

HOLOCENE FIRE AND VEGETATION HISTORY OF
THE OREGON COAST RANGE, USA

by

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"Holocene Fire and Vegetation History of the Oregon Coast Range, USA," a dissertation prepared by Colin James Long in partial fulfillment of the requirements for the Doctor of Philosophy degree in the Department of Geography. This dissertation has been approved and accepted by:

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The role of fire in seasonal rain forests is poorly known because such disturbances are relatively infrequent, the dominant species are long-lived, and dendrochronological methods of reconstructing fire history are limited by rapid wood decomposition rates. High-resolution charcoal and pollen analyses of lake sediments were undertaken at three lakes to reconstruct the fire and vegetation history of the Oregon Coast Range for the last 9000 years. The sites were located along a precipitation gradient and changes in fire-episode frequency and vegetation provided information on the nature of this gradient in the past. Comparison of sites allowed the examination of fire-vegetation-climate linkages on millennial as well as shorter time scales in different locations. Fire episodes were more frequent or near present rates during the early Holocene (ca. 9000 to 6500 cal yr B.P.) as a result of warmer drier summer conditions than at present. Forests composed of fire-adapted taxa, such as *Pseudotsuga menziesii* and *Alnus rubra* accompanied the

increase in fire occurrence. As conditions became cooler and wetter in the late Holocene (ca. 6500 cal yr B.P. to present), fire return intervals lengthened and fire-sensitive taxa, such as *Tsuga heterophylla*, *Thuja plicata*, and *Picea sitchensis* increased in abundance. The records also indicate periods of heightened fire activity between ca. 8200 and 6900 cal yr B.P. and ca. 4500 and 3000 cal yr B.P., likely in response to centennial-scale drought. During these periods, fire episodes were synchronized at all sites, despite local climatic differences.

The paleoecological records suggest that fire has been an important disturbance in seasonal rain forests and variations in fire activity respond to changes in climate on multiple time scales. Given projections of warmer conditions and more fires in the future, as a result of increased greenhouse gases in the atmosphere, the response of fire to past variations in climate should be considered in forest management plans.

This dissertation includes previously published co-authored materials.

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INTRODUCTION

CHAPTER I

The Oregon Coast Range is located in the southern portion of the seasonal rain forest ecoregion. This ecoregion occupies a narrow strip, 60 to 200 km wide, along the northwestern coast of North America from Vancouver Island to northern California (Alaback and Pojar, 1997). The Coast Range is a highly dissected landscape with steep slopes and typical crest elevations of less than 1000 m above sea level (Hemstrom and Logan, 1986; Spies et al., 2002). The climate of the Coast Range is dominated in summer by the expansion of the Pacific subtropical high-pressure system and northward movement of the polar jet stream, which results in increased large-scale subsidence and the suppression of precipitation. In winter, the Pacific subtropical high-pressure system weakens and shifts southward in conjunction with a southward shift in the polar jet stream. Storm systems that originate in the Gulf of Alaska are moved onshore by strengthened westerlies in winter and the bulk of annual precipitation is delivered then from moisture derived ultimately from the subtropical Pacific (Redmond and Taylor, 1997). The results of this large-scale circulation shift are a climate with warm dry summers and cool wet winters throughout the Coast Range.

Within the large-scale climate pattern there also exists a north-to south environmental gradient with locations in the northern Coast Range receiving more precipitation in winter and having lower temperatures in summer than locations in the

southern Coast Range (Franklin and Dyrness, 1988). This gradient is a result of the preferred latitude of the winter storm track and is evident throughout the seasonal rain forest ecoregion from Vancouver Island to northern California (Redmond and Taylor, 1997). The Coast Range also provides the first significant orographic barrier to storm systems coming off the Pacific Ocean, which results in a west-to-east precipitation gradient with more precipitation falling on the coastal and western portion than the eastern slopes (Taylor, 1993; Alaback and Pojar, 1997).

Coast Range forests consist of *Tsuga heterophylla* (western hemlock), *Thuja plicata* (western red cedar), and *Pseudotsuga menziesii* (Douglas-fir) with *Picea sitchensis* (Sitka spruce) and *Pinus contorta* (lodgepole pine) becoming prominent along the coast. *Pinus monticola* (western white pine) is present in drier locations and *Abies grandis* (grand fir) and *Abies procera* (noble fir) can be found at higher elevations. Cool wet sites are dominated by shade-tolerant and fire-sensitive taxa, such as *Tsuga heterophylla* and *Thuja plicata*. On drier sites *Pseudotsuga menziesii* is common because it is both shade-intolerant and fire-adapted (Minore, 1979; Pojar and MacKinnon, 1994). Deciduous trees, such as *Alnus rubra* (red alder) and *Acer macrophyllum* (big-leaf maple) are common throughout the Coast Range. *Alnus rubra* is the dominant pioneer and riparian tree species in the Coast Range. It can be present in large, even-aged stands from sea level to high elevations (Hemstrom and Logan, 1986; Alaback and Pojar, 1997). Fire and wind are the primary disturbance agents in the seasonal rain forest (Lertzman et al., 1996), and fire is important in the southern portions of the ecoregion, including the Coast Range (Agee, 1990; 1993). Fires in the Coast Range tend to occur

from June through mid-October in association with dry summer conditions (Hemstrom and Logan, 1986). Information about past fires in the region comes from archival records, dendrochronologic data (Morris, 1934; Juday, 1977; Impara, 1997; Teensma et al., 1991), and one lake-sediment charcoal record (Long et al., 1998). Archival records span the past 150 years and paint a picture of high-severity crown fires that burned large areas (Morris 1934; Juday, 1977). For example, the Yaquina fire in A.D. 1868 was ca. 51,000 ha in size in the central Coast Range and the Tillamook fire of A.D. 1933 covered ca. 106,000 ha in the northern Coast Range (Morris, 1934; Juday, 1977). Dendrochronologic data in the form of tree-rings (Impara, 1997) and stand age information (Teensma et al., 1991) indicate that widespread fires have occurred throughout the Coast Range for the last ca. 500 years and have fire return intervals (the time between successive fires) that span 150 to 350 years.

A 9000-year charcoal record from Little Lake, located in the central Coast Range, shows highest fire activity in the early Holocene, ca. 9000 to 6000 years ago, when paleoclimate model simulations and pollen data indicate that the climate was warmer and drier than at present, and xerophytic fire-adapted taxa, such as *Pseudotsuga menziesii*, *Alnus rubra*, and *Quercus garryana* (Oregon white oak), were more abundant (Long et al., 1998). The climate conditions of the early Holocene have been attributed to higher-than-present summer insolation values, which increased the strength of the Pacific subtropical high during the summer months, resulting in higher summer temperatures and decreased effective moisture (i.e., precipitation minus evapotranspiration) (Whitlock, 1992; Thompson et al., 1993; Worona and Whitlock, 1995; Bartlein et al., 1998). In the

late Holocene, ca. 6000 years ago to present, fire intervals increased and mesophytic fire-sensitive taxa, such as *Tsuga heterophylla*, *Thuja plicata*, and *Picea sitchensis*, became more prominent at Little Lake (Long et al., 1998). The cooler wetter conditions have been attributed to decreased seasonality that led to a weakening of the Pacific subtropical high. As a result, summer temperatures decreased and effective moisture has increased in the last 6000 years producing decreased moisture stress on vegetation during the summer months (Thompson et al., 1993; Worona and Whitlock, 1995).

Although archival and dendrochronologic data describe the present-day fire regime, they do not provide information to address changes in fire regimes when climate was different than today. The charcoal and pollen record provides a longer time perspective, but it is unknown how well the reconstruction from Little Lake represents the fire and vegetation history of other Coast Range locations with different environmental conditions. The objective of this research was to gain a better picture of the response of fire and vegetation to changes in climate along the environmental gradient found in the Coast Range by addressing the following questions:

How have fire regimes and forest vegetation responded to millennial- and sub-

millennial-scale changes in climate?

How have local environmental conditions affected long-term fire and vegetation

histories?

How representative are the paleoecological records from the Oregon Coast Range

of the seasonal rain forest ecoregion at large?

How can long-term fire and vegetation histories inform forest management about future forest conditions?

The approach that I took to answer these questions was to compare three long-

term fire and vegetation records from different environmental settings: Taylor Lake, a wet north-coast maritime site; Lost Lake, a moist high-elevation site in the north Coast Range; and Little Lake, a central Coast Range dry site (Long et al., 1998). Lake-

sediment cores were collected and macroscopic charcoal and pollen analyses of the cores provided the data used to reconstruct the fire and vegetation histories from each site. The chronologies of each record were based on ^{210}Pb dating of the upper-most lake sediments, and radiocarbon dating of the rest of the core. The charcoal analysis identified times of significant charcoal accumulation and designated those as fire episodes (one or more closely timed fires). Fire return-intervals and fire frequencies over time were based on the fire episode data (Long et al., 1998; Whitlock and Larson, 2001). Changes in the abundance of pollen through time were the basis for identifying changes in vegetation (Fægri et al., 1989). In discussing changes over time I used the term "millennial" to represent time periods on the order of 1000 to 10,000 years, and "centennial" to represent time periods on the order of 100 to 1000 years.

I also examined the contribution that paleoecological data can make to the current discussion concerning the management of Coast Range forests. For example, questions such as, how long have present-day fire-return intervals been present, and how will future climate change affect fire regimes are discussed using the data from Taylor, Lost, and

Little lakes as case studies to examine the sensitivity of rain forests to past environmental change.

The dissertation is organized into three major chapters that are meant to be read as stand-alone papers, although each chapter includes information presented in earlier chapters. Chapter II describes the record from Taylor Lake located on the coastal lowlands of the Oregon Coast Range. The Taylor Lake record spans the last 4600 years and provides a fire history from a *Picea sitchensis* forest. The chapter has been published in *Quaternary Research* as a co-authored manuscript with Cathy Whitlock from the University of Oregon. Dr. Whitlock provided funding, critical discussions, and editorial assistance.

Chapter III examines a ca. 8400-year vegetation and fire history from Lost Lake, located in the northern Oregon Coast Range. The chapter compares this record with those from Taylor Lake and Little Lake to evaluate the effect of the environmental gradient on fire regimes and vegetation in the Oregon Coast. The records from Taylor, Lost, and Little lakes are then compared to millennial-scale fire and vegetation reconstructions from other seasonal rain forest locations in order place the Oregon Coast Range sites in the context of the entire seasonal rain forest ecoregion. This chapter is being prepared as a manuscript for submission to *Ecology* with Cathy Whitlock and Patrick Bartlein, from the University of Oregon, as co-authors. Dr. Whitlock provided funding for field work and laboratory analysis, helped with the interpretations of the paleoecological data, and offered editorial assistance; and Dr. Bartlein provided funding

for the developed of software for the statistical analysis of charcoal data, provided

modern climate data, and assisted with climate interpretations.

Chapter IV addresses the usefulness of paleoecological data to forest managers.

The data from the Taylor, Lost, and Little lakes are presented as a case study of how

long-term fire and vegetation records can inform forest management. Information about

the natural variability of seasonal rain forest ecosystems, the use of long-term fire

frequencies as estimates and verification for landscape model parameters of disturbance,

and verification of predictive models about future forest conditions are discussed. The

chapter is being prepared as a co-authored manuscript for submission to the *International*

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Chapter V summarizes the major findings of the dissertation.

CHAPTER II

FIRE AND VEGETATION HISTORY FROM THE COASTAL RAIN FOREST OF THE WESTERN OREGON COAST RANGE

Introduction

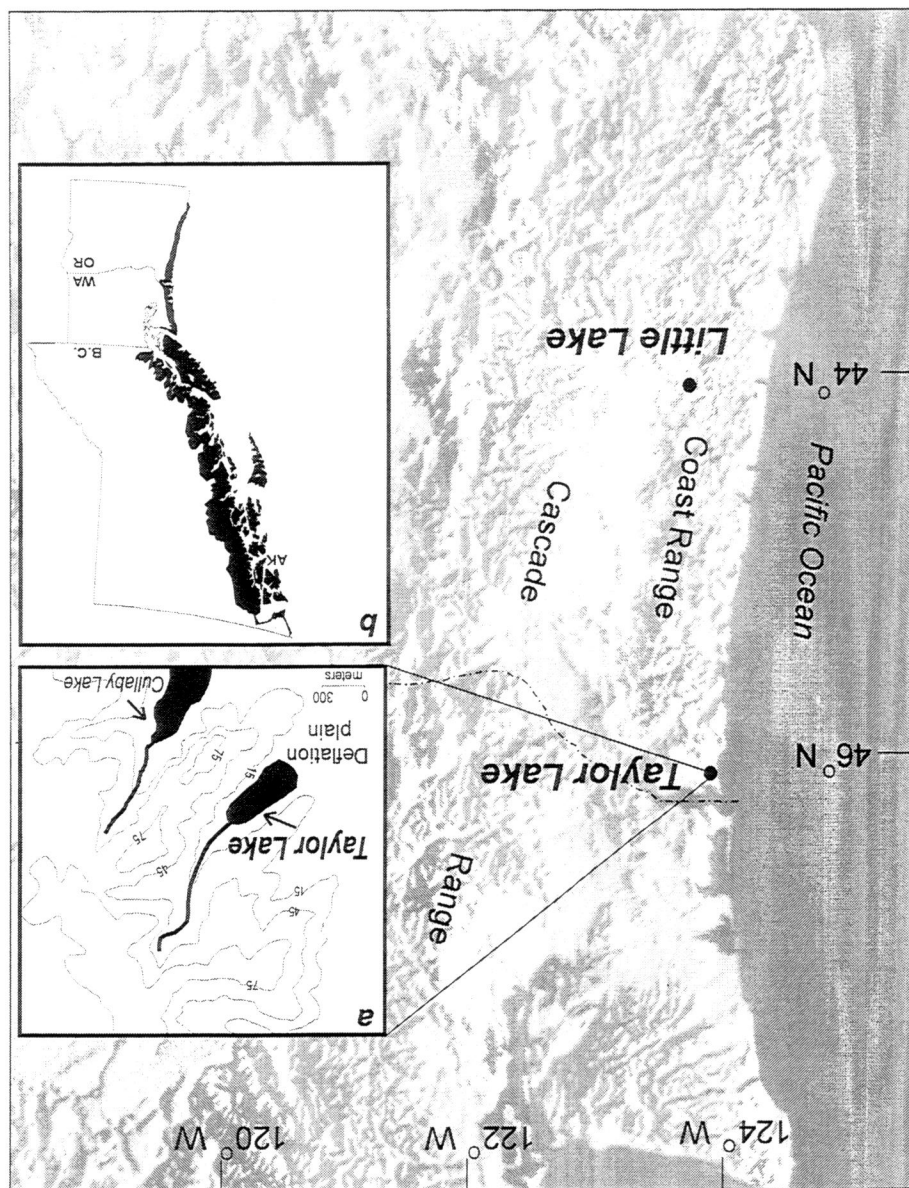
Picea sitchensis forests extend from the coastal mountains of southeastern Alaska to the southern Coast Range of Oregon (Veblen and Alaback, 1996). They are the wettest forests in North America, are characterized by dense stands of *Tsuga heterophylla* (western hemlock), *Picea sitchensis* (Sitka spruce), and *Alnus rubra* (red alder), and have some of the highest growth rates in North America (Grier, 1978). The value of these forests in timber production and as unique environments to a variety of species has brought these forests to public attention during the 20th century. However, little is known of the time of their establishment or their disturbance history. It is generally thought that wind storms, which create gaps in the forest canopy as the result of blown-down trees, are the primary disturbance. These gaps provide an opportunity for colonization by new individuals (Ruth and Harris, 1979; Harcombe, 1986; Lertzman et al., 1996).

The role of fire as a disturbance agent is poorly understood in *Picea sitchensis* forests of the Pacific Northwest (PNW). One source of fire history information comes from tree-ring records but such data have been difficult to acquire because wood decay rates in the Coast Ranges of Oregon and Washington exceed all other forests in the PNW (Ruth and Harris, 1979) and fire scars on tree rings are not preserved well in the

dominant trees (Grier, 1978). Another difficulty is that fires have caused high tree mortality, and evidence of older fires is confined to only a few surviving individuals (Agee, 1993; Impara 1997). The age of a cohort of trees (stand-age class data) is often used to establish the dates of past fires. Stand-age class data from western Oregon and Washington have been used to infer a mean fire interval (MFI), or the average time between fires, of between ca. 400 years (Andrews and Cowlin, 1940) and ca. 1100 years (Agee and Flewelling, 1983) for *Picea sitchensis* forests in the PNW. Fires described in historical journal accounts confirm that large, infrequent, stand-replacing, (i.e., high severity), fires have occurred during the last few centuries (Morris, 1934; Juday, 1977; Agee 1993). For example, the Nestucca Fire of A.D. 1848 burned approximately 120,000 ha and the Tillamook fire of A.D. 1933 burned approximately 106,000 ha of *Picea sitchensis* and *Tsuga heterophylla* forests of the northern Oregon Coast (Munger, 1944). Whether this fire regime of widespread, infrequent, high severity fires has persisted over time in *Picea sitchensis* forests requires information on the long-term fire history and a better understanding of the relationship between fire occurrence, climate, and forest responses in these extremely mesic ecosystems.

We report on the fire and vegetation history at Taylor Lake (Lat. 46° 06' 02"N, Long. 123° 54' 24"W, elev. 4 m.) located in the *Picea sitchensis* forest on the northern Oregon coast (Fig. 2.1). Taylor Lake lies on the Clatsop Plain, an area of sand aggradation south of the mouth of the Columbia River (Orr et al., 1992). The lake is 4 ha in size with a maximum water depth of 4.5 m and simple bathymetry, and was formed when coastal dunes advanced inland as a result of late-Holocene sea-level rise and

Figure 2.1. Location of Taylor Lake and other physiographic features mentioned in the text. Inset *a* shows Taylor Lake and surrounding vicinity. Inset *b* shows the extent of *Picea sitchensis* forests in northwestern North America (Alaback and Pojar, 1997).



dammed a stream in the coastal headland (Rankin, 1983). Continued sand accumulation has moved the shoreline westward ca. 2 km, and eolian activity has created an 800-m wide deflation plain west of the lake.

Picea sitchensis forests are distinguished from the inland *Tsuga heterophylla* forests by the diminished presence of *Pseudotsuga menziesii* (Douglas-fir) (Franklin and Dyrness, 1988; Alaback and Pojar, 1997). The major conifer taxa of *Picea sitchensis* forests, *Tsuga heterophylla*, *Picea sitchensis*, and *Thuja plicata* (western red cedar), have higher tolerance for salt spray, higher soil-moisture optimum, and lower tolerance for drought than *Pseudotsuga menziesii* (Minore, 1979). The present forest that surrounds Taylor Lake is typical of *Picea sitchensis* forests with *Tsuga heterophylla*, *Picea*

sitchensis, and *Thuja plicata* as the dominant tree taxa, while *Pseudotsuga menziesii* is a minor constituent. *Alnus rubra* grows in recently disturbed sites and riparian areas. Understory taxa include *Sambucus racemosa* (elderberry), *Rubus spectabilis*

(salmonberry), *Gaultheria shallon* (salal), *Polystichum munitum* (sword fern), *Blechnum spicant* (deer fern), and *Dryopteris austriaca* (mountain wood fern). *Acer circinatum* (vine maple) and *Pteridium aquilinum* (bracken) are also present on drier sites. *Salix hookeriana* (Hooker willow) and *Phalaris arundinacea* (Reed canarygrass) are abundant in wetlands on the deflation plain west of the lake. Nomenclature follows Hitchcock and Cronquist (1973).

Temperatures at Taylor Lake average 4.7°C in January and 15.1°C in August, and most of the ca. 2000 mm of precipitation falls as rain between October and May (Taylor, 1993). The A.D. 1961-1998 precipitation data from Seaside, OR (8 km south of Taylor

Lake) indicate that approximately 12% (229 mm out of 1987 mm) of yearly precipitation falls between June and September (GHEN, 2000). The climate of the region is influenced by the position of the polar jet stream and the eastern Pacific subtropical high pressure system. In winter, precipitation comes from onshore storms associated with the southward movement of the polar jet stream from southeast Alaska and British Columbia to Washington and Oregon, and the contraction of the Pacific subtropical high southward. Summer conditions are typified by the expansion northward of the Pacific subtropical high as a result of increased summer insolation in the northern hemisphere. Warm conditions at mid-latitudes force the polar jet northward from Washington and Oregon to southeast Alaska and British Columbia. The large-scale subsidence associated with the Pacific sub-tropical high inhibits the formation of precipitation (Redmond and Taylor, 1997). The Taylor Lake watershed experiences drier summers than comparable settings farther north (Veblen and Alaback, 1996). However, coastal summer fog during an otherwise dry season helps maintain moist conditions necessary for *Picea sitchensis* forest assemblages (Ruth and Harris, 1979; Alaback and Pojar, 1997). Fog occurred at Astoria, Oregon, 10 km northeast of Taylor Lake, on 65% (73 of 112 days) of days during the fire season (from July 1 to Oct 20) from A.D. 1995-2000 (NOAA, 2001). As in other forest types, conditions necessary for fires in *Picea sitchensis* forests are low fuel moisture and an ignition source. Fires are most likely to occur from June through mid October in conjunction with increased temperature and decreased precipitation. Fuel moisture in coastal forests is typically high throughout the year but may be lowered to flammable levels, 100% of dry weight in live fuels or ca. 20% of dry

weight in dead fuels, by the end of the summer drought (Huff and Agee, 1980; Chandler et al., 1983). Strong adiabatically warmed winds from the east can emanate from high-pressure centers that become established east of the Coast Range in summer. These winds dry fuels by lowering local humidity (Schroeder and Buck, 1970; Huff and Agee, 1980). Lightning, while uncommon during the summer, occurs frequently enough during the fire season (July 1 to October 20) to provide an occasional ignition source (Agee, 1993; Impara, 1997). Between A.D. 1985-1995 an average of 6.18 ± 6.43 positively charged lightning strikes per year occurred in the 1° latitude by 1° longitude area surrounding Taylor Lake (WRCC, 1996). Positively charged lightning strokes are of longer duration and provide more energy to ignite fuels (Fuquay, 1980). In the absence of lightning, human-caused ignitions during dry, east wind conditions have been responsible for the major fires in the Coast Range during the last 100 years (Morris, 1934; Impara, 1997).

