest, during the post-glacial period.

Historical documents, ethnographic accounts, and archaeological records were examined from the Willamette Valley, the Willamette National Forest, and the Blair Lake watershed. This data provided information on human activity in the Willamette Valley and the surrounding mountains of the Cascade Range. More specifically, it provided details on when humans were living in the region, who those people were, what benefits montane forests and meadows provided those people, and possible ways in which fire was beneficial to these landscapes and the humans living there.

Significance

This research is significant for several reasons. First, charcoal and pollen analyses from Blair Lake will complement the vegetation and fire history data previously obtained for the northwestern United States by filling the gaps between low-elevation valley lakes (Long and Whitlock, 2002; Brown and Hebda, 2002a; Walsh et al., 2008, 2010a and b) and high-elevation subalpine lakes (Gavin et al., 2001; Hallett et al., 2003; Lukens, 2013; Minckley and Long, 2016). In addition, the data will provide comparative data for low-elevation valley floors and upland meadows of the Willamette Valley. This information may be used to understand the role that fire has played in creating the past fire and vegetation regimes of the western Cascades of Oregon.

Second, comparisons of historical documents and archaeological records from sites in and around Blair Lake will add another facet to the information provided by the charcoal and pollen data. Few studies in the western Cascades have combined archaeological data with paleoenvironmental reconstructions in order to better understand the role that humans may have played in the creation and/or use of montane forests, and whether human activity, climate, or a combination of the two was the primary driver of past fire and vegetation history. This study attempts to correlate the fire and vegetation history of the Blair Lake watershed with dates of human occupation and historical and archaeological evidence of human use of fire in the western Cascades.

Lastly, analyses of past climate records in relationship to the paleoecological history at Blair Lake may provide answers about the drivers of fire history in the Pacific Northwest in the past, present, and future. The data from these analyses can be used to determine if there are possible connections between known climate events and climatic variability in the western Cascades and the changes in the fire and vegetation history of the Blair Lake watershed. This will provide a better understanding of the relationship between fire and climate and the role that climatic variability may have played in the creation and/or maintenance of mid-elevation montane forests and meadows. New information may then be used to project how the Blair Lake watershed may respond to future changes in climate.

CHAPTER II

LITERATURE REVIEW

Montante Forest, Meadows, and Conifer Encroachment

Montane Forests of the Pacific Northwest

Montane forests are biological hotspots with high plant and animal biodiversity, and they are important sources of economic resources and recreational opportunities. They sequester carbon, prevent soil erosion, and enhance water quality (Price et al., 2003; McKinley et al., 2011). Montane forests in the PNW are often categorized into four different zones based on environmental conditions and types of vegetation (Franklin and Dyrness, 1973; 1988). The *Picea sitchensis* zone is found in coastal regions and is characterized by high annual precipitation with averages over 2,000 mm (Franklin and Dyrness, 1973; 1988). Three of the four zones can be found in the interior region of the western Cascades. The *Tsuga heterophylla* zone is found at elevations between 600-1,000 m and typically receives an average of 1,500-3,000 mm of precipitation annually. Common tree species found in this zone include *Pseudotsuga menziesii* (Douglas-fir), *Tsuga heterophylla* (western hemlock), *Thuja plicata* (western redcedar), *Abies grandis (*grand fir), *Pinus contorta* (lodgepole pine), and *Pinus monticola* (western white pine) (Franklin and Dyrness, 1973; 1988).

At higher elevations (~1,000-1,500 m) the *Abies amabilis* zone is found. Associated trees in this zone include *Abies amabilis* (Pacific silver fir), *Tsuga heterophylla*, *Abies procera (*noble fir), *Pseudotsuga menziesii*, *Thuja plicata*, and *Pinus monticola*. *Tsuga mertensiana* (mountain hemlock) and *Cupressus nootkatensis* (Alaska yellow-cedar) appear at the upper margins of this zone (Franklin and Dyrness, 1973; 1988). The *Tsuga mertensiana* zone exists at the highest elevations (>1,500 m) and contains two subzones; a lower subzone of closed forest and a higher subzone consisting of patches of trees mixed in with subalpine shrubs or herbs (Franklin and Dyrness, 1973; 1988).

Fires can impact montane forest environments in many ways. In addition to the direct effects on vegetation composition and structure, fires can reduce habitats and food resources for wildlife (Pyne et al., 1996). Fires often kill soil microorganisms and reduce soil nutrients, and increased soil temperatures can affect the ability of soil to absorb and store water. The removal of plant cover may enhance erosion on hillsides and slopes (Pyne et al., 1996). Fire may also have positive impacts on forest environments. Infrequent surface fires often create meadows or other openings that provide habitat or forage for wildlife and eliminate accumulations of litter that could result in large, stand-replacing fires.

Montane Meadows

Healthy montane meadows serve many functions including: (1) increased biodiversity as they support many plant species (some rare and endemic) and provide forage and habitat for wildlife (Hickman, 1976; Halpern, 1999; Loheide II et al., 2008, Stillwater Sciences, 2012); (2) increased late summer water storage (Stillwater Sciences, 2012); and (3) improved water quality (Jackson et al., 2002, Stillwater Sciences, 2012). In the western Cascade Range of Oregon, montane meadows make up a small portion of the otherwise forested landscape (Hickman, 1976; Halpern, 1999; Clark, 2009). However, these meadows are important sources of biodiversity (Hickman, 1976; Fites-Kaufman, 2007; Thompson et al., 2009). Deer and elk use meadows for forage, birds of prey use meadows as hunting grounds, many butterflies and insects use meadows for pollen and nectar, and many plants found within meadows could not survive under the forest canopy (Thompson et al., 2009). Meadows aid in sediment stabilization, maintain summer stream base flows, and provide flood water retention (Hatfield and LeBuhn, 2007; Roche et al., 2012; Acreman and Holden, 2013; Roche et al., 2014). They also serve as important carbon and nitrogen sinks (Norton et al., 2011; Roche et al., 2014).

The type and abundance of vegetation found in montane meadows is constrained by environmental conditions such as temperature and moisture (Knight, 1994; Debinski et al., 2000). Meadows may be indicators of environmental or climatic changes; short-term changes in temperature or moisture may be manifested as changes in vegetation health, while long-term changes may influence species composition or diversity (Harte and Shaw, 1995; Debinski et al., 2000) and may reduce or eliminate habitat for plants and wildlife (Romme and Turner, 1991; Debinski et al., 2000).

Forest Encroachment and How It Links To Fire

It is unclear what role fire has played in the creation and maintenance of montane meadows (Burke, 1979; Vale, 1981; Teensma, 1987, Halpern, 1999), but it seems likely that both natural and anthropogenic burning may have been important in the development of these openings in the past (Halpern, 1999). Historic and ethnographic records indicate that burning by Native Americans was done to maintain open conditions in the Willamette Valley (Johannessen et al., 1970), but little is known about anthropogenic burning in the meadows found at higher elevations of the western Cascades (Halpern, 1999). During the period from ca. 1850-1890, European settlers used fires in association with building roads, sheep grazing, and camping (Burke, 1979; Vale, 1981; Halpern, 1999). Following that period, fire suppression policies of the twentieth century may be responsible for the succession of these meadows to forest (Halpern, 1999). Hadley (1994) found that on south-facing slopes fire suppression has increased the rate of Douglas-fir invasion into meadows.

Today prescribed burning is being proposed as a tool to restore meadow structure and composition in many forests of the PNW (Halpern, 1999). However, more studies and controlled experiments are needed to fully understand the consequences that prescribed burning will have on ground-layer communities (Halpern, 1999). It is unclear whether areas that have already undergone significant tree invasion will respond by returning to open meadows, or if burning will encourage new invasion of seedlings or early seral species (Halpern, 1999). It is also possible that invasive species in or near the meadows may benefit from fire because it is common for exotic species to invade harvested and burned forests in this region (Halpern, 1999).

Fire Regimes

Fire is a natural disturbance in western ecosystems, and healthy forests depend on fire to maintain their stand structure and composition (Agee, 1993, 1998; Rorig and Ferguson, 1999; Dwire and Kauffman, 2003). Fire regimes characterize natural fires that are typical of an ecosystem (Agee, 1993; Pyne, 1996) and are classified using the following descriptors: frequency; predictability; extent; magnitude; synergism; and timing (Agee, 1993).

Fire frequency is based on an average return interval, or length of time between subsequent fire events, while predictability refers to the variation in fire frequency. Extent refers to the amount of ground the fire has covered, whereas magnitude describes the intensity (the amount of fuel consumed and the rate at which the fire has spread) and severity (the effects of the fire on the dominant vegetation). Synergism describes how fire may interact with other disturbance agents, such as insect outbreaks, and how these interactions may increase or decrease the effects of a particular fire event. Timing, or seasonality of burning, also plays an important role in the effects of a fire (Agee, 1993).

While ignition and combustion are determined by the fire triangle of oxygen, ignition source, and fuels, the frequency and intensity characteristics of a fire are determined by the fire behavior triangle consisting of weather, topography, and fuels (Agee, 1993). Local weather, which drives fire activity, is the result of atmospheric and oceanic circulation patterns, which in turn, are driven by solar energy (Agee, 1993). Topography, which consists of elevation, slope, aspect, and physiography, is another important influence on fire behavior (Agee, 1993). Temperature decreases and precipitation generally increases with elevation, and as a result, elevation can affect the distribution and type of vegetation and the length of both the growing season and the fire season (Agee, 1993). Slope may affect the rate at which a fire spreads, and combined with aspect may affect a fire indirectly by impacting available moisture, and the physiography, or shape, of an area can influence the way winds are funneled across an area (Agee, 1993).

Fire Regimes of the Pacific Northwest

Three classification systems have been developed for the forests of the PNW, and there are no clear advantages to using one system over another (Agee, 1993). Heinselman (1981) used fire characteristics, such as frequency and intensity, to create a system for the Midwest (Table 2.1) that was later adapted for the PNW by Agee (1981). This system rates fire on a scale ranging from 0 to 6, although for the PNW the scale ranges from 2 to 6. A fire regime classified as a 2 describes light surface fires that burn frequently, while a fire classified as a 6 describes crown fires with long return intervals.

A second system used to classify fire regimes, based on habitat characteristics of the vegetation of an area, was developed by Davis et al. (1980) to define fire groups of the Lolo National Forest in Montana (Table 2.2). Although these fire groups are based on local vegetation, the system could be modified to describe fire regimes in other forested areas (Agee, 1993).

The third, and simplest, classification system is based on fire severity (the effects of a fire on the dominant vegetation). Fires are ranked from low to high severity. Low-severity regimes are defined as those in which the trees have twenty percent or less of their basal area removed by a fire, while high-severity regimes are defined as those in which the trees have seventy percent or more of their basal area removed (Table 2.3) (Agee, 1990).

Table 2.1 Fire Regimes Defined by the Nature of the Disturbance
Source: Heinselman, 1973.

FIRE REGIME NUMBER	DESCRIPTION
0	No, or very little natural fire
1	Infrequent surface fires (more than 25-year return intervals)
2	Frequent surface fires (1-25-year return intevals)
3	Infrequent surface fires (more than 25-year return intervals)
4	Crown fires with short return intervals (25-110-year return intervals)
5	Crown fires with long return intervals (100-300-year return intervals)
6	Crown fires with very long return intervals in combination with severe surface fires (more than 300-year return intervals)

Table 2.2 Fire Groups Based on Potential Vegetation of the Site
Source: Davis et al., 1980.

FIRE REGIME NUMBER	**DESCRIPTION**
0	Heterogeneous collection of special habitats; scree, forested rock meadow, grassy bald, and alder glade
1	Dry limber pine (*Pinus flexilis*) habitat types
2	Warm, dry ponderosa pine (*Pinus ponderosa*) types. These sites may be fire-maintained grasslands.
3	Warm, moist ponderosa pine types. These sites will support dense thickets of ponderosa pine in the absence of frequent fires.
4	Warm, dry Douglas-fir (*Pseudotsuga menziesii*) habitat types. These sites are dominated by ponderosa pine and experience understory thickets of Douglas-fir if protected from disturbance.
5	Cool, dry Douglas-fir habitat types. Douglas-fir is often the only conifer on these sites.
6	Moist, Douglas-fir habitat types.
7	Cool habitat types usually dominated by lodgepole pine (*Pinus contorta*).
8	Dry, lower subalpine types.
9	Moist, lower subalpine types. Fires are infrequent but severe.
10	Cold, moist upper subalpine and timberline habitat types. Fires are usually infrequent due to fuel limitations, but have longstanding effects.
11	Warm, moist grand fir (*Abies grandis*), western redcedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*) habitat types. Fires are infrequent but severe.

Table 2.3 Fire Regimes Based on Severity
Source: Agee, 1990.

FIRE SEVERITY	DOMINANT VEGETATION
LOW	Oak woodland Ponderosa pine Mixed conifer
MODERATE	Dry Douglas-fir Red fir Mixed evergreen
HIGH	Pacific silver fir Subalpineforests Western hemlock/Douglas-fir

Fire Regimes in PNW Montane Forests

Fire regimes in the PNW forests are often categorized according to severity and climax vegetation, and fire return intervals in these forests range from light, frequent surface fires with a fire return interval of 1-25 years to crown fires in combination with surface fires that have a fire return interval of over 300 years (Agee, 1993). Low-severity fire regimes are often found in oak woodlands, or forests of ponderosa pine or mixed conifers; moderate-severity fires are often found in forests with dry Douglas-fir or red fir; and high-severity fires are often found in subalpine forests or forests containing Pacific silver fir (Agee, 1993).

Future Fire Regimes in the PNW

Many climate models predict increases in warming, with temperatures expected to rise between 0.9 to 4.5°C, and increases in many northwestern states are expected to exceed average increases on a global basis (Whitlock et al., 2003). In the PNW wildfires are expected to be larger and more frequent (McKenzie et al., 2004; Littell et al., 2010; Rogers et al., 2011;

Wimberly and Liu, 2014), and, proportionally, increases in area burned will be largest in moist forests (Littell et al., 2010; Rogers et al., 2011; Wimberly and Liu, 2014).

Climatic Influences on Fire in the Pacific Northwest

Climate of the PNW

The Cascade Mountains divide the PNW into two different climate regions (Mote et al., 2003). The climate west of the Cascades is considered maritime, with wet winters and dry summers. Temperatures are generally mild, and, except at higher elevations, snow seldom stays on the ground for extended periods of time (Mote et al., 2003). Most areas receive more than 750 mm of precipitation annually, and some mountain areas receive more than 1,500 mm (Mote et al., 2003). Climate east of the Cascades is much drier, with most places receiving less than 500 mm of precipitation annually, and some areas receiving as little as 180 mm (Mote et al., 2003). Temperatures east of the Cascades are similar to those found west of the Cascades, but daily and annual ranges are larger, resulting in hotter summers and colder winters (Mote et al., 2003).

According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007), temperatures in the PNW rose 0.8°C during the 20th century. Other observed changes include increases in winter temperatures, greater variability in precipitation during the cool season, decrease in amount of snowpack seen on April 1 between 1995 and 2000, and earlier season peak water runoff (IPCC, 2007).

Fire-Climate Linkages

Climate, and on shorter timescales, weather, are considered to be the primary drivers of fire activity in the western United States (Weber and Flannigan, 1997; Flannigan et al., 2000; Brown et al., 2004; Schoennagel et al., 2004; Westerling et al, 2006; Schoennagel et al., 2007; Hyerdahl et al., 2008; Flannigan et al., 2009; Marlon et al., 2012; Pausas and Keeley, 2014). High temperatures and low precipitation are linked to years of high fire activity and greater area burned (Westerling et al., 2006; Littell et al., 2009; Littell and Gwordz, 2011). High temperatures during fire season can produce convective storms and lightning ignitions, while high temperatures in winter can lead to decreases in snowpack, resulting in less effective moisture for soils and vegetation (Marlon et al., 2012). Lightning-caused fires occur most frequently in mid-elevation forests, a pattern associated with types of fuel and available fuel moisture (Bartlein et al., 2008). Seasonality also plays a role, and most lightning-caused fires occur in summer, particularly in July or August (Bartlein et al., 2008).

Weather and climate influence fire spatially and temporally on different time scales ranging from hours to millennia (Walsh et al., 2015). In turn, fire can also influence weather and climate by producing aerosols into the atmosphere and by changing albedo levels of the earth's surface (Bowman et al., 2009). *Fire weather* refers to elements such as winds, temperature, humidity, precipitation, thunderstorms, and lightning that contribute to the daily fire potential of an area (Pyne et al., 1996). Wind has a major impact on fire behavior, and temperature, relative humidity, and precipitation all influence fuel moisture (Pyne et al., 1996). *Fire season* refers to changes in weather and climate that influence the occurrence of wildfire on a yearly basis (Pyne et al., 1996).

Fire behavior in any one fire season is heavily influenced by factors such as fuel moisture and rates of ignition, which are affected by weather conditions, such as precipitation, humidity, air temperature, and wind (Rothermal, 1972; Weber and Flannigan, 1997; Flannigann et al., 2000; Whitlock et al., 2010). These short-term weather conditions are part of larger scale climate patterns that develop over a period of months to years to make up the *fire climate* and affect the changing frequency of fire and annual area burned (Pyne et al., 1996; Skinner et al., 1999; Kitzberger and Veblen, 2003; Littell et al., 2009; Whitlock et al., 2010).

On an interannual (i.e., year-to-year) basis, the persistence and frequency of large atmospheric circulation systems anomalies are the primary factors influencing fuel moisture and ignition rates responsible for years in which large numbers of acres burn in the PNW (Whitlock et al., 2010; Walsh et al., 2015). In some regions of North America the link between fire and climate is related to systems of climate variability, such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) (Whitlock et al., 2010).

ENSO plays a major role in interannual climate variability in both the southwest and northwest regions of the country. In both regions, prolonged periods of severe drought, leading to high fire activity have been linked to ENSO, although El Niño and La Niña events affect each region differently (Schoennagel et al., 2004; Whitlock et al., 2003; Gedalof et al., 2005; Fauria and Johnson, 2008; Heyerdahl et al., 2008; Littell et al., 2009; Whitlock et al., 2010; Marlon et al., 2012;). During La Niña years, the PNW experiences wet conditions and fewer fires, while dry conditions and large fires are found in the Southwest. The pattern is reversed in El Niño years (Schoennagel et al., 2004; Gedalof et al., 2005; Fauria and Johnson, 2008; Heyerdahl et al., 2008; Littell et al., 2009; Whitlock et al., 2010; Marlon et al., 2012). Dry conditions result from a persistent trough over the northeastern Pacific Ocean and an associated ridge over the West Coast, which leads to years of high fire activity. Wet conditions and years of low fire activity are linked to a weak Aleutian Low in the central North Pacific Ocean and stronger than normal jet stream (Bartlein et al., 1998; Gedalof et al., 2005; Schoennagel et al., 2005; Anderson et al., 2008; Whitlock et al., 2008; Whitlock et al., 2010).

On longer timescales, high fire activity in western North America has been associated with warm, dry periods, such as the Medieval Climate Anomaly (~ AD 900-1300) and the

Roman Warm Period (~200 BC-AD 600) when conditions were warm and dry (Swetnam, 1993; Cook et al., 2004; Pierce et al., 2004; Whitlock et al., 2010; Walsh et al., 2015). The Little Ice Age (~ AD1600-1850) was characterized by a shift to cold conditions and a reduction in fire activity (Whitlock et al., 2010; Marlon et al., 2012; Walsh et al., 2015). Lastly, long-term, millennial-length variations in seasonal and annual solar insolation influence fire activity in the PNW. These factors affect fire climate and the composition of vegetation available for fuel (Whitlock et al., 2010).

Pleistocene/Holocene Climate of the PNW

To gain a better understanding of past climate variability in the PNW, it is necessary to understand the linkages between fire and climate during the late glacial period and the Holocene. At the time of the Last Glacial Maximum (LGM), ca. 20,000 cal yr BP, the Cordilleran and Laurentide ice sheets were at their greatest extent, and summer and winter insolation values were similar to those of today (Thompson et al., 1993; Bartlein et al., 1998; Whitlock et al., 2003). During the early Holocene (11,000-7,000 cal yr BP), variations in the tilt of the earth's axis and in timing of perihelion, summer insolation was 8% higher and winter insolation was 8% lower than today, resulting in warmer summers and colder winters (Imbrie et al., 1984; Whitlock et al., 2003). The higher-than-present levels of summer insolation led to higher-than-present summer temperatures and reduced effective moisture in the summer-dry PNW, while summer-wet areas in the southwestern United States were even wetter (Thompson et al., 1993; Whitlock and Bartlein et al., 1993; Bartlein et al., 1998; Anderson et al., 2008; Whitlock et al., 2003; Whitlock et al., 2008; Whitlock et al., 2010). This increase in insolation also led to enhanced atmospheric circulation systems, reducing summer precipitation and encouraging the growth of fire-adapted vegetation (Thompson et al., 1993; Whitlock and Bartlein, 1993; Bartlein et al., 1998; Long et al., 1998; Whitlock et al., 2003; Anderson et al., 2008; Walsh et al., 2008; Whitlock et al., 2008; Whitlock et al., 2010).

During the middle Holocene (ca. 7,000-4,000 cal yr BP), summer insolation decreased and winter insolation increased, resulting in the modern climate and vegetation regimes seen in the PNW today (Thompson et al., 1993; Whitlock et al., 2003). Summer-dry regions of the PNW and Rocky Mountains became cooler and wetter between 5,000 and 3,000 cal yr BP, and mesophytic vegetation became established. Fluctuations in climate during the late Holocene (4,000 cal yr BP-present) may be linked to short-term climate variations, such as the Medieval Warm Period (ca. 900-600 cal yr BP) and the Little Ice Age (ca. 550-150 cal yr BP) (Whitlock et al., 2003; Mann et al., 2009). Although the causes of these variations are not known, evidence indicates drought-like conditions occurred in the Sierra Nevada mountain range during the Medieval Warm Period, and cooler temperatures and glacial activity were present in the PNW and Rocky Mountains during the Little Ice Age (Luckman et al., 1993; Whitlock et al., 2003; Gavin et al., 2006).