The historical and dendrochronological evidence of fires within the Taylor Lake watershed is scant. Government surveys of the Taylor Lake watershed in A.D. 1856 did not report dead or burned timber (Trutch, 1856), and few if any fires have occurred there in the 20th century. The area was extensively logged in the early A.D. 1900s, and portions of the watershed and adjacent areas were logged in A.D. 1953, 1963 and 1972. Small slash fires accompanied the logging in A.D. 1972, and probably also in 1963 and 1953. Elsewhere, Impara (1997) used fire-scar and stand-age data to identify 27 fires over the last ca. 500 years in a 137,500 ha transect of the central Oregon Coast Range. The fires ranged from large high-severity fires to small mixed-severity events and suggest

that past fires were variable in spatial extent and severity. Teensma et al. (1991) used government vegetation surveys and forest stand-age maps to reconstruct preliminary maps of broad-scale patterns of fire for the entire Oregon Coast Range from A.D. 1850 to 1940. Their evidence along with reconstruction of fires using historical documentation by Morris (1934) and Juday (1977) identified large burned areas throughout the Coast Range from A.D. 1849 to 1910.

Conceptual model for charcoal data analysis

The approach used in this study follows that of Clark and Royall (1996), Long et al. (1998), and Millspaugh et al. (2000) in that it divides the charcoal record into two components: background and peaks. The background component consists of the low-frequency accumulation of charcoal particles, which varies as a result of changes in (1) fuel composition, (2) inputs of secondary charcoal introduced from the watershed or littoral zone of the lake, or (3) charcoal introduced from fires outside the watershed. The peak component is a higher frequency signal composed primarily of the charcoal produced by a single fire or series of closely spaced fires (hereafter termed a fire episode) in the watershed or sometimes in adjacent watersheds (Millspaugh and Whitlock, 1995; Whitlock and Millspaugh, 1996). A locally-weighted mean function (Cleveland, 1979) is used to determine the background component. The peak component is identified as positive deviations from background that exceed a "threshold-ratio value." The selection of the locally weighted window width and the threshold-ratio value is based on two factors. The first is the estimated fire-return intervals for the area. The second is the correlation of the uppermost peaks in charcoal to times of known or suspected fires

within the catchment. The fire episode frequency is calculated by averaging peak occurrence over time.

Methods

High-resolution charcoal analysis was used to reconstruct the fire history, measurements of sediment magnetic-susceptibility provided information on the sedimentation history, and pollen analysis was the basis for reconstructing the vegetation history at Taylor Lake.

Field collection

A 0.45-m-long short core and a 3.43-m-long core were collected within 5 m of each other from the deepest part of the lake. The short core was obtained with an 8-cm-diameter gravity sampler that preserved the mud-water interface intact. The core was extruded in the field at 1-cm intervals, and stored in plastic bags. The long core was obtained with a 5-cm-diameter modified Livingstone sampler. Core segments were extruded in the field wrapped in cellophane and aluminum foil and transported to the laboratory where they were refrigerated along with the short core samples.

Chronology

Seventeen ^{210}Pb -age determinations were used to establish a chronology for the short core (Table 2.1). Ages were plotted against core depth using linear interpolation to construct an age-versus-depth curve. This analysis indicated that the 45-cm-long short core spanned the last ca. 250 years. It should be noted that this age model extends beyond the range of ^{210}Pb dating and the age-versus-depth extrapolation was based on the

TABLE 2.1
²¹⁰Pb dates for the Short Core and Calibrated and Uncalibrated
¹⁴C Radiocarbon Ages and Age Model^a for Long Core from Taylor Lake

Depth (cm)	Age (A.D.)	Error of Age ± 1 SD	Depth (cm)	Age (A.D.)	Error of Age ± 1 SD
1-2	1995	1.4	14-15	1953	12.9
3-4	1990	6.1	16-17	1945	20.7
4-5	1988	6.4	19-20	1931	23.9
5-6	1985	7.2	20-21	1921	29.6
7-8	1979	7.8	22-23	1916	34.1
9-10	1972	7.9	23-24	1911	37.8
10-11	1969	8.5	25-26	1900	50.7
11-12	1965	9.2	27-28	1889	79.8
13-14	1957	10.6			

Depth (m)	Calibrated age (cal yr B.P. ± 2 SD)	Uncalibrated ¹⁴ C age	Material	Lab number
0.23 ^b	90		Sediment	
0.69-0.72	1060 (951-1161)	1130 ± 40	Charcoal	AA-30945
1.59-1.60	2470 (2348-2741)	2435 ± 60	Charcoal	AA-30946
2.40-2.42	3370 (3264-3465)	3145 ± 45	Charcoal	AA-30947
3.33-3.43	4590 (4574-4802)	4160 ± 70	Sediment	Beta-120001

^a ²¹⁰Pb ages provided by D. Edgington, Great Lakes Water Institute, University of Wisconsin-Milwaukee.

^b Age based on correlation with ²¹⁰Pb dated charcoal peak in short core.
^c Age model: Age (cal yr B.P.) = -238.318 + 1901(depth) - 139.610(depth)².

assumption of a constant sedimentation rate. Four AMS radiocarbon dates were obtained from the long core, calibrated to calendar years, and rounded to the nearest decade (CALIB 4.2, Stuiver et al., 1998) (Table 2.1). Similar charcoal stratigraphy, including a prominent peak at 0.23-m depth provided a basis for correlation between the cores. The ^{210}Pb chronology from the short core assigned this peak an age of 90 cal yr B.P (A.D. 1911). An age model based on this event and the four calibrated radiocarbon dates indicated that the long-core record spanned ca. 4600 cal years. Sedimentation rates ranged from 9.05 yr/cm at the top of the core to 18.52 yr/cm at the base, with an average time of 13.4 years represented in 1 cm of sediment.

Charcoal analysis

Subsamples of 2.5 cm^3 were taken from contiguous 1-cm intervals for the length of the short and long cores and disaggregated in a 5% solution of sodium hexametaphosphate for 24 h. Samples were then gently washed through nested sedimentological screens of 125 and $250\text{ }\mu\text{m}$ mesh size. All charcoal particles, $>125\text{ }\mu\text{m}$ in minimum diameter were tallied, because studies of charcoal deposition after recent fires have shown that this particle size is not transported long distances and thus provides a record of watershed fires (Millsbaugh and Whitlock, 1995; Clark and Patterson, 1997; Gardner and Whitlock, 2001). Charcoal counts were converted to concentration data (particles/cm) and then divided by the sample deposition time (yr/cm) to calculate charcoal accumulation rates (CHAR) (particles $\text{cm}^{-2}\text{ yr}^{-1}$). The CHAR record was then converted to pseudo-annual values and averaged at 10-year intervals to avoid biases caused by changing sedimentation rates over the length of the core.

In order to assign background window widths and threshold-ratio values, three obvious peaks were identified in the untransformed and log-transformed CHAR data for the last 1000 yr (marked by arrows in Fig. 2.2) and considered to be fire episodes. The three CHAR peaks were easily distinguished from background by visual inspection, and three fire episodes/1000 yr falls within the range of MFI estimates based on

dendrochronological data for modern *Picea sitchensis* forests (Agee and Flewelling, 1983; Agee, 1993). A series of weighted-running means were applied to determine the most appropriate value to use in determining the average or background CHAR for each decade. Window widths of between 300 and 900 yr showed generally similar trends and an intermediate window width 600-yr was selected. A range of threshold-ratio values from 1.00 to 1.30 was evaluated to determine an optimum value for identifying peaks using a 600-year-background window. Threshold-ratio values between 1.00 and 1.20 identified more than three peaks over that last 1000 years. A threshold-ratio value of 1.25 was chosen to identify fire episodes above background, because it successfully identified the three peaks of the last 1000 years but no additional peaks. Peak occurrence was then averaged using a 2000-year moving window and fire episode frequency was plotted as fire episodes/1000 years.

Lithologic analysis

Weight-loss after ignition was used to determine the amount of organic and carbonate material in the sediment at 1-cm intervals in the short core and at 10-cm intervals in the long core (Dean, 1974). Subsamples of 1 cm³ were placed in crucibles and heated for two hours at 550°C and for two hours at 900°C. The weight loss after each

burning was used to calculate the percent of organic matter and carbonate content respectively.

Magnetic-susceptibility analysis was used to assess the input of clastic material from the watershed (Thompson and Oldfield, 1986). Fires can defoliate and destabilize slopes (Swanson, 1981; Benda, 1994) and heat soils (Longworth et al., 1979), which can increase the amount of paramagnetic minerals washed into lakes (Gedye et al., 2000). These processes can increase the magnetic susceptibility of lake sediments (Millsbaugh and Whitlock, 1995). Other events unrelated to fires, such as variations in surface runoff, stream flow and mass movements within the catchment, can also produce changes in clastic input that are reflected in the magnetic susceptibility of lake sediment (Dearing and Flower, 1982).

Magnetic susceptibility readings were taken on an 8-cm³ subsample from each 1-cm interval prior to charcoal analysis. Subsamples were put into a plastic cup and placed in a cup-coil magnetic susceptibility instrument by Sapphire Instruments. Sediment magnetic-susceptibility values were converted to concentration values, expressed as electromagnetic units per cubic centimeter (emu/cm³), and divided by the sample deposition time (yr/cm) to calculate magnetic-susceptibility accumulation rates (emu cm⁻² yr⁻¹) (Fig. 2.2). These data were then analyzed in the same way as the CHAR data, with peak intervals interpreted as pulses of allochthonous input into the lake, hereafter referred to as a sedimentation episode. The conversion of bulk magnetic susceptibility values to accumulation rates was done in order to facilitate comparison with the CHAR record.

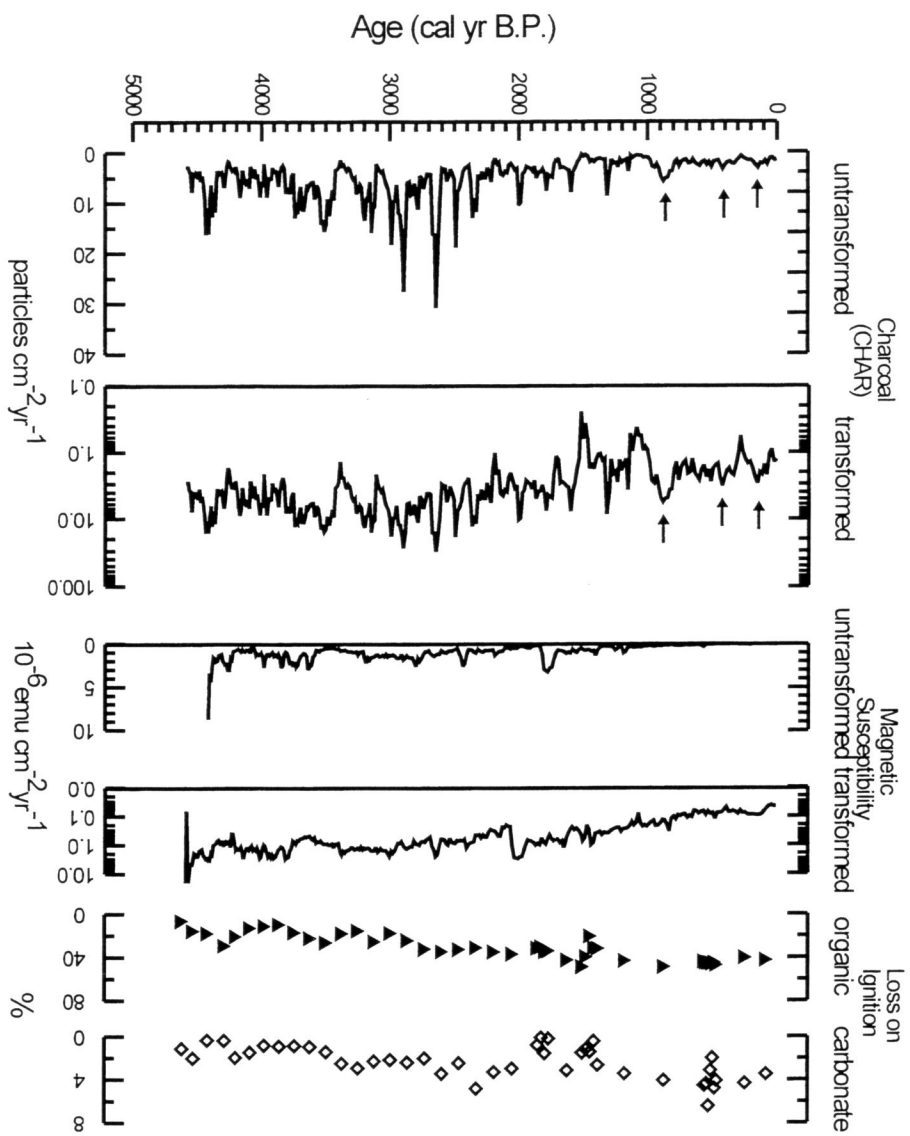


Figure 2.2. Untransformed and log-transformed charcoal (CHAR), magnetic susceptibility accumulation rates, and data from loss on ignition analysis plotted against age of the long core. CHAR peaks assumed to be watershed fires in the last 1000 years are marked with arrows ($\uparrow$).

Pollen analysis

Pollen analysis was undertaken at 10-cm intervals to reconstruct the vegetation at ca. 135-year intervals. One-cm³ samples were processed for analysis with standard methods (Faegri et al., 1989). Pollen was identified to the lowest taxonomic level possible based on modern pollen collections at the University of Oregon and published atlases (Bassett et al., 1978; Moore et al., 1991). A minimum of 400 terrestrial grains were identified. Haploxylon-type and Diploxylon-type *Pinus* grains were assigned to *P. monticola* (western white pine) and *P. contorta* (lodgepole pine) respectively, based on their present coastal distribution. *Pseudotsuga*-type pollen was attributed to *P. menziesii* (Douglas-fir), and *Picea* pollen was assumed to represent *P. sitchensis*. *Abies* pollen was attributed to *A. grandis* (grand fir) and *A. amabilis* (Pacific silver fir), both of which grow above 1000 m elevation in the northern Oregon Coast Range as well as in the Cascade Range. Cupressaceae pollen was attributed to *Thuja plicata* (western red cedar) and *Chamaecyparis nootkatensis* (yellow cedar), which occurs rarely in the Oregon Coast Range, is also a possible contributor. Pollen grains that could not be identified were labeled "Unknown." Terrestrial percentages were based on the sum of arboreal and nonarboreal pollen and spores, excluding *Polystichum*-type spores which overwhelmed the pollen percentages. Pollen zones were constructed based on results of a constrained cluster analysis of arboreal pollen percentages (CONISS, Grimm, 1988). Assemblages were then compared to modern pollen rain from different vegetation types to infer past vegetation and climate (Pellatt et al., 1997; Minckley and Whitlock, 2000).

Results

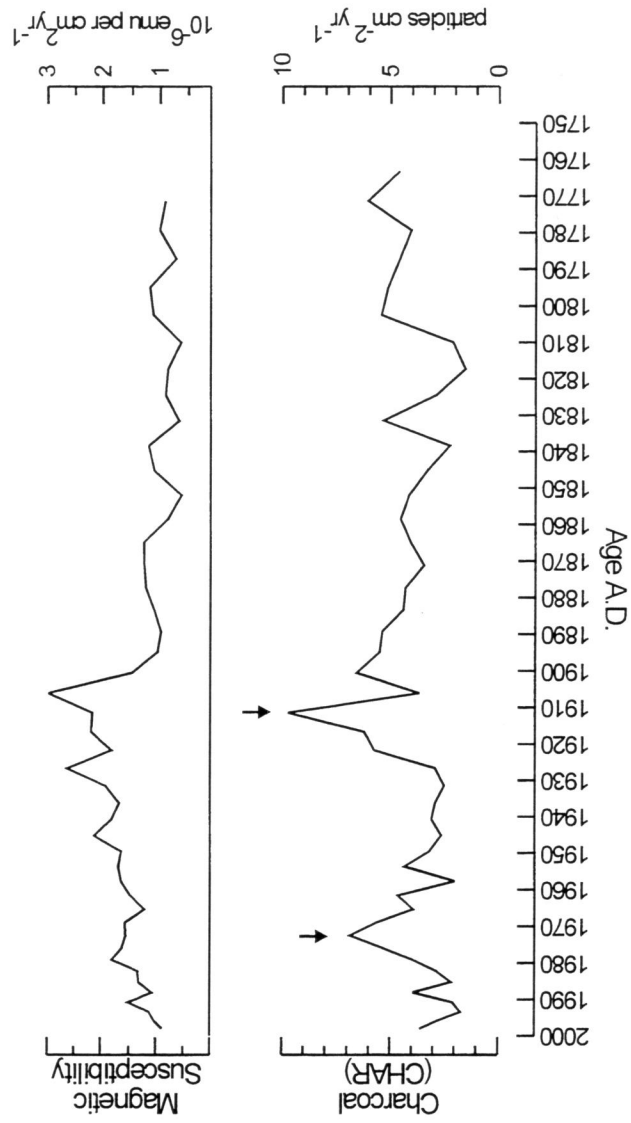
Core description

The long core consisted of dark brown (10YR 2/2) fine-to-medium detritus gyttja with dark gray (5Y 3/1) clay lenses 1-2 cm in thickness. The bottom 2 cm consisted of a sand layer with small pebbles. Organic content averaged 18% between 3.41 and 2.00 m depth then increased to 38% from 2.00 m depth to the top of the core. Carbonate content averaged 2% (Fig 2.2).

Historical CHAR and magnetic susceptibility records

Two CHAR peaks, dated at A.D. 1973 and 1911, were identified by visual inspection of the short core CHAR record (Fig. 2.3). The peak centered on A.D. 1973 is likely associated with a slash burn following the logging of a 200-ha area on the eastern side of the watershed in the early A.D. 1970s. The peak at ca. A.D. 1911 may be the result of a local undocumented fire, on the grounds that many fires took place in A.D. 1910 in western Oregon (Morris, 1934; Juday, 1977). The associated CHAR peaks indicate that significant peak values are 2 to 3 times larger than the background levels. The magnetic susceptibility record shows low values from A.D. 1770-1900 (Fig. 2.3). Values rise at ca. A.D. 1900, reach highest levels at ca. A.D. 1906 and 1925, and then decline to present-day values. Increases in sediment magnetism after A.D. 1900 may be associated with increased erosion from logging and slash fires. Magnetic susceptibility values from the early A.D. 1900s to the present are higher than those prior to A.D. 1900,

Figure 2.3. Log-transformed charcoal (CHAR) and magnetic susceptibility accumulation plotted against age for the short core. Core intervals marked (→) are associated with known or suspected watershed fires in A.D. 1972 and 1911.



suggesting that logging or other anthropogenic activities within the catchment has

provided continuous clastic input.

Prehistoric CHAR and magnetic susceptibility records

The CHAR record from the long core was divided into two zones based on visual

inspection of trends in peak frequency and background CHAR. The first zone TL1 (ca. 4600-2700 cal yr B.P.) is characterized by relatively high fire episode frequency and

background CHAR, and the second zone TL2 (ca. 2700 cal yr B.P. to present) features a

decrease in fire episode frequency and background CHAR levels (Fig. 2.4). Six to seven

fire episodes/1000 yr occurred during Zone TL1 and then declined to three episodes/1000

yr in Zone TL2. The MFI, expressed as the average time between peaks, indicate that

fire episodes in Zone TL1 occurred every 140 ± 30 yr and increased to 230 ± 30 yr in

Zone TL2. Although the difference in the MFI between Zone TL1 and Zone TL2 is not

statistically significant at $p = 0.05$, the trend in the data is clear. The mid-Holocene

period (Zone TL1) experienced more frequent fires than the late-Holocene period (Zone

TL2), with the last 1000 yr recording the fewest fires in the record.

The change in background CHAR values between Zones TL1 and TL2 were not

statistically significant but did display trends over time. CHAR values were low (5

particles $\text{cm}^{-2} \text{yr}^{-1}$) at 4600 cal yr B.P., then increased to moderate levels (9 particles cm^{-2}

yr^{-1}) at ca. 2700 cal yr B.P., and declined to present-day values of 1-2 particles $\text{cm}^{-2} \text{yr}^{-1}$

by ca. 1500 cal yr B.P. The increase in background CHAR between ca. 4600 to 2700 cal

yr B.P. suggests that charcoal production and delivery to the lake was greater than at

present. This increase could also result from re-deposition of sequestered charcoal in the

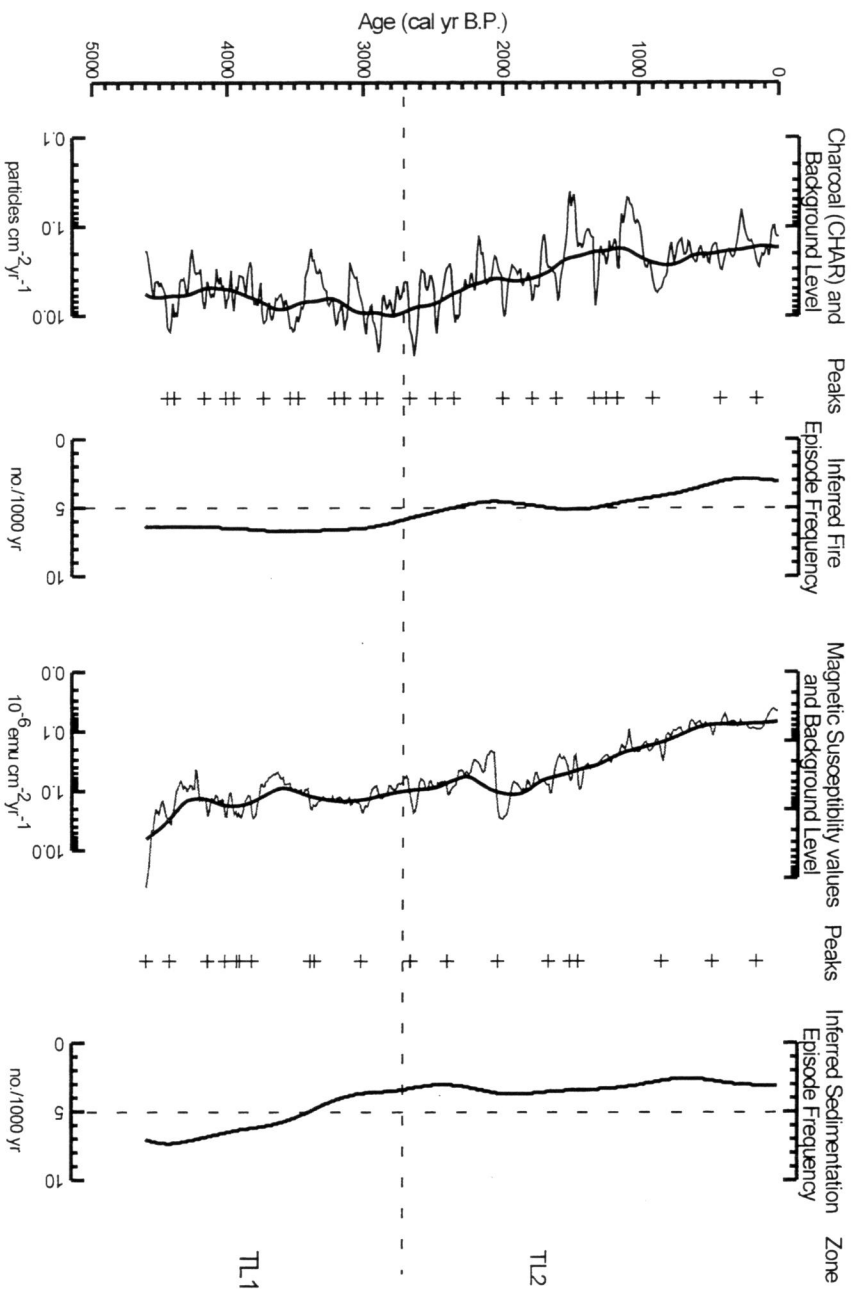


Figure 2.4. Log-transformed charcoal (CHAR) and magnetic susceptibility accumulation values, background levels, peaks, and inferred fire frequency and sedimentation event frequency for the Taylor Lake long core. A 600-year background window width and a 1.25 threshold-ratio value were used to determine background and peak series. The horizontal line marks the boundary between pollen zones TL1 (ca. 4600 to 2700 cal yr B.P.) and TL2 (ca. 2700 cal yr B.P. to present).

watershed or littoral zone, but the higher fire occurrence during this period suggests that the background CHAR values reflect greater charcoal production. The decline in background CHAR values after ca. 2700 cal yr B.P. indicates less charcoal produced during a time of few fires.

Peaks in the magnetic susceptibility record are more frequent early in the record and could be the result of local mass movement associated with severe storm or winter-related precipitation (Reneau and Dietrich, 1990) and also greater slope destabilization as a result of high fire frequency (Swanson, 1981; Benda, 1994) (Fig. 2.4). Six to seven

of sedimentation events declined to between three and four events/1000 yr by ca. 2700 cal yr B.P., and three to four events/1000 yr were recorded in the last ca. 2700 yr. Background magnetic susceptibility records showed moderate values (5.0×10^{-6} emu cm² yr⁻¹) from 4600 to 3700 cal yr B.P., and low values from 3700 cal yr B.P. to the present (between 0.075 and 1.25×10^{-6} emu cm² yr⁻¹).

A Pearson cross-correlation between peaks in CHAR and magnetic susceptibility records showed little correlation ($r = -0.026$ ($p = 0.575$)). This lack of correlation suggests that charcoal peaks are not associated with fire-related erosion events. Benda (1994) proposed that several years may lapse between a fire event and slope

destabilization in the Oregon Coast Range. To examine the possibility of a lagged response in the Taylor Lake record, magnetic susceptibility peaks and CHAR peaks were compared with lags of 10, 20, 30, 40, and 50 years. The correlation did not improve, the highest being a 20-yr time lag ($r = 0.085$ ($p = 0.069$)), suggesting that sedimentation

events were not associated with fires in a systematic way. The weak correlation between fire occurrence (peaks in CHAR) and erosional events (peaks in magnetic susceptibility) is similar to that found at another Coast Range site (Long et al., 1998). Other processes, such as precipitation events, stream erosion, or earthquakes may serve as primary triggers of sedimentation events.

Vegetation reconstruction

The period from ca. 4600 to 2700 cal yr B.P., (Zone TL1), was characterized by relatively high percentages of *Alnus rubra*-type (25-44%) *Tsuga heterophylla* (10-38%), *Picea* (14-30%), and Cupressaceae (5-17%) pollen. *Pseudotsuga*-type, *Pinus contorta*-type, *Abies*, *Sambucus*, and *Salix* pollen occurred in smaller amounts (<3% each) (Fig. 2.5). *Polystichum*-type spores were the most common nonarboreal species, with lesser amounts of Poaceae and *Pteridium*-type spores. The high amounts of *Alnus* pollen and *Polystichum*-type spores for this period suggest a more open forest than at present. Based on comparisons with modern pollen samples from the *Picea sitchensis* forests (Pellatt et al., 1997; Minckley and Whitlock, 2000), the vegetation was composed of stands of *Alnus rubra* on disturbed sites and riparian areas and upland forests of *Tsuga heterophylla*, *Picea sitchensis* and *Thuja plicata*. The understory consisted of *Polystichum munitum* (the likely contributor of *Polystichum*-type spores) with *Pteridium aquilinum* on drier sites or open areas. *Salix hookeriana* (a probable contributor of the pollen) and grasses covered the deflation plain to the west. Interpretation of the pollen data from ca. 4600 to 2700 cal yr B.P. (TL1) suggests a cool moist climate which is

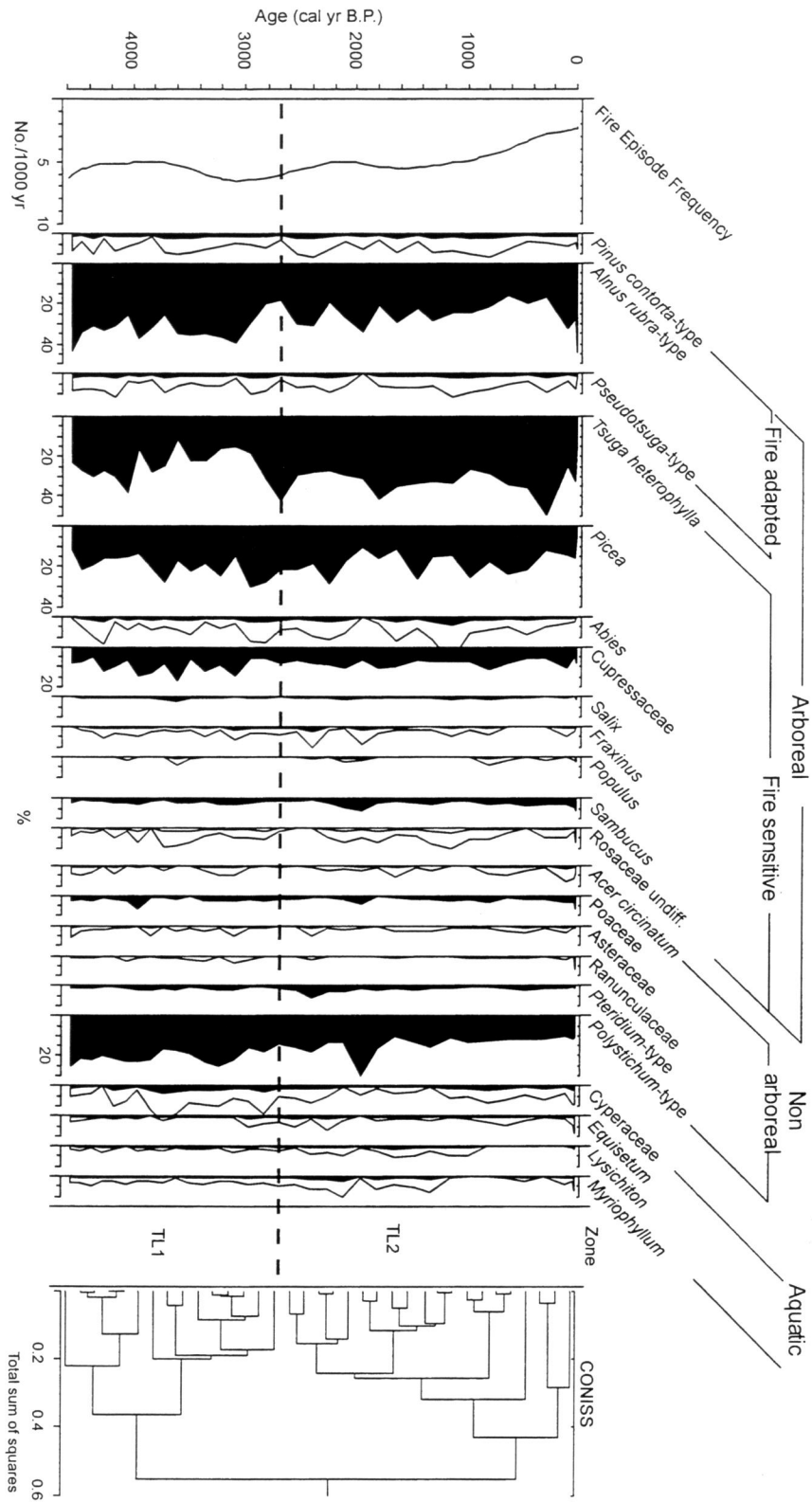


Figure 2.5. Inferred fire frequency, pollen percentages, and constrained cluster analysis (CONISS, Grimm, 1988) from Taylor Lake long core. Open curves represent a 5 times exaggeration of black curves. Arboreal taxa are grouped as fire adapted or fire sensitive (after Minore, 1979; and Agee, 1993).

similar with regional climate reconstructions for the mid-Holocene (Whitlock, 1992;

Worona and Whitlock, 1995).

The period from ca. 2700 cal yr B.P. to present (Zone TL2) showed an overall increase in *Tsuga heterophylla* (17-49%) and a decrease in *Alnus rubra*-type (16-44%) with *Picea* (6-28%) and Cupressaceae (5-11%) percentages remaining about the same as Zone TL1 (Fig. 2.5). *Pseudotsuga*-type, *Pinus contorta*-type, *Abies*, and *Salix*

contributed a minor component (<3% each) to the pollen rain. Nonarbooreal taxa, such as Poaceae, *Pteridium*-type, and *Polystichum*-type, were most common. This zone marks the establishment of closed *Picea sitchensis* and *Tsuga heterophylla* forest and suggests increasing year-round effective moisture in the last three millennia. This is similar with regional climate reconstructions for the late-Holocene (Whitlock 1992), however pollen evidence from an inland site, Little Lake, located 240 km southeast in drier *Tsuga*

heterophylla forests suggest a slight warming over the last ca. 2700 cal yr B.P. (Worona and Whitlock, 1995; Long et al., 1998). The rise in *Alnus rubra*-type and decrease in *Tsuga heterophylla* and *Picea* percentages at the top of the zone are a reflection of disturbance from logging activities over the last century.

Discussion

Late Holocene fire history, vegetation, climate reconstruction

Changes in Holocene climate in PNW are inferred from a network of vegetation reconstructions based on fossil pollen and plant macrofossil data. The major forcing mechanism of climate change in this region is the long-term variations in the seasonal

cycle of insolation generated by changes in the timing of perihelion and tilt of the Earth's axis (Berger and Loutre, 1991; Kutzbach et al., 1993b). Greater-than-present summer insolation in western North America and the PNW between ca. 14000-8000 cal yr B.P. increased summer temperatures as well as strengthened the influence of the eastern Pacific subtropical high in summer. The result of these shifts was a warmer drier climate in the PNW than today (Whitlock and Grigg, 1999). Decreased summer insolation since ca. 8000 cal yr B.P. has weakened the eastern Pacific subtropical high and resulted in the onset of cooler wetter conditions in the PNW (Whitlock, 1992; Thompson et al., 1993). Variations in climate on sub-millennial time scales that affect the PNW, such as El Niño/Southern Oscillation (ENSO) (Diaz and Markgraf, 2000) and the Pacific Decadal Oscillation (Biondi et al., 2001), may be responsible for centennial or decadal variations in precipitation. Decadal droughts affect fuel moisture within forests, and thus fire occurrence. The Taylor Lake record matches well with the general pattern of regional climate changes. The shift from open to closed forest over the last 4600 years indicates an increase in effective moisture (Mathewes, 1985; Thompson et al., 1993). Frequent fires between ca. 4600 and 2700 cal yr B.P. at Taylor Lake suggest greater seasonal drought than today, and forest stands were dominated by disturbance-adapted *Alnus rubra*, and an understory of abundant *Polystichum munitum* and *Sambucus racemosa* (Fig. 2.5). A MFI of 140 ± 30 yr during this period is similar to that at Little Lake located 240 km southeast in more xeric *Tsuga heterophylla* forest (Long et al., 1998). After 2700 cal yr B.P., interannual drought may have been less regular, allowing fire intervals to increase to 230 ± 30 yr. Longer periods between fires allowed shade-tolerant

and fire-sensitive species, such as *Tsuga heterophylla*, to become more prominent within the forest. The decrease in seasonal drought at Taylor Lake may be related to increased summer fog after ca. 2700 cal yr B.P. If climate conditions became slightly warmer and drier inland, as suggested by paleoecological data from Little Lake (Worona and Whitlock, 1995; Long et al., 1998), summer fog would have become a regular feature of the coastal climate and kept local conditions cooler and wetter. The increase in *Tsuga heterophylla* and *Picea sitchensis* is consistent with more humid conditions.

Increased anthropogenic fires may also explain the higher-than-present fire frequencies from ca. 4600 to 2700 cal yr B.P. People have inhabited the Oregon Coast for at least the last 5000 years, and as many as 30,000 people occupied the coastal strip of Oregon and Washington at the time of European contact (Suttles and Ames, 1997).

Disease introduced in the early A.D. 1700s led to a rapid decline in Native American populations (Ubelaker, 1988), and the Lewis and Clark expedition estimated that only 1200 Natives lived in the vicinity of Fort Clatsop, 8 km northeast of Taylor Lake, in A.D. 1804 (Clark, 1990). Archeological evidence suggests that coastal subsistence activities did not require the deliberate use of fire inasmuch as fishing and marine invertebrates were the primary food sources (Boyd, 1999). It is possible that an occasional brush fire turned into a larger forest fire, as has occurred frequently in the last 100 yr with slash burns, but if anthropogenic activity were the sole explanation for fires during this period, it is not clear why fires became less frequent after ca. 2700 cal yr B.P. when Native populations were still high. Increased summer moisture after ca. 2700 cal yr B.P. seems to be the primary explanation for decreased fire activity regardless of the ignition source.

Conclusions

The Taylor Lake record shows that fire is an important agent of disturbance in the southern *Picea sitchensis* forests and that fire occurrence has changed with climate change over the last 4600 years. From ca. 4600 to 2700 cal yr B.P. frequent fires helped maintain *Alnus rubra* and other disturbance-adapted taxa in the watershed, and the decrease in fire occurrence over the last 2700 years has led to a closing of the forest, perhaps caused by protracted summer fog and shorter summer drought.

An increase in regional summer temperatures in the future is projected as a result of higher greenhouse gas concentrations in the atmosphere (IPCC, 2001). In the PNW, model simulations of future climate conditions suggest that summer temperatures will increase (Leung and Ghan, 1999). Warmer summer conditions could increase the advective fog formation along the coastal margin and keep summer conditions moist and retard fire activity. Contrary to projections of increased fire activity in the future in the interior U.S. (Franklin et al., 1992; Price and Rind, 1994; Bartlein et al., 1997), along the coast the present-day regime of infrequent fires may persist despite a warmer climate.

CHAPTER III

HOLOCENE-SCALE VARIATIONS IN VEGETATION AND FIRE HISTORY OF
THE SOUTHERN SEASONAL RAIN FOREST, OREGON COAST RANGE, USAIntroduction

Variations in climate during the last 20,000 years have been a major cause of

vegetation change in Pacific Northwest (PNW) (Heusser, 1985; Brubaker, 1991;

Whitlock, 1992; Thompson et al., 1993; Worona and Whitlock, 1995). Fire is an

important disturbance in PNW forests (Agee, 1993) and can act as a catalyst in shaping

vegetation patterns (Hemstrom and Franklin, 1982; Spies, 1991). Therefore, when

climate changes, forests may respond not only to the large-scale long-term changes in

climate, but also to short-term local changes in disturbance regimes (Cwynar, 1987).

Clark (1990), Swetnam (1993), and Grissino-Mayer and Swetnam (2000) have

demonstrated changes in fire occurrence in connection with climate variations in other

regions of western North America. Such responses provide a basis for assessing potential

effects of climate change on biota in the future with projected increase in greenhouse

gases in the atmosphere. Therefore, a better understanding of the climate-dependent

relationship between vegetation and fire in PNW forests can provide a model for future

vegetation and fire relations in this region.

The seasonal rain forest occupies a narrow strip along the Pacific slope, covering

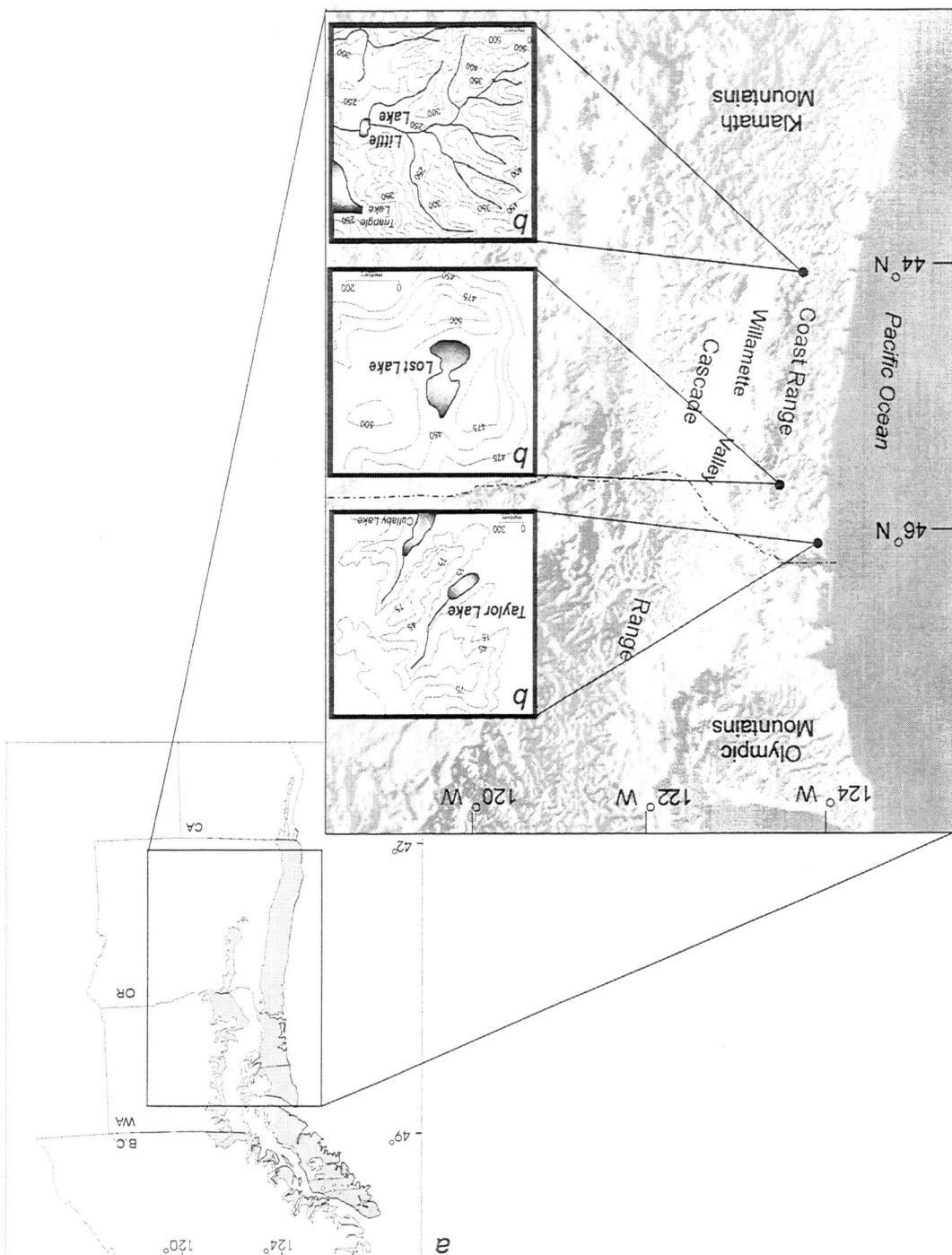
most of Vancouver Island and extending into northern California (Alaback and Pojar,

1997). These forests range from 60 to 200 km inland and cover the Coast Ranges and the western slopes of the Cascade Range in the PNW (Fig. 3.1). This study focuses on a southern portion of the ecoregion located in the Oregon Coast Range.