Future Climate Change in the PNW

Temperatures in the PNW have already started to rise and are expected to rise even more (Mote and Salathé, 2010). Climate model simulations predict that temperatures will rise an average of 0.3° per decade, and by the 2080s, temperatures could be as much as 5.7°C higher than they are today (Mote and Salathé, 2010). Precipitation is expected to increase in the winter and spring, but decrease in the summer. Overall precipitation will could decrease as much as 20%. This increase in spring precipitation and warmer temperatures, the result of higher concentrations of atmospheric carbon dioxide, could result in higher forest productivity and longer growing seasons, but may also result in longer fire seasons (Mote and Salathé, 2010; Rogers et al., 2011).

Since 2000, many western states have experienced their largest wildfires in history, and the six worst wildfire seasons since 1960 have occurred since 2000 (USFS, 2015). The number of acres burned annually has doubled in the last thirty years, and climate change has extended the fire season, which is now 78 days longer than in 1970 (USFS, 2015). Intense drought plagued most of the western states throughout much of 2015, and there were 30% more fires than average in the PNW during the 2015 fire season (NFIC, 2015). Fire seasons will likely only get worse given the projected changes in climate for the PNW.

Human Interactions with Fire in the Pacific Northwest

Archaeology of the Western Oregon Cascades and the Willamette Valley

Terminal Pleistocene/Early Holocene (~13,000-7,500 cal yr BP)

The early archaeological record is thin for the Willamette Valley of Oregon, but evidence suggests that the region was continuously occupied for at least the last 10,000 years (White, 1979). The presence of projectile points, baking ovens, and charred camas bulbs indicates that both hunting and food processing were important activities throughout this time period. There are several sites that contain evidence of even earlier occupation, but there are no radiocarbon dates associated with the cultural material at these sites. Clovis projectile points, which consistently date to around 12,000 cal yr BP, in North America, have been found in at least four different locations: Mohawk Valley (Allely, 1975), Cottage Grove (Minor, 1985), Blue River Reservoir (Ozbun and Steuber, 2001), and Fern Ridge Reservoir (Connolly, 1994), all located within 100 kilometers from the town of Oakridge (which is near the study site used in this research). Some archaeological sites were used year round, while others were used on a seasonal basis. Many sites, such as the Hannavan Creek, Flanagan, Benjamin, and Hurd sites, show evidence of continuous occupation over multiple time periods.

The Hannavan Creek site (35LA647) is located along a tributary of the Long Tom River just a few miles from the town of Eugene and may provide the earliest evidence of food processing. Fragments of ground stone indicate they were used to pound and grind plant foods. The association of fire-cracked rocks with over 350 charred camas bulbs is thought to represent cooking hearths and baking ovens (Cheatham, 1988). Radiocarbon dates obtained on two sets of camas bulbs produced dates of approximately 8,500 and 7,650 cal yr BP (Cheatham. 1988; O'Neill et al., 2004; Aikens et al, 2011). Projectile points, scrapers, and knives found at the site suggest that hunting and butchering were important activities, and the presence of hammerstones, anvils, cores, flaked stone debris, choppers, drills, spokeshaves, and gravers indicate manufacturing of tools made of stone, bone, and wood (Cheatham, 1988). Large, broad-necked dart points indicate early occupation of the site, while small arrow points suggest that the site was also used more recently (Cheatham, 1988; Aikens et al., 2011).

Located just upstream of the Hannavan Creek site, the Ralston site (35LA625) contained a similar oven, dating to about 7,500 cal yr BP (Cheatham, 1988; O'Neill et al., 2004; Aikens et al., 2011). Artifacts suggesting that the site was used as a hunting and food processing camp included chopped stone scrapers, knives, hammer stones, anvils, choppers, drills, spokeshaves, and gravers (Cheatham, 1988).

Baby Rock Shelter (35LA53), located about eight kilometers west of Oakridge, is an east-facing rock shelter situated in steep terrain about 730 meters above sea level (asl). It is one of the oldest upland sites known from western Oregon, and four distinct geologic strata, each with evidence of human occupation, were identified at this site (Olsen, 1975). Strata A and B contained both cultural artifacts and faunal remains. Stratum C consisted of non-organic light grayish-tan material with bands of pumice that were identified as originating from the Mount Mazama eruption. This layer contained artifacts similar to those found in Stratum B, but with more faunal remains than any other layer. Stratum D was a layer of undisturbed, non-organic aeolian silt ranging in color from light tan to yellowish with flecks of pumice containing deer bones, one biface, one used flake, and some chipped stone (Olsen, 1975).

The majority of artifacts were made of stone and were found in Strata A, B, and C. Items made of jasper, chert, and basalt were recovered, but obsidian tools and flakes were the most common (Olsen, 1975). The upper three strata contained tools such as bifaces, end scrapers, side scrapers, gravers, perforators, spokeshaves, flake tools, hammerstones, manos, pestle fragments, and ground stone fragments. Corner-notched, side-notched, Desert-side-notched, and Cottonwood Triangular projectile points were also found (Olsen, 1975).

Obsidian hydration dating and the presence of pumice overlying the earliest cultural material provide evidence that the Baby Rock Shelter site was occupied before and after the Mount Mazama eruption, making the initial occupation contemporaneous with that at Cascadia Cave (approximately 8,650 cal yr BP) (Aikens et al., 2011). A red pictograph featuring what appears to be a horse and rider provide evidence that the site was used into the historic period as well (Olsen, 19975, Aikens et al., 2011). The presence of Mount Mazama tephra, along with the archaeological evidence, indicates that humans were using upland sites in the Western Cascades as early as the last 8,000 years.

Cascadia Cave is a similar upland rock shelter located in the foothills on the north bank of the Santiam River near the town of Cascadia in Linn County. More than four hundred artifacts were recovered from the site, including more than one hundred Cascade-type projectile points.

Chipped stone tools, such as knives, drills, scrapers, and worked flakes, were also found, and petroglyphs were found on the cave walls (Newman, 1966; Aikens et al., 2011). In addition, faunal remains of ground squirrel, marmot, deer mouse, snowshoe rabbit, dog or coyote, weasel, deer, and elk were found. Also found were the remains of a type of game bird that may have been grouse. Plant remains included blackberry, salmonberry, wild rose, wild strawberry, skunk cabbage, hazelnut, and salal berries (Newman, 1966). The site was most likely a seasonal hunting and gathering camp used during the spring and summer that was initially occupied about 8,650 cal yr BP (Newman, 1966; Aikens et al., 2011). Additional excavations were undertaken in 1990, producing two more radiocarbon dates, 7,230 cal yr BP and 5,650 cal yr BP (Aikens et al., 2011).

The Cascade points found at the site suggest a relationship with groups from the Columbia Plateau, and the petroglyphs and non-Cascade points found near the surface may reflect a relationship with the Desert Culture near the terminal date of site occupation (Newman, 1966). The pattern of artifacts at Cascadia Cave seems to indicate that over a several-thousand-year period cultural relationships may have shifted from ties with groups in the Columbia Plateau to include part of the Great Basin (Newman, 1966; Aikens et al., 2011).

In addition to projectile points, tools used for hide processing and woodworking, items associated with hunting and butchering, such as scrapers, knives, and ground stone tools were found. No fish bones were recovered, but bones of elk, snowshoe rabbit, marmot, weasel, and grouse were found. Deer bones were found at every level of the excavation. Hazelnuts and grinding stones were also discovered, suggesting processing of vegetables, seeds, and nuts (Newman, 1966). The high frequency of scrapers found in the upper levels compared to the lower levels may reflect a shift over time from more generalized hunting and foraging to more specialized hunting and processing of game (Newman, 1966).

Radiocarbon dates at both Baby Rock Shelter and Cascadia Cave provide evidence of human occupation in the western Cascades during the early Holocene. The archaeological evidence indicates that mountain areas were important in seasonal migration patterns and gathering of high-elevation resources, such as huckleberries, as well as hunting and game processing, were important activities conducted at upland sites (Aikens et al., 2011).

The Geertz site (35CL1) and the Ripple site (35CL55) are upland sites located in the Clackamas River drainage that feature Cascade-type points and tool assemblages similar to the one found at Cascadia Cave, suggesting early Holocene use (Minor and Toepel, 1984). The Geertz site is located above a tributary of the Clackamas River and contained foliate projectile points, but no other types (Aikens et al., 2011). Based on the presence of the foliate projectile points and the absence of ground stone tools, Woodward (1972) concluded that this site was used for hunting and game processing (as cited in Aikens et al., 2011). At the Ripple site, both foliate and broad-necked notched points were recovered, suggesting occupation contemporary with the Geertz site and possibly later (Aikens et al., 2011).

The Canyon Owl (35LIN366) site is also an upland site, located in the upper South Santiam River drainage (Aikens et al, 2011). Blood protein analysis conducted on the points found at the site indicate that mountain sheep, deer and/or elk, and upland game birds were hunted, and the recovery of chert from nearby sources and obsidian from the Obsidian Cliffs located farther away indicate that the site was also used as a lithic reduction station (Aikens et al., 2011). Obsidian hydration dates, along with the presence of Cascade and more recent projectile points led Fagan et al. (1992) to conclude that the site was probably used intermittently throughout the Holocene (as cited in Aikens et al., 2011).

<u>The Middle Holocene (~7,500-3,000 cal yr BP)</u>

Camas was an important resource for humans living in the interior PNW, and archaeological evidence points to increased use of camas during the Middle Holocene. Sites in and around the Willamette Valley were mostly located on floodplains or along streams or rivers, all areas where camas is frequently found (Cheatham, 1988; O'Neill et al, 2001; Aikens et al., 2011).

There are many sites in the Willamette Valley that contain evidence of middle Holocene occupation, but most of these are located along Mill Creek in the central part of the valley and along the Long Tom River in the upper valley (Aikens et al., 2011). The Mill Creek sites are a set of sites located near Salem, Oregon, on a former channel of Mill Creek. Early radiocarbon dates indicate that early occupation at these sites occurred more than 3,500 years ago and continued into the Late Holocene. Most of the dates were obtained from rock-lined pit ovens used for processing camas bulbs and other plant-based foods, indicating that all sites were occupied during the last 6,000 years. Some of the ovens were more than two meters in diameter, suggesting that camas processing was an important subsistence activity (Aikens et al., 2011).

Pettigrew (1980) describes three Middle Holocene sites located in a wooded area along a former channel of Mill Creek, formerly known as Hagar's Grove. Two of the three sites (35MA7 and 35MA9) were excavated. The third (35MA8) only yielded two unifacially flaked basalt cobbles and a tip from a cryptocrystalline silica (CSS) biface and was determined not to be culturally significant for excavation (Pettigrew, 1980).

The first site, 35MA7, consisted of four distinct geologic strata, with two of these containing cultural material. The upper layer found in Strata 2 was designated MA7U, and the lower layer found in Strata 3 was designated MA7L (Pettigrew, 1980). Both layers contained evidence of food processing in the form of baking ovens, pits, hearths, fire-cracked rock, and charcoal, as well as charred botanicals. Tools included flake unifaces, hammerstones, unifacially flaked basalt cobbles, and projectile points. The upper level also contained one triangle-tipped biface and three triangular bifaces, all made from cryptocrystalline silica (CSS).

Most of the artifacts found in both layers were made of cryptocrystalline silica (CSS), but the use of obsidian increased over the time the site was occupied (Pettigrew, 1980). Of a total of twelve obsidian flake unifaces, all but two were found in 35MA7U. Botanical remains found at the site included camas, hazelnuts, onions, acorns, and cherries, all charred. While the majority of the botanicals in 35MAU was camas, no camas was found in 35MA7L (Pettigrew, 1980).

At least seven other Middle Holocene sites located at Mill Creek have produced radiocarbon ages spanning the last 6,000 years. Food processing ovens, frequently containing charred camas bulbs and occasionally charred hazelnuts or acorns, provide the major evidence of middle Holocene occupation at the Mill Creek sites, suggesting that the baking of camas and the drying of nuts were primary activities conducted at the sites (Aikens et al., 2011). Artifacts found at these sites include chipped projectile points and ground stone tools. Projectile points ranged from fairly large, leaf-shaped ones to large stemmed ones to side-notched ones that were probably used to tip darts for use with an atlatl. These sites appear to have been used primarily for seasonal food gathering and processing (Aikens et al., 2011).

The Chalker site (35LA420) is located at the edge of a small oxbow on the flood plain of the Long Tom River. Three cultural components were identified at the site, two with evidence of

Late Holocene occupation, and one associated with the Middle Holocene (O'Neill and Connolly (2004). Two radiocarbon dates were obtained from Component 3. Charcoal from an earthen oven yielded a date of 4,610 cal yr BP, while a sample from the opposite side of the test pit yielded a date of 3,350 cal yr BP, indicating that this level contained the remains of at least two periods of occupation (O'Neill and Connolly, 2004). Fire pits and clusters of fire-cracked rock were found, along with bifaces, scrapers, used flakes, split obsidian pebbles, a hammerstone, and two pestles. The projectile points found in this strata were the heavy broad-necked type, and plant remains included charred acorn and hazelnut shells, and one charred camas bulb (O'Neill and Connolly, 2004).

The Long Tom site (35LA439) is located on the south side of the Long Tom River floodplain, approximately 1220 m west of the Chalker site (O'Neill and Connolly, 2004). Three cultural components were identified at the site, each component representing a Holocene time division. Component 1 contained no cultural features or concentrated areas of charcoal, so no radiocarbon dates were obtained. (O'Neill and Connolly, 2004). Artifacts included chipped stone tools, such as scrapers, bifaces, and projectile points. The lithic debitage was dominated by obsidian. Two of the three projectile points were typical of late Holocene tool assemblages and consisted of small stemless and narrow-necked points. Historic items, such as baling wire, nails, and concrete were also found in this component (O'Neill and Connolly, 2004).

Component 2 contained the remains of 21 earth ovens and fire pits, as well as post molds, and clusters of fire-cracked rock (O'Neill and Connolly, 2004). Seven radiocarbon dates were obtained, ranging from ~ 5290 cal yr BP to ~ 3835 cal yr BP. The majority of the dates were clustered around 4400 cal yr BP. Chipped stone tools included projectile points, mostly of the broad-necked variety, drills, formed bifaces, unifaces, utilized flakes, flake knives, flake scrapers, and chopper/cores. Peck and ground stone tools included hammerstones, pestles, anvils, pitted stones, and one rubbing stone (O'Neill and Connolly, 2004).

The Flanagan site (35LA218) is another site in the upper Long Tom River drainage. Occupation at the Flanagan site appears to have originated during the middle Holocene and continued into the late Holocene, and evidence suggests that regular use of the site increased in more recent times (Aikens et al., 2011). Deposits up to three feet deep have yielded over a dozen radiocarbon dates concentrated at 6500, 3500, 1700, 900, and 500 cal yr BP (Beckham, Minor, and Toepel, 1981; Toepel 1985; Aikens et al, 2011). Evidence of the preparation and processing of vegetables and nuts includes rock-lined pit ovens, fire-cracked rock, charcoal fragments, charred bulbs of what were likely camas, acorn hulls, and pits of wild cherry and Klamath plum (Aikens et al., 2011). Projectile points and butchering and hide-processing tools, such as biface knives, scrapers, perforators, and use-modified flakes indicate that hunting was also an important activity. Hammerstones, choppers, drills, spokeshaves, and sandstone abraders provide evidence of wood and bone working for tool manufacture (Aikens et al., 2011).

The Lingo site (35LA29) is an open midden site located about 300 meters east of the Long Tom River. Projectile points, drills, gravers, scrapers, bifaces, retouched flakes, ground stone pebbles, one stone bead, and two river cobbles were found as well as four burials (Cordell, 1975). Cultural features included fire pits and ash lenses containing carbonized camas bulbs. Testing on charcoal found at the site yielded radiocarbon dates of ca. 2,200 cal yr BP and 120 cal yr BP. No bone tools or faunal remains were found, indicating that the site was used seasonally for the gathering and processing of camas (Cordell, 1975). Although the dates indicate late Holocene occupation, evidence of nut and camas processing, common in middle Holocene site, suggest that the Lingo site was initially occupied during that time (Aikens, et al., 2011).

The Late Holocene (~ 3,500 cal yr BP-Euro-American contact [ca. AD 1805]):

Evidence of increased sedentism emerges in late Holocene sites, and many sites are ones that experienced intermittent occupation during the middle Holocene appear to have been continuously or nearly continuously occupied during the last 2,000 to 3,000 years (Aikens et al., 2011). These sites include Benjamin (35LA41, -42), Lingo (35LA29), Lynch (35LIN36), Hurd (35LA44), Flanagan (35LA218), Chalker (35LA420), Calapooia Midden (35LIN468), and Mill Creek (35MA7, -9, -64,65) (Aikens et al., 2011). Most of the sites are located near rivers or other bodies of water on the valley floor.

The Benjamin sites (35LA 41-42) are a cluster of eleven circular mounds located on an old meander of the Long Tom River north of Fern Ridge Lake (Miller, 1975). Five of the middens were tested, and two were excavated, showing evidence of human occupation during the late Holocene (Miller, 1975). No dwelling structures or burials were found. All artifacts were either chipped or ground stone. The majority of stone tools were made from obsidian, but chert and basalt were also used (Miller, 1975; Aikens et al., 2011). No bone or shell implements were recovered, but over 250 projectile points, both stemmed and unstemmed, were found. Other artifacts included scrapers, drills, bifaces, and retouched flakes. Fire hearths and large earth ovens were represented by fire-cracked rock, burnt earth, and charcoal. Charred camas bulbs and mortar and pestle fragments suggest that food processing was an important activity at the site (Miller, 1975). Radiocarbon dating of the charred camas bulbs produced dates of approximately 2,300 cal yr BP and 1,600 cal yr BP. However, the styles of projectile points found at the site indicate that the site was used earlier and occupation continued beyond those dates (Miller, 1975).

Several middens (35LA565-568) dating from the last 3,000 years were excavated on the Long Tom River upstream from the Benjamin sites. Aikens et al. (2011) suggest that these middens were all occupied roughly during the same time period, but appeared to serve different functions and were probably used by small groups for both residential sites and seasonal camps.

The Lynch Site (35LA36) is located on an alluvial plain on the banks of the Little Muddy Creek about 22 miles north of Eugene (Sanford, 1975). Three burials were found containing the remains of six individuals. The remnants of 27 fire pits assumed to be baking ovens were found. Charred camas bulbs and fire-cracked rock were found in some of these pits. Faunal remains included deer, elk, squirrel, beaver, mouse, and hare (Sanford, 19975). No bone implements were found, but over 400 projectile points, representing 18 different types were recovered from the site. There were also eight unique points. Artifacts included a basalt charm stone, fragments of a bowl, scrapers, drills, awl-gravers, spokeshaves, chopping tools, bifaces, pestles, manos, pipe fragments, and abrading stones (Sanford, 1975). Four radiocarbon dates were obtained. Two of these were on charcoal and were recent, ~80 cal yr BP and ~90 cal yr BP. The other two dates were obtained on carbonized camas bulbs, ~800 cal yr BP and ~1,280 cal yr BP. No dwelling structures were found, and it seems likely that the site was used as a seasonally to process camas and possible retool projectile points (Sanford, 1975; Aikens et al., 2011).

The Hurd Site (35LA44) is a valley-floor site located about one-half mile east of the town of Coburn near the junction of the McKenzie and Willamette Rivers. The site is situation on a geologic terrace overlooking a floodplain and contained the remains of a subterranean house (White, 1975). A fire hearth, located on the house floor, produced a radiocarbon date of approximately 2,800 cal yr BP, and a second hearth that intruded into the house produced a date of approximately 2,820 cal yr BP. The house contained a central hearth, and several post holes were also found, suggesting that the site may have served as a semi-permanent winter village (White, 1975; Aikens et al., 2011). Eleven radiocarbon dates from fire hearths and earth ovens indicated that there was a second major period of occupation at the site that extended from approximately 1,100 cal yr BP into the late pre-contact era (White, 1975; Aikens et al., 2011). There was no housing structure found for this period, but there were many earth ovens, both large and small, and several fire hearths, in addition to charred camas bulbs, pestle and mortar fragments, and hundreds of projectile points (White, 1975).

Component 1 contains evidence of late Holocene use. Testing on charcoal in this level yielded three radiocarbon dates, 510 cal yr BP, 580 cal yr BP, and 660 cal yr BP. Fire pits, along with charcoal and baked earth, were found in this level with the remains of hazelnuts, acorns, camas, bedstraw, and thimbleberry (O'Neill and Connolly, 2004). Tools recovered were all made from chipped stone and included projectile points, formed and unformed bifaces, scrapers, obsidian pebbles, and utilized flakes. There were thirteen projectile points of four different types: narrow-necked, small stemless, heavy stemless, and heavy broad-necked (O'Neill and Connolly, 2004).

Six radiocarbon dates from the Chalker site (35LA420) ranged from ~925 cal yr BP to 1,280 cal yr BP. Features included fire pits and charcoal-stained earth, post molds, and the possible outline of a small structure (O'Neill and Connolly, 2004). Small stemless and heavy broad-necked projectile points were found, but most of the points were narrow-necked. The majority of the lithic debitage was obsidian, but CCS and basalt artifacts were also found. Tools included formed and unformed bifaces, drills, scrapers, utilized flakes, chopper/cores, hammerstones, a hammer/anvil stone, and split and unsplit obsidian pebbles. Macrobotanicals included carbonized hazelnut and acorn husks, bedstraw, camas bulbs, and chokecherry seeds (O'Neill and Connolly, 2004).

Component 3 of the Long Tom site (35LA439) contained fire-cracked rock, ceramic, and charcoal, as well as only one unifacially worked obsidian pebble. Radiocarbon testing on charcoal from this level yielded a date of ~ 9,950 cal yr BP, consistent with dates from other sites nearby (O'Neill and Connolly, 2004).

The Perkins Park Site (35LA282) is located less than one mile from Hannavan Creek and contained numerous fire-cracked rocks and chipped stone tools (Aikens et al., 2011). Plant remains included charred camas bulbs, hulls from acorns and hazelnuts, and cherry seeds. The remains of various birds and mammals were also recovered from the site, but the bones were too fragmentary to allow for identification. Radiocarbon dates indicate that the site was occupied between ~1,300 and 1,000 years ago (Cheatham, 1988; Aikens, et al., 2011).

Rigdon's Horse Pasture Cave is a rock shelter located in the upper drainage of the Middle Fork of the Willamette River. The main cave contains two small rock shelters and three smaller caves (Baxter et al., 1983). The site, situated at 975 meters in elevation is not far from two other upland sites, Cascadia Cave and Baby Rockshelter (Baxter et al., 1983). The site sits in an area that is considered to be the homeland of the Molallas and is believed to be a seasonal upland hunting camp. Radiocarbon dates obtained from the deposits near the bottom of the cave yielded a date of 2500 BP or approximately 2580 cal yr BP (Baxter et al., 1983; Aikens et al, 2011). Stone artifacts included twenty-two types of projectile points, hammerstones, anvils, choppers, ground stone fragments, and cobbles with edge grinding. Also found were metates and manos, flat stones with concave surfaces and grinding stones, used together to grind grains or other plant-based foods (Baxter et al, 1983). Additionally, fourteen cultural features, all fire hearths, and two fragments of basket were found. Botanical remains included pine nuts, hazel nuts, western chokecherry, wild cherry, and Oregon grape. Deer, squirrel, cougar, rabbit, porcupine, bobcat, rodent, and remains of unidentified small and large mammals formed the faunal assembly (Baxter et al., 1983).

Many late Holocene sites in the Willamette Valley are mounds, large hand-built earthen structures. The presence of a large number of these mounds provides evidence of increased sedentism and a larger population than sites dating from the middle Holocene (Aikens et al., 2011). All radiocarbon dates from these mounds fall within the last 3,000 years, although some were occupied earlier (Aikens et al., 2011).

The Fanning Mound is located on a terrace near the Yamhill River approximately ten kilometers from the town of Whiteson, Oregon, and contained eighteen burials with associated grave goods. Over 500 stone artifacts were recovered, including twenty-one types of projectile points, knives, perforators, drills, and scrapers (Murdy and Wentz, 1975a). Camas-digging handles made of antler, bone and antler flaking tools, bone awls or needles, bone and antler wedges, and bone barbs and harpoon points were also found (Murdy and Wentz, 1975a). There were also trade goods, such as metal beads, glass beads, brass buttons, a brass thimble, brass finger rings, and a brass spike, and items such as an abalone shell pendant and dentalium shell suggest contact with coastal groups (Murdy and Wentz, 1975a).

The Fuller Mound is located south of the Yamhill River approximately five kilometers from the town of Whiteson, Oregon, and about ten kilometers down the river from Fanning Mound (Murdy and Wentz, 1975b). Forty-one burials with associated grave goods were found, including five burials with historic artifacts (Woodward et al., 1975). There were also thirteen types of projectile points, knives, scrapers, one obsidian ceremonial blade, and one obsidian biface (Woodward et al., 1975). Items made from antler included digging stick handles, flakers, wedges, ear spools, picks, and fish gorges. There were also bone artifacts, such as bird bone beads, whalebone fish clubs, eyed needles, awls, blades, saws, nose ornaments, and dice (Woodward et al., 1975). Trade items included glass beads, brass buttons, copper bangles, and copper, and ornaments made from several types of shells were recovered (Woodward et al., 1975).

The Indian Ridge site (35LA194) is an upland site located within the McKenzie River drainage about 72 kilometers east of Eugene. The site is situated at approximately 1,463 meters in elevation and was most likely used as a base camp on a seasonal basis (Henn, 1975). There is evidence of multiple usage at the site. Sinker stones, bone gig barbs, bone harpoon collars, fish vertebrae, and fresh water mollusk remains provide evidence of fishing, and flake and core spokeshaves, scraper planes, unifacial and bifacial chopper-axes, mauls, reamers, wood scrapers, stone chisels, graving tools, wedges, denticulates, and drills suggest that woodworking was an important activity at the site (Henn, 1975). Food preparation was evidenced by the presence of mortars, pestles, manos, and grinding slabs (Henn, 1975).

<u>Summary</u>

The extent to which Native Americans used fire in mid-to-high-elevation areas is not clear, but the archaeological evidence supports the idea that humans were using upland sites as early as the early Holocene. At Baby Rock Shelter, evidence of occupation both before and after the Mount Mazama eruption indicates that humans were using sites in the foothills by 8,000 cal yr BP (Olsen, 1975; Aikens et al., 2011). Evidence from the Canyon Owl site, such as the remains of mountain sheep, deer, elk, and upland game birds, suggest that hunting was an important activity conducted at higher elevations (Aikens et al., 2011).

The charred remains of camas, nuts, and berries, in association with cooking hearths and baking ovens at most of the early archaeological sites, provide evidence that fire was important for cooking and heating, and possibly for other uses. It is known that in post-settlement times the Kalapuya burned camas fields after harvest to encourage future yields (Boyd, 1999), and it is likely that this practice was done prior to settlement as well. Fire was also used to clear trails, provide forage for wildlife, and to improve cultivation of nuts and berries (Norton et al., 1999). These would have been important activities in the early Holocene, and it is likely that fire was used for a variety of reasons in upland areas.

Pre-Euro-American Settlement Human History

At the time of Euro-American contact, four groups of Native Americans inhabited the areas within and adjacent to the Willamette National Forest, each speaking different languages. Linguistically, the languages of the Kalapuya, the Molalla, and the Tenino were related, belonging to Penutian phylum, while the Northern Paiute spoke a Uto-Aztecan language (Minor and Pecor, 1977; Minor et al., 1987).

There is little available ethnographical or ethnohistorical information about the Tenino. There were four groups, the Tenino proper, the Wayam or Lower Deschutes, the John Day, and the Tygh or Upper Deschutes. Each group occupied two villages: one temporary dwelling to be used during the warmer months for fishing and one permanent dwelling, located several miles away with access to water and fuel during the winter months (Minor and Pecor, 1977). Fishing was the primary means of subsistence for the Tenino, with salmon being the most important staple. Steelhead trout, lamprey eels, dog salmon, sturgeon, suckers, chubs, smelt, and freshwater clams were also eaten (Minor and Pecor, 1977). Game animals included deer, elk, pronghorn, brown bear, grizzly bear, rabbit, mountain sheep, and mountain goats. Roots, such as camas, kouse, and lupine were valued resources, as were serviceberry, huckleberry, chokecherry, strawberry, pine nuts, sunflower seeds, and acorns (Minor and Pecor, 1977).

Trade was also important to the Tenino, and they were part of a trade network ranging from the Columbia River to the Pacific Ocean on the west, into the Columbia Plateau on the north, the edges of the Great Plains on the east, and down into California on the south (Minor and Pecor, 1977). Trade items contributed by the Tenino included salmon, oil, and furs. In exchange, they received dentalia and other shells, bison hides, slaves, baskets, beads, eagle feathers, and bows (Minor and Pecor, 1977).

The Northern Paiute, consisting of 21 bands, inhabited a large area in the northwestern part of the Great Basin in California, Nevada, Oregon, and Idaho. Most of their territory was desert, which they made more hospitable by bringing water down into the region from mountain streams. They also traveled into the mountains to access hunting grounds and to gather berries (Minor and Pecor, 1977). Plant-based foods were the primary resource and included acorns, grass seeds, roots, berries, and sunflower. Large game, such as deer, pronghorn, and mountain sheep were hunted, but small game, such as rabbits, squirrels, and chipmunks provided the main source of meat. Fish, such as salmon, trout, suckers, and minnows were important foods, as were insects, such as caterpillars, ants, crickets, and grasshoppers (Minor and Pecor, 1977).

The Kalapuyan-speaking groups of the upper Willamette Valley did not have access to major anadromous fish resources and were primarily hunter/gatherers living in small, mobile groups (White, 1979). Plants made up the majority of the Kalapuyan diet, with camas being the most important food source. Other foods included wapato, tarweed seeds, hazel nuts, acorns, and assorted berries. Meat was obtained from deer, elk, lampreys, various birds, small mammals, and insects (Zenk, 1990). The Kalapuya were the original inhabitants of the Willamette Valley, and their territory extended into a portion of the Umpqua River drainage to the south. There were as many as thirteen groups who spoke many different dialects (Zenk, 1990). Several of the better documented groups included the Tualatin, Yamhill, Pudding River, Luckiamute, Santiam, Mary's River, and Yoncalla, while lesser known groups included the Kalapuya proper, Muddy Creek, Tsankupt, Long Tom, Chaffin, Mohwak, and Winefelly (Minor and Pecor, 1977).

The Kalapuya maintained permanent villages in the winter, but at other times of year they resided in transitional, seasonal camps in order to be near important resources. Due to lack of access to anadromous fishing sites, they lived solely inland, and most of their subsistence activities were restricted to the valley floor (White, 1979, Zenk, 1990). However, during the summer, they traveled to higher elevations, such as those found within the Willamette National Forest, in order to hunt big game and collect berries (Minor and Pecor, 1977). Camas was the most important food staple, but other staple food sources included lampreys, grasshoppers, a certain type of caterpillar, birds, small mammals, black-tailed and white-tailed deer, and black bear. Grizzly bears and coyotes were hunted, but never eaten (Zenk, 1990).

The Molalla were a small aboriginal group who resided primarily in the mountains of the Central Cascades, but, like the Tenino, there is little ethnographic or ethnohistorical information available (Minor and Pecor, 1977; Minor et al., 1987). The Molalla were probably the primary inhabitants in and around what is now the Willamette National Forest, and a major portion of their subsistence strategies was based on upland activities. They lived in small family groups and practiced bilateral kinship (Minor and Pecor, 1977). Groups spent the winters in small villages along the rivers, but in the summer they moved to higher elevations to hunt deer and elk, gather berries, and fish for salmon, steelhead, trout and eels in lakes and streams (Aikens, 1993). There were two groups of Molalla, the Northern, sometimes called the Upper or Valley Molalla, and the Southern, sometimes called the Lower or Mountain Molalla's (Johnson, 1999). The differences were mostly regional, and each group's subsistence strategy was influenced by the local environment. The Valley Molalla shared hunting grounds with the Kalapuya, and like the Kalapuya, their primary resources were plants and small game commonly found in the valley. The Mountain Molalla were more reliant on hunting large game found at higher elevations (Johnson, 1999).

Post-Settlement Human History

Euro-American settlement of the upper Willamette Valley began as early as AD 1812 when clerks of the Pacific Fur Company (PFC) erected a trading outpost in the upper Willamette Valley near the present site of Newberg (Bowen, 1978). Many French Canadian fur trappers married Native American women and started families. When their terms of service had expired, rather than be repatriated to their countries of origin, these men requested that they be allowed to stay in Oregon and start farms (Bowen, 1978). The fur companies, not wanting these men to leave behind children who would be raised as Indians, provided the men with farms in the Willamette Valley.

These farms were located on a stretch of grassland between the Willamette and Pudding Rivers, known as the "French District" or "French Prairie" (Bowen, 1978). Beginning in AD 1840, American settlers began migrating to Oregon and settling in the Willamette Valley with the purpose of establishing farms. The next several years brought even more newcomers, and by AD 1845, a census estimated the population of Oregon south of the Columbia River to be 8,779 people, excluding Native Americans (Bowen, 1978).

Before and during contact, Native Americans in the PNW suffered from a variety of diseases associated with their fishing and foraging lifestyle and seasonal movement. However, most of these diseases were chronic and usually not contagious (Boyd, 2013). As Euro-American explorers and settlers moved into the region, they brought with them four diseases unknown to native populations: smallpox, malaria, viral influenza, and measles. Two of these, smallpox and malaria, were especially devastating to the groups living in the area, and their population numbers crashed as a result (Boyd, 2013).

Smallpox in Chinookan people was first documented by Meriwether Lewis in AD 1806, referring to an epidemic that had occurred in AD 1801-1802, but oral traditions indicate an earlier epidemic happened during the late 1770s or early 1780s (Boyd, 2013). Beginning in AD 1831, the Willamette Valley and the lower Columbia Valley Indians were hit by malaria each summer (Boyd, 1999). The population of 9,000, estimated by Lewis and Clark in AD 1805-1806, fell to approximately 600 by AD 1841 (Boyd, 1999).

Diseases were not the only consequence of Euro-American contact. As settlers moved westward and settled claims, they claimed acres of land seen as perfect for farming. They drained wetlands, plowed camas and tarweed fields and prevented Native American burning (Thompson, 2006). Settlers coming into the Willamette Valley saw the Kalapuyans as “savages,” and Methodist missionaries tried to convert the Kalapuyans and urged them to assimilate into society (Thompson, 2006). As more and more settlers moved westward into the region, the Molalla’s hunting grounds began to shrink, causing conflict between the two groups (Johnson, 1999). In AD 1847, the Molalla engaged in an uprising known as the Molalla War. They planned to attack during the winter when a large number of settlers would be away from their villages fighting in the Cayuse uprising, an act thought to have been a diversion to draw the settlers away.

However, the settlers were warned of the plan, and some local Indians sided with them. Many Molalla were slaughtered, including women and children (Minor and Pecor, 1977).

Beginning in AD 1851 the federal government began to attempt negotiations with the Kalapuya and other regional Native American groups. The intent was to remove them from western Oregon to lands east of the Cascades (Mackey, 1974). The Kalapuya and the Molalla signed the Dayton treaty, which was finally ratified in AD 1855. Along with the Upper Umpqua, they were removed to the Grand Ronde Reservation in AD 1856. The Tenino signed the Middle Oregon Treaty in 1855, and they were removed to the Warm Springs Reservation along the Deschutes River (Minor and Pecor, (1977).

Fire Suppression/Management Policies

Following several large fires in the late 1800s, the United States government began to set aside parcels of land as national forest reservations in an effort to protect timber supplies (USFS, 2016). When the United States Forest Service (USFS) was established in AD 1905, these parcels were renamed national forests, and the new agency was given managerial control of these reservations. In AD 1910 a series of large fires, known as the "Big Blowup" burned over 1 million hectares in Montana, Idaho, and Washington in just two days. Eighty-five people were killed (USFS, 2016). As a result of the AD 1910 fires, the Forest Service decided that total fire suppression was necessary to prevent more devastation. Roads, ranger stations, and lookout towers were constructed in order to spot fires early and quickly suppress them. Although many farmers and ranchers used light burning to improve landscape conditions, the Forest Service opposed any type of fire (USFS, 2016).

There was also a financial incentive to suppress fires. The Forest Fires Emergency Act, passed by Congress in AD 1908, allowed the Forest Service to be reimbursed for any money spent on fire suppression. The fires of AD 1910 cost the Forest Service $1.1 million, a sum that amounted to 20% of the total annual budget (Pyne, 1982: Berry, 2007). In 1978, the Forest Fires Emergency Act was repealed, and the Forest Service altered its policy, allowing some fires to burn (Pyne, 1982; Berry, 2007). However, the number of large fires has increased in the last twenty-five years, and fire suppression now consumes 50% of the Forest Service's annual budget, leaving little money for forest management strategies, such as thinning, or land restoration (USFS, 2016).

Paleoecological Reconstructions of Fire and Vegetation History

Fire History Reconstructions

Reconstructing previous fire events is a crucial step in understanding the role that fire has played in an ecosystem in the past and in projecting the role that fire may play in that ecosystem in the future. Fire histories can be reconstructed using multiple types of data, including magnetism and geochemistry, palynology and paleoecology, or historical documents and photographs (Conedera et al., 2009). Two of these methods, fire scars on surviving trees and charcoal found in lakes or wetlands, are the primary lines of evidence used in establishing fire history databases (Whitlock and Anderson, 2003).

Fire scars on trees are created when the temperature from a fire becomes hot enough to heat the bark and kill part of the cambium (Agee, 1993; Conedera, 2009). The major advantages of using fire scars include the ability of dating fires with annual precision and the possibility of synchronizing records from multiple specimens to reconstruct fire events over hundreds of years (Conedera et al., 2009). However, there are several limitations to using fire scars, including the following: (1) fire scars are typically not present in high-severity fire regimes (Agee, 1993; Conedera, 2009); (2) insects, diseases, wildlife, and even humans frequently leave scars on trees that may be confused with scars from fires (Agee, 1993); (3) fire scars provide an incomplete record because individual trees do not consistently record fire events (McBride, 1983; Dieterich and Swetnam, 1984); (4) recent fire events may have eliminated evidence of prior fire events (Van Horne and Fulé, 2006); and (5) factors such as wind velocity and fuel conditions may influence scar formation (McBride, 1983).

Charcoal, which is created from the incomplete combustion of vegetation, is obtained from lake sediments and be used to reconstruct local and/or regional fire history. The size and abundance of charcoal particles produced are influenced by fire size and severity and may be deposited in a lake in one of two ways. Primary charcoal refers to particles that are transported by wind during or shortly after a fire and is dependent on size and location of area burned (Whitlock and Anderson, 2003; Higuera et al., 2007). Secondary charcoal may be deposited during non-fire years as a result of surface runoff and redeposition and may be deposited onto lake surfaces anywhere from several years to several decades after a fire (Anderson et al., 1986; Whitlock and Millspaugh, 1996; Whitlock and Anderson, 2003; Higuera et al., 2007). These particles sink to the bottom and accumulate over time (Whitlock and Anderson, 2003). Large particles, those larger than 125 micrometers, normally fall within 5-10 km from the location of the fire and provide evidence of local fire activity (Whitlock and Millspaugh, 1996; Clark and Patterson, 1997; Whitlock and Anderson, 2003). Smaller particles travel longer distances and may indicate regional fire events (Whitlock and Anderson, 2003).

Vegetation Reconstructions

Pollen, which is the male gametophyte of flowering plants, can be obtained from lake sediments and visually identified to typically the genus or species level (Faegri et al., 1989). Pollen provides evidence of past vegetation and changes in the abundance of different taxa reflect fluctuations in vegetation as a response to fire activity or climate change (Davis, 2000). Like charcoal, pollen is transported by the wind and may be deposited onto the surface of a lake where it is mixed with the lake sediments (Davis, 2000). Pollen records, when combined with charcoal analyses, can be used to reconstruct the history of a watershed and the surrounding vegetation. Typically, pollen records provide evidence of past plant succession, related to fire events, and its response to climatic shifts (Tolonen, 1986).

CHAPTER III

RESEARCH AREA

The study site used in this research is located in the Willamette National Forest, which is situated in the Western Cascades Mountain Range. The Cascades form a 965 kilometer-long chain that extends from northern California, through Oregon and Washington, and into British Columbia. In Oregon, the Cascades are divided into two distinct formations: the older Western Cascades and the younger High Cascades (Orr and Orr, 2012).

The Willamette National Forest

Bordered by the Willamette Valley on the west, Windigo Pass on the east, Mount Hood National Forest on the north, and Umpqua National Forest on the south, the Willamette National Forest extends for more than 177 km (km) along the western slope of the Cascade Range in Oregon (Figure 3.1). The forest encompasses almost 724,768 hectares (ha) of land, of which approximately 680,000 ha are National Forest land. The other approximately 44,768 ha are privately owned or under the direction of other public agencies (USFS, 2015).

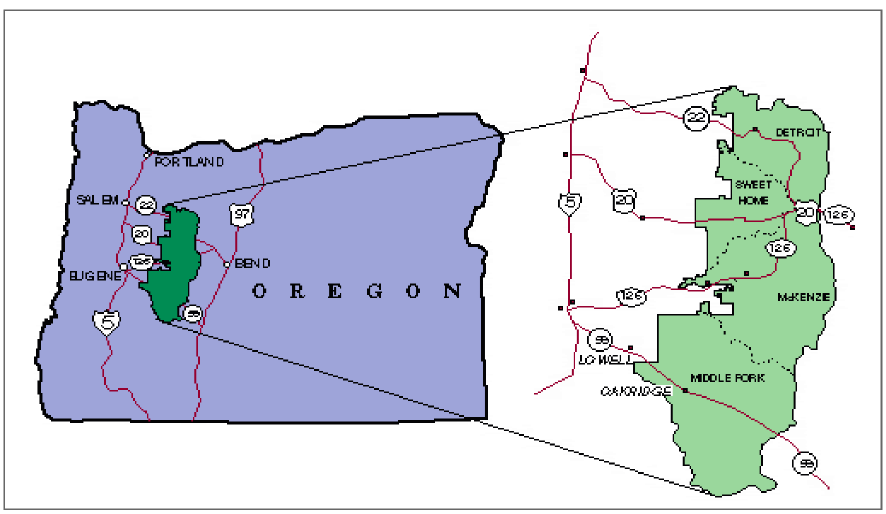

Figure 3.1 Map of Oregon showing location of Willamette National Forest.
Source: United States Forest Service (USFS).

There are almost 10,000 km of road in the Willamette National Forest, more than 375 lakes, and over 2,000 km of rivers. Two of these rivers, the McKenzie River and the North Fork of the Middle Fork of the Willamette River, have been declared Wild and Scenic Rivers (National Forest Foundation, 2015). About one-fifth of the forest (over 153,000 ha) was designated by Congress as wilderness and contains seven major mountain peaks, Mt. Jefferson, Mt. Washington, Three Fingered Jack, Diamond Peak, and North, Middle and South Sisters (National Forest Foundation, 2015).

Geology

The Cascade Mountains were formed as a result of volcanic activity that began about 40 million years ago (mya) and are comprised of two mountain ranges, the older Western Cascades and the younger High Cascades (Sherrod and Smith, 2000). The Western Cascades, adjacent to the Willamette Valley, have been deeply eroded and range in elevation from just over 500 meters (m) on the western side to almost 1,800 meters on the eastern side, where they are flanked by the High Cascades. The High Cascades are roughly twice as high, with some peaks reaching over 3,300 m (Orr and Orr, 2012).

The oldest rocks in the Cascades (45-35 mya) are volcanic in nature, and volcanic activity was widespread in the Cascades from 35 to 17 mya, forming strike faults that created the northwest and northeast-trending drainages of the Western Cascades (Sherrod and Smith, 2000). Eastward tilting and warping of rock in the Western Cascades helped to form the topography of the region, but the age of these mechanisms is not clearly understood (Sherrod and Smith, 2000). About 5 mya further tilting of the Western Cascades created a steep face on the east side and a sloping ramp on the west side that casts a rain shadow over eastern Oregon. This rain shadow has a major influence on the climate in this area (Orr and Orr, 1992).