The Pacific slope of the PNW is characterized by steep gradients in climate, both latitudinally and longitudinally. A north-to-south precipitation gradient results from seasonal shifts in the location and intensity of the northeastern Pacific subtropical high-pressure system (STH) and polar jet stream. In summer, the STH expands and the jet stream retreats northward, which results in increased large-scale subsidence and the suppression of precipitation in Oregon and Washington. In autumn, westerly flow increases as the STH weakens and shifts southward. In winter, the westerlies are strongest and at their farthest southward location, and deliver the bulk of annual precipitation to Oregon and Washington, as storm systems that originate in the Gulf of Alaska release moisture ultimately derived from the subtropical Pacific. Westerly flow decreases in spring as temperatures rise and the STH increases in strength and expands northward again. The effect of these shifts in atmospheric circulation is a latitudinal increase in annual precipitation and a decrease in annual temperature from southern Oregon to Vancouver Island (Mock, 1996; Redmond, and Taylor, 1997).

The elevational range within the Coast Range is moderate, with typical crest elevations less than 1000 m above sea level, whereas Cascade crests rise to ca. 1500 to 2000 m. These mountain ranges provide significant orographic barriers to storm systems resulting in a west-to-east precipitation gradient.

Figure 3.1. Location of Little, Lost, and Taylor lakes and other physiographic features mentioned in the text. Inset *a*, shows extent of seasonal rain forest (Alaback and Pojar 1997). Inset *b*, shows watershed topography at each site in meters.



Forests of *Tsuga heterophylla* (western hemlock), *Thuja plicata* (western red cedar), and *Pseudotsuga menziesii* (Douglas-fir) characterize the seasonal rain forest. *Pinus monticola* (western white pine), *Abies grandis* (grand fir), and *Abies procera* (noble fir) are also present at higher elevations. Cool wet sites are dominated by shade-tolerant and fire-sensitive taxa, such as western hemlock and western red cedar. On drier sites Douglas-fir prevails because it is both shade intolerant and fire adapted. Fire-sensitive and shade-tolerant grand fir and noble fir are common species at higher elevations (Minore, 1979; Pojar and MacKinnon, 1994). Within 10 km of the coast, fire-sensitive *Picea sitchensis* (Sitka spruce) replaces Douglas-fir as a major forest conifer because of its higher tolerance for salt spray, higher soil-moisture optimum, and lower tolerance for drought (Minore, 1979; Peterson et al., 1997). *Pinus contorta* var. *contorta* (shore pine) is present at coastal locations in nutrient-poor soils (Franklin and Dyrness, 1988). Latin names are used in reference to pollen data while common names refer to vegetation. Nomenclature follows Hitchcock and Cronquist (1973).

Deciduous trees are generally minor constituents of mature seasonal rain forests and are restricted to young stands, recently disturbed sites, or riparian areas. *Alnus rubra* (red alder) is an important nutrient fixer and pioneer species in the Coast Range and can be present in large, even-aged stands from sea level to the crest (Hemstrom and Logan, 1986; Alaback and Pojar, 1997). Fire and wind are the primary disturbance agents in the seasonal rain forest (Agee, 1990; 1993). Because of the latitudinal precipitation gradient, it is believed that the role of fire declines in wetter forests to the north (Ruth and Harris,

1979; Peterson et al., 1997). Fires occur during the summer-dry season and over the past 150 years have included high-severity widespread events (Morris, 1934; Juday, 1977). In most areas, high wood decay rates and the fact that evidence of older fires is destroyed by more recent fires (Agee, 1993) have limited dendrochronological records of fires to the last ca. 500 years (Teensma et al., 1991; Impara, 1997). How well these estimates of fire severity and frequency represent disturbance regimes before ca. A.D. 1500 is not clear.

The purpose of this chapter is to reconstruct the Holocene vegetation and fire history from the Oregon Coast Range based on three sites in different environmental settings and examine their climatic and environmental controls on several temporal and spatial scales. To accomplish these objectives this chapter provides Holocene vegetation and fire records from Lost Lake and compares them with data from Little Lake (Long et al., 1998) and Taylor Lake (Chapter 2). I also compare the vegetation and fire history from the Oregon Coast Range with other locations in the seasonal rain forest in order to provide a regional picture of environmental change.

Study Sites

Lost Lake (45°49'30"N, 123°34'40"W, 460 m elevation) is located in a fault block 30 km east of the Pacific Ocean (Fig. 3.1) (Oregon Department of Geology, 1973). It has a surface area of 6 ha, maximum water depth of 6 m, simple bathymetry, and no discernable outflow channel. The watershed (33 ha) experiences January and July mean monthly temperatures of 2.9°C and 14.9°C, and a mean annual precipitation of ca. 2050 mm. (Thompson et al., 2000; P. J. Bartlein, unpublished data 2002). Western hemlock,

western red cedar, and Douglas-fir grow throughout the watershed, with Sitka spruce and grand fir restricted to northern aspects. Red alder, is confined to riparian areas and recently disturbed sites. *Salix sitchensis* (Sitka willow) and *Salix scouleriana* (Scouler's willow) grow in riparian areas. *Rubus spectabilis* (salmonberry), *Acer circinnatum* (vine maple), *Sambucus racemosa* (elderberry), *Vaccinium* L. spp. (huckleberry), *Corylus cornuta* (hazelnut), and *Pteridium aquilinum* (bracken) are found on drier upland slopes. *Blechnum spicant* (deer-fern) and *Dryopteris spinulosa* (wood-fern) are common understory species in cool moist locations, and *Polystichum munitum* (sword fern) is ubiquitous.

Recent fires in the Lost Lake area have been associated with dry, hot summer conditions and strong, easterly winds produced by interior high-pressure cells centered east of the Cascade Range (Schroeder and Buck, 1970; Agee, 1993). Logging activities have been the main ignition source since the early 1900s (Agee, 1993). The well-known Tillamook fires burned south of Lost Lake in A.D. 1933, 1939, 1945 and 1951, and trace their ignition to logging activities. In the Lost Lake watershed, the A.D. 1933 Wolf Creek fire burned ca. 2500 ha of old-growth forest, including the entire watershed, and was started by logging activities east of Lost Lake (Oregon Department of Forestry, 1975; Juday, 1977). Lightning is frequent enough to be a significant ignition source near Lost Lake. For example, a mean of 12 and up to 22 cloud-to-ground lightning strikes occurred per year between 1986 and 1996 in the 1° lat. x 1° long rectangle that contains Lost Lake (Agee, 1993; WRCC, 1996).

Evidence of fires prior to ca. 1900 come from sources such as journal and government land survey records. None place fires or burned areas within the Lost Lake watershed. Morris (1934), Judy (1976), and Agee (1993) document large fires (>100,000 ha) in the Coast Range between A.D. 1849 and 1902, and in some years, such as A.D. 1910, many local fires occurred. Impara (1997) used a transect of fire-scarred tree-ring records and stand-age data along an east-to-west transect in the central Oregon Coast Range to identify 27 fires in the last 500 years over a 137,500 ha area. These fires ranged from ca. 100 ha to greater than 50,000 ha. Fires were broadly oriented in a west-to-east direction reflecting prevailing easterly winds during the fire, and more fires burned in the eastern portion of the transect (Impara, 1997).

Little Lake (44°09'56"N, 123°34'14"W, 210 m elevation) is a landslide-dammed lake in the central Coast Range of Oregon, 45 km east of the Pacific Ocean (Fig. 3.1). It has a surface area of 1.5 ha, maximum water depth of 5 m, simple bathymetry, and perennial inflowing and outflowing streams that drain an area of 600 ha. The forests are similar to those at Lost Lake, with the addition of more xeric species, such as *Quercus garryana* (Oregon white oak) which grows in nearby valleys and the Willamette Valley to the east (Long et al., 1998). The Little Lake watershed experiences warmer, drier conditions than Lost Lake, with January and July mean monthly temperatures averaging 4.5°C and 16.9°C respectively and mean annual precipitation of ca. 1600 mm (Thompson et al., 2000; P. J. Bartlein, unpublished data 2002).

Archival records and charcoal analysis indicate fires occurred in A.D. 1910, 1929, 1967, and 1982 in or near the Little Lake watershed. Those in A.D. 1967 and 1982 were

associated with debris burning after logging operations in the western portion of the watershed (Long et al., 1998). Unfortunately there is little information on the A.D. 1910 and 1929 fires, and early government surveys in A.D. 1894 did not indicate dead or burned timber in the area (Gesner, 1894).

Taylor Lake (Lat. 46° 06' 02"N, Long. 123° 54' 24"W, elev. 4 m.) is located on the northern Oregon coast (Fig. 3.1). The lake is 4 ha in size with a maximum water depth of 4.5 m, simple bathymetry, and a seasonally active outflow channel that drains a watershed of ca. 63 ha. The lake is the result of sand dunes damming the outlet stream (Rankin, 1983). The forests around Taylor Lake are dominated by western hemlock, Sitka spruce and western red cedar, and red alder grows in recently disturbed sites and riparian areas. *Salix hookeriana* (Hooker's willow) and *Phalaris arundinacea* (canarygrass) are abundant in the wetlands west of the lake. Temperatures at Taylor Lake average 4.7° C in January and 15.1° C in July, and the watershed receives ca. 2000 mm of precipitation (Oregon Climate Service, 2002).

Government surveys of the Taylor Lake watershed in A.D. 1856 did not report dead or burned timber (Trutch, 1856). Charcoal analysis of lake sediment identified fires in A.D. 1911 and 1973 (Chapter 2). The fire dating to A.D. 1911 may be from an undocumented fire or nearby fires in A.D. 1910 in western Oregon (Morris, 1934; Juday, 1977). The A.D. 1973 fire is likely associated with a debris burn following logging on the eastern side of the watershed in the early A.D. 1970s.

The methods used to reconstruct the fire and vegetation history at Lost Lake generally follow those used at Little Lake (Long et al., 1998) and Taylor Lake (Chapter 2).

Methods

Field work

A 5.13-m-long core was collected from the deepest part of Lost Lake using a 5-cm-diameter modified Livingstone sampler (Wright et al., 1983). A short core, 0.45-m in length, was collected using an 8-cm-diameter gravity sampler, which preserved the mud-water interface intact. The cores consisted of non-laminated sediment and were extruded, described and wrapped in plastic wrap and aluminum foil in the field. In the laboratory, both long and short cores were sliced into 1-cm intervals, placed in plastic bags, and refrigerated at the University of Oregon paleoecology lab.

Chronology

Thirteen ^{210}Pb dates were used to establish a chronology for the Lost Lake short core. Ages were plotted against core depth, using linear interpolation to establish an age-versus-depth model. The short core spanned the last 180 years. The chronology for the long core was based on five AMS radiocarbon dates and the age of Mt. Mazama "O" tephra, 7750 ± 75 calendar years before present (cal yr B.P.) (Hallet et al., 1997). All ^{14}C ages were converted to calendar years based on CALIB 4.2 (Stuiver et al., 1998). An interval of abundant charcoal between 0.19 and 0.23 m depth present in both short and long cores was used for correlation. In the short core this peak was dated at A.D. $1929 \pm$

41 years A.D. and corresponds well with the Wolf Creek fire of A.D. 1933 that burned the entire watershed (Oregon Department of Forestry, 1975). This date (70 years before present) was assigned to the correlated peak in the long core and included in the age model calculations. A third-order polynomial regression curve provided the age model for the long core (Table 3.1, Fig. 3.2), and a basal age of ca. 10,270 cal yr B.P. was obtained by extrapolation. However the bottom 0.45 m of sediment was not analyzed because of its lack of organic material (see Results). The age assigned to 4.60 m depth, the lowest depth analyzed, was ca. 8380 cal yr B.P.

Lithological analysis

Weight-loss after ignition was measured at 1-cm intervals in the short core and at 10-cm intervals in the long core to determine the amount of organic and carbonate material in the sediment (Dean, 1974). Subsamples of 1 cm³ were placed in crucibles and heated for two hours at 550°C and for two more hours at 900°C. The weight loss after each burning was used to calculate the percent of organic matter and carbonate content respectively.

Magnetic-susceptibility analysis was used to assess the input of clastic material from the watershed (Thompson and Oldfield, 1986; Oldfield, 1991). Fires can defoliate and destabilize slopes (Swanson, 1981; Benda, 1994) and heat soils, which can increase the amount of ferrimagnetic oxides washed into lakes (Thompson and Oldfield, 1986; Gedye et al., 2000). Increases in the magnetic susceptibility of lake sediments are

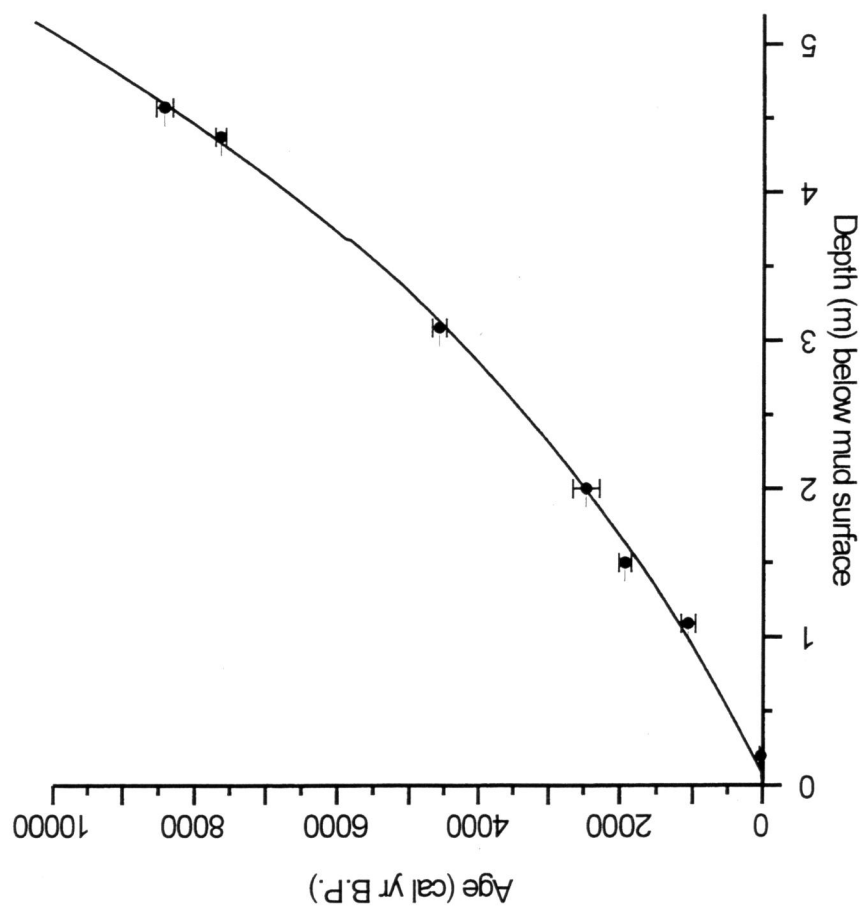
assumed to come from these processes (Rummery et al., 1979; Millspaugh and Whitlock,

TABLE 3.1
Calibrated and Uncalibrated Radiometric Ages Used in the Age Model^a for
Lost Lake Long Core

Depth (m)	Calibrated age (cal yr B.P.) ^b (cal yr B.P. $\pm$ 2 SD)	Uncalibrated ¹⁴ C age	Material	Lab number
0.20 ^c	70		Sediment	
1.09-1.10	1060 (962-1166)	1154 $\pm$ 40	Charcoal	AA-22230
1.48-1.51	1930 (1824-2019)	1990 $\pm$ 50	Charcoal	AA-30943
2.00-2.01	2470 (2349-2723)	2454 $\pm$ 42	Charcoal	AA-22231
3.08-3.10	4530 (4414-4618)	4058 $\pm$ 44	Charcoal	AA-22232
4.38-4.39	7550 (7470-7620)	6730 $\pm$ 40	Mazama O	Hallet et al., 1997
4.53-4.63	8450 (8380-8590)	7680 $\pm$ 70	Sediment	Beta-87049

^a Age model: Age = -78 + (1086.0 • Depth) + (56.0 • Depth²) + (23.4 • Depth³).
^b Based on CALIB 4.2 (Stuiver et al., 1998).
^c Age based on correlation with ²¹⁰Pb dated charcoal peak in short core.

Figure 3.2. Age-versus-depth relations for Lost Lake long core based on the age model information in Table 2. Error bars indicate two standard deviations of the calibrated ^{14}C years.



1995). Events unrelated to fires, such as variations in surface runoff, stream flow and mass movements within the catchment, may also produce changes in clastic input that are reflected in the magnetic susceptibility of lake sediment (Dearing and Flower, 1982; Long et al., 1998; Gedye et al., 2000).

Magnetic susceptibility readings were taken on 8-cm³ subsamples from each 1-cm interval prior to charcoal analysis. Subsamples were put into a plastic cup and placed in a cup-coil magnetic susceptibility instrument. Sediment magnetic-susceptibility values were converted to concentration values, expressed as electromagnetic units per cubic centimeter (emu·cm⁻³), and then divided by the sample deposition time (cm·yr⁻¹) to calculate magnetic-susceptibility accumulation rates (emu cm⁻² yr⁻¹) (Fig. 3.3).

Pollen analysis

Pollen analysis was performed only on the Lost Lake long core and followed the procedures of Faegri et al. (1989). Samples of 1 cm³ were taken every 10 cm and known amounts of *Lycopodium* spores were added to each sample to calculate pollen concentration (grains cm⁻³). A minimum of 400 terrestrial pollen grains per sample were examined at 400 and 1000x magnification. Identification of taxa was based on modern pollen collection and published atlases (e.g., Bassett et al., 1978; Moore et al., 1991) with unidentified grains labeled "unknown". Pollen accumulation rates (grains cm⁻² yr⁻¹) were calculated by dividing pollen concentrations by deposition time. Terrestrial pollen percentages, calculated using the sum of terrestrial pollen and spores, were divided into zones based on constrained cluster analysis (CONISS; Grimm, 1988). *Pseudotsuga*-type pollen was assumed to represent *Pseudotsuga menziesii*, a major forest constituent in the

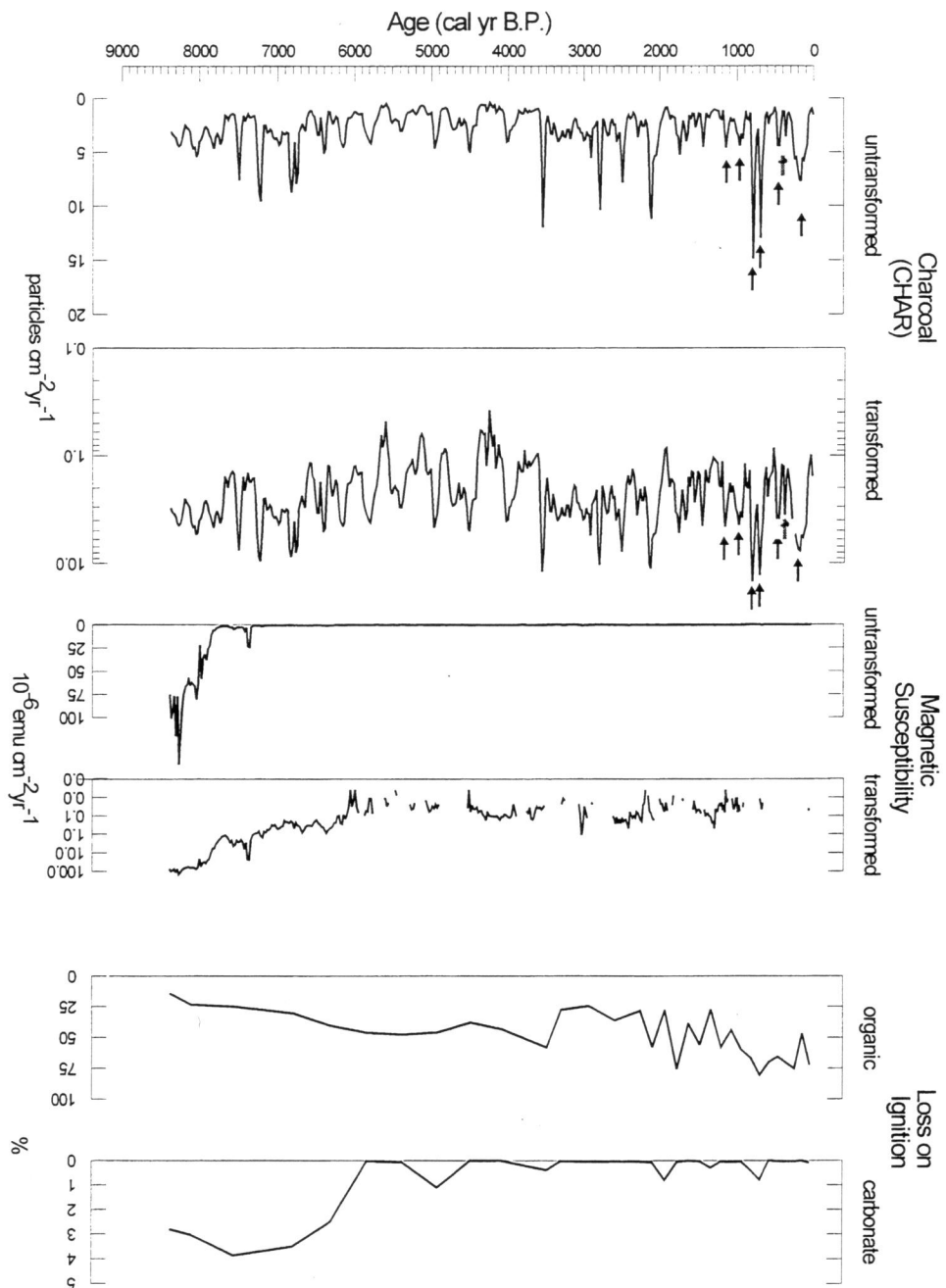


Figure 3.3. Untransformed and log-transformed charcoal accumulation rates (CHAR), magnetic susceptibility accumulation rates, and organic and carbonate content for Lost Lake plotted against age for the long core. CHAR peaks that are identified as local fire episodes and used to calibrate the rest of the charcoal record are marked with arrows. The first two CHAR peaks corresponded in depth to the two peaks identified in the short core record.