Numerous volcanic eruptions have occurred in the Cascades during the last 15,000 years, producing large volumes of tephra and pyroclastic flows (Bacon, 1983; Druitt and Bacon, 1986). From about 7,015 to 6,845 radiocarbon (^{14}C) years ago, ash and lava from a series of Mount Mazama eruptions covered the entire present-day Willamette National Forest. The initial tephra deposits ranged in thickness from 4-5 cm at 1,000 km from the volcano to 40 cm at a distance of 200 km (Hoblitt, Miller, and Scott, 1987). Two episodes of pyroclastic flows followed the tephra. The first episode was small, but the second episode projected pyroclasts in all directions, reaching distances of 60 km^3. The total amount of magma deposited during the eruptions was about 50-60 km^3, and layers have been found in eight western states and three Canadian provinces (Hoblitt, Miller, and Scott, 1987). These eruptions coincided with human occupation of the area, but their impact is thought to have been minimal on human activity for two reasons: (1) the areas most affected by ash fall were only used seasonally by prehistoric groups; and (2) present-day observations of ash fall suggest that environmental damage caused by tephra is short-lived (Skinner and Radosevich, 1991).

Hydrology and Climate

The majority of lakes in the Oregon Cascades formed as a result of either volcanic eruptions or glacial activity (Orr and Orr, 2012). The most famous of these is Crater Lake, a caldera created by the eruption of Mount Mazama approximately 7,600 years ago (Zdanowicz et al., 1999). Further north, lakes such as Odell and Crescent in the Deschutes National Forest and Waldo in the Willamette National Forest, lie in glacially carved basins (Orr and Orr, 2012). These lakes are all within 65 km of the town of Oakridge and less than 80 km from each other. The Willamette National Forest receives a large amount of precipitation each year, primarily from October through April. This precipitation, rain at lower elevations and snow at higher elevations, drains into the headwaters of the McKenzie, Santiam, and Willamette Rivers, and then flows out of the Willamette National Forest to the north into the lower Columbia River Valley (USFS, 2015).

The climate of the Western Cascades is characterized as a maritime climate with cool, wet winters, and warm, dry summers (Sea and Whitlock, 1995). The majority of the precipitation falls between October and March, and very little occurs during July and August. Annual precipitation ranges from 1,000-1,300 mm in the valley to more than 5000 mm in the highest elevations (Uhrich and Wentz, 1999).

Data observations obtained from the McKenzie Bridge Ranger Station in the Willamette National Forest (Figure 3.2) for the period from 1981 through 2010 show that the average minimum January temperature is 0.1ºC and the average maximum July temperature is 30.3ºC. Total annual precipitation averages 1,736 mm, with most of that occurring during the months of November (264 mm) and December (313 mm). On average, very little precipitation occurs during the months of July (21 mm) and August (26 mm) (WRCC, 2016).

Flora and Fauna

The Willamette National Forest is home to more than fifteen species of conifers, including Douglas-fir (*Pseudotsuga menziesii),* the state tree of Oregon. Franklin and Dyrness (1973) described three vegetation zones found in the forests of the Western Cascades: the *Tsuga heterophylla* zone, found in temperate lowlands at elevations ranging from 150-1,000 m; the *Abies amabilis* zone, found on western slopes and at elevations from 1,000-1,500 m; and the *Tsuga mertensiana* zone, found in subalpine areas at elevations ranging from 1,700-2,000 m (Table 3.1).

More than 300 species of fish and wildlife are found in the Willamette National Forest. Fish include steelhead, bass, Chinook and kokanee salmon, and trout. Roosevelt elk, black bear, cougar, and black-tailed and mule deer are examples of large mammals that reside in the forest (USFS, 2015).

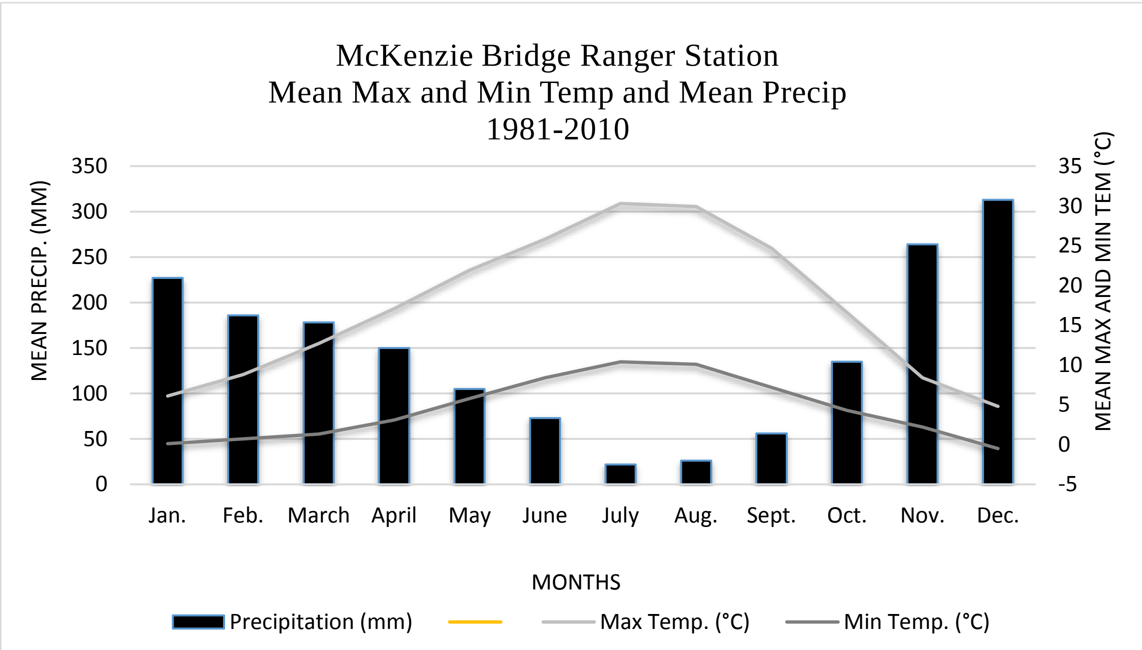

Figure 3.2 Climograph of McKenzie Ranger Station (1981-2010).
Source: Western Regional Climate Center (2016).

Table 3.1 Vegetation Zones of Pacific Northwest Forests.
Source: Franklin and Dyrness, 1973, 1988.

Forest Zones of the Western Cascades		
***Tsuga heterophylla* Zone**	***Abies amabilis* Zone**	***Tsuga mertensiana* Zone**
	Dominant Trees:	
Tsuga heterophylla	*Abies amabilis*	*Tsuga mertensiana*
Pseudotsuga menziesii	*Tsuga heterophylla*	*Abies amabilis*
Thuja plicata	*Abies procera*	*Abies lasiocarpa*
Libocedrus decurrens	*Pseudotsuga menziesii*	*Abies magnifica*
Pinus lambertiana	*Thuja plicata*	*Abies procera*
Acer macrophyllum	*Pinus monticola*	*Chamaecyparis nootkatensis*
Arbutus menziesii	*Tsuga mertensiana*	*Pinus contorta*
	Dominant Shrubs:	
Acer circiniatum	*Acer circiniatum*	*Vaccinium membranaceum*
Rhododendron macrophyllum	*Gultheria shallon*	*Vaccinium scoparium*
Vaccinium parvifolium	*Rubus lasiococcus*	*Vaccinium deliciosum*
Corylus cornuta	*Vaccinium membranaceum*	*Rhododendrum albiflora*
Cornus nutalli	*Vaccinium parvifolium*	*Spirea* sp.
Taxus brevifolia	*Vaccinium alaskaense*	*Sorbus* sp.

Land Use

Logging

Logging was and continues to be important in the Willamette National Forest. The Timber and Stone Act was passed in 1878, allowing the sale of 65-hectare tracts of non-mineral land considered not suitable for human habitation (Rakestraw and Rakestraw, 1991).

There were relatively few large timber sales in the Willamette National Forest until the mid-1920s. Before then, timber was primarily harvested with animal power, and the logs were driven down the river to be sold (Rakestraw and Rakestraw, 1991). That began to change in 1915 when the proposed building of the Southern Pacific Railroad from Oakridge to Klamath Falls prompted the Forest Service to begin organizing large timber sales. Shortly after, the railroad stopped building, and those sales fell through (Rakestraw and Rakestraw, 1991). In 1923 construction started again, and a sale for 13,300 acres of timber on the North Fork of the Willamette River was made to the Westfir Lumber Company of Oakridge. Other sales followed, and the mill town of Westfir was established (Rakestraw and Rakestraw, 1991).

Major changes occurred in the lumber industry in the period from 1933 to 1945. One of these was a shift from private to public lands on national forests as a source of timber (Rakestraw and Rakestraw, 1991). The idea of sustained yield became the goal in Forest Service management, and it was accompanied by changes in technology and cutting practices (Rakestraw and Rakestraw, 1991). Heavy equipment and gasoline-powered power saws improved efficiency, and more efficient mills prompted the development of the plywood industry, utilizing trees that were formerly thought to be worthless (Rakestraw and Rakestraw, 1991). For a time, selective logging replaced clearcutting, but in 1941 large timber demands due to World War II lead to a return to clearcuts (Rakestraw and Rakestraw, 1991).

Between 1945 and 1970 logging practices changed a great deal. One change was the implementation of patch cutting. This entailed clearcutting in small blocks in an effort to enable more light to come through and ultimately encourage seedling growth (Rakestraw and Rakestraw, 1991). In the late 1960s clearcutting was modified to fit the shape of the terrain. New techniques, such as cable logging, aerial transport, and the use of rubber-tired tractors, were implemented to minimize soil damage caused by logging (Rakestraw and Rakestraw, 1991).

From the 1950s through the 1970s there was more timber harvested from the Willamette National Forest than from any other national forest in the United States (Rakestraw and Rakestraw, 1991). However, during the 1970s conflict developed between forest managers who felt that clearcutting was an effective management tool for some areas of the forest and environmental groups who protested clearcutting on the basis that it was detrimental to the forest (Rakestraw and Rakestraw, 1991).

Grazing

In 1891 the Oregon State Senate passed legislation that set aside land from use in order to create national parks, protect salmon spawning grounds, and preserve irrigation water. Two years later the Willamette National Forest was established as the Cascade Range Forest Reserve (Rakestraw and Rakestraw, 1991). Stockmen, especially sheepherders, had been using areas of the Cascades for grazing since the 1880s, and the new law was disliked and often disregarded. It was common practice for herders to take their sheep into the mountains after lambing season in late spring, and the average flock ranged from 1,500 to 2,500 sheep (Rakestraw and Rakestraw, 1991).

Conflict developed with recreationists who claimed that the grazing sheep damaged hunting and fishing areas and huckleberry patches in the area used by Native Americans and local residents. Ranchers, too, were in opposition to grazing and claimed that sheep, on their way to summer grazing lands, would consume grass they needed for their horses and cattle (Rakestraw and Rakestraw, 1991). In 1896 several sheep herders were arrested for trespassing, and law suits were filed in the U.S. District Court to prevent owners from grazing their sheep within the reserve (Rakestraw and Rakestraw, 1991).

The following year Frederick V. Colville, a botanist with the U.S. Department of Agriculture (USDA), conducted a study to assess the impacts of grazing. He proposed that a toll be imposed on sheep that crossed county lines and that huckleberry patches and public resort areas be preserved and closed to grazing. He also suggested that grazing permits be issued. These permits would be good for a period of five years and would specify the areas where sheep could graze, the number of days grazing would be permitted, and the number of sheep allowed to graze. Furthermore, sheep owners would be responsible to see that man-made wildfires would not occur in their permitted areas (Rakestraw and Rakestraw, 1991).

Colville's suggestions were implemented as regulations and became part of forest administration policy in 1898, allowing grazing on the reserve. Grazing remained one of the primary economic activities in the forest for the next several decades, but it was not until 1906 that fees were charged to ranchers or sheepherders wanting to graze their animals on public lands (Rakestraw and Rakestraw, 1991).

Study Site

Blair Lake is located in Lane County, Oregon, less than 33 km from the town of Oakridge, in the Willamette National Forest (Fig. 3.3). The lake (43º50.096'N, 122º14.361'W) has an elevation of 1,451 m. Blair Lake was chosen as a research site based on the following criteria: it is a naturally formed lake; the lake has limited inflow and outflow channels, reducing the possibility of bioturbation; the depth of the lake was at least five meters; and roads leading right up to the edge of the lake provided ease of access.

Climate

Climate data for Blair Lake was obtained from the Oakridge Fish Hatchery, the nearest weather station. A climate summary for the period from 1981-2010 shows that the average minimum January temperature is -0.3ºC, and the average maximum August temperature is 27ºC (Figure 3.4). Total annual precipitation averages 1150 mm, with most of that occurring during the months of November (185 mm) and December (186 mm). Very little precipitation occurs during the months of July (18 mm) and August (18 mm) (WRCC, 2015).

Figure 3.3. Map of Willamette National Forest showing site of Blair Lake.
Source: United States Forest Service (2016).

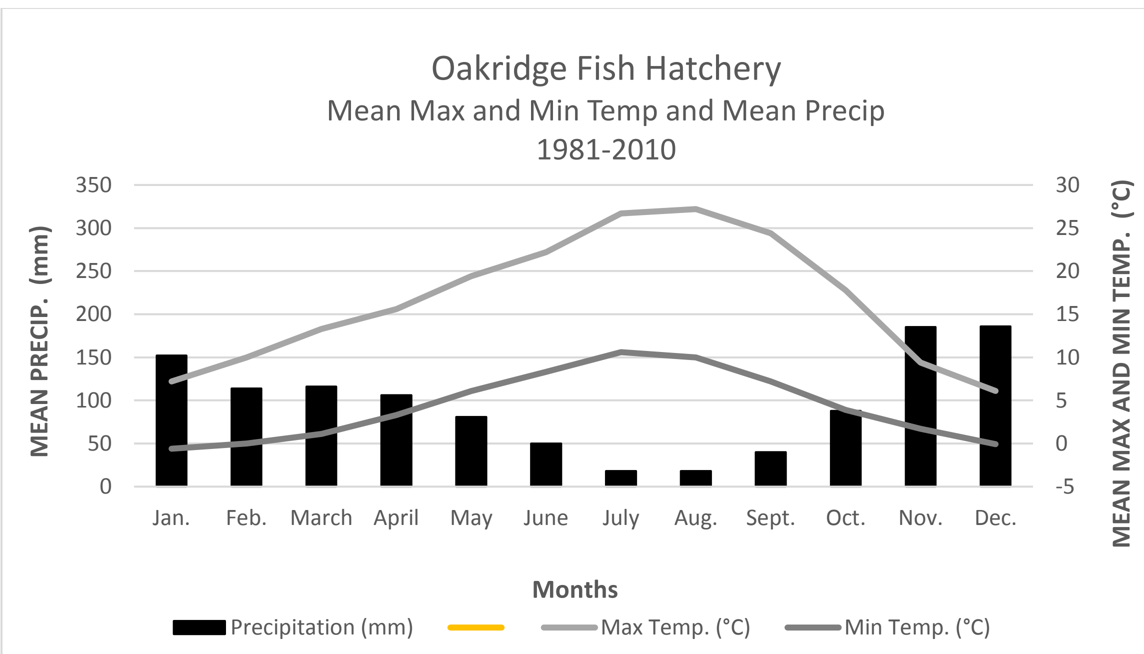

Figure 3.4 Climograph of Oakridge Fish Hatchery (1981-2010).
Source: Western Regional Climate Center (2016).

Hydrology

The Willamette National Forest was glaciated in the past, and Blair Lake is a natural lake that formed as a result of the receding of an alpine glacier following the last glacial maximum (LGM) approximately 19,000 cal yr BP (Clark et al., 2009). Blair Lake has no inflow, and only one small outflow, indicating that rainfall and snowmelt and possibly ground water are the primary sources providing water into the lake. The sole outflow is a stream that flows into Wall Creek, which flows into Salmon Creek, which, in turn, drains into the Middle Fork of the Willamette River near Oakridge.

Flora and Fauna

Blair Lake exists in the *Abies amabilis* zone (Table 3.2) described by Franklin and Dyrness (1973; 1988). An informal vegetation survey of the area immediately surrounding Blair Lake was conducted in the summer of 2012 and again in the summer of 2103. Numerous sedges, grasses, and rushes line the lakeshore, and western skunk cabbage (*Lysichiton americanus)* is found along many of the wetter areas along the shore. Yellow water lily (*Nuphar lutea)* and wapato (*Sagittaria latifolia*) are both found in the lake.

The north side of the lake consists largely of meadows containing large amounts of annual herbs and various shrubs before grading into forest. Western bistort (*Polygonum bistortoides*) is found in large amounts, and helleborus (*Helleborus* sp.), cow parsnip (*Heracleum maximum*), mountain boykinia *(Boykinia major*), and Sierra bog orchid (*Platanthera leucostachys*) are also present.

More meadow exists on the southeast side of the lake, some of it wet. There is a small indentation in the shoreline on the northwest side and another on the northeast side, both surrounded by willow trees (*Salix* sp.). Other vegetation on the southeast side of the lake includes arrow-leaved groundsel (*Senecio triangularis*), spirea (*Spiraea splendens),* thimbleberry (*Rubus parviflorus*), and elderberry (*Sambucus racemosa*).

The south side of the lake is heavily forested, with Pacific silver fir (*Abies amabilis*) being the dominant tree. Mountain hemlock (*Tsuga mertensiana)* is the next most common tree, and western hemlock (*Tsuga heterophylla*), subalpine fir (*Abies lasiocarpa*), western white pine (*Pinus monticola*), and lodgepole pine (*Pinus contorta*) are also found on this side of the lake. Black huckleberry (*Vaccinia membranaceum*) is the prevailing understory vegetation, but other shrubs include Sitka alder (*Alnus viridis*), Sitka mountain-ash (*Sorbus sitchensis*), western bistort (*Bistorta bistortoides*), beargrass, thimbleberry and elderberry. Wildflowers present include bunchberry dogwood (*Cornus canadensis*), queen's cup (*Clintonia uniflora*), helleborus, foamflower (*Tiarella trifoliate)*, and wild strawberry (*Fragaria vesca*).

Table 3.2 Blair Lake Vegetation.

Trees, Herbs, Aquatics, and Wildflowers found at Blair Lake			
TREES	SHRUBS	HERBS /AQUATICS	WILDFLOWERS
Abies amabilis	*Vaccinium membranaceum*	*Lysichiton americanus*	*Cornus canadensis*
Tsuga mertensiana	*Alnus viridis*	*Nuphar lutea*	*Clintonia uniflora*
Tsuga heterophylla	*Sorbus sitchensis*	*Sagittaria latifolia*	*Helleborus* sp.
Abies lasiocarpa	*Rubus parviflorus*	*Polygonum bistortoides*	*Tiarella trifoliata*
Pinus monticola	*Sambucus racemosa*	*Bistorta bistortoides*	*Fragaria vesca*
Pinus contorta		*Heracleum maximum*	
Salix sp.		*Boykinia major*	
		Senecio triangularis	
		Spirea splendens	
		Sambucus racemosa	
		Xerophyllum tenax	
		Rubus parviflorus	

Numerous species of birds and butterflies are found in the meadows near the lake, and the lake is stocked regularly with brook and rainbow trout (USFS, 2015). Salamanders were observed in the lake during the research visit.

Pre-Settlement Human History

Blair Lake lies in a basin that has been heavily logged in the past, and as a result, the majority of the archaeological work done near the site has been preliminary surveys or as a follow-up to surface finds. No major excavations have been conducted near the site. There are, however, several nearby sites that suggest that Native Americans used the region seasonally to hunt game and gather huckleberries.

The Cayuse Head site (35LA516) was recorded in 1981 by Debra Young and was discovered as a part of a preliminary survey conducted prior to a timber sale. No ^{14}C dates were obtained from the site. The site was found at approximately 1,500 m in elevation along a trail thought to have been used by Native Americans to travel between the upper Willamette Valley and the Cascade divide (Claeyssens, 1983). The find consisted of two obsidian flakes that were between two and three cm long and between one and two cm wide, one gray chert flake between two cm long and two cm wide, and two tiny obsidian flakes that were smaller than one-half cm (Young, 1981).

The Spring Meadow site (35LA375) is situated in a beargrass meadow at approximately 1700 m in elevation. The site was originally recorded in 1979 by Paul Claeyssens, updated in 1986, and another survey occurred in 2004. The finds consisted of several cairns, one large obsidian side-notched projectile point, one broad-necked projectile point, some corner-notched points, core fragments and flakes (Claeyssens, 1979). Based on the presence of projectile points and a large amount of stone debitage, the site was interpreted as a tool manufacturing and hunting site. The artifacts found provide evidence of prehistoric occupation, but the meadow has been used historically also. Ranchers have been using the meadow for cattle since the early 1900s (Claeyssens, 1979).

The Blair Lake site (35LA373) was discovered in 1979 and was heavily disturbed, probably due to logging operations in the area. The site is approximately 1432 m in elevation and is located on the north side of Wall Creek, just west of Blair Lake (Claeyssens, 1979). There were many flakes and some fractured microflakes. Projectile points were found near the lake and on the Blair Lake Trail. In 1981, four isolated items were found at or near the site. They consisted of a red jasper projectile point fragment, a small obsidian flake, and two black obsidian flakes. One had a gray band, and both showed signs of retouching. The site appears to have been used as a seasonal camp (Claeyssens, 1979).

The Ridge Runner Unit I site (35LA753), ranging from approximately 1389 to 1414 m in elevation, is on a ridge between Huckleberry Mountain and the Blair Lake/Mule Mountain area. The site was located by Barbara Crenshaw, a forestry technician, while inspecting a tree planting contract. The site was heavily disturbed due to road construction, timber harvesting, and tree planting conducted nearby (Claeyssens, 1986). An inventory of the site reported one jasper unifacial end scraper, three obsidian modified flakes, and unmodified flakes made of obsidian. Subsequent isolated finds in the vicinity included an unmodified obsidian flake found about one-half km southwest of the site and a small lithic scatter with five modified obsidian flakes found about one-half km west of the site (Claeyssens, 1986).

Other nearby prehistoric sites include the Tillicum Creek site (35LA548), a light lithic scatter containing ten obsidian and ignimbrite flakes and Hemlock Cairns (35LA740), a relatively undisturbed site containing two rock cairns made of angular basalt cobbles. One historic site was also found in the surrounding area. The Wall Creek Guard Station is a dump site with a scatter of historic artifacts (Cox, 1990).

All of the sites mentioned above are less than 10 km from Blair Lake and were investigated as part of preliminary surveys conducted to determine if logging activities would impact archaeological finds in the area. No excavations were performed, and no radiocarbon dates were obtained. However, the presence of projectile points and other tools made of chert, basalt, CCs, and obsidian provide evidence of prehistoric use of Blair Lake and the surrounding meadow areas. It is known that Native Americans used upland sites on a seasonal basis for hunting and to gather berries and other high-elevation food sources, and it seems likely that Blair Lake was part of a regular seasonal round.

Post-Settlement Human History

The earliest known post-settlement history of the Blair Lake area is that it was used as a summer encampment for forest patrols; a guard station was built in the 1930s or 1940s for this purpose. Today, a trail shelter used by these patrols still exists near Blair Lake campground. According to Brian McGinley of the USFS (e-mail message to author, October 27, 2015), the Willamette National Forest was grazed by a large number of flocks of sheep in the early 1900s, and many of those sheep likely wandered through the Blair Lake basin during the summer. Extensive logging occurred in the Blair Lake basin during the 1950s and 1960s, and the Blair Lake campground was built in the 1970s, most likely because logging roads provided easy access to the lake (Brian McGinley, e-mail message to author, October 27, 2015).

CHAPTER IV

METHODS

Field Methods

Sediment cores were obtained from Blair Lake (N 43°50.096’, W 122°14.361’) during July of 2012. In order to avoid contamination from sediments that may have slumped into the basin from erosion or mass-wasting events, cores were collected from the near the middle of the lake (depth =5.91 m; Fig. 4.1) A hand-operated Livingstone piston corer was lowered from a floating platform (Fig. 4.2) in order to retrieve the long cores (Wright et al., 1984), and a Bolivia piston corer was used to collect the short core, which included the sediment-water interface (Myrbo and Wright, 2008).

The long core was extruded in the field, measured, and the lithology described before being wrapped first in plastic wrap and then in aluminum foil and secured in split PVC pipes for transport. The short core was subsampled into Whirl-pak bags in the field at 1-cm intervals. The cores were then transported to the Paleoecology Laboratory at Central Washington University and placed in cold storage.

Figure 4.1 Extruded long core drive from Blair Lake.

Figure 4.2 Coring from floating platform at Blair Lake, July, 2012.

Laboratory Methods

Magnetic Susceptibility Testing

Magnetic susceptibility is a measure of the ability of a material to be magnetized (Sandgren and Snowball, 2002) and provides evidence of events such as volcanic eruptions, and erosional events recorded in the lake sediments (Dearing and Flower, 1982). Each intact core drive was run through a Sapphire Instruments magnetic susceptibility ring sensor, and measurements were taken at contiguous 1-cm intervals (Thompson and Oldfield, 1986).

Chronology and Lithology

Once magnetic susceptibility measurements were completed, the core drives were then prepared for further analysis by splitting them longitudinally (Figure 4.3). Once split, photographs were taken of each core segment, and the core lithology (i.e., color, texture) was described both visually and with the use of a Munsell color chart. The core segments were examined for macrofossils to be used for radiocarbon dating, and the presence of tephra layers was noted.

No macrofossils were found, so bulk sediment was used for dating purposes. The sediment was dried at 90°C, and samples of 2 cm^3 were sent to DirectAMS in Seattle, Washington, for radiocarbon dating. An age-depth model was created based on five AMS ^{14}C determinations and the known age of the Mount Mazama O eruption (Zdanowicz et al., 1999; Fig. 4.4). Dates were converted to calendar years before present using CALIB 5.0.2 (Stuiver et al., 2010).

Due to runoff, the top 24 cm of the short core (BLL12A) was added to the top of the first long core (BLL12B). This was done visually by comparing trends in charcoal concentrations. Initially, seven drives were taken to obtain the long core (BLL12B), with each drive spanning approximately 100 cm of sediment. During the seventh drive (1200-1300 cm), the piston slipped, and a new core was needed to obtain the rest of the sediment. Three drives were taken to obtain the new core (BLL12C). The top of BLL12B and the bottom of BLL12C were then combined, along with the short core, and hereafter referred to as BLL12D. The cores were correlated using the presence of Mount Mazama O tephra (Zdanowicz et al., 1999) to create a continuous record for the entire lake history. A constrained cubic smoothing spline was used to fit the age model (Telford et al., 2004).

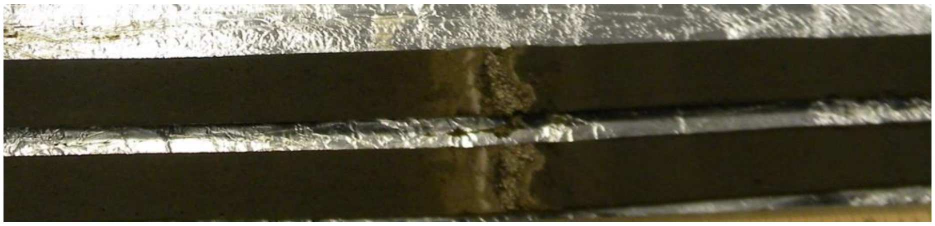

Figure 4.3 Blair Lake core split longitudinally.

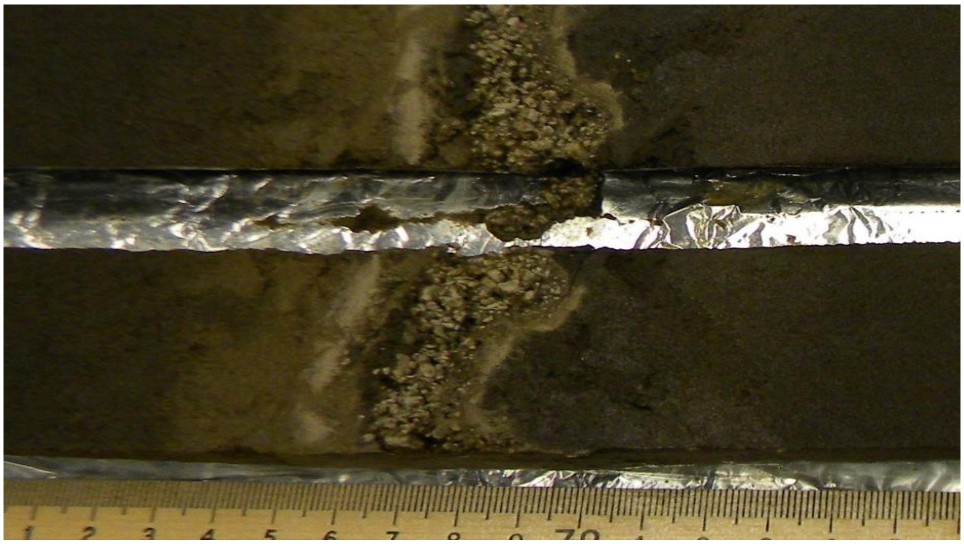

Figure 4.4 Mount Mazama Tephra O in Blair Lake core.

Loss-On-Ignition

Samples were taken at 5-cm intervals for loss-on-ignition analysis throughout the length of the core by gently packing sediment into a modified syringe. Loss-on-ignition was performed in order to determine the water, organic and carbonate content of the sediment (Dean, 1974). For each loss-on-ignition sample, a dry crucible was weighed while empty, filled with one cubic centimeter (cc) of sediment, and then weighed again. After this, it was placed in a drying oven at 90ºC and left overnight. The next day the crucible was placed in a desiccation tank to cool, weighed again, and burned in a muffle furnace at 550°C for two hours. After burning, the sample was then placed in a desiccation tank to cool. Once cool, the crucible was weighed again. The first firing removed the organic content of the sample. The percent organic content of each sample was determined by using the following calculation: ((dry weight before 550°C ignition – dry weight after 550°C ignition)/dry weight before 550°C ignition)*100 (Heiri et al., 2001).

The crucibles were then placed back in the muffle furnace at 900ºC for two hours to remove any carbonate content. After cooling in the desiccation chamber, the crucibles were weighed for a final time. Carbonate content was determined using the following calculation: ((dry weight before ignition –dry weight after ignition)/dry weight before ignition*1.36)*100 (Heiri et al., 2001).

Charcoal Analysis

Charcoal samples of 1 cc were taken at contiguous 1-cm intervals throughout the length of the long core and the short core by gently packing sediment into a modified syringe. Each sample was placed into a plastic vial with approximately 10 ml of a 5% solution of sodium hexametaphosphate and allowed to sit for at least 24 hours (Whitlock and Anderson, 2003). Approximately 10 ml of commercial bleach was then added to each sample for one hour prior to sieving (Walsh et al., 2008).

After the samples had soaked, each charcoal sample was sieved through nested mesh screens of 250 and 125µm sizes and washed into gridded petri dishes for counting (Long et al., 1998). Each charcoal sample was counted under a stereo microscope at 10-40X magnification, and charcoal particles were recorded as either wood or herbaceous charcoal, based on appearance (Jensen et al., 2007; Walsh et al., 2008, 2010a, 2010b, 2014). Flat particles with stomata were counted as herbaceous charcoal, representing vegetation that has a photosynthetic stem (e.g., grasses, other forbs, and herbs). All other was counted as woody charcoal, representing trees and shrubs.

Charcoal concentration (particles/cm^3) was calculated by dividing the number of charcoal particles counted in each sample by the volume of that sample. The charcoal data were then analyzed using the CharAnalysis program (Higuera et al., 2008; http://CharAnalysis.googlepages.com), which separates the data into a peaks and background component to identify fire events and reconstruct local fire history. The CharAnalysis program first interpolated the charcoal concentration data to a constant 23-year interval, which was the median resolution of the core. For this analysis, the data were not log-transformed. The program then calculated the charcoal influx (particles/cm^3 /yr; also known as charcoal accumulation rate: CHAR) of the record.

The CHAR background component is a measure of the low–frequency trends in the interpolated record and was defined for Blair Lake by a 600-year window and described using a Lowess smoother function (robust to outliers). Sensitivity analysis of window widths of 400, 500, and 600 years showed that the signal-to-noise ratio (a measurement of the distance between the peaks and non-peaks) at Blair Lake was maximized at 600 years.

The CHAR peaks component is a measure of the high-frequency trends after the background CHAR is removed and was represented by the residuals after the background values were subtracted from the interpolated time series. Using a Gaussian mixture model, a locally determined threshold for peak identification was set at the 95th percentile of the noise distribution. Only peaks that met this threshold were determined significant and used to develop the fire frequency (# of fire episodes/1000 years) curve.

Pollen Analysis

Thirty-two 1-cc pollen samples were taken from the long cores at approximately 10-cm intervals by gently packing sediment into a modified syringe and processed following techniques described in Faegri et al. (1989). In order to determine pollen accumulation rates, *Lycopodium* was added to each sample as an exotic tracer, and a minimum of 400 pollen grains were counted for each sample.

Identification of pollen types was determined using the Central Washington University reference collection and pollen reference manuals (Faegri and Iverson, 1964; Erdtman, 1969; Moore and Webb, 1978; Kapp et al., 2000). Pollen counts were then converted to percentages of the total pollen found in each sample, and pollen accumulation rates (PAR; grains/cm^2) were calculated by dividing pollen concentrations by the deposition time (yr/cm) of each sample. Aquatic pollen counts were omitted when determining the terrestrial pollen total percentages. The arboreal/non-arboreal pollen (AP/NAP) ratio was calculated by dividing the arboreal sum by the total arboreal plus non-arboreal sum.

CHAPTER V

RESULTS

Chronology and Lithology

Age-depth model

The combined BLL12D core was 556 cm in length. An age-depth model for BLL12D was created using five AMS ^{14}C determinations and the presence of the Mount Mazama O tephra O (Table 5.1; Figure 5.1). Dates were converted to calendar years before present using CALIB 5.02 (Stuiver et al., 2010). The resulting age model for BLL12D suggests a basal date of 16,240 cal yr BP with a median resolution of 23 years per centimeter.

Table 5.1 Age and depth calculations for Blair Lake Core 12D

Depth (cm below mud surface)	Lab number	Source Material	Age (^{14}C yr BP)[a]	Age (cal yr BP)[b]
85	D-AMS-004902	Bulk Sediment	1575 ± 34	1460 (1395-1544)
186	D-AMS-004903	Bulk Sediment	3399 ± 32	3640 (3568-3719)
287	D-AMS-004904	Bulk Sediment	5161 ±35	5920 (5887-29992)
		Mount Mazama tephra		7627 (7577-7777)[c]
462	D-AMS-004905	Bulk Sediment	9723 ±43	11190 (11084-11235)
553	D-AMS-004906	Bulk Sediment	13362 ±85	16080 (15799-16316)

[a] ^{14}C age calculations were conducted at DirectAMS, Seattle, WA
[b] Calendar ages with the 2 sigma age ranges determined using Calib 5.0 html (Stuiver and Reimer, 1993 version 5.0)
[c]Known age of Mount Mazama eruption

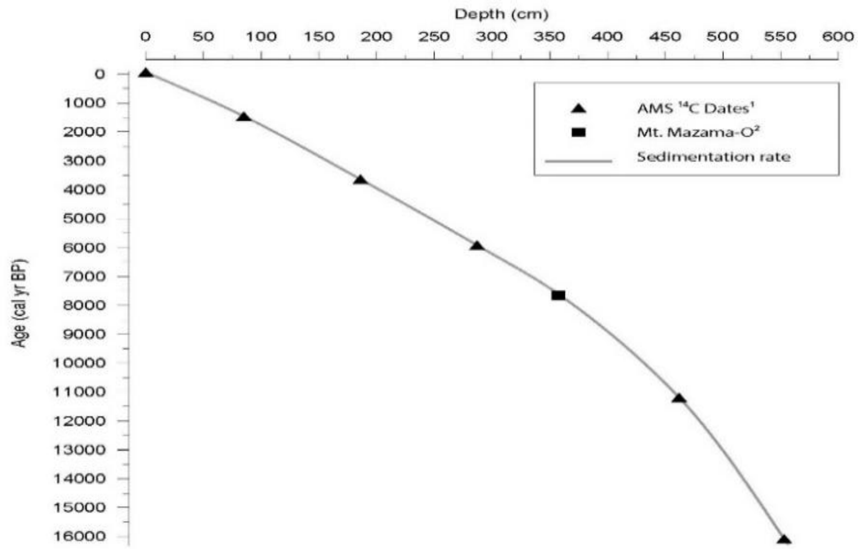

Figure 5.1 Age versus depth relations for Blair Lake (BLL12D)

Sedimentation Rate

Generally, sedimentation rate increased throughout the core (Figure 5.2). The rate at the bottom of the core (ca. 16,240 cal yr BP) was 0.019 cm/yr and the average sedimentation rate ranged from between 0.017 cm/yr and 0.20 cm/yr until reaching a depth of 482 cm (ca. 12,050 cal yr BP). From 481 to 446 cm (ca. 12,050 to 10,500 cal yr BP), the sedimentation rate increased gradually from 0.20 cm/yr to 0.25 cm/yr. From 445 to 402 cm (ca. 10,500 to 8,930 cal yr BP), the sedimentation rate continued to increase from 0.26 cm/yr to 0.30 cm/yr. From 401 to 339 cm (ca. 8,930 to 7,100 cal yr BP), the rate continued to climb, increasing from .30 cm/yr to .40 cm/yr. From 338 to 291 cm (ca. 7,100 to 5,990 cal yr BP), the rate increased from 0.41 to .044 cm/yr. The rate then decreased to 0.43/cm/yr at 290 cm (ca. 5,990 cal yr BP) before increasing again to 0.44 cm/yr at 269 cm (ca. 5,500 cal yr BP). From 268 to 95 cm (ca. 5,500 to 1,640 cal yr BP), the rate increased from 0.45 to 0.50 cm/yr. From there the rate continued to climb, reaching 0.59 cm/yr at the top of the core.

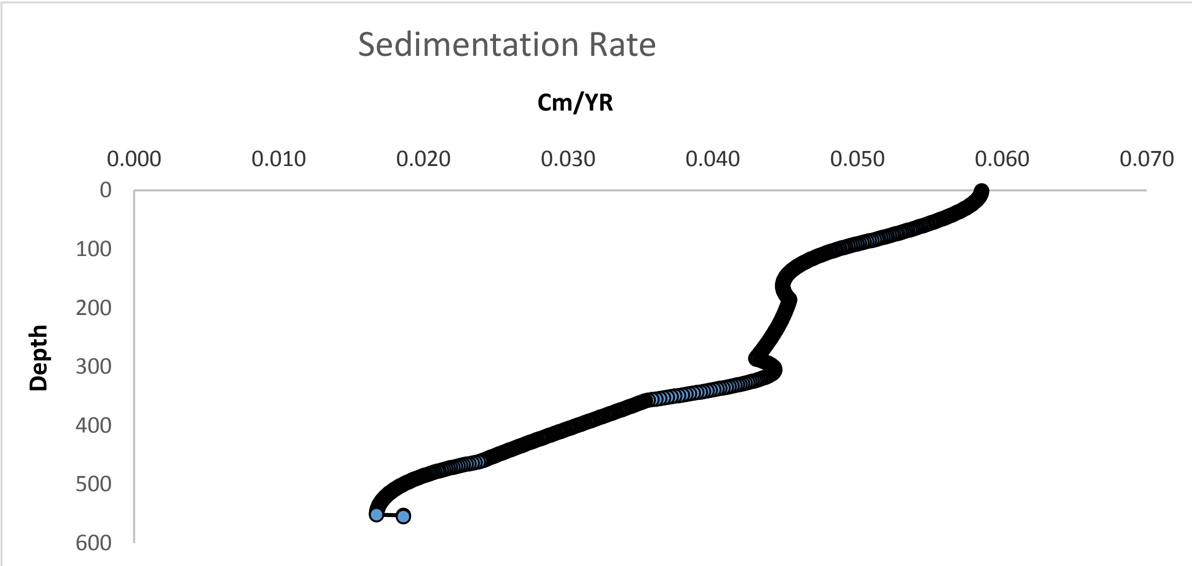

Figure 5.2 Blair Lake Core (BLL12D) sedimentation rate

Magnetic Susceptibility

Magnetic susceptibility analysis showed little evidence of allocthonous material in the Blair Lake sediment core, except near the very bottom of the sediment core (Figure 5.3). Values were initially high until a depth of 550 cm (ca. 15,600 cal yr BP) but declined sharply and neared zero soon after ~525 cm (ca. 14,080 cal yr BP). Throughout the remainder of the core values stayed low except for a brief increase at a depth of ~335 cm (ca. 7,597 cal yr BP) at which point they rose briefly in association with the deposition of the Mount Mazama O tephra layer, and then declined again and remained near zero from that point to the top of the core.

Loss-on-Ignition

Organic content was relatively high throughout most of the core (Figure 5.3). Values were initially low, less than 10% but ranged from 16-21% between 524-509 cm (ca. 15,530-14,660 cal yr BP). Values then decreased significantly to 9% at 504 cm (ca. 14,370 cal yr BP). Shortly after that, values increased and ranged from 18-26% between 499-399 cm (ca. 14,080-9,730 cal yr BP) before decreasing to 12% at 389 cm (ca. 9,370 cal yr BP). Values then increased again and ranged from 15-24% between 384-380 cm (ca. 9,200-9,060 cal yr BP). Another decrease occurred at 374 cm (ca. 8,870 cal yr BP) to 4%. Between 369-364 cm (ca. 8,710-8,550 cal yr BP), values increased again and ranged from 17-23%. Values fell to between 4-13% between 358-334 cm (ca. 8,360-7,000 cal yr BP). Values then increased and ranged from 20-29% between 329-93 cm (ca. 6,880-1,620 cal yr BP). There was another large decrease from 83-33 cm (ca. 1,420-510 cal yr BP) when values ranged from 0.3-10% before increasing significantly to 57% at 28 cm (ca. 420 cal yr BP). Values were fairly consistent for the remainder of the core and ranged from 29-35%.

Carbonate values were very low throughout almost the entire core (Figure 5.3). Values ranged from 0.76-13% from the bottom of the core until 380 cm (ca. 9,060 cal yr BP). Values then increased significantly to 30% at 374 cm (ca. 8,870 cal yr BP). Values then decreased slightly before increasing again, ranging from 16-32% between 349-334 cm (ca. 8,090-7,660 cal yr BP). They then decreased significantly and ranged from 0.13-9% from 329 cm (ca. 7,520 cal yr BP) until the top of the core.

Charcoal and Pollen

Late Glacial (Zone BLL12D-4: 562-481 cm; ca. 16,240-12,000 cal yr BP)

Charcoal

Charcoal values were generally low in this zone (Table 5.2; Figure 5.4). Average charcoal concentration was 3.1 particles/cm^3, and average CHAR values were 0.05 particles/cm^2/yr. Fire frequency was also the lowest of the entire record with an average of 2.5 episodes/1,000 yr, while peak magnitude averaged 45 particles/cm^2. Fire frequency started low at the beginning of the record (~1.5 episodes/1,000 yr) but increased to ~3 episodes/1,000 yr by ca. 14,800 cal yr BP. Both fire frequency and peak magnitude reached their maximum values during this zone between ca. 15,000-14,000 cal yr BP. Following that, there was a sharp decrease in both fire frequency and peak magnitude near the end of the late glacial period. Fire frequency continued to decrease, reaching its lowest point at ca. 12,500 cal yr BP. Eight fire episodes were recorded in this zone, and the fire return interval averaged 427 years.