Coast Range rather than *Larix*, which is found in northeastern Oregon (Franklin and Dyrness, 1988). *Abies* pollen was attributed to grand fir and Pacific silver fir, both of Coast Range rather than *Larix*, which is found in northeastern Oregon (Franklin and Dyrness, 1988). *Abies* pollen was attributed to grand fir and Pacific silver fir, both of which grow in the Coast Range today. Cupressaceae pollen was assigned to *Thuja plicata* (western red cedar), a common arboreal species in the Oregon Coast Range, although *Chamaecyparis nootkatensis* (yellow cedar) and *Chamaecyparis lawsoniana* (Port Orford cedar) may also be minor contributors. Haploxydon-type and Diploxydon-type *Pinus* grains were assigned to western white pine (*P. monticola*) or lodgepole pine respectively, based on present-day ranges. *Pinus* grains that could not be differentiated were listed as "*Pinus*". Because of their low percentages, Haploxydon, Diploxydon, and undifferentiated *Pinus* were combined in the pollen diagram.

Charcoal analysis

Subsamples of 2.5 cm³ were taken from contiguous 1-cm intervals for the length of the short and long cores. These subsamples were disaggregated in a 5% solution of sodium hexametaphosphate for 24 hours and gently washed through nested sedimentological screens of 125 and 250 µm. All charcoal particles >125 µm in diameter were tallied, because studies of charcoal deposition after recent fires have shown that particles of this size are not transported long distances during a fire and thus indicate a watershed fire (Millsbaugh and Whitlock, 1995; Whitlock and Millsbaugh, 1996; Clark and Patterson, 1997; Ohlson and Tryterud, 2000; Gardner and Whitlock, 2001). Charcoal

counts for each sample were converted to concentration (particle cm^{-1}) and then interpolated to pseudo-annual values. These values were then averaged over an averaging interval (e.g., decade). Charcoal accumulation rates (CHAR) (particles $\text{cm}^{-2} \text{yr}^{-1}$) were calculated as averaged concentration divided by average span where average span is the average deposition time over the averaging interval (e.g., decade). This approach preserves the total mass of charcoal better than if "raw" influx was simply interpolated (Fig 3.3).

Variations in charcoal accumulation rates (CHAR) provided the fire history reconstruction. Charcoal accumulation records can be observed to consist of long-term, order-of-magnitude changes in levels with short-term variations superimposed on the long-term changes. Our conceptual model of these records considers the long-term variations to represent "background" changes in charcoal influx and the short-term variations to represent fire-related peaks of charcoal deposition (Clark and Royall, 1996; Long et al., 1998). The background component is thought to consist of the low-frequency variations in the accumulation of charcoal particles, which varies as a result of changes in fuel composition, inputs of charcoal introduced from the watershed or littoral zone of the lake, or charcoal introduced from fires outside the watershed (Long et al., 1998; Millspaugh et al., 2000). The peak component is thought to be composed of charcoal particles that are deposited during or soon after a local fire or several closely spaced local fires (Clark, 1990; Millspaugh and Whitlock, 1995; Clark and Patterson, 1997; Gardner and Whitlock, 2001). Consequently, the charcoal record was decomposed into two components: background CHAR, which describes the slowly varying trend in

charcoal accumulation, and peak CHAR, which are positive deviations from background. The background component was determined using a moving, locally weighted mean with the weights determined by the "tricube weight function" (Cleveland, 1979). The peak component was determined by comparing the CHAR for each time step to the background value assigned to that time step. If the CHAR exceeded the background CHAR at that time by a particular threshold ratio, it was designated a peak. CHAR peaks will be hereafter referred to as "fire episodes", as opposed to "fire events" as was used in a previous study (Long et al., 1998). The term fire episode seems more appropriate because a charcoal peak may represent one or more fire events. The number of CHAR peaks per unit of time is designated as the "fire-episode frequency". These values were calculated by averaging peak occurrence, with the "tricube weight function", through time.

Seven peaks were identified in the last 1200 years based on visual inspection and correlation with the short-core record (marked by arrows in Fig. 3.3). This frequency falls within the present-day range of fire occurrence for moist *Tsuga heterophylla* forests (ca. 1 fire/170 years) (Teensma et al., 1991; Agee, 1993; Impara, 1997). The seven peaks helped in the selection of appropriate background and peak parameters (window width and threshold ratio) for the long core (see Results for parameter selection process). As is the case for other paleoenvironmental indicators present in lake sediments (e.g., pollen, diatoms), CHAR data are approximately log-normally distributed. Consequently these data were log (base 10) transformed before analysis (Long et al., 1998).

Results

The Lost Lake Record

The Last 200 Years

Examination of the short-core record suggests that peak values are 3 to 5 times larger than background CHAR levels (ca. 8.8 particles cm yr⁻²). Two prominent peaks were evident from visual examination of the short-core CHAR (ca. A.D. 1929 and 1863 as dated by ²¹⁰Pb method and marked by arrows in Fig 3.4). These peaks were assigned to the A.D. 1933 Wolf Creek fire (Oregon Department of Forestry, 1975) and A.D. 1868 Tillamook fire (Morris, 1934; McQuinn 1892) respectively.

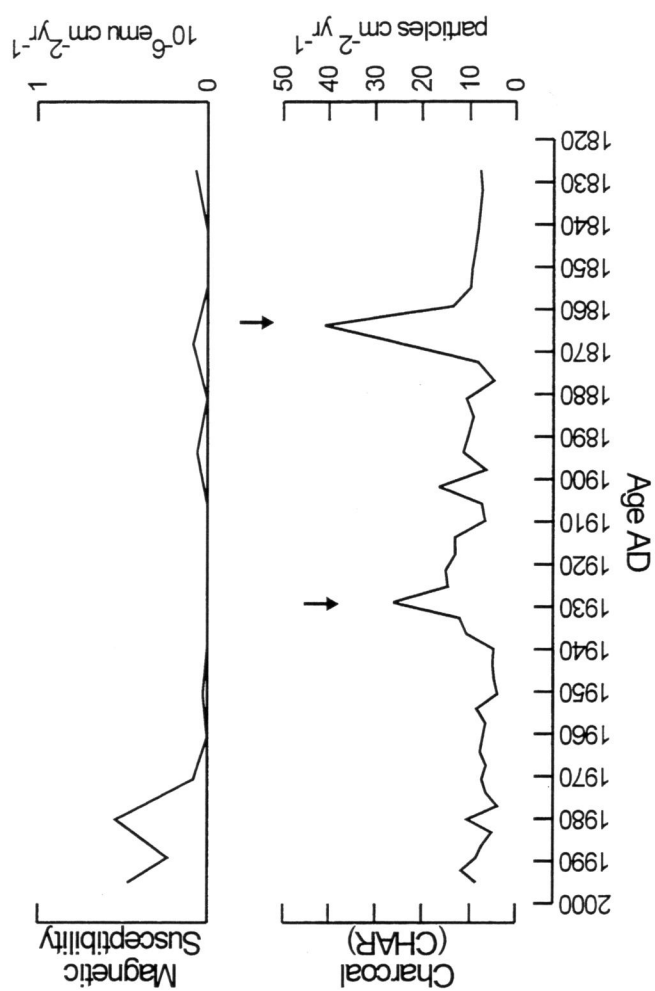
Magnetic susceptibility values in the short core were low before ca. A.D. 1970 (Fig. 3.4). The rise at ca. A.D. 1970 is attributed to road building and logging activities within the watershed. Little or no increase in magnetic susceptibility values was associated with the two charcoal peaks at A.D. 1929 or 1865. Apparently, the small size and low relief of the watershed minimized inwashing of clastic material.

The Last 8300 Years

Lithology

The long core from Lost Lake consisted of nonlaminated, dusky brown (5YR 2/2), fine-detritus gyttja from 0.00-4.68 m depth, with organic content ranging from ca. 24 to 75 % (49% average). An ash layer at 4.38-4.39 m depth had an interpolated age of 7810 cal yr B.P. and was assigned to Mt. Mazama "O" layer, which is noted in other

Figure 3.4. Lost Lake short core charcoal accumulation rates (CHAR) and magnetic susceptibility rates for Lost Lake plotted against age. Core intervals marked with arrows are associated with known or suspected watershed fires in 1933 and 1863.



nearby sites including Battle Ground Lake (Barnosky, 1985) and Little Lake (Long et al., 1998). The true age of the ash (7550 ± 75 cal yr B.P., Hallet et al., 1997) was used in the age-versus-depth model. From 4.68-5.17 m depth, the core consisted of organic clay (ca. 8% organic matter) and pebbles. Because the organic content of the core was low from ca. 4.68-5.17 m depth, pollen and charcoal analysis was limited to the top 4.60 m of sediment, corresponding with the last ca. 8380 cal yr B.P. Average deposition for the interval from 0.00 to 4.60 m depth was 20.1 ± 7.6 years cm^{-1} .

Magnetic susceptibility values were low throughout the record. Values declined from ca. 60.0×10^{-8} to 1.00×10^{-8} (emu cm^{-3}) between ca. 8380 and 7100 cal yr B.P. From ca. 7100 cal yr B.P. to present, values were $< 1.00 \times 10^{-8}$ (emu cm^{-3}) close to the minimum levels of detection by the instrument (Fig. 3.3). Organic content of the sediment from ca. 8380 to 6000 cal yr B.P. increased steadily from ca. 14 to 40%. From ca. 6000 to 750 cal yr B.P. organic content averaged ca. 45%, and then increased over the last ca. 650 years to ca. 70%. Carbonate values were between 2 and 4% from ca. 8320 to 6000 cal yr B.P., and then declined to between 0.5 and 1.0% over the last ca. 6000 years (Fig. 3.3). The low magnetic susceptibility values suggest little clastic input to the lake after ca. 7100 cal yr B.P. Prior to ca. 7100 cal yr B.P., high magnetic susceptibility

values are consistent with the deposition of inorganic sediments at that time. The low magnetic susceptibility readings for most of the record did not allow a comparison of magnetic susceptibility and CHAR data (Millspaugh and Whitlock, 1995; Long et al., 1998).

The Lost Lake pollen record was divided into two major zones and four subzones

using constrained cluster analysis (CONISS, Grimm, 1988) (Table 3.2, Fig. 3.5). Pollen accumulation rates are high (8130 to 28,900 grains $\text{cm}^{-2} \text{yr}^{-1}$) for the length of the record and indicate a closed forest. Zone LOL 1 (ca. 8380 to 6930 cal yr B.P.) is characterized

by high mean percentages of *Alnus rubra* (40%) with *Pseudotsuga*-type (27%) and *Abies* (5%) (Table 3.2, Fig. 3.5). Low values of *Quercus* (<3%) and *Pinus* (<3%) pollen likely came from xeric sites near the watershed. This pollen profile is similar to mid-elevation slopes of the western Cascades of Oregon (Barnosky, 1985; Minckley and Whitlock,

2000) and suggests stands of red alder on disturbed or riparian sites with mixed forest stands of Douglas-fir and grand fir or noble fir occupying the remainder of the watershed and surrounding slopes.

Subzone LOL 2a (ca. 6930 to 5600 cal yr B.P.) shows mean increases in *Tsuga heterophylla* (25%), Cupressaceae (8%) and *Salix* pollen (5%) compared with Zone LOL 1, and declines from Zone LOL 1 in *Alnus rubra* (30%) and *Pseudotsuga*-type pollen (19%). *Pteridium*-type spores (<5%), and *Corylus cornuta* (<5%) are present in pulses (Table 3.2, Fig. 3.5). The abundance of shade-tolerant western hemlock and western red cedar in this sub-zone suggest that forest stands were more closed than before. The increase in *Salix* pollen implies an expansion of riparian vegetation and accompanies a rise in *Alnus rubra* at the top of the zone. This pollen assemblage is similar to modern mid-elevation forest of the mesic northern-facing slopes of the Olympic Mountains (Heusser, 1969).

TABLE 3.2
Description of the Lost Lake Pollen Percentage Diagram

Pollen zone	Depth (m)	Age (cal yr B.P.)	Description
LL-2d	0.00-0.70	0-700	High percentages of <i>Alnus rubra</i> (29%), <i>Tsuga heterophylla</i> (26%), Cupressaceae (16%), <i>Pseudotsuga</i> -type (14%); minor amounts of <i>Picea</i> and <i>Abies</i> (<2%); understory taxa of <i>Dryopteris</i> -type (4%), <i>Salix</i> (3%), and <i>Pteridium</i> -type (2%). Total accumulation rates of terrestrial pollen and spores (PAR): 14,600-22,100 grains cm ⁻² yr ⁻¹ .
LL-2c	0.70-1.30	700-1450	High percentages of <i>Tsuga heterophylla</i> (33%), <i>Alnus rubra</i> (20%), Cupressaceae (18%), and <i>Pseudotsuga</i> -type (16%); minor amounts of <i>Picea</i> and <i>Abies</i> (<2%); <i>Dryopteris</i> -type (4%) and <i>Salix</i> (3%) prominent understory taxa. PAR: 13,800-20,800 grains cm ⁻² yr ⁻¹ .
LL-2b	1.30-3.60	1450-5600	High percentages of <i>Alnus rubra</i> (29%), <i>Tsuga heterophylla</i> (24%), Cupressaceae (20%), <i>Pseudotsuga</i> -type (14%); minor amounts of <i>Abies</i> (2%); <i>Salix</i> (5%), <i>Dryopteris</i> -type (3%) and <i>Pteridium</i> -type (<1%). PAR: 9,800-28,900 grains cm ⁻² yr ⁻¹ .
LL-2a	3.60-4.10	5600-6930	High percentages of <i>Alnus rubra</i> (30%), <i>Tsuga heterophylla</i> (25%), <i>Pseudotsuga</i> -type (19%), Cupressaceae (8%) and <i>Abies</i> (5%); <i>Salix</i> (5%), <i>Dryopteris</i> -type (4%), and minor amounts of <i>Quercus</i> , <i>Pinus</i> , <i>Corylus cornuta</i> and <i>Pteridium</i> -type (<1%). PAR: 8,130-14,200 grains cm ⁻² yr ⁻¹ .
LL-1	4.10-4.60	6930-8380	High percentages of <i>Alnus rubra</i> (40%), <i>Pseudotsuga</i> -type (27%), <i>Tsuga heterophylla</i> (14%) and <i>Abies</i> (6%); <i>Quercus</i> , <i>Pinus</i> (<3%), <i>Dryopteris</i> -type (4%), <i>Pteridium</i> -type (2%) and Poaceae (<1%) present. PAR: 13,200-18,300 grains cm ⁻² yr ⁻¹ .

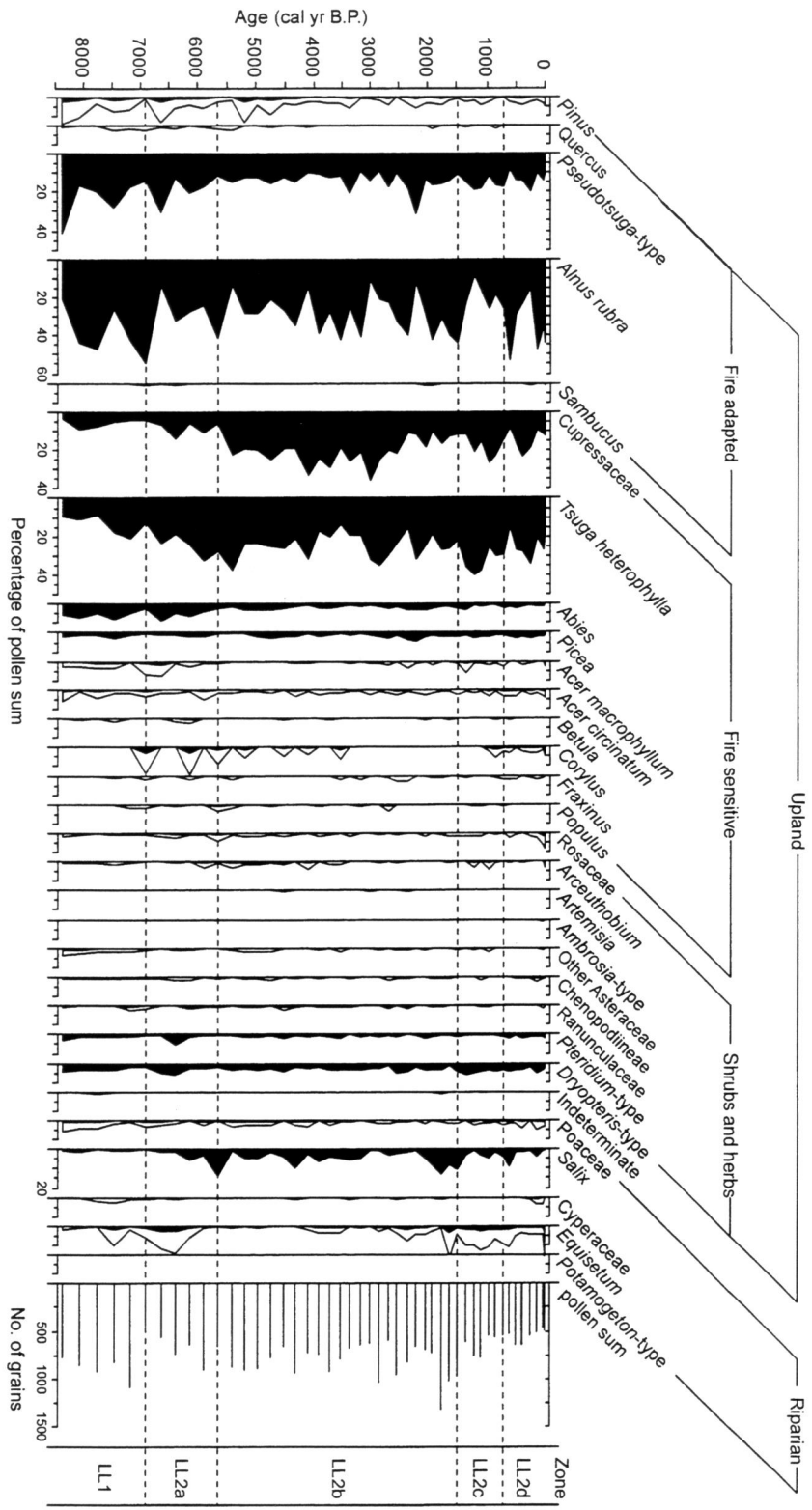


Figure 3.5. Pollen percentages of selected taxa from Lost Lake plotted against age. Taxa are designated as fire-adapted or fire-sensitive (Minore, 1979; Agee, 1993; Pojar and Mackinnon, 1994). Open pollen curves are a five-fold exaggeration of black curves. Horizontal lines mark pollen-zone boundaries based on a constrained cluster analysis (CONISS; Grimm 1988).

Subzone LOL 2b (ca. 5600 to 1450 cal yr B.P.) shows mean percentages of *Tsuga heterophylla* (24%), *Alnus rubra* (29%) and Cupressaceae (18%), with a diminished presence of *Pseudotsuga*-type pollen from Zone LOL 2a (14%). Continued presence of *Salix* pollen (3%) suggests the persistence of a well-vegetated riparian area around the lake. This pollen spectra resembles modern pollen collected from *Tsuga heterophylla* forests in the western Cascade Range of Oregon (Minckley and Whitlock, 2000) (Table 3.2, Fig. 3.5).

Subzone LOL 2c (ca. 1450 to 700 cal yr B.P.) is characterized by a mean decrease in *Alnus rubra* (20%). Mean-zone increases in *Tsuga heterophylla* (33%), Cupressaceae pollen (18%), and *Dryopteris*-type spores (4%) suggest a more closed forest than before. This zone is similar to modern pollen samples from coastal British Columbia (Pellatt et al., 1997), where closed mesic forests of western hemlock and western red cedar dominate, with Douglas-fir on drier sites and red alder growing in riparian areas.

Subzone LOL 2d (ca. 700 cal yr B.P. to present) features mean percentages of *Alnus rubra* (29%), *Tsuga heterophylla* (26%), Cupressaceae (16%), with some *Pseudotsuga*-type (14%). *Dryopteris*-type spores (4%) indicate a closed forest canopy. High values of *Alnus rubra* and increases in Rosaceae pollen (> 1%) are probably associated with increases in shade-intolerant shrubs and alder following the A.D. 1933 fire. This zone is characteristic of the moist *Tsuga heterophylla* forest of coastal Oregon and Washington (Franklin and Dyrness, 1988; Minckley and Whitlock, 2000).

CHAR data from the long core were decomposed using a variety of background window widths and threshold-ratio values. Window widths < 300 years resulted in a charcoal background component that tracked the CHAR so closely that small fluctuations in the large A.D. 1929 peak were identified as several distinct fire episodes. Window widths > 900 years generalized the data and obscured what were probably important differences in CHAR in the middle and late Holocene. Window widths between 300 and 900 years produced similar appearing background curves and an intermediate window width of 600 years was selected as most appropriate (Fig. 3.6). A range of threshold-ratio values from 1.00 to 1.30 was evaluated to determine an optimum value for identifying peaks with a 600-year-background window (Fig. 3.6). Threshold-ratio values between 1.00 and 1.19 identified the seven prominent peaks but also identified up to three additional peaks. Threshold-ratio values of 1.21 to 1.23 also identified an additional peak. Threshold-ratio values of 1.24 and greater failed to identify one of the seven known or suspected fire-related peaks. A threshold-ratio value of 1.20 was therefore selected because it identified the seven pre-selected peaks and no others (Fig. 3.6). Fire-episode frequency was calculated using a 2000-year window and plotted as number of fires per 1000 years.

Visual inspection of the CHAR record indicated distinct trends in fire episode frequency over the last ca. 8380 years (Fig. 3.7). In Interval 1 (ca. 8380 to 5400 cal yr B.P.) fire episode occurrence was consistent at four to five episodes / 1000 years, with the highest fire activity at ca. 8200 cal yr B.P. Average time between episodes was 220 ± 30

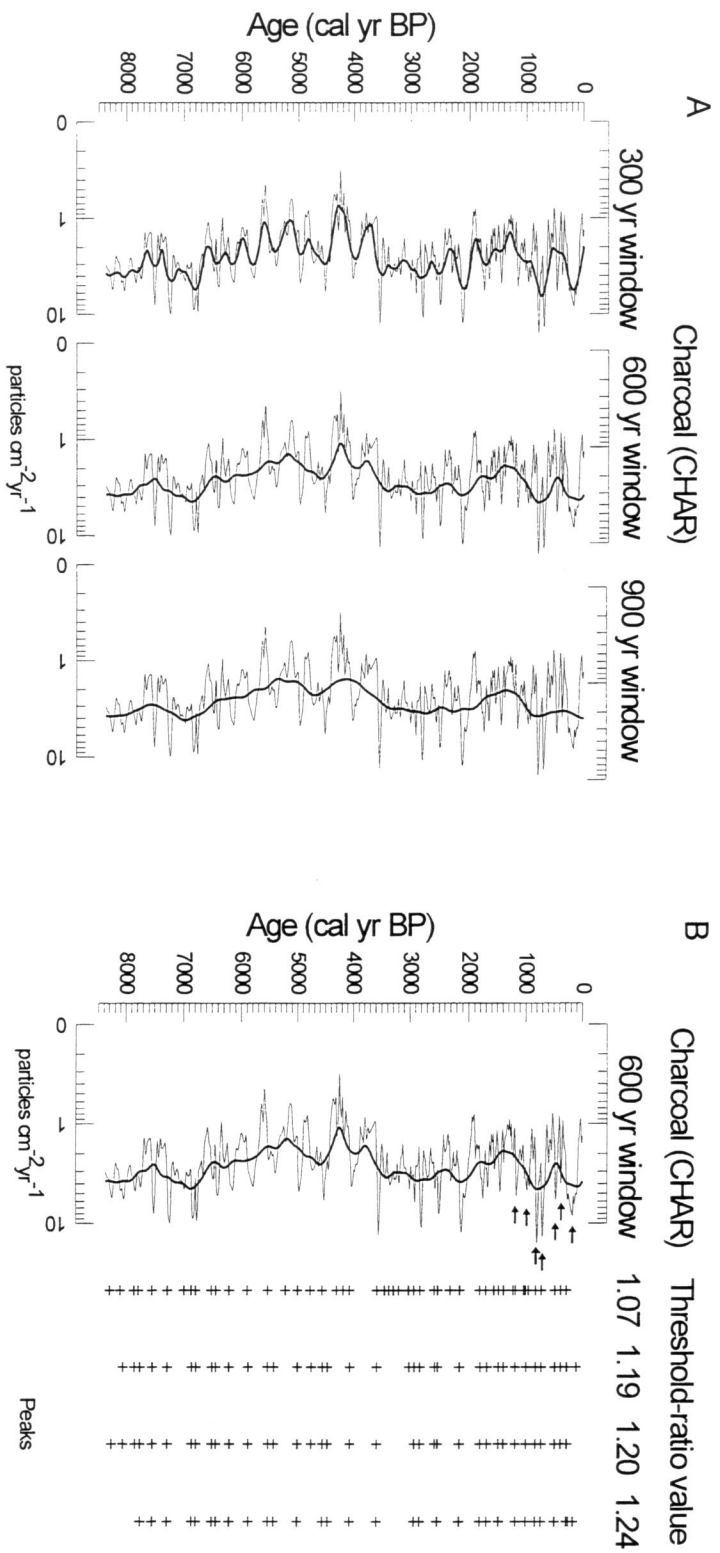
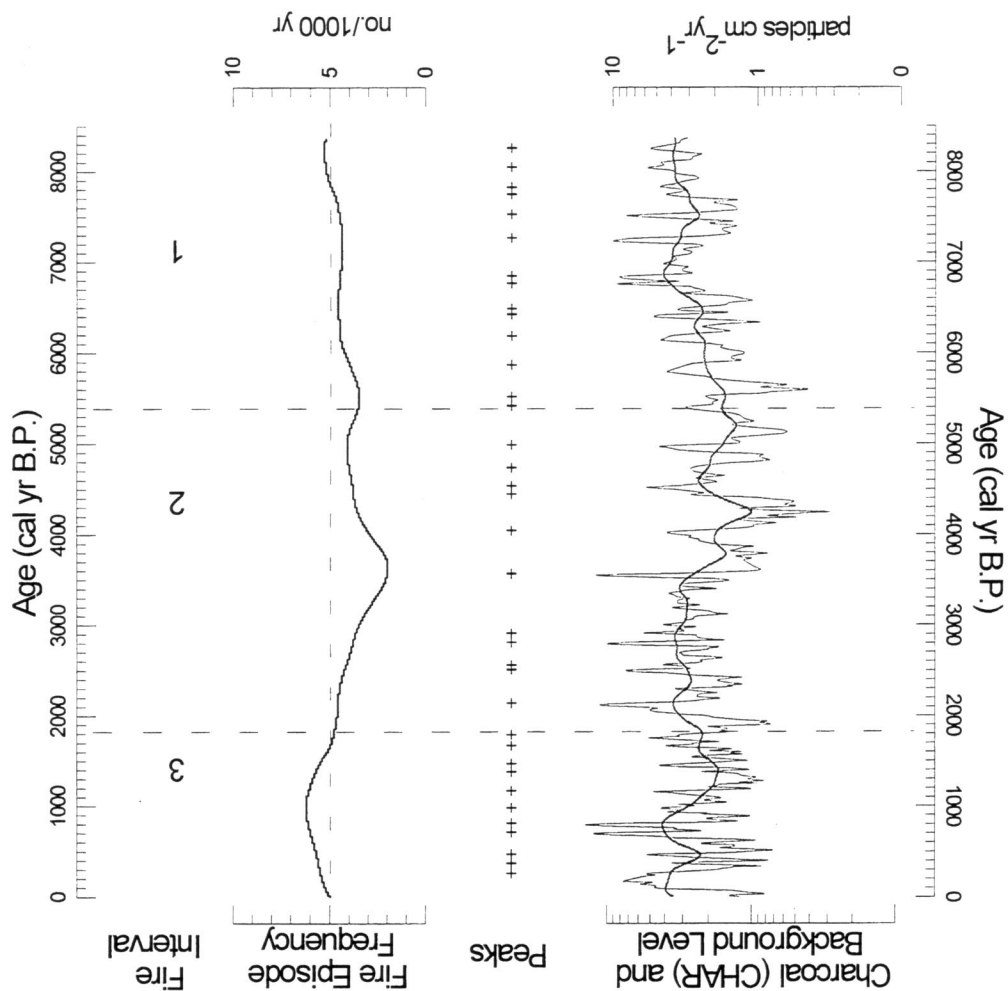


Figure 3.6. A. Comparison of window widths of 300, 600, and 900 years in defining background levels of log-transformed CHAR for Lost Lake. CHAR values interpolated to a constant time step. The 600-year window width was selected for the fire-history reconstruction. B. Comparison of threshold-ratio values of 1.07, 1.19, 1.20, and 1.24 in the detection of peaks in log-transformed CHAR using a background window width of 600 years. High CHAR values identified as local fire episodes, and used to calibrate the rest of the record, are marked with arrows. Peaks (+) indicate a fire episode. A threshold-ratio value of 1.20 was selected for the fire-history reconstruction.

Figure 3.7. Log-transformed CHAR, background level, peaks, and fire episode frequency for Lost Lake using a 600-year background window width and a 1.20 threshold-ratio value. The major fire intervals are noted: Interval 1 (ca. 8380 to 5400 cal yr B.P.), Interval 2 (ca. 5400 to 1800 cal yr B.P.), and Interval 3 (1800 cal yr B.P. to present).



years (mean $\pm$ standard error of the mean) (range 60-420, $n = 13$). During Interval 2 (ca. 5400 to 1800 cal yr B.P.) fire episodes were less common, two to four episodes/1000 years, with four fire-free periods (ca. 5400 to 4990 cal yr B.P., ca. 4450 to 4050 cal yr B.P., ca. 4040 to 3570 cal yr B.P., and ca. 3560 to 2910 cal yr B.P.) that were 400 years or greater. An average of 300 ± 50 yr (range 50-660, $n = 12$) occurred between fire episodes, with the lowest frequency of the record centered at ca. 3500 cal yr B.P. In Interval 3 (ca. 1800 cal yr B.P. to present), fire episodes increased to between five and six episodes /1000 years, with the highest frequency at ca. 1000 cal yr B.P. The average time between fire episodes was 150 ± 20 years (range 90-2400, $n = 10$) (Fig. 3.7).

A test of homogeneity of (within-interval) variance of peak frequency was performed and the null hypothesis that the within-group variances were similar was not supported using Levene's test ($L = 5.255$, $p = 0.011$) (Levene, 1960). Such changes in variability among the intervals make it difficult to detect significant differences among group means (Underwood, 1997). However, the trends in the data do suggest a shift in the occurrence of fire episodes from more frequent in the Interval 1 (ca. 8380 to 5400 cal yr B.P.), to less frequent in Interval 2 (ca. 5400 to 1800 cal yr B.P.) and an increased fire episode frequency in Interval 3 (ca. 1800 cal yr B.P. to present).

Background CHAR levels show little variability through the record. Values were initially ca. three to four particles·cm⁻²·yr⁻¹ at 8380 cal yr B.P., then decreased to one to two particles·cm⁻²·yr⁻¹ by ca. 6200 cal yr B.P. From ca. 6200 to 3600 cal yr B.P. values remained low before increasing to three to four particles·cm⁻²·yr⁻¹ over the last 3600 cal yr B.P. with only a brief period, ca. 1600 to 1100 cal yr B.P. when background levels

were ca. two particles·cm⁻²·yr⁻¹ (Fig. 3.7). Beginning ca. 6800 cal yr B.P. charcoal production in the vicinity of Lost Lake decreased, implying less biomass consumed during fires, fewer fires in general, or a decrease in transport of charcoal to the lake. The increase in background CHAR after ca. 3600 cal yr B.P., likely reflects an increase in the production of charcoal and/or more effective transport and incorporation of charcoal into the lake sediment. This result implies more fire episodes during the last ca. 3600 years or increased precipitation and enhanced surface transport of sequestered charcoal within the watershed.

Discussion

The Holocene vegetation and fire history from Oregon Coast Range sites reveal the effects of climate on vegetation and fire occurrence. Pollen studies from Heusser (1960, 1985), Hebda (1983), Barnosky (1985), Wainman and Mathewes (1987), Brubaker (1991), Whitlock (1992), Worona and Whitlock (1995), and Grigg and Whitlock (1998) describe the response of forest vegetation to past climate changes west of the Cascade crest in the PNW. Changes in taxa are evident in nearly all sites during the course of the Holocene, and can be attributed to a large-scale climatic shift from warm, dry conditions to cool, wet conditions after ca. 6000 cal yr B.P. The discussion that follows will 1) identify the modern climate gradient in the Oregon Coast Range and situate Lost, Little, and Taylor lakes within that gradient; 2) compare the records from Lost, Little, and Taylor lakes in terms of their vegetation, fire, and climate history along the environmental gradient; and 3) examine a transect of pollen and charcoal records

along the Pacific slope to better understand the Holocene vegetation and fire history of the seasonal rain forest.

Environmental history of the Oregon Coast Range

Modern fire conditions and environmental gradients within the Oregon Coast Range

Weather regulates fuel moisture content and flammability of fuels as well as ignition sources (Chandler et al., 1983) and climate determines the length and severity of the fire season through variations in the timing and amounts of precipitation (Heyerdahl et al., 2002). Historically fires in the Oregon Coast Range occur from June through mid October in conjunction with increased temperature and decreased precipitation. Drying by easterly winds during the summer drought lowers fuel moisture to flammable levels (Huff and Agee, 1980; Agee and Flewelling, 1983; Chandler et al., 1983; Woodard et al., 1983). Two weather scenarios produce east-west pressure gradient conditions that cause dry east winds in the Oregon Coast Range (Schroeder and Buck, 1970; Agee, 1993). The first condition occurs when a trough is situated along the Oregon Coast. The second involves the development of high pressure east of the Cascade Range, which produces inflow of continental air from the east (Schroeder and Buck, 1970; Pickford et al., 1980). Both conditions provide diminished onshore flow and subsidence that leads to adiabatic warming of air descending the western slopes of the Coast and Cascade ranges resulting in lower relative humidity that, in turn, leads to drying of fuels over a few days or weeks (Huff and Agee, 1980).

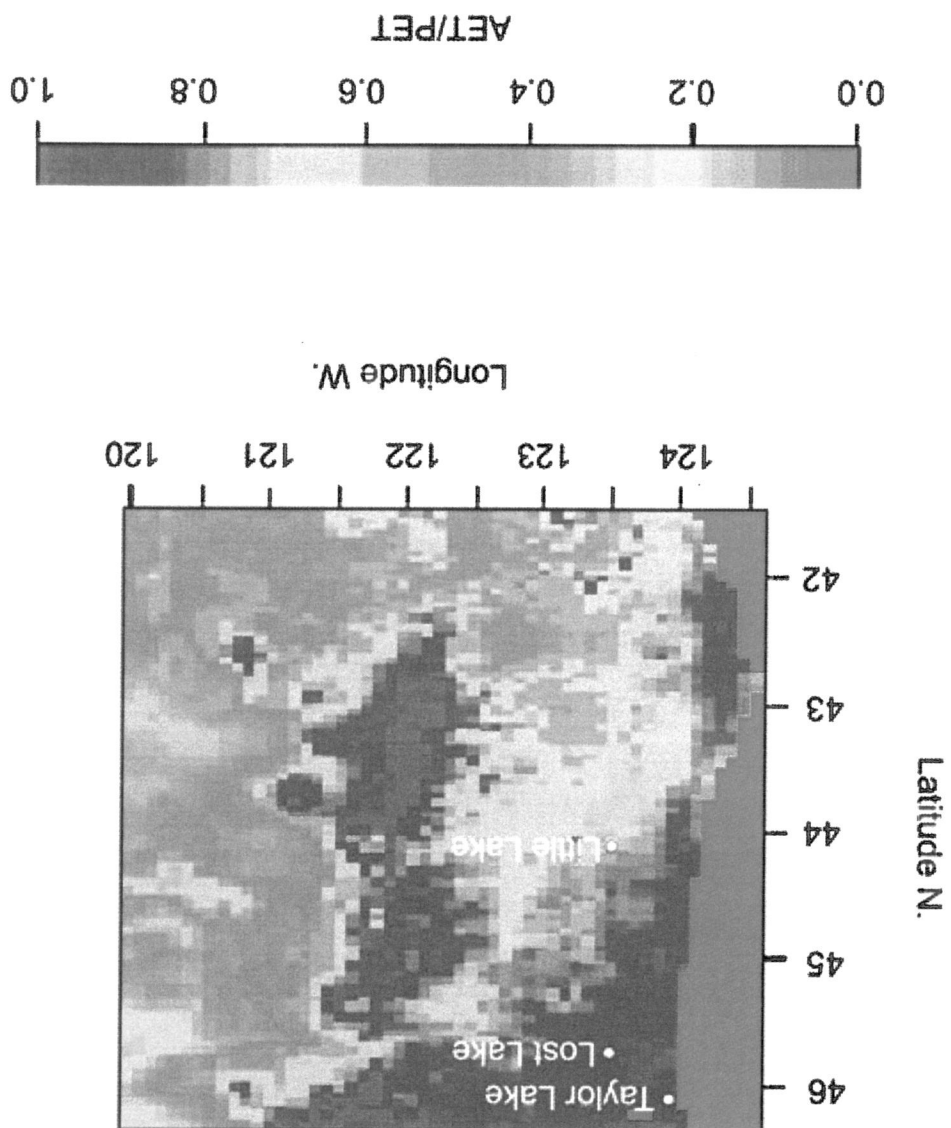
Vegetation determines the availability, condition, and arrangement of fuels in an area (Chandler et al., 1983; Agee, 1993). Fuel condition, or flammability, is determined by the fuel moisture content which, in the absence of east winds, remains high enough to discourage combustion. Moisture content that is equal to or below ca. 100% of dry weight in live fuels or ca. 20% of dry weight in dead fuels is required for combustion to take place (Chandler et al., 1983; Agee, 1993). Between A.D. 1985 and 1995 an average of 12.64 ± 9.11 , 13.20 ± 13.79 , and 6.18 ± 6.43 positively charged lightning strikes per year occurred in the 1° latitude by 1° longitude area surrounding Lost, Little and Taylor lakes respectively (WRCC, 1996). Lightning occurs frequently enough in the Oregon Coast Range to act as an ignition source (Agee, 1993; Impara, 1997).

Lost, Little, and Taylor lakes lie along an environmental gradient that gives each site unique climate conditions. The spatial variability in precipitation, seen as a latitudinal gradient from south to north in the Oregon Coast Range and seasonal rain forest in general, is explained by the regional-scale shift in storm tracks over the year (Alaback and Pojar, 1997). At the scale of individual watersheds, topographic differences evoke a non-uniform response to inter-annual scale variations in circulation patterns may occur (Mock, 1994; Hemstrom and Logan, 1986). The amount of effective moisture available during the summer fire season is a product of the amount of evapotranspiration that takes place in a particular watershed (Chandler et al., 1983). Watersheds, or specific slopes within a watershed, that experience effective moisture deficits during the dry season are more likely to have low fuel moistures and be more susceptible to fire (Schroeder and Buck, 1970; Agee and Flewelling, 1983; Agee, 1993).

A bioclimatic variable, the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET) (the Priestly-Taylor "alpha"; Prentice et al., 1992; Shafer et al., 2001; P. J. Bartlein, unpublished data 2002) was used to represent effective moisture availability for plants (Fig. 3.8). AET and PET were derived from an interpolated 25-km equal area grid of climate data from North America including adjustments for elevation. The climate data were based on A.D. 1951-1980 monthly temperature and precipitation station means (Thompson et al., 2000; Shafer et al., 2001). When "alpha" is close to 1.0, the AET value is close to the PET value, which is an indication of high effective moisture. When "alpha" is < 1.0 , or AET is lower than PET, it is an indication of less evaporation taking place than could potentially occur and signifies conditions of low effective moisture (or greater drought stress). Forests in an area with a high moisture index should experience less moisture stress during the summer months than forests with a lower moisture index. Lower moisture stress during the summer maintains high levels of live fuel-moisture, inhibiting conditions conducive for fire. Conversely, high moisture stress during the summer allows live fuels to dry increasing the likelihood of fire.