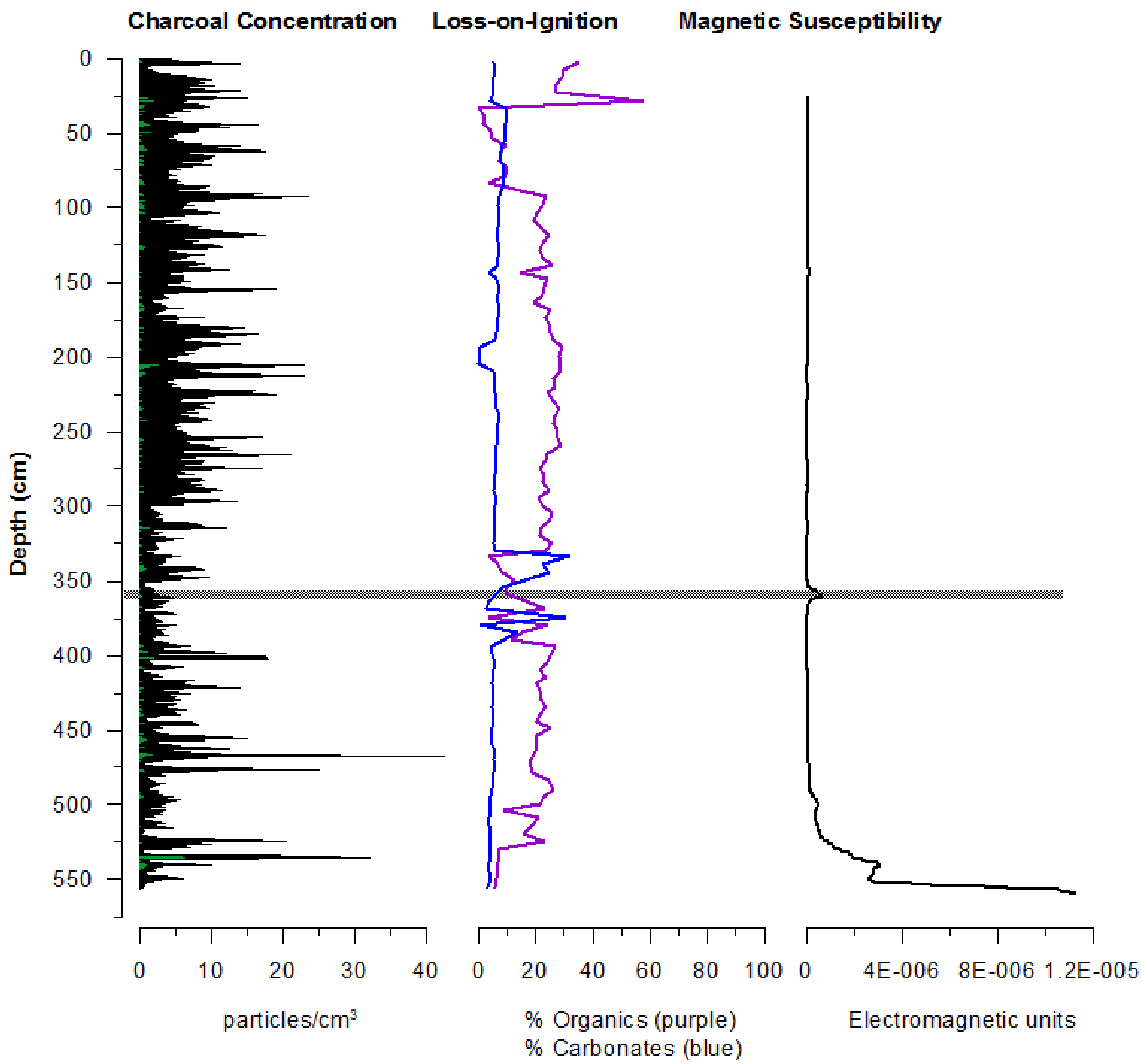

Figure 5.3 Blair Lake charcoal concentration (green curve: herbaceous charcoal: black curve: total charcoal), loss-on-ignition, and magnetic susceptibility.

Pollen

Pinus and *Abies* were the dominant pollen taxa in this zone (Figure 5.5). At the beginning of the zone *Pinus* pollen percentages were ~76%, but decreased to ~52% at ca. 13,100 cal yr BP. *Pinus* then increased to ~58% at ca. 12,650 cal yr BP, before increasing to ~74% near the top of the zone. Overall, percentages of *Pinus* represented ~66% of the pollen taxa for this zone. *Abies* pollen percentages ranged from ~13-20% in this zone, averaging ~18%. *Abies* percentages reached a maximum peak of ~20% in this zone at ca. 14,300 cal yr BP. Although *Alnus sinuata*-type only represented ~11% of the overall pollen taxa for this zone, percentages increased significantly and reached close to 24% at ca. 13,100 cal yr BP. Percentages then decreased to ~18% at ca. 12,650 cal yr BP before decreasing to ~5% near the top of the zone. *Artemisia* was present in smaller amounts. Percentages averaged ~2%, but gradually increased to almost 4% near the top of the zone. *Tsuga heterophylla* percentages averaged ~1% for this zone but reached almost 2% at ca. 12,650 cal yr BP. Percentages of *Pseudotsuga*/*Larix*-type were less than 1%.

Early Holocene (Zone Bll12d-3: 481-372 Cm: Ca. 12,000-8,000 Cal Yr BP)

Charcoal

Charcoal values increased considerably in this zone (Table 5.2; Figure 5.4). Average charcoal concentration was 4.9 particles/cm^3, and average CHAR values were 0.18 particles/cm^2/. Fire frequency averaged 4.5 episodes/1,000 yr, while peak magnitude decreased slightly from the previous zone to an average of 40 particles/cm$^{2.}$ Fire frequency increased from the beginning of the zone to a local maxima of ~3 episodes/1,000 yr by ca. 10,900 cal yr BP. After that, fire frequency decreased to ~1.8 episodes/1,000 yr by ca. 9,700 cal yr BP. Fire frequency then increased sharply and reached its highest peak for this zone at ca. 9,000 cal yr BP

(~5 episodes/1,000 yr), followed by a decrease to ~3.7 episodes/1,000 yr by the end of the zone. Peak magnitude values varied considerably in this zone, but were generally higher near the beginning and generally lower near the end of the zone. Thirteen fire episodes were recorded in this zone, and the fire return interval for this time period averaged 297 years.

Pollen

As seen in Zone BLL12D-4, *Pinus* pollen dominated this zone and made up ~65% of the total record in Zone BLL12D-3. *Pinus* percentages were at their highest values of ~71% at ca. 10,600 cal yr BP and at their lowest values of ~58% at ca. 9,900 cal yr BP. Percentages were high again, ~65%, near the top of the zone. Average percentages of *Alnus sinuata*-type (~16%) were higher than average *Abies* percentages (~11%) in this zone. At ca. 9,900 cal yr BP, percentages of *Alnus sinuata*-type increased significantly and reached ~26%. Percentages then decreased to ~8% at ca. 9,100 cal yr BP before increasing again and reaching ~15% near the top of this zone. Percentages of *Abies* were low in the beginning of this zone and ranged from ~6-7% throughout most of this zone. Percentages were lowest at ca. 9,900 cal yr BP, ~6%. They then increased and reached ~15% at ca. 8,500 cal yr BP. *Artemisia* percentages averaged ~3% for this zone. Percentages were close to 4% at the beginning of this zone, but gradually decreased to ~1% near the top of the zone. *Pseudotsuga*/*Larix*-type increased in this zone and averaged ~2%, with the highest value of 2.4% at ca. 9,100 cal yr BP. More herbaceous pollen was present in this zone than during the late glacial period and included small amounts of *Poaceae* (~1%), *Cyperaceae* (~0.5%), and *Pteridium aquilinum* (~1%).

Middle Holocene (Zone Bll12d-2: 372-204 Cm: Ca 8,000-4,000 Cal Yr BP)

<u>Charcoal</u>

Charcoal values continued to rise in this zone. Average charcoal concentration increased to 5.6 particles/cm^3, and CHAR values increased to an average of 0.24 particles/cm^2/yr (Table 5.2; Figure 5.4). Fire frequency averaged 5 episodes/1,000 yr, while peak magnitude decreased significantly to an average of 25 particles/cm^2. Fire frequency generally increased from the beginning of the zone to its highest point at ca. 5,500 cal yr BP (~6 episodes/1,000 yr), but then decreased to the end of the zone (~4 episodes/1,000 yr). Peak magnitude generally increased during the zone and was at its highest near the end of this time period at ca. 4,500 cal yr BP (~31 particles/cm^2. There were 14 fire episodes, and the average fire return interval was 231 years.

<u>Pollen</u>

Pinus percentages continued to be the dominant vegetation in this zone, but average percentages remained generally the same as those in Zone BLL12D-3 (~65%). Percentages reached their highest values of ~75% at ca. 5,500 cal yr BP and their lowest values of ~57% at ca. 4,500 cal yr BP. *Abies* percentages averages increased slightly to ~19%. They were ~26% at the beginning of this zone, down to ~12% at ca. 5,500 cal yr BP, up to ~25% at ca. 5,000 cal yr BP, and down to ~15% near the top of the zone. *Alnus sinuata*-type averages decreased slightly to ~10% in this zone. *Alnus* was very low at the beginning of the zone, but increased to ~13% at ca. 6,600 cal yr BP. It then decreased to ~9% at ca. 5,000 cal yr BP and increased to ~14% near the top of the zone. *Tsuga heterophylla* percentages averaged ~2% for this zone. Percentages were very small at the beginning (~.6%) but increased to ~4% near the top of the zone. Only trace amounts of *Artemisia* were found in this zone. *Pteridium* percentages averaged ~.7% in this zone. Percentages increased to ~1% at ca. 6,100 cal yr BP, decreased to 0 at ca. 5,900 cal yr BP, increased to ~2% at ca. 5,000 cal yr BP, and then decreased to ~.6% near the top of the zone. Percentages of Poaceae averaged ~5% or less for most of this zone, but reached ~1% near the top of the zone. Cyperaceae does not appear until ca. 5,000 cal y BP. Percentages were less than 1% throughout the remainder of this zone. There were also small amounts of *Tsuga mertensiana* (~.4%) and *Pseudotsuga*/Larix-type (~.7%).

Late Holocene (Zone Bll12d-1: 204-0 Cm; Ca. 4,000 Cal Yr BP-Present)

<u>Charcoal</u>

Charcoal values continued to increase during the Late Holocene, and charcoal concentration averaged 6.4 particles/cm^3 (Table 5.2; Figure 5.4). CHAR values also continued to increase and averaged 0.32 particles/cm^3. Fire frequency decreased during this time period and averaged 4 episodes/1,000 yr, but peak magnitude increased to 40 particles/cm^2. Fire frequency decreased significantly to ~2 episodes/1,000 yr at ca. 3,300 cal yr BP, increased to ~3 episodes/1,000 yr at cal yr BP, and to ~4 episodes/1,000 yr at cal 2,500 cal yr BP. It decreased again to ~3 episodes/1,000 yr at ca. 625 cal yr BP where it stayed for the remainder of this zone.

<u>Pollen</u>

Percentages of *Pinus* were still high, but decreased significantly near the top of this zone. The average percentage was ~56%, and the highest values (~65%) were at ca. 1,700 cal yr BP. Values then decreased to ~45% at the top of the zone, the lowest values for the entire record. *Abies* percentages ranged from ~16-20% throughout most of the zone but were at ~23% near the beginning, and the average was ~19%. Percentages of *Alnus sinuata*-type were lower in this zone than in any other, averaging ~8%. The lowest values (~3%) were found at ca. 1,100 cal yr BP but then increased to ~9% at the top of this zone. *Tsuga heterophylla* percentages were very low

(< 2%) at the beginning of this zone, but increased to ~8% at ca. 1,100 cal yr BP before decreasing to ~7% at the top of this zone. Overall average percentage was ~5%. *Tsuga mertensiana* was present in this zone but in very low percentages (average ~.5%). Values were at 0 at ca. 1,900 cal yr BP, increased to slightly over 1% at ca. 1,700 cal yr BP, and then decreased to ~.7% near the top. *Pseudotsuga*/*Larix*-type percentages were very low (~1%) at the beginning but gradually increased throughout this zone, reaching almost 7% near the top. *Artemisia* percentages were very low throughout this zone and averaged ~1%. Values increased until ca. 750 cal yr BP where they reached almost 5% before decreasing again to ~.7% near the top. Cyperaceae increased in this zone, averaging ~3%. Percentages were lowest (~.6%) at ca. 3,700 cal yr BP but incrased to more than 5% at the top of the zone. Overall percentages of Poaceae were low in this zone, averaging ~.4%. However, at both the beginning and end of this zone, percentages were over 1%. Percentages of *Pteridium* were also low in this zone, averaging ~.7%. Percentages increased to over 1% at ca. 1,500 cal yr BP and to almost 2% at ca. 1,700 cal yr BP. Percentages then decreased again to slightly more than 0.6% at the top of the zone.

Table 5.2 Average Charcoal Concentration Values, CHAR Values, Fire Frequency, Fire-Episode Magnitude, and Mean Fire-Return Interval for Blair Lake Core (BLL12D)

Zone : age (cal yr BP)	Charcoal concentration (particles/cm^3)	CHAR (particles/ cm^2/yr)	Fire frequency (episodes/1000 yr)	Fire episode magnitude (particles/cm^2)	Mean fire-return interval
BLL12D-1 4,000-Present	6.4	0.32	4	40	292
BLL12D-2 : 8,000-4,000	5.6	0.24	5	25	231
BLL12D-3 12,000-8,000	4.9	0.18	4.5	40	297
BLL12D-4 16,241-12,000	3.1	0.05	2.5	45	427

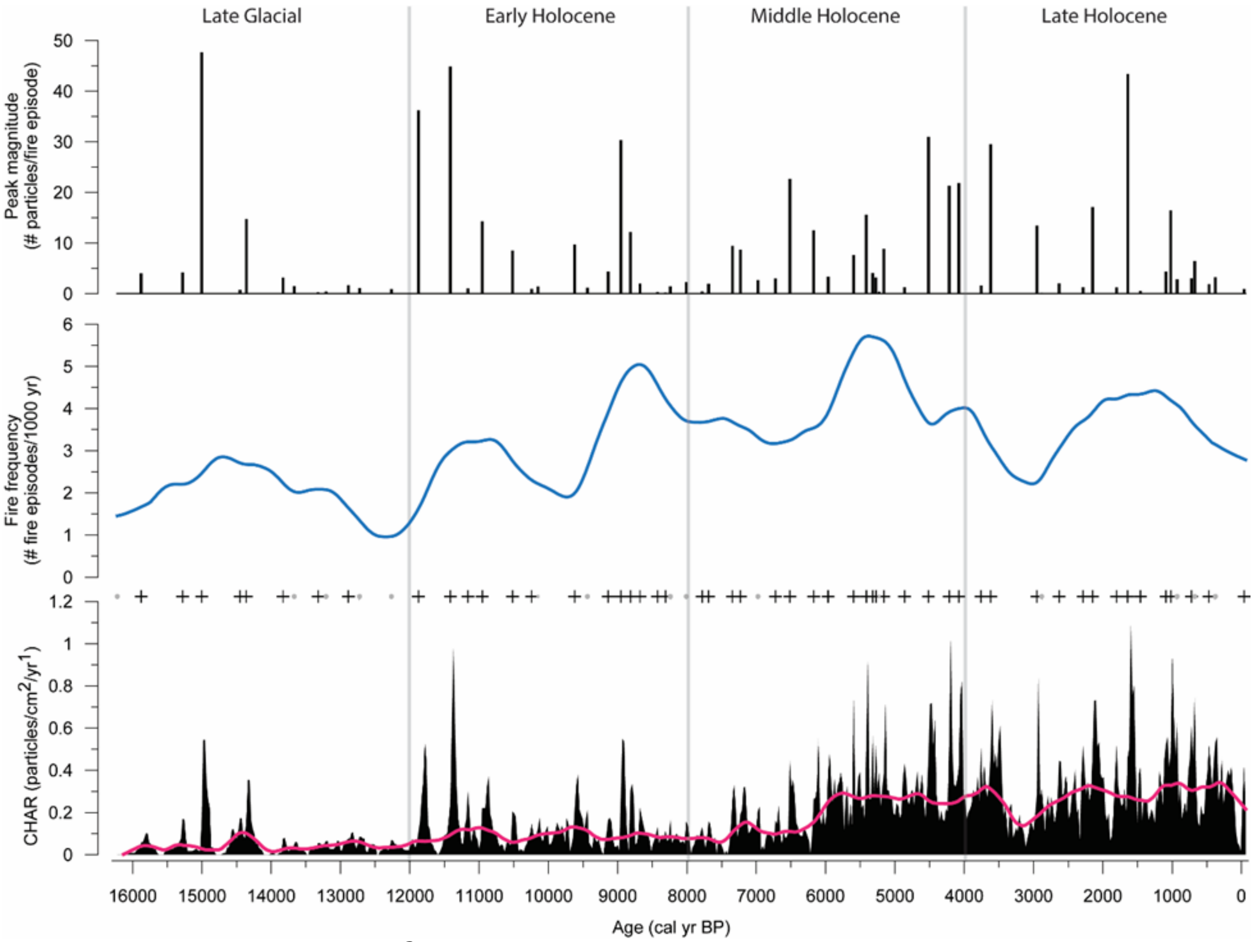

Figure 5.4 CHAR (particles cm^2/yr), Fire Frequency (# episodes/1,000 yr), and Peak Magnitude (# particles /fire episode) for Blair Lake Core (BLL12D)

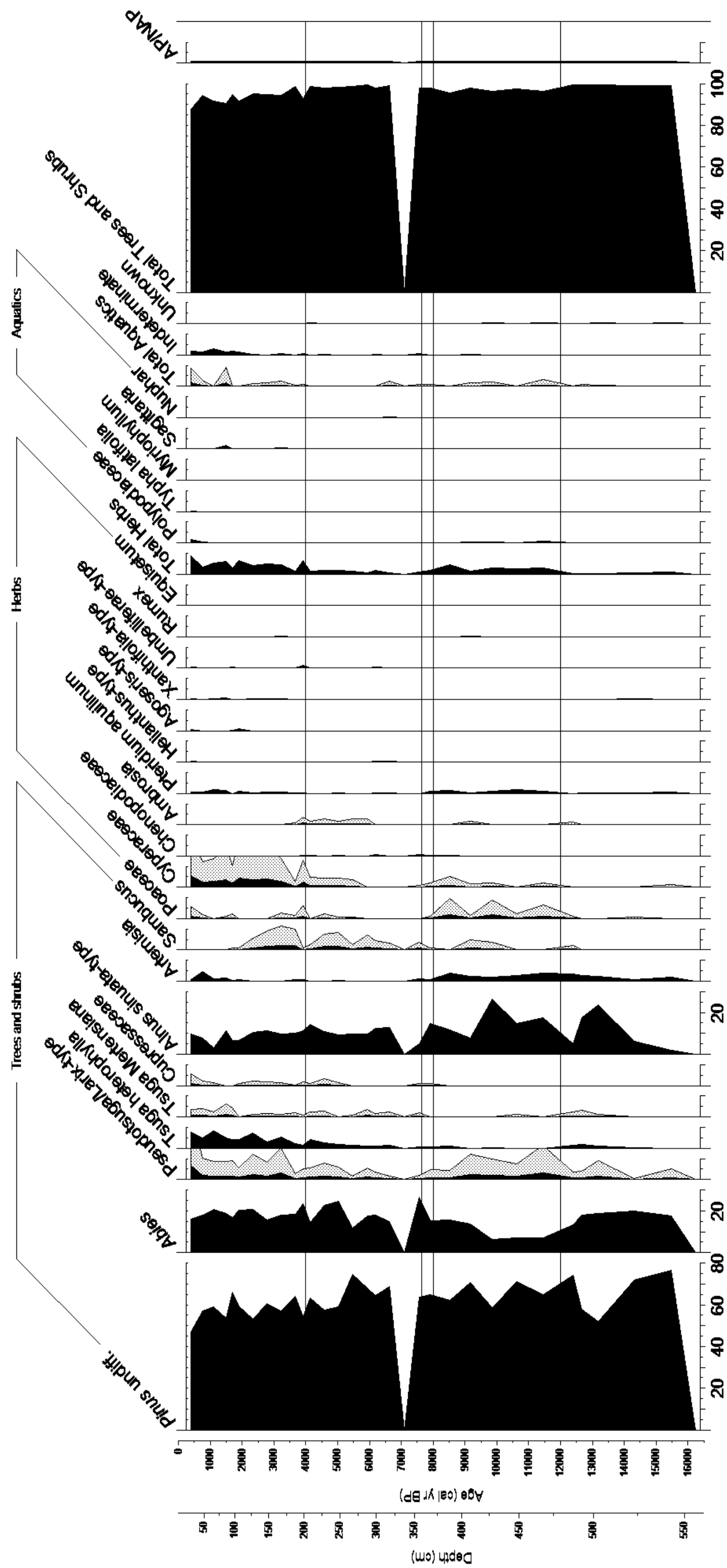

Figure 5.5 Pollen Percentage Diagram of Select Taxa from the Blair Lake Core (BLL12D)

CHAPTER VI

DISCUSSION

Fire-Vegetation-Climate Interactions at Blair Lake

Late Glacial (Ca. 16,240-12,000 Cal Yr BP)

Blair Lake is one of the oldest known lakes in the Cascade Mountains (ca. 16,240 cal yr BP). Other mid-to-high-elevation lakes in the Pacific Northwest older than 12,000 years old include Frozen Lake (ca. 12,340 cal yr BP), Prophyry Lake (ca. 14,980 cal yr BP), Walker Lake (ca. 15,400 cal yr BP), Martins Lake (ca. 12,010 cal yr BP), Yahoo Lake (ca. 14,660 cal yr BP), and Sunrise Lake (ca. 14,510 cal yr BP) (Gavin et al., 2001; Brown and Hebda, 2003; Hallett et al., 2003; Gavin et al., 2013; Lukens, 2013; see Walsh et al., 2015 for locations). Of these, only Sunrise Lake is located in the Cascades (Lukens, 2013). The lithology of the Blair Lake core bottom, which consisted a small amount of clay and rock, the high magnetic susceptibility values at that time, and the age of the core, suggest that the lake formed soon after the retreat of the alpine Cascades glaciers following the last glacial maximum (ca. 19,000 cal yr BP) (Clark et al., 2009).