The latitudinal gradients of precipitation and net radiation in the Oregon Coast Range are evident in the variations in annual AET / PET from site to site. For example, Little Lake experiences 21% less precipitation while having 2°C higher mean July temperatures than Lost Lake. The result is a higher annual AET (642.38 mm) and a moisture index of 0.72 at Little Lake, compared to 0.89 at Lost Lake where calculated AET is lower (623.57 mm) (Thompson et al., 2000; Shafer et al., 2001; P. J. Bartlein, unpublished data 2002) (Fig. 3.8). Thus, the moisture available for plants is greater at

Figure 3.8. Moisture index of western PNW as derived from AET / PET and mapped on a 25 km equal area grid of climate data for North America (Thompson et al., 2000; Shafer et al., 2001; P. J. Bartlein, unpublished data 2002).



Lost Lake than at Little Lake. Moisture index values at Taylor Lake (0.89) imply that these forests have high live-fuel moisture contents and live-fuel moistures similar to Lost Lake. Taylor Lake also experiences frequent fog which provides moisture and high humidity during the summer months (Franklin and Dyrness, 1988; Alaback and Pojar, 1997). The study sites exemplify the environmental gradient within the Oregon Coast Range with Taylor Lake being the most mesic and least susceptible to fire, and Little Lake the least mesic and most susceptible to fire as a result of their locations.

Environmental history on orbital to millennial time scales

The climate of the PNW has varied through the Holocene as a result of changes in the latitudinal seasonal distribution of insolation and ocean-atmospheric interactions, that in turn control the strength and location of circulation features such as the STH. The long-term variations in the seasonal cycle of insolation result from changes in the timing of perihelion and tilt of the Earth's axis (Berger and Loutre, 1991; Kutzbach et al., 1993b). Greater-than-present summer insolation between ca. 14,000 and 8000 cal yr B.P. likely increased summer temperatures, decreased effective moisture, and strengthened the influence of the STH in summer (Bartlein et al., 1998). The result of these shifts was a warmer drier climate in northwestern North America than today (Thompson et al., 1993; Whitlock and Grigg, 1999). Decreased summer insolation since ca. 8000 cal yr B.P. has weakened the STH and allowed more storm systems to penetrate the region, and created cooler summers than before (Whitlock, 1992; Thompson et al., 1993; Worona and

Whitlock, 1995). The long-term climate history can be generalized as follows: a warm dry early-Holocene period (ca. 10,500 to 6700 cal yr B.P.), was followed by a period of

decreased temperatures and increased precipitation in the mid Holocene (ca. 6700 to 2900 cal yr B.P.) in turn followed by establishment of modern conditions in the late Holocene (ca. 2900 cal yr B.P. to present) (Worona and Whitlock, 1995; Hebda and Whitlock, 1997; Long et al., 1998). Heusser (1985) proposed a similar climate sequence for the Holocene with some fluctuations in moisture during the "Hypsiothermal" or mid Holocene (ca. 8500 to 3000 C¹⁴ yr B.P.), in Alaska and coastal British Columbia. Drier, warmer conditions in the early Holocene affected the vegetation and frequency of fire episodes in the Oregon Coast Range. At Lost Lake disturbance-adapted species, such as red alder and Douglas-fir, were abundant near the site, as well as xerophytic species, such as fir, pine, and oak (Fig 3.9). As the time between fire episodes lengthened the abundance of fire-sensitive species, such as western hemlock and western red cedar, increased, and fire-adapted species, such as red alder, Douglas-fir, fir, pine and oak, decreased (Fig. 3.5, 3.9). Despite the relatively long periods between fires (ca. 200 years), the composition of the forest is consistent with warm, dry conditions at Lost Lake. Increases in western red cedar, along with the continued presence of western hemlock and a decline in Douglas-fir and fir, are consistent with the climate becoming cooler and wetter during the mid Holocene. Periods of abundant *Alnus rubra* pollen percentages (i.e., ca. 5650, 3920, 3540, and 3170 cal yr B.P.) may have been times of local fires. The average time between fire episodes increased from that of the early Holocene, likely in response to cooler wetter conditions.

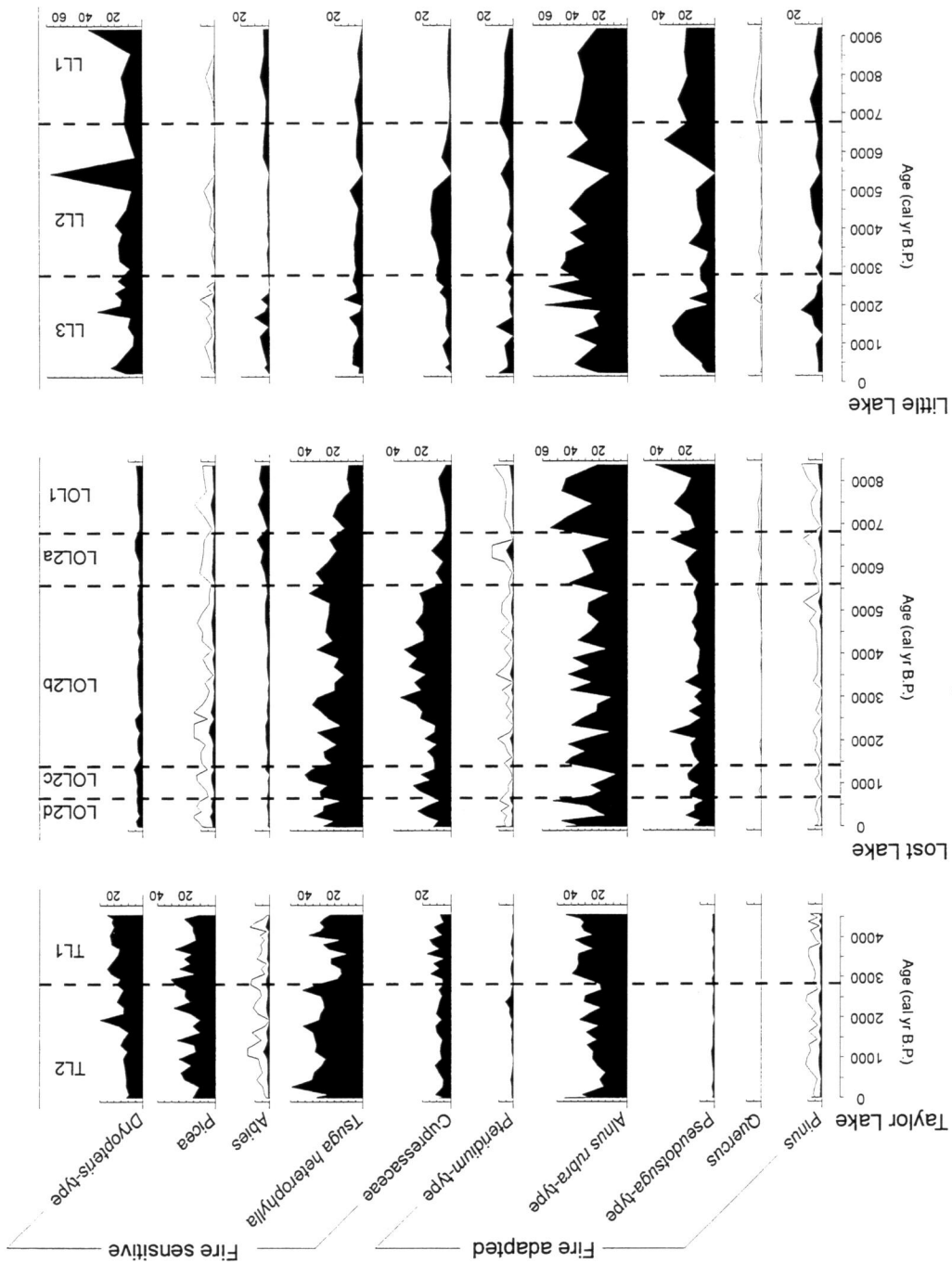


Figure 3.9. Pollen percentage rates for selected taxa from Taylor Lake, Lost Lake and Little Lake plotted against the age for each core. Taxa are designated as fire-adapted or fire-sensitive (Minor, 1979; Agee, 1993; Pojar and MacKinnon, 1994). Horizontal lines mark pollen-zone boundaries based on a constrained cluster analysis (CONISS; Grimm 1988). The zone boundary between TL1 and TL2 is at ca. 2900 cal yr B.P. (Long and Whitlock 2002). The zone boundary between LL1 and LL2 is ca. 6850 cal yr B.P., and between LL2 and LL3 is ca. 2750 cal yr B.P. (Long et al., 1998).

In the late Holocene, forest composition remained dominated by mesophytic species, such as western hemlock and western red cedar, although red alder was abundant at ca. 1940, 1480, 600 cal yr B.P. Fire episodes became more frequent beginning ca. 1800 cal yr B.P. and the frequency of fire episodes remained consistent to the present day. The period from ca. 1450 to 700 cal yr B.P. showed a decrease in red alder despite several charcoal peaks during that time (Fig. 3.5, 3.9) suggesting that fires were not widespread in the watershed or of low severity. An increase in *Alnus rubra* and a decrease in *Tsuga heterophylla*, *Pseudotsuga*-type, and Cupressaceae pollen occurred in association with the A.D. 1933 Wolf Creek fire.

The Little Lake fire history previously described by Long (1996) used a linear interpolation deposition model to calculate sediment accumulation rates. This age model was replaced by a polynomial age model in Long et al. (1998) for the CHAR analysis, but sediment influx was still calculated using the linear interpolation model of Long (1996). In this study sediment influx was calculated using the polynomial age model of Long et al. (1998). The results did not alter the interpretation of the Little Lake record but did provide a smoother transition of sediment deposition rates within the core. The data presented below reflects the use of the proper sediment-deposition model. It should also be noted that the identification of peaks in the last ca. 1200 cal yr B.P. in the Little and Taylor Lake CHAR records were explicitly used as a means of selecting background and threshold-ratio values for the rest of each record (see Lost Lake Fire history record, Long et al., 1998; Chapter 2).

The Little Lake pollen record of the last ca. 9000 years indicates the presence of Douglas-fir forests during the early Holocene, with red alder growing on disturbed sites and oak present on the driest sites (Worona and Whitlock, 1995; Long et al., 1998) (Fig. 3.9). The average time between fire episodes was 110 ± 20 years (range 30-300, $n = 17$) (Fig. 3.10). During the middle Holocene, increases in shade-tolerant, fire-sensitive species, including western hemlock, western red cedar, and Sitka spruce, along with the continued presence of Douglas-fir and red alder, suggests forest closure in wetter areas, while drier slopes supported xerothermic species. Fire episodes occurred on average every 150 ± 20 years (range 30-320, $n = 28$). In the late Holocene, Douglas-fir and red alder were still major constituents of the forest, but increases in fire-sensitive Sitka spruce and grand fir indicate undisturbed mesophytic forest stands. The average time between fire episodes increased to 210 ± 30 years (range 60-400, $n = 12$) and is similar to present-day values in the central Oregon Coast Range (Teensma et al., 1991; Impara, 1997). The vegetation and fire history at Taylor Lake spanned the last ca. 4600 years (Chapter 2) (Fig. 3.9). During the mid Holocene, red alder and Douglas-fir were present and probably confined to disturbed sites. Western red cedar, Sitka spruce, and western hemlock occupied cooler, wetter slopes in the watershed. The interval between fire episodes averaged 140 ± 40 years (range 20-460, $n = 10$) (Fig. 3.10). During the late Holocene, forest stands were dominated by fire-sensitive species, such as western hemlock, Sitka spruce, and western red cedar. Douglas-fir became a minor forest constituent but red alder was still prominent, probably in lowland areas and recently

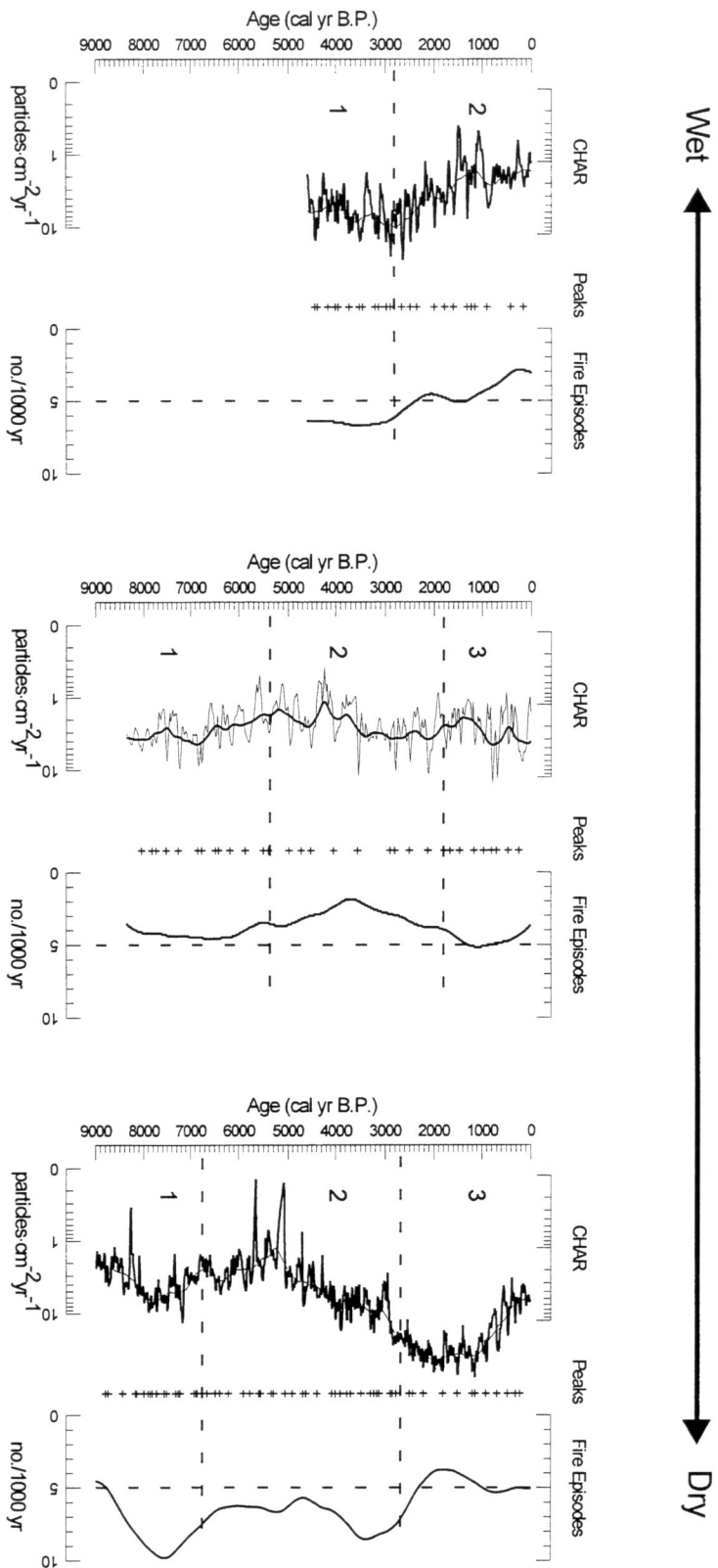


Figure 3.10. Comparison of fire-episode frequency on millennial time scales at Taylor Lake, Lost Lake, and Little Lake (Long et al., 1998). Horizontal lines mark the boundary between fire intervals. The interval boundaries are: ca 2900 cal yr B.P. at Taylor lake; ca. 5400 and ca. 1800 cal yr B.P. at Lost Lake; and ca. 6750 and ca. 2750 cal yr B. P. at Little Lake.

disturbed slopes. The average time between fire episodes increased to 220 ± 30 years (range 80-430, $n = 13$), similar to that in *Picea sitchensis* forests today (Agee, 1993). Lost, Little, and Taylor lakes demonstrate that at millennial scales the shifts in forest composition and fire-episode frequency are consistent with warm, dry conditions in the early Holocene, cooling in the mid Holocene, and the establishment of present-day climate in the last ca. 2000 years (Whitlock, 1992; Thompson et al., 1993; Whitlock and Hebb, 1997).

The pollen records show the influence of the environmental differences among Taylor, Lost, and Little lakes on Holocene vegetation (Fig. 3.9). The percentages of mesophytic taxa, such as *Picea* and *Tsuga heterophylla*, are highest at the wettest site, Taylor Lake, and lowest at the driest site, Little Lake. In contrast, percentages of xerophytic taxa, such as *Pinus*, *Quercus* and *Pseudotsuga*-type, show the opposite trend with higher values at Little Lake and low values or absence at Taylor Lake (Fig. 3.9). Although each record has unique qualities, the fire history at Lost, Little, and Taylor lakes share common features. Fire-episode frequency declined from the early Holocene to the present, and this decline was accompanied by the development of forests of mesophytic and fire-sensitive species. The change in fire-episode frequency and forest composition at the regional scale strongly points to climate as a control.

Environmental history at submillennial time scales

Over the last ca. 10,000 years, submillennial-scale variations in climate have been superimposed on the long-term variations in the seasonal cycle of insolation (Bartlein, 1997). Examples include the climate reversal at ca. 8200 cal yr B.P. recorded in the

North Atlantic and Greenland as well as other regions (Alley et al., 1997), the Medieval Climatic Anomaly, ca. A.D. 900 to 1200, noted in various places in Europe and North America (Stine, 1994; Hughes and Diaz, 1994) and the Little Ice Age, ca. A.D. 1450 to 1850, a cool period in many parts of the world (Grove, 1988). Even shorter time-scale variations in climate have been noted in paleoclimatic records, such as those represented by the interannual El Niño/Southern Oscillation (ENSO) variations (Cayan et al., 1999; Diaz and Markgraf, 2000) and the decadal Pacific Decadal Oscillation (PDO) (Mantua et al., 1997). Changes in phase, positive or negative, of ENSO and the PDO have been associated with precipitation variations in the PNW at inter-annual and decadal scales respectively (Mantua et al., 1997; Cayan et al., 1999; Heyerdahl et al., 2002). For example, during El Niño (La Niña) years, or a negative (positive) ENSO Index, the PNW receives less (more) precipitation than the ca. 100-year average (McCabe and Dettinger, 1999). During the positive (negative) phase of the PDO, the PNW receives less (more) precipitation than the decadal average over the last century (Mantua et al., 1997).

On centennial time scales, Weisberg and Swanson (2003) identified two periods of extensive fires, A.D. 1400s to ca. 1650 and A.D. 1801 to ca. 1925 in tree-ring studies in western Oregon and Washington. The regional synchronicity of these fires suggests times of intensified summer drought and/or decreased winter precipitation (Berkley, 2000; Weisberg and Swanson, 2003).

To identify centennial-scales trends in fire episode occurrence in the Oregon Coast Range over the last ca. 8300 cal yr B.P., the timing of fire episodes at the three lake sites was compared (Fig. 3.11). Episodes that began within 20 years of each other were

Inferred Climate	warm and dry	cool and wet	increased seasonal drought	decreased seasonal drought	modern climate
	widespread Douglas fir, red alder	increased w. hemlock, w. red cedar	increasing frequency	decreasing frequency	increasing frequency
Vegetation					
Fire History	high frequency	low frequency	increasing frequency	decreasing frequency	increasing frequency

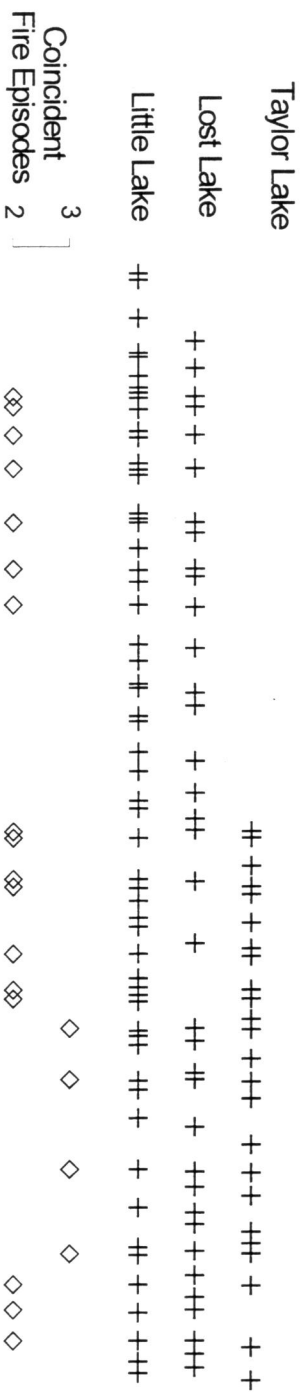


Figure 3.11. Reconstructed climate and fire history from Taylor, Lost, and Little lakes. Peaks in each record marked with (+). Fire episodes marked (◇) are registered at 2 or 3 sites.

considered to be synchronous, given the uncertainties associated with chronologies based on radiometric dating methods. Twenty years or two time steps was selected because that resulted in a fifty-year window (i.e., 20 years prior, the current 10 year interval, and 20 years post) to identify coincident CHAR peak starts. It was also similar to the smoothing used by Weisberg and Swanson (2003). Fire episodes at all three locations were noted at ca. 1150, 1800, 2500, and 2900 cal yr B.P. Fire episodes occurred at Little and Lost Lakes at ca. 470, 4060, 6200, 6480, 6850, 7260, 7530, 7750, and 7830 cal yr B.P.; fire episodes occurred at Taylor and Little Lakes at ca. 900, 3130, 3220, 3490, 4000, and 4390 cal yr B.P., and at Taylor and Lost Lakes at 4440 cal yr B.P. Thirty-three percent of the fires at Little Lake (19 of 57) were shared by other sites, 40% (14 of 35 fire episodes) of those at Lost Lake, and 48% (11 of 23 fire episodes) at Taylor Lake were also found in the other sites.

Times of synchronous fire activity suggest regional climate played an important role in drying fuels and providing ignitions sources at all three sites. For example, during the period from ca. 8200 to 6900 cal yr B.P. five of the seven fire episodes recorded at Lost Lake, a mesic site, were also recorded at Little Lake, the most xeric site. The period from ca. 4400 to 2900 cal yr B.P., which includes the record from Taylor Lake, the most mesic site, also showed a cluster of fire episodes at all three sites (Fig 3.11). These particular periods likely mark drought events severe enough to override the environmental differences among sites. In contrast, the periods from ca. 6100 to 4500 cal yr B. P. and ca. 2900 to 1000 cal yr B. P. showed asynchronous fire activity, implying that climate conditions that promoted fires were more localized (Fig. 3.11).

Periods of closely timed fire episodes could have been periods when annual precipitation was low. Graumlich (1993) used tree-ring data to reconstructed annual precipitation in the central Sierra Nevada for the last ca. 1000 years and identified several multidecadal drought periods (e.g., ca. 1020 to 1070 cal yr B.P. and ca. 1250 to 1360 cal yr B.P.). Graumlich and Ingram (2000) suggest that droughts of this length occurred through out much of western United States over the last 1000 years and may represent a persistent northward shift of the midlatitude storm track over North America during this period. Heyerdahl et al. (2002) connected fire activity in northeastern Oregon with short-term decreases in precipitation following El Niño years (Redmond and Koch, 1991). It is reasonable to assume that similar variability in seasonal precipitation has existed in the Oregon Coast Range. On decadal time-scales variability in the north Pacific sea surface temperatures (Mantua et al., 1997; Cayan et al., 1999) may be connected to shifts in precipitation in the Oregon Coast Range. The fire-episode records from Little and Lost Lakes suggest that only severe droughts allowed burning at Lost Lake, whereas less intense drought created fire conducive conditions at Little Lake.

Fire episodes have occurred at each lake independent of the others, suggesting local variability in fuel moistures and ignition. However, despite the distinct moisture gradient in the Oregon Coast Range, there have been several periods, e.g., 8200 to 6900 cal yr B.P. and 4500 to 3000 cal yr B.P., when fire episodes were more common among all sites. Climate models that project future changes in precipitation (Leung and Ghan, 1999) and moisture index (Shafer et al., 2001) in the PNW imply that the present latitudinal moisture gradient will persist in the future. Based on the information on past

fire activity at Lost, Little, and Taylor lakes, only extreme drought events will promote widespread fire susceptibility throughout the Oregon Coast Range.

Anthropogenic controls on Oregon Coast Range fire regimes

Humans have inhabited the northwest Pacific coast for the last ca. 8000 years or more (Suttles and Ames, 1997). Population estimates for the PNW coast and interior valleys at the time of European contact in the ca. A.D. 1700s were between 30,000 and 60,000 people, but these populations declined rapidly with the introduction of disease (Boyd, 1999; Suttles and Ames, 1997). By the A.D. 1860s, most Native people in the PNW had been relocated to reservations (Zenk, 1990). Fire was probably used as a tool for maintaining open space to aid in hunting and warfare in prehistoric times (Pyne, 1982; 1991; 1997; Boyd, 1999; Whitlock and Knox, 2002) but the importance of anthropogenic burning at Lost, Little, and Taylor lakes is not clear. Most Native

subsistence activities in coastal areas were focused on maritime resources (Boyd, 1999). In this study ignition sources for past fires are inferred to be largely from lightning in the absence of ethnographic or historic evidence of Native burning in the Oregon Coast Range. Human-set fires may have occurred but the ability to spread depended on fuel conditions.

It is possible to examine the paleoecological evidence from Lost, Little, and Taylor lakes and test for the impact of widespread human burning. Archeological

evidence suggests that significant economic and cultural development by the Oregon coast peoples began ca. 3000 cal yr B. P. (Ross, 1990; Suttles and Ames, 1997). If Native peoples had been actively burning forests, the pollen records would show a dominance of

disturbance-adapted taxa, such as *Alnus rubra* and *Pseudotsuga*-type, with the development of young successional stands. The charcoal records would likely register lower CHAR background values (lower fuel loads) and more frequent fires from ca. 3000 cal yr B.P. to present than before.

In contrast to this model, the vegetation reconstructions from Little and Lost lakes indicate increases in late-successional and fire sensitive taxa, such as western hemlock, western red cedar and Sitka spruce, from ca. 6500 cal yr B.P. to the present. At Taylor Lake, the shift to western hemlock and Sitka spruce forests occurs after ca. 3000 cal yr B.P. (Fig. 3.9). Although red alder was present at each site, large portions of the B.P. The background values from Lost Lake show consistently low values and the record from Taylor Lake shows declining values beginning ca. 3000 years ago. Fire-episode frequency does not increase at Little or Taylor Lakes although it rises at Lost Lake at ca. 3000 cal yr B.P. (Fig. 3.10). The average time between fire episodes did not shorten as has been observed in other parts of North America where Native peoples regularly burned forests (Pyne, 1982; 1997). It is impossible to rule out the presence of small, low-intensity burning set by Native peoples but such events and their ecological impact are not registered in either the pollen or charcoal data.

In contrast, a dramatic change occurred in the fire regime when Euro-American activities began. Logging and slash burning caused fires at Lost, Little, and Taylor lakes, as well as at other locations in the Oregon Coast Range (Morris, 1934; Juday, 1977,

Teensma et al., 1991; Long et al., 1998; Chapter 2). Widespread fires, such as the Tillamook fires of A.D. 1933, 1939, 1945, and 1951, and the Oxbow Fire of A.D. 1966 in the central Oregon Coast Range, were started by logging activities and spread by easterly winds and low relative humidity (Oregon Department of Forestry, 1975; Juday, 1977). Juday (1977), Teensma et al. (1991) and Impara (1997) used tree-ring and stand-age data to show that the east-to-west pattern of these fires resembled prehistoric burn patterns and suggested similar weather conditions. Clearly, anthropogenic activities are an important source of ignition in the last ca. 150 years, but the role of humans does not diminish the importance of climatic conditions as critical factors in the initiation and spread of fires.

Environmental history of the seasonal rain forests along the Pacific slope

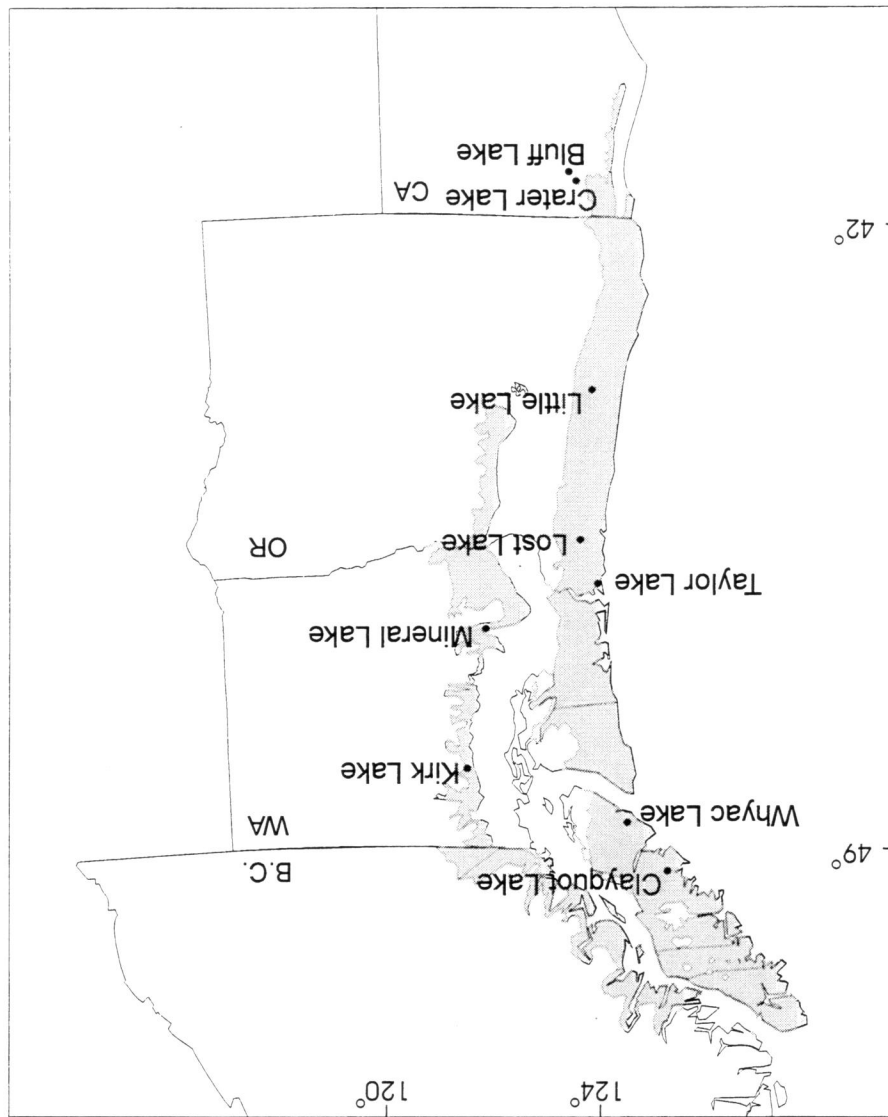
The vegetation and fire history from Lost, Little, and Taylor lakes was compared to similar reconstructions in other parts of the seasonal rain forest. Previous studies by Heusser (1960, 1985; Whitlock, 1992; Hebda and Whitlock, 1997) surveyed records from multiple sites and reconstructed postglacial vegetation changes in the PNW. Other studies have examined evidence for fire in seasonal rain forests from multiple sites (Tsukada et al., 1981; Dunwiddie, 1986; Mohr et al., 2000; Brown and Hebda, 2002) but none at a regional scale. This regional synthesis includes vegetation and fire reconstructions from pollen and charcoal records from Vancouver Island (Gavin, 2000; Gavin et al., 2003; Brown and Hebda, 2002), the Washington Cascade Range (Cwynar, 1987), the Puget Lowland (Tsukada et al., 1981), and the Klamath Mountains of Northern California (Mohr et al., 2000) (Table 3.3, Fig. 3.12). Gavin (2000) and Gavin et al.

TABLE 3.3
Seasonal Rain Forest Study Sites used in Regional Comparison

Site	Location, elevation	Lake size	Charcoal size analyzed	Method of analysis ^a
Clayoquot Lake, BC	Lat. 49° 15' N Long. 125° 30' W elev. 17 m	47 ha	150 -500 µm	Macroscopic sieving
Gavin (2000)	Long. 125° 30' W elev. 17 m			
Gavin et al. (2003)	Long. 124° 51' W elev. 15 m			
Brown and Hebda	Long. 124° 51' W elev. 15 m	2.5 ha	150-500 µm	Macroscopic sieving
Wyhac Lake, BC	Lat. 48° 40' N Long. 124° 51' W elev. 15 m			
Kirk Lake, WA	Lat. 48° 14' N Long. 121° 37' W elev. 190 m	1 ha	>50 µm	Pollen slide
Cwynar (1987)	Long. 121° 37' W elev. 190 m			
Mineral Lake, WA	Lat. 46° 44' N Long. 122° 12' W elev. 436 m	120 ha	> 44 µm	Pollen slide
Tsukada et al. (1981)	Long. 122° 12' W elev. 436 m			
Taylor Lake, OR	Lat. 46° 06' N Long. 123° 54' W elev. 4 m	4 ha	>125µm	Macroscopic sieving
Chapter 2	Long. 123° 54' W elev. 4 m			
Lost Lake, OR	Lat. 45° 49' N Long. 123° 35' W elev. 460 m	6 ha	>125µm	Macroscopic sieving
This study	Long. 123° 35' W elev. 460 m			
Little Lake, OR	Lat. 44° 10' N Long. 123° 34' W elev. 210 m	2 ha	>125µm	Macroscopic sieving
Long et al. (1998).	Long. 123° 34' W elev. 210 m			
Crater Lake, CA	Lat. 41° 24' N Long. 122° 35' W elev. 2288 m	0.5 ha	>125µm	Macroscopic sieving
Mohr et al. (2000)	Long. 122° 35' W elev. 2288 m			
Bluff Lake, CA	Lat. 41° 20' N Long. 122° 33' W elev. 1981 m	0.5 ha	>125µm	Macroscopic sieving
Mohr et al. (2000)	Long. 122° 33' W elev. 1981 m			

^aMethods described in Whitlock and Larson (2002).

Figure 3.12. Location of seasonal rain forest sites discussed in text. Shading depicts extent of seasonal rain forest bioregion (Alaback and Pojar, 1997).



(2003) described an 1800-yr-long fire history at Clayoquot Lake in central Vancouver Island (Fig. 3.12). They extended the fire reconstruction record back to ca. 11,000 cal yr B.P. with soil charcoal evidence (Gavin et al., 2003). The lake-sediment record Gavin (2000) identified the period of ca. 1700 to 1200 cal B.P. as one with frequent fires. The soil-charcoal record identified the periods from ca. 3000 to 2000 cal yr B.P. and 11,000 and 9000 cal yr B.P. as intervals of frequent fire (Gavin et al., 2003). Areas affected by fire tended to be dry, southern exposure slopes that supported Douglas-fir, in contrast with cool northern slopes that experienced fewer fires and were dominated by western hemlock, western red cedar, and Sitka spruce (Fig. 3.13).

Brown and Hebda (2002) reconstructed fire history using macroscopic charcoal analysis at ca. 10 cm (ca. 300 years) intervals from Wyhac Lake on the western coast of Vancouver Island (Fig 3.12). They inferred a high fire period from ca. 12,000 to 7000 cal yr B. P. in association with forests of disturbance-adapted red alder and the presence of Douglas-fir. After ca. 7000 cal yr B.P., fires became infrequent and forests were composed of Sitka spruce, western hemlock and western red cedar (Fig 3.13).

Tsukada et al. (1981) at Mineral Lake and Cwynar (1987) at Kirk Lake (Fig 3.12) reconstructed fire history by examining microscopic charcoal particles during pollen analysis. The resolution of the record did not permit fire events to be detected but a regional trend of high fire frequencies in the early Holocene, ca. 11,000 to 6000 cal yr B.P. at Mineral Lake and ca. 12,500 to 8000 cal yr B.P. at Kirk Lake were associated with Douglas-fir and red alder. The middle and late Holocene showed western hemlock

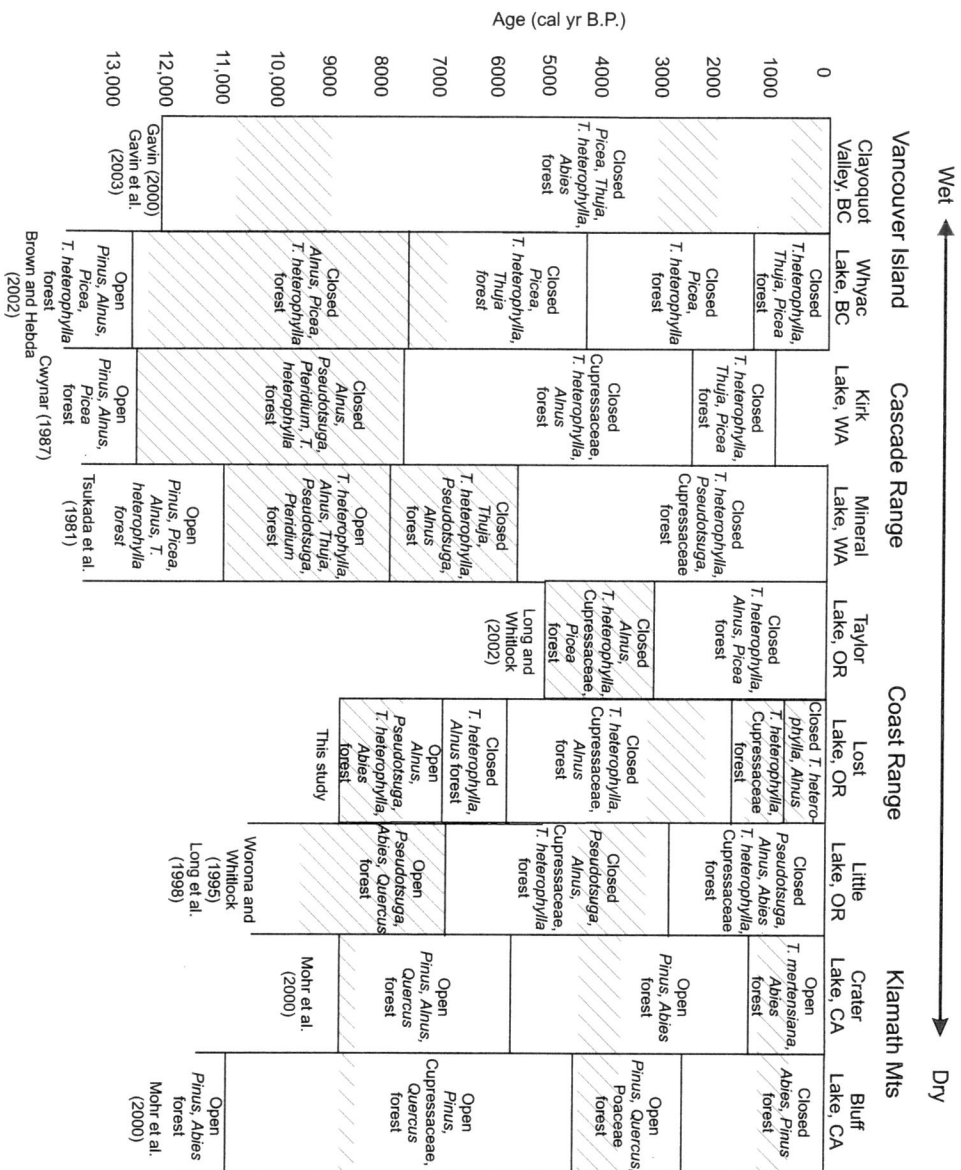


Figure 3.13. Summary of Holocene vegetation and fire histories for selected sites within the seasonal rain forest of British Columbia, Washington, Oregon, and the Klamath Mountains of California. Striped bands indicate periods of high fire frequency as defined by each study.

and western red cedar were major forest constituents (Tsukada et al., 1981; Cwynar,

1987) (Fig. 3.13).

Mohr et al. (2000) used high-resolution charcoal analysis, similar to the analysis described in this study, to reconstruct fire periods from two sites, Bluff and Crater lakes in the Klamath Mountains of northern California (Fig 3.12). These sites are located in the driest portion of the seasonal rain forest (Brown et al., 1998). The records suggest three periods of high fire occurrence at ca. 8500 to 8300 cal yr B.P., ca. 4100 to 3900 cal yr B.P., and 1100 to 900 cal yr B.P. These periods were also associated with changes in forest composition from fire-sensitive *Tsuga mertensiana* (mountain hemlock) and fir to pine and oak (Fig. 3.13).

Although the methods and temporal resolution differed among sites, the evidence suggests that, fire episodes were more common in the early Holocene than today, and

began to decrease in frequency from ca. 6000 cal yr B.P. to the present. In addition, two periods from ca. 4000 to 3000 cal yr B.P. and ca. 1000 to present featured increased fire frequencies at times when the regional climate was becoming more mesic. The greater seasonal variability during the early Holocene likely resulted in intensified summer drought leading to more fires. Also, similar summer drought conditions, from ca. 4000 to

3000 cal yr B.P. and ca. 1000 cal yr B.P. to present, may have led to more fire activity.

Conclusions

The vegetation and fire histories from Lost, Little, and Taylor lakes describe the response of vegetation and fire activity to climate changes occurring during the Holocene in the Oregon Coast Range. Several conclusions can be made:

1. The paleoecological data from the Oregon Coast Range sites suggest that vegetation and fire occurrence responded to millennial-scale variations in climate over the course of the Holocene. During the early Holocene amplification of the seasonal cycle of solar radiation resulted in seasonal differences greater than present. Forests dominated by disturbance- or fire-adapted species developed and fire episodes occurred at rates similar to present at Lost Lake, or higher than present at Little Lake. As seasonal variability decreased in the middle and late Holocene more mesophytic species, including western hemlock, western red cedar, and Sitka spruce, became prominent. Fire-episode frequency decreased during the middle Holocene, and the present-day fire regime was established at ca. 2000 cal yr B.P.

2. Periods of widespread fire activity were probably associated with decadal- to centennial-scale variations in drought. From ca. 8200 to 6900 cal yr B.P., five of the seven fire episodes at Lost Lake occurred within 50 years of fires at Little Lake. From ca. 6100 to 4500 cal yr B.P. and ca. 2900 to 1000 cal yr B.P., the sites burned asynchronously suggesting periods when the environmental differences among sites were greatest.

3. Anthropogenic activities likely played only a minor role in fire ignitions prior to ca. 150 years ago. Vegetation reconstructions do not indicate a consistent presence of disturbance-adapted taxa to suggest regular burning by Native people. Also, fire-episode frequency does not follow trends in Native population size. For example, fire decreases at ca. 2000 cal yr B.P. when Native populations were highest. It is impossible to rule out

Natives as active managers of forests through the use of fire, but the evidence from this study suggests that their influence was minimal or limited.

4. Other rain forest records show broadly similar patterns to those of the Oregon