Overall fire frequency was lowest at Blair Lake during the late glacial period than at any other time in the record, but peak magnitude was the highest (Figure 6.1). The climate of the Pacific Northwest was still cool and dry at this time due to the presence of the retreating Cordilleran ice sheet (Braconnot et al., 2007; Power et al, 2008), and average fire frequency at Blair Lake was very low (~1.8 episodes/1,000 yr). The presence of the Laurentide ice sheet on the North American continent until ca. 12,000 cal yr BP continued to affect the climate of the Pacific Northwest by splitting the North American jet stream, which shifted storm tracks away from their normal positions, resulting in decreased moisture for the region (Broccoli and

Manabe, 1987; Whitlock 1992; Bartlein et al., 1998). The height of the ice sheet also generated an anticyclonic circulation pattern, resulting in stronger easterly winds and colder, drier conditions (Broccoli and Manabe, 1987; Whitlock, 1992; Bartlein et al., 1998). These colder, drier conditions led to less terrestrial biomass and limited fuel availability during even the immediate post-glacial period (Francois et al., 1999; Power et al., 2008) and, therefore, a low of amount of fire activity at Blair Lake and most other sites in the PNW.

The Puget Lobe of the Cordilleran ice sheet reached its southernmost point at ca. 17,000 cal yr BP and began retreating within 100 years (Porter and Swanson, 1998). Following the retreat of the ice sheet, CO_2 concentrations and insolation began to increase in the PNW (Bartlein et al., 2014), and increased fire activity at Blair Lake was likely a result of these changes. Fire frequency reached its peak during the late glacial period at ca. 15,000 cal yr BP (slightly less than 3 episodes/1,000 yr) and remained relatively high until ca. 13,500 cal yr BP. Fire episode magnitude was also highest at this time (~50 particles/fire episode), indicating potentially larger or higher severity fires at that time, or ones that burned closer to the lake (Gavin et al., 2003; Gavin et al., 2013).

Sunrise Lake, a subalpine lake (1,768 m) in Mount Rainier National Park in the central Cascades of Washington, experienced a similar increase in fire activity from ca. 14,500-12,000 cal yr BP (Lukens, 2013), indicating that this is a somewhat regional trend (Figure 6.1). Following that, there was a sharp decrease in fire frequency at Blair Lake at ca. 13,000 cal yr BP that continued until ca. 11,700 cal yr BP. This trend is seen in other lakes in the Pacific Northwest and is believed to be associated with the Younger Dryas Chronozone (YDC), a period of cold, dry conditions that existed from ca. 12,900-11,700 cal yr BP (Marlon et al., 2009). Breitenbush Lake is a high-elevation (1,700 m) lake in the southern Cascades of Oregon dominated by *Abies amabilis*, *Abies procera, and Tsuga mertensiana* (Minckley and Long, 2016). The fire frequency curve of Breitenbush Lake is similar to that of Blair Lake during the late glacial period, but the Breitenbush record only dates to ca. 13,200 cal yr BP and does not reflect the relatively high fire frequency seen at Blair Lake between ca. 15,000 and 13,500 cal yr BP. However, from ca. 13,200-12,100 cal yr BP, there was little or no fire at Breitenbush Lake (Minckley and Long, 2016).

Arboreal pollen dominated the pollen assemblage at Blair Lake during the late glacial period, and by ca. 16,000 cal yr BP, a forest consisting of *Pinus* (likely *Pinus contorta*) and *Abies* (likely *Abies lasiocarpa* or *Abies amabilis)* was already established. *Alnus* (likely *Alnus sinuata*) is a pioneering species that often colonizes a site after a disturbance (Gavin et al., 2005), and its presence after ca. 13,000 cal yr BP may be the result of frequent avalanche activity in the watershed. The presence of *Pseudotsuga/Larix*-type (likely *Pseudotsuga menziesii*), particularly in slightly higher abundance after ca. 14,000 cal yr BP, suggests generally less dry conditions than at the beginning of the record, but the presence of *Artemisia* suggests a still relatively dry, open forest environment. Similar conditions existed at Breitenbush Lake during the late glacial period. An open-canopy forest of *Pinus* and *Picea* was already established by ca. 13,200 cal yr BP, along with high percentages of *Artemisia* and Poaceae (Minckley and Long, 2016).

Early Holocene (Ca. 12,000-8,000 Cal Yr BP)

In general, fire activity increased at Blair Lake during the early Holocene, likely as the result of increased summer insolation due to changes in the perihelion of the sun and tilt of the earth's axis (Figure 6.1D) (Bartlein et al., 1998; Kutzbach and Guetter, 1986; Whitlock, 1992; Bartlein et al., 2014). Between 10,000 and 9,000 cal yr BP, radiation values peaked and were 8% higher in summer and 10% lower in winter, intensifying summer drought conditions in the PNW

(Kutzbach and Guetter, 1986; Whitlock, 1992; Sea and Whitlock, 1995; Bartlein et al., 1998). This likely explains why fire frequency was still low at Blair Lake at the beginning of this period (~1.3 episodes/1,000 yr) but began increasing soon after and remained relatively high for most of this period (~4.5 episodes/1,000 yr). However, fire activity did not only increase during the early Holocene; lower fire frequency values occurred between ca. 10,500-9,500 cal yr BP.

The fire frequency curve at Blair Lake from the early Holocene is somewhat similar to the regional PNW biomass burning curve, which is a composite of 34 macroscopic charcoal-based fire history records (Figure 6.1; Walsh et al., 2015). Both the regional curve and the Blair Lake record reflect increased fire activity after ca. 12,000 cal yr BP. However, the regional curve then shows decreased fire activity after ca. 10,000 cal yr BP, and then another peak in fire activity by ca. 8,000 cal yr BP (Walsh et al., 2015). The Blair Lake curve shows a sharp decrease in fire activity after ca. 10,500 cal yr BP, then an increase after ca. 9,500 cal yr BP, which lasted until ca. 8,500 cal yr BP, and then another decrease until the end of the period. While the general patterns are similar, suggesting that regional climatic changes were responsible for the overall shifts in fire activity, the discrepancies between the two curves likely arises because the composite curve includes lakes of all elevations in the PNW, not just those found at mid-to-high-elevations (Walsh et al., 2015).

The early Holocene fire frequency at Blair Lake seems most similar to that of Panther Potholes, a mid-elevation lake (1,100 m) in North Cascades National Park in Washington (Prichard et al., 2009). At Blair Lake, fire frequency increased after ca. 9,500 cal yr BP and did not decrease until after ca. 8,000 cal yr BP. Fire frequency at Panther Potholes was relatively high from 10,500-8,000 cal yr BP, reaching its highest level from 9,200-8,200 cal yr BP (Prichard et al., 2009). Given the relative coherence between these two Cascade Mountain sites, this again suggests that regional climatic changes were the likely factor influencing fire activity at Blair Lake during the early Holocene.

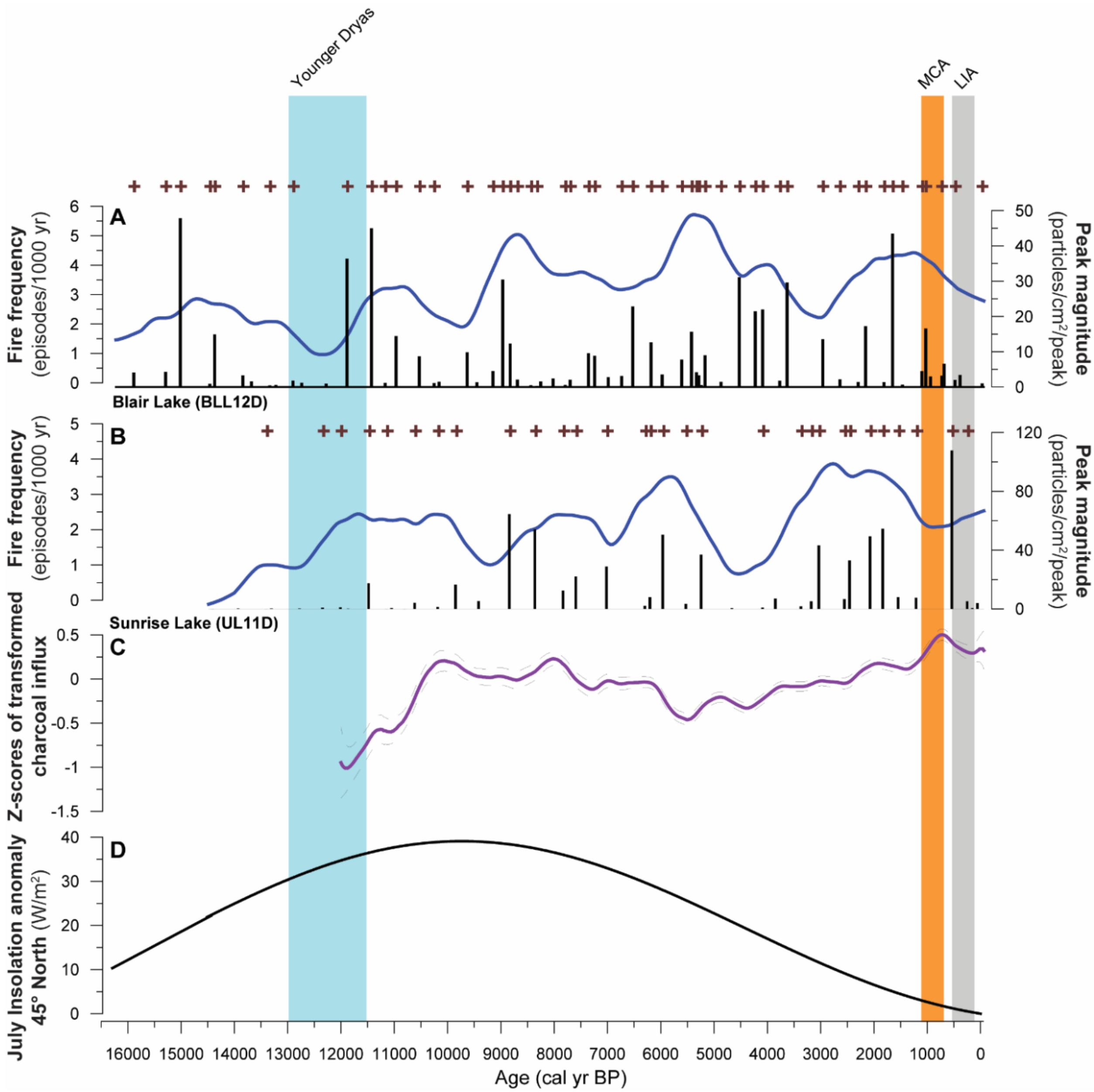

Figure 6.1 Blair Lake and Regional Trend Comparisons: A. Blair Lake (BLL12D) Fire Frequency and Peak Fire Magnitude; B. Sunrise Lake (UL11D)Fire Frequency and Peak Magnitude; C. PNW Regional Biomass Burning Curve; D. Late Glacial and Holocene insolation Curve

As seen during the late glacial period, *Pinus*, *Abies* (likely *Abies amabilis*), and *Alnus* were still dominant at Blair Lake during the early Holocene, but *Pseudotsuga* percentages increased during this time period, and herbaceous pollen, including *Artemisia*, Poaceae, and Cyperaceae were also present, indicating that conditions at Blair Lake were warmer and even drier than during the late glacial, and that meadows or other openings were potentially part of the forest surrounding the lake in the early Holocene. The relatively high percentages of *Pinus*, *Abies*, and *Alnus* seen at Blair Lake during the early Holocene are also seen at Breitenbush Lake (Minckley and Long, 2016) and Moose Lake, a mid-elevation lake (1,508 m) on the Olympic Peninsula in Washington (Gavin et al., 2001).

Furthermore, a dry montane forest consisting of *Pinus contorta*, *Pinus monticola*, *Pseudotsuga menziesii*, and *Abies lasiocarpa* existed at Panther Potholes during the early Holocene, and suggests that summers were warm and dry (Prichard et al., 2009). High levels of *Artemisia* and Poaceae indicate an open canopy, and similar to Blair Lake, the increased percentages of *Alnus sinuata* pollen from ca. 10,200-9,800 cal yr BP indicates more frequent disturbance, such as fire or possibly avalanche activity (Prichard et al., 2009).

Middle Holocene (Ca. 8,000-4,000 Cal Yr BP)

At the beginning of the middle Holocene, summers were still generally warm and dry in the PNW (Bartlein et al., 1998; Gavin et al., 2013), and may explain the still relatively high fire frequency at Blair Lake at that time (~ 3.5 episodes/1,000 yr). In general, fire activity was highest during the middle Holocene than at any other time in the record. Charcoal concentration and CHAR increased during the middle Holocene as compared to the early Holocene (Table 5.2), but peak magnitude decreased, and values for both were lower than at any other time in the Blair Lake record. This suggests that as fires became more frequent they also became smaller, likely because there was less time for fuel to accumulate between fire events. However, conditions gradually became cooler and wetter in the PNW during the middle Holocene and may explain the decrease in fire frequency between ca. 8,000-7,000 cal yr BP (Bartlein et al., 1998; Brown and Hebda, 2003; Prichard et al., 2009; Walsh et al., 2015). Climatic changes do not appear to explain the increase in fire frequency that occurred at ca. 5,500 cal yr BP, which led to the highest fire frequency of the entire record (~5.5 episodes/1,000 yr).

The fire frequency trend at Blair Lake during the middle Holocene is in direct contrast to the PNW regional biomass burning curve, particularly between ca. 6,500-5,500 cal yr BP. The Blair Lake curve shows that fire frequency was generally lower at the beginning of the middle Holocene than at the end of the early Holocene, but the regional fire frequency curve indicates that fire activity increased steadily from the beginning of the middle Holocene until the end of the late Holocene (ca. 5,500-900 cal yr BP; Walsh et al, 2015). While fire frequency began to increase at Blair Lake at ca. 6,000 cal yr BP and reached its highest point at ca. 5,500 cal yr BP, it steadily decreased until ca. 4,500 cal yr BP and then increased slightly at the end of the middle Holocene. The trend seen at Blair Lake during the middle Holocene also stands in direct contrast to the composite biomass burning curve for 19 other high-elevation sites in the PNW (Walsh et al., 2015).

However, several other records from the PNW show similar changes to those seen at Blair Lake during the middle Holocene. The fire frequency curves at Panther Potholes and Frozen Lake show similarly low fire frequency to that observed at Blair Lake between ca. 7,000 and 6,000 cal yr BP (Hallet et al., 2003; Prichard et al., 2009). Mount Barr Cirque Lake, a mid-elevation lake (1,376 m) in the Cascade Mountains of British Columbia, also experienced a decrease in fire frequency at this time (Hallett et al., 2003). The decrease in fire frequency seen at the above-mentioned lakes, as well as Blair Lake, is likely associated with cooler, moister conditions present in the middle Holocene as compared to earlier (Bartlein et al., 1998; Bartlein et al., 2014; Gavin et al., 2015).

The pollen assemblage from Blair Lake indicates that cooler, wetter conditions prevailed during the middle Holocene than what was observed during the early Holocene, and these changes are similar in timing to vegetation shifts observed at other sites in the PNW (Whitlock, 1992; Gavin et al., 2001; Brown and Hebda, 2003; Walsh et al., 2015). Percentages of *Pinus* and *Abies* were still high at Blair Lake in the middle Holocene, but percentages of *Tsuga heterophylla* and *Tsuga mertensiana* also increased at this time, indicating increased effective moisture. Additionally, *Pseudotsuga* and *Alnus* decreased during the middle Holocene, suggesting a more closed canopy forest as climatic conditions changed. These changes are similar to those observed at Breitenbush Lake (Minckley and Long, 2016) and Panther Potholes (Prichard et al., 2009) where *Tsuga heterophylla* increased and *Alnus* decreased at ca. 7,700 cal yr BP. *Tsuga heterophylla* also increased at this time at Porphyry and Walker Lakes, two lakes in the Mountain Hemlock Zone (900-1,400 m) of southern Vancouver Island in British Columbia (Brown and Hebda, 2003), indicating that a region-wide cooling was experienced.

Late Holocene (Ca. 4,000 Cal Yr BP-Present)

Fire activity decreased somewhat at Blair Lake during the late Holocene as compared to the middle Holocene; fire frequency was lower than before at ~ 4 episodes/1,000 yr, but charcoal concentration, CHAR, and peak magnitude were higher, indicating that likely large or high-severity fires were very much part of the landscape during the late Holocene. Fire frequency reached its lowest point since the late glacial period at ca. 3,000 cal yr BP, while fire magnitude was greatest at ca. 2,000 cal yr BP. Fire frequency began increasing after ca. 3,000 cal yr BP

(~1.8 episodes/1,000 yr), until ca. 900 cal yr BP (~4 episodes/1,000 yr). After that it steadily declined for the remainder of the late Holocene. The generally high fire frequency between ca. 2,000-900 cal yr BP is likely associated with the Medieval Climate Anomaly (MCA), a warm, dry period that prevailed in the PNW from ca. 1,100-700 cal yr BP and may have increased fire activity at the site (Mann et al., 2009). This was probably the result of more frequent drought conditions, or perhaps greater lightning strikes and fire-conducive weather (Walsh et al., 2010b; 2015).

The fire frequency curves at both Frozen Lake and Mount Barr Cirque are very similar to the trends seen at Blair Lake during the late Holocene. Both sites experienced a decrease in fire frequency at the beginning of the late Holocene, and fire frequency was lowest for both lakes at ca. 3,000 cal yr BP (Hallett et al., 2003). However, the highest fire frequency at Frozen Lake during the late Holocene was at ca. 2,000 cal yr BP, while the highest fire frequency for Mount Barr Cirque occurred a short time later, at ca. 1,700 cal yr BP (Hallett et al., 2003). At Panther Potholes, fire frequency was high between ca. 3,000 and 2,000 cal yr BP and between 1,000 and 500 cal yr BP (Prichard et al., 2009). While the fire frequency curve at Blair Lake indicates that fires were less frequent during the late Holocene than in the middle Holocene, the regional curve depicts increased fire frequency from ca. 4,000-900 cal yr BP, and illustrates that fire activity was highest during the late Holocene that at any other time in the 12,000-year long record (Walsh et al., 2015). The discrepancies between Blair Lake and other lakes in the PNW may be explained by local controls, such as weather, elevation, topography, aspect, and differences in vegetation and fuels (Gavin et al., 2006).

Although the fire frequency curve at Blair Lake does not correspond well with the regional composite biomass burning curve, fire activity at Blair Lake was similar in part to the biomass burning trend observed at other high-elevation sites in the PNW during the late Holocene (Walsh et al., 2015). These sites show high biomass burning from ca. 2,000-700 cal yr BP, followed by a decrease to the present. The high fire activity at this time was again likely related to the warm, dry conditions of the MCA. However, human populations in the PNW are thought to have been highest during this part of the late Holocene (Prentiss et al., 2005), therefore, human ignitions may have contributed to the fire activity at the site at this time (discussed below). The very prominent trend of decreased fire activity in the PNW composite curve after ca. 900 cal yr BP and in the high-elevation sites composite curve after ca. 700 cal yr BP is consistent with the decline in fire activity at Blair Lake after ca. 900 cal yr BP (Walsh et al., 2015). In fact, this is the most prominently shared characteristic of fire history curves in the PNW (Marlon et al., 2012), either the result of the cooler climate associated with the Little Ice Age (LIA; 500-100 cal yr BP; Grove, 2001) or decreased human populations and use of fire (Prentiss et al., 2005; Walsh et al., 2015).

Pinus percentages decreased at Blair Lake during the late Holocene, but *Pinus* (likely *Pinus contorta* or *Pinus monticola*) and *Abies* were still the dominant vegetation. Percentages of *Pseudotsuga* increased, and an increase in *Tsuga heterophylla*, *Tsuga mertensiana*, and *Cupressaceae* (likely *Juniperus communis*) indicate that conditions were cold and wet in the PNW during the late Holocene (as they are today), and as a result, the forest surrounding Blair Lake became more closed than earlier. This interpretation is further supported by the fact that *Artemisia* is absent from the late Holocene Blair Lake pollen assemblage until ca. 200 cal yr BP; it returned likely as a result of decreased temperatures and precipitation observed during the LIA (Cook et al., 2004). Similar late Holocene increases in *Tsuga heterophylla, Tsuga mertensiana*, and *Cupressaceae* occurred at Porphyry and Walker Lakes at ca. 4,870 cal yr BP, and many other sites around the PNW, suggesting cooler conditions and increasing precipitation (Whitlock, 1992; Brown and Hebda, 2003; Walsh et al., 2015). However, percentages of Poaceae, Cyperaceae, and Chenopodiaceae increased, and overall percentages of herbaceous pollen were higher during the late Holocene than at any other time in the Blair Lake record, suggesting that openings (perhaps created by fire), such as meadows, were still an important component in the forest.

Anthropogenic Influences on Fire

It is difficult to determine the impact that human activity may have had on montane forest environments, such as those surrounding Blair Lake. It is known that Native American groups, such as the Kalapuya and Molalla, used fire to modify their environments to maximize food resources (Aikens et al., 2011). In the Willamette Valley of Oregon, the Kalapuya burned vegetation in the fall in order to encircle and trap deer as part of the annual communal deer hunt (Boyd, 1999). Also, prairies were burned in the summer so that tarweed seeds and grasshoppers could be gathered. Fire was used to burn underneath trees and shrubs to facilitate the collection of acorns and hazelnuts, and berries, such as huckleberries, thimbleberries, wild blackberries and strawberries, blackcaps, and salmonberries, which grow faster and bear more fruit in areas that have been burned over (Boyd, 1999). Fire was also used to encourage the growth of root plants, such as camas and wild onions and in the cultivation of tobacco (Boyd, 1999). In upland areas, the use of fire increased productivity of berries (Mack and McClure, 2002; Lepofsky, 2003;), and the Molallas burned to enhance plant resources, both as food and as forage for wildlife (Swanson et al., 2002).

Presettlement use of fire in upland environments is not well understood (Williams, 2003). Most Native American groups did not live in the mountains, but, instead, used them seasonally in summer and fall as part of their subsistence strategies (Williams, 2003). While archaeological evidence is scarce, there are plenty of ethnographic and historical accounts of Native American groups using fire in many different environments for many different reasons, and these accounts may help shed light on the fire activity at Blair Lake (Wilkes, 1926; Douglas, 1959; Clyman, 1960).

Late Glacial (Ca. 16,240-12,000 Cal Yr BP)

Early humans were living in North America at least by 13,000 cal yr BP, however, some archaeological evidence suggests an even earlier date (Waters and Stafford, 2007; Goebel et al., 2008). Sites such as Meadowcroft Rockshelter in Pennsylvania, Page-Ladson in Florida, and Paisley Cave in Oregon provide dates that indicate human occupation south of the Laurentide ice sheet by at least ca. 14,600 cal yr BP, but these dates are still being debated (Goebel et al., 2008). Genetic and archaeological evidence suggests that humans occupied Siberia as early as 32,000 cal yr BP, migrated across the Bering Land Bridge sometime after ca. 16,500 cal yr BP, and dispersed along the coastline of the Pacific Northwest as early as ca. 15,000 cal yr BP (Goebel et al., 2008). Another possibility is that when humans left Siberia they traveled by boat along the coastline, making use of abundant marine resources (Erlandson et al, 2007; Anderson et al., 2013). Rising sea levels may have eliminated evidence of early coastal sites, but the availability of resources along the coast may also explain why human occupation at sites in the interior occur much later (ca. 13,000 cal yr BP). The use of Clovis projectile points, dated to ca. 13,000 cal yr BP, appears to be an adaptation used to procure resources found in the interior of the continent (Anderson et al., 2013). This may have been a response to increased human populations and the need for additional food sources.

Although humans may have reached the PNW by as early as ca. 15,000 cal yr BP, there is no evidence of human use or occupation of mid-elevation sites in the late glacial period. The climate at that time was still cold and dry, likely limiting access to regions at higher elevations, and plant resources would have been scarce at that time.

Early Holocene (Ca. 12,000-8,000 Cal Yr BP)

The earliest archaeological sites situated in or around the Willamette Valley date back to the early Holocene and provide evidence of human occupation and use of fire at these sites (Aikens et al., 2011). Several sites located along the Long Tom River contained charcoal, burned earth, hearths, and baking ovens in addition to faunal remains and charred acorns, hazelnuts, and camas bulbs (Aikens et al., 2011). Cascadia Cave and Baby Rockshelter are early Holocene sites located in the foothills of the western Cascades that demonstrate the use of sites other than the valley floor at this time (Newman, 1966; Olsen, 1975; Aikens et al., 2011). Both sites contained a significant number and type of projectile points, as well as faunal and plant remains, suggesting that these sites may have been used as seasonal hunting and or food/processing camps (Newman, 1966; Olsen, 1975; Aikens et al., 2011). Camas fields were often burned after harvest. This facilitated future growth, and tarweed seeds and grasshoppers could be collected from the burned over areas (Boyd, 1999).

Fire frequency generally increased at Blair Lake during the early Holocene, however, the regional climate at that time was becoming warmer and drier and was likely responsible for the increase in fire activity from the late glacial through the early Holocene. Regional archaeological evidence suggests that human populations were still relatively small during that time (Aikens et al., 2011), and, therefore, unlikely to have a major impact on the fire regime. However, evidence of humans in upland environments may indicate that they were using burned areas or even ignited areas to enhance forage for wild game, harvest tarweed and insects, and to encourage larger yields of berries.

Middle Holocene (Ca. 8,000-4,000 Cal Yr BP)

Conditions in the Pacific Northwest became both cooler and wetter during the middle Holocene (Bartlein et al., 2014; Gavin et al., 2015), however, fire frequency was its highest overall at Blake Lake during this period, especially between ca. 5,500-4,500 cal yr BP. This increase was possibly the result of larger human populations, and human use of fire, in and around the Willamette Valley and the Cascade Mountains at this time (Aikens et al., 2011). Many of the middle Holocene sites in and around the Willamette Valley, such as the Benjamin sites (Miller, 1975), the Lingo site (Cordell, 1975), and the Chalker site (O'Neill et al., 2004; Aikens et al., 2011) suggest they were used for multiple resource activities. Most of these sites are located near Mill Creek or along the Long Tom River and contained a greater abundance of items seen in the early Holocene: hearths and baking ovens, charred acorns and camas bulbs, as well as stone tools and projectile points (Aikens et al., 2011). Increases in population are also indicated by the increase in number and size of food-processing ovens, suggesting that camas may have been processed in bulk to be used in trade (Aikens et al., 2011). In the Willamette Valley, the Kalapuya burned the camas fields after the harvest in order to encourage new growth. Fire was also used to cultivate tobacco, harvest tarweed seeds and grasshoppers, hunt deer and in the production of basket-making materials (Boyd, 1999).

Hunting and game processing were also important activities in the western Cascades, as evidenced by the number of flaked cobble choppers, flake tools, and dart-sized corner-notched projectile points in addition to butchering and hide-processing tools. These include biface knives, scrapers, perforators, and used-modified flakes, and the presence of hammerstones, choppers, drills, spokeshaves, and sandstone abraders provide evidence of tool manufacturing (Aikens et al., 2011). The fact that fire was used as an important tool in both hunting and berry harvesting as it was used to burn undergrowth and provide forage for wild game, and berry patches were burned after harvesting to enhance cultivation and prevent invasion from trees (Boyd, 1999), could help explain the higher than normal fire frequency at Blair Lake during this period. However, it is difficult to test this hypothesis without further, local archaeological evidence from the Blair Lake watershed.

Late Holocene (Ca. 4,000 Cal Yr BP-Present)

Fire frequency was lower at Blair Lake during the late Holocene than during the middle Holocene; however, it was relatively high from ca. 2,000-900 cal yr BP. The increase in fire frequency at this time is difficult to explain based solely on climatic changes and could be related to larger human populations during the late Holocene (Prentiss et al., 2005) and an increased use of fire in the Blair Lake watershed. However, if this is the case, then it is difficult to explain the decrease in fire frequency from ca. 4,000 to 3,000 cal yr BP. This decrease is also seen at Panther Potholes (Prichard et al., 2009) and Breitenbush Lake (Minckley and Long, 2016), two other mid-to-high-elevation lakes in the Cascades, which suggests that a climatic explanation is more likely.

Whether or not human activity in the mountains augmented the fire activity at Blair Lake during the late Holocene, it is clear that human populations increased during this time and were likely making greater use of burned environments, both in low- and high-elevation environments. The remains of a subterranean house and the presence assumed post holes suggest increased seasonal sedentism in and around the Willamette Valley during the late Holocene (Aikens et al., 2011). Additionally, there are also indications of increased use of upland meadows in the western Cascades during the late Holocene for hunting and gathering huckleberries (Aikens et al., 2011).

Rigdon's Horse Pasture Cave is an upland site (975 m) that is thought to have been a seasonal hunting camp used by the Molallas (Baxter et al., 1983). The site is located in the upper drainage of the Middle Fork of the Willamette River and is not far from two other upland sites, Cascadia Cave and Baby Rockshelter. Food processing tools, such as manos and grinding stones as well as plant remains of pine nuts, hazelnuts, western chokecherry, wild cherry, and Oregon grapes provide evidence of food processing (Baxter et al, 1983). Projectile points and faunal remains of deer, squirrel, cougar, rabbit, porcupine, bobcat, rodent, and unidentified small and large mammals indicate that hunting was also conducted at Rigdon's Horse Pasture Cave (Baxter et al., 1983). Deposits near the bottom of the cave yielded a date of ca. 2,850 cal yr BP (Baxter et al., 1983; Aikens et al., 2011). It seems likely that fire was used near these sites to encourage the growth of forage for wild game as an important hunting tool. For example, ethnographic evidence shows that Kalapuya hunters would surround deer and then ignite a series of small fires to trap the animals, making them easier to kill (Boyd, 1999). This technique may have been used in mountain environments as well.

Indian Ridge is a mid-elevation site (1,463 m) in the western Cascades located approximately 72 km east of Eugene that appears to have been used as a seasonal base camp for multiple activities (Henn, 1975). Sinkers, bone barbs, fish vertebrae, and fresh-water mollusk remains indicate that fishing was important at this site (Henn, 1975). Other artifacts included woodworking tools such as spokeshaves, scrapers, unifacial and bifacial choppers, mauls, chisels, and drills in addition to food processing tools such as mortars, manos, pestles, and grinding slabs (Henn, 1975). Projectile points, flake scrapers, and handstones found at the site suggest that deer hunting and plant collecting were important activities (Henn, 1975). As hypothesized above, fire was likely used to aid in these activities, or possible to clear trails in order to access important resource sites (Norton et al., 1999).

Projectile points and other prehistoric artifacts provide evidence that sites in the Blair Lake watershed were also used during the late Holocene. However, it is difficult to determine exactly when and to what extent these sites were used, as the archaeological evidence consists primarily of undated items found on the surface. Many sites located at higher elevations have only been surveyed or sampled to prevent further disturbance, and many upland activities, such as gathering berries or other plant resources do not generally show up in the archaeological record (Aikens et al., 2011).

Blair Lake is located in what was formerly the homeland of the Molallas, and archaeological evidence from other upland sites indicate that hunting and berry harvesting were important activities in the western Cascades at this time (Baxter et al., 1983). Considering that huckleberries and other important plant foods are currently found at Blair Lake, it is likely that the Molallas and Kalapuyans from the Willamette Valley visited the site, making use of or perhaps contributing to the burned environments found there.

CHAPTER VII

CONCLUSIONS

The purpose of this research was to reconstruct the fire and vegetation history at one study site in the western Cascade Mountains of Oregon, Blair Lake, using macroscopic charcoal and pollen analysis of a lake sediment core. The goal of this research was to better understand past interactions between fire, vegetation, climate, and humans in the montane forest surrounding Blair Lake during the past ~ 16,000 years. There were three primary research questions that drove this research, and the conclusions reached are summarized below:

(1) How has the fire and vegetation history of the Blair Lake watershed changed during the past ~ 16,000 years?

Charcoal and pollen records of the Blair Lake watershed reveal that the fire history has varied widely during the past ~16,000 years, however, the composition of the vegetation surrounding Blair Lake has remained relatively stable. Fire activity was relatively low at Blair Lake during the late glacial period and fires were the least frequent. The fires at this time were a mixture of large and small magnitude episodes, indicating that fire severity or size of the fires varied widely (or perhaps their proximity to the lake), but for the most part they were relatively small. The open-canopy forest at this time was dominated by *Pinus* and *Abies*, with moderate amounts of *Alnus* and small amounts of *Tsuga heterophylla*. Climate was relatively cold and dry this time and the forest of Blair Lake was primarily conifers. *Pinus* was the dominant tree, followed by *Abies. Pinus* pollen is generally overrepresented in the pollen record and is often blown from other locations (Dunwiddie, 1987; Hebda and Allen, 1993; Allen et al., 1999; Brown, 2000; Brown and Hebda, 2003). In contrast, *Abies* is frequently underrepresented in pollen assemblages (Dunwiddie, 1987), so it is likely that the forest at Blair Lake contained a higher percentage of *Abies* trees than was reflected in the pollen record.

The most variation in fire frequency at Blair Lake occurred during the early Holocene (Figure 6.1), but there was not much change in the vegetation. Although there was a decrease in the amount of *Abies* and increases in the amount of *Tsuga heterophylla* and *Alnus*, those species were still well represented in the pollen assemblage, and *Pinus* was still the dominant species. Relatively small amounts of Poaceae, Cyperaceae, and *Artemisia* were also present during the early Holocene, likely an indication of a somewhat open forest with meadows or other openings. The second highest peak in the Blair Lake fire frequency record occurred during the early Holocene, at ca. 9,000 cal yr BP (Figure 6.1), but the composition and seemingly the structure of the forest changed little in response to this (except for perhaps a slight opening of the forest canopy as indicated by minimally lower AP/NAP values immediately after this time).

Generally, the highest fire frequency at Blair Lake occurred during the middle Holocene (Figure 6.1). Fire frequency was relatively low at the beginning of (ca. 8,000-7,000 cal yr BP) and reached its lowest peak for the middle Holocene at ca. 7,000 cal yr BP, likely due to cooler, wetter conditions in the PNW at that time. After that fire frequency began to increase, reaching its highest peak for the entire record at ca. 5,500 cal yr BP, in direct contrast to the regional biomass burning curve. Fire frequency generally decreased from ca. 5,500-4,500 cal yr BP, before increasing slightly near the beginning of the late Holocene. The increase of *Tsuga heterophylla* and *Tsuga mertensiana*, along with the decrease of *Pseudotsuga* and *Alnus*, suggest possibly colder conditions and a return to a more closed canopy.

Fire frequency decreased from the beginning of the late Holocene until ca. 2,500 cal yr BP, reaching the lowest point of the entire record at ca. 3,000 cal yr BP (Figure 6.1). After that fire frequency began to increase until ca. 900 cal yr BP and then decreased toward present. Cold and wet conditions during the late Holocene likely explain the increase in the percentages of *Tsuga mertensiana* and Cupressaceae in the Blair Lake pollen assemblage. Although *Pinus* and *Abies* were still dominant, *Pinus* percentages decreased, and *Tsuga heterophylla* and *Pseudotsuga* increased.

The changes observed in the fire and vegetation history records from Blair Lake indicate that while climatic variability (and possibly human activity) influenced the observed trends, there seems to be little indication that fire activity influenced vegetation changes, and vice versa. However, there appears to be some sort of relationship between the abundance of *Pseudotsuga* and fire frequency. When fire frequency was low, so were *Pseudotsuga* percentages, and percentages increased when fire frequency was higher. During the late glacial, overall fire frequency was low and so were percentages of *Pseudotsuga*. Fire frequency increased during the early Holocene, and so did *Pseudotsuga.* Although overall fire frequency is higher during the middle Holocene, both the beginning and end show decreases in fire frequency, and *Pseudotsuga* was low at this time. Although fire frequency was relatively low at the beginning of the late Holocene, overall fire frequency was relatively high, and *Pseudotsuga* percentages were higher during the late Holocene than at any other time in the record.

Additionally, percentages of *Alnus* seemed to vary more when fire frequency was lower, but with increased fire frequency *Alnus* percentages were more stable. Although there appears to a slight correlation with fire frequency and changes in vegetation, the major plant species seem to be resilient over time at Blair Lake and do not change significantly over the course of the record. This pattern is also seen at Breitenbush Lake, leading the authors to conclude that fire events were not sufficient to trigger a shift in vegetation and that climate was the major control (Minckley and Long, 2016).

Fire frequency appears to have a greater impact on the abundance of herbaceous pollen than on arboreal pollen, and percentages of herbaceous pollen are highest during the middle and late Holocene when fire frequency is highest. Herbaceous pollen may be an indicator that the forest at Blair Lake was more open with abundant understory or meadow vegetation. This suggests that although fire activity had little impact on the overall composition of the vegetation, it may have been important in creating and maintaining these forest openings.

(2) What role has climate variability played in influencing the fire and vegetation history of the Blair Lake watershed during the post-glacial period?

Climate appears to be the primary driver of fire activity at Blair Lake during the post glacial period. The overall fire frequency was low during late glacial period, but there is an increase at ca. 15,000 cal yr BP. This increase in fire activity is likely related to an increase in solar radiation and CO_2 concentrations following the retreat of the Cordilleran ice sheet (Figure 6.1) (Bartlein et al., 2014). A similar increase is seen at Sunrise Lake in Mount Rainier National Park (figure 6.1) (Lukens, 2013). Fire frequency at Blair Lake decreased from ca. 13,000-11,600, a trend that is seen at other lakes in the PNW and is likely associated with the YDC, a period of cold, dry conditions that existed from ca. 12,900-11,600 cal yr BP (Marlon et al., 2008).

While climate remained the most important control of fire activity in the early Holocene, there are some inconsistencies. Fire frequency generally increased during this period, likely caused by changes in seasonal insolation resulting in warmer, drier summers (Thompson et al., 1993; Bartlein et al., 2014), but it is difficult to explain the large decrease in fire frequency at

Blair Lake that began at ca. 10,500 cal yr BP and continued until ca. 9,500 cal yr BP, especially when regional fire frequency was increasing at this time. However, it could be that there were local changes in climate not reflected in the regional climate signal that explain the decreased activity at this time.

Fire frequency remained relatively high at the beginning of the middle Holocene when summers were still relatively warm and dry, but it generally decreased as the climate became cooler and wetter after ca. 7,000 cal yr BP (Bartlein et al., 1998; Gavin et al., 2013). However, when the regional fire frequency curve shows a low point in fire activity at ca. 5,500 cal yr BP, the fire frequency at Blair Lake is at its highest for the entire record, suggesting that factors other than overall climatic conditions (such as greater climate variability; Walsh et al., 2015) may have been an important influence on the Blair Lake fire regime during the middle Holocene.

Fire frequency at Blair Lake decreased from the middle Holocene (ca. 5,500 cal yr BP), until the late Holocene at ca. 3,000 cal yr BP. This was likely a result of even cooler and wetter conditions during this period. However, the large decrease at is in contrast to regional fire frequency. Fire frequency is relatively high at ca. 2,000 cal yr BP and is highest during the late Holocene at ca. 900 cal yr BP. This may be associated with the MCA that occurred between ca. 1,100-700 cal yr BP (Mann et al., 2009). However, this increase at Blair Lake began earlier, at ca. 2,500 cal yr BP, indicating that local factors combined with the MCA to influence fire behavior. Fire frequency decreased at ca. 900 cal yr BP and remained low for the rest of the late Holocene, which was likely a result of the cooler and possibly drier conditions associated LIA that occurred between ca. 500-100 cal yr BP (Grove, 2001).

Although there are some inconsistencies, the overall fire frequency at Blair Lake seems to be primarily driven by climate during the late glacial and early Holocene periods. Even though climate still appears to be important during the middle and late Holocene periods, other factors, such as weather, topography, elevation, and aspect, as well as differences in vegetation and fuel, may have combined with climatic influences to drive fire behavior.

(3) How were montane forest environments important to humans, and in what ways did humans possibly modify or at least utilize these environments to maximize the benefits they provide?

Native Americans were using fire to maintain meadows and prairies in the PNW, particularly during the late Holocene (Turner, 1999; Peter and Shebitz, 2006; Weiser and Leopfsky, 2009; Walsh et al., 2010a, b). In the Willamette Valley, fire was used to encourage the growth of root plants, and fields were burned after crops were harvested to encourage future growth, to collect grasshoppers and tarweed seeds, and to cultivate tobacco (Boyd, 1999). Understory trees and shrubs were also burned to facilitate the collection of nuts and berries and to encourage forage for game (Boyd, 1999). In upland areas, fire was also used. The Molallas burned in the forest and meadows to enhance plant resources, to provide forage for wild game, and to increase productivity of berries (Mack and McClure, 2002; Lepofsky, 2003; Swanson et al., 2002).

At Blair Lake it is not possible to separate the human signal from the climate signal, but humans were likely using the upland areas surrounding the lake. The increases in fire frequency during the middle and late Holocene are consistent with increases in human population, but to what extent anthropogenic burning had on the fire regime at Blair Lake is not clear. Herbaceous pollen does increase at Blair Lake during the late Holocene, but the forest vegetation remains largely unchanged from previous periods, suggesting that the montane forest environment at

Blair Lake has been fairly resilient over the last 16,000 years. It appears that climate was the primary driver of fire for most of the Blair Lake record, but humans most likely contributed to the climatic influences, particularly during the middle and late Holocene.

Implications for Future Change

The general consensus of all future climate models seem to be that the Pacific Northwest will see increased temperatures, especially in the summers, and increased precipitation in the winter and decreased precipitation in the summer (Mote and Salathé, 2010; Rogers et al., 2011). Mesic forests in the western United States will be most vulnerable to changes in temperature and precipitation (Rogers et al., 2011). Soils in these forests will be saturated in winter, and increased precipitation will run off, rather than be absorbed for future use (Rogers et al., 2011). Increases in summer temperatures, without increased spring precipitation, and increased CO_2 may lead to longer growing seasons and higher productivity at higher elevations, but increases in drought and fire occurrence in wet forests west of the Cascades could decrease the forests' ability to sequester carbon. It is possible that by the end of the twenty-first century those forests could lose up to 1.2 Pg of carbon (Rogers et al., 2011). Blair Lake is a mesic montane forest and is likely at risk of increased fire activity. The fire regime at Blair Lake is one of infrequent, large (often stand-replacing) fires. If future climate predictions are correct, fires could be more frequent and even larger. Although the forest surrounding Blair Lake has shown to be fairly resilient over the past 16,000 years, it is not clear what impact larger, more frequent fires will have on the forest ecosystem.

Blair Lake is surrounded by a mesic forest and both wet and dry meadows. The area receives most of its precipitation in November and December, and there is ample snowpack during the winter months to ensure that the forest retains much of its moisture throughout the warm summer. At this time it may be appropriate, and better for the forest ecosystem, to let natural wildfires burn in this type of forest, rather than expend resources trying to fight them. However, there is a campground at Blair Lake, and this campground is most frequently occupied during the summer months when the risk of wildfires is greatest. The threat posed to human lives may call for evacuation of the campground before allowing any fires to burn.

Different management strategies may be called for in the future. If temperatures continue to increase as predicted by climate model simulations, these forests could see longer growing seasons, resulting in increased fuel accumulation and longer fire seasons. The projected increase in winter precipitation will not make up for the expected decrease in summer precipitation, and any excess moisture will be lost as runoff. Warmer summer temperatures, combined with less summer precipitation, could result in more lightning ignitions, resulting in more frequent fires. If wildfires become larger and more frequent in mesic forests, like the one surrounding Blair Lake, more pre-emptive measures may be required. Strategies, such as thinning or prescribed burns, may be sufficient in preventing some fires from spreading out of control. However, if fires are very large, large-scale firefighting efforts may be necessary. These efforts would put further pressure on a Forest Service firefighting budget that is already stretched too thin. This could mean that the Forest Service may be unable to fund other forest management strategies, such as land restoration, resulting in a decline in the overall health of the forest ecosystem and the potential for even larger, more frequent fires.

Future Research Opportunities

Although the data obtained from the research at Blair Lake is important and will add to the growing body of literature about fire and vegetation history in the PNW, more information is needed. Blair Lake is just one site, but there are many more lakes in the Willamette National

Forest that could provide greater detail. While many lakes at low elevations have been examined, more data from mid-to-high-elevation lakes located near Blair Lake could provide more robust fire and vegetation histories and could possibly shed more light on the roles that climate and humans may have played in creating and/or maintaining the montane forest environments that exist at Blair Lake today. While there is abundant archaeological evidence from sites on the valley floor, information is still lacking about upland sites and how they were used. Further research needs to be conducted and more data needs to be obtained, not just about upland sites themselves, but about connections between sites at different elevations and between local and regional fire activity in the PNW.

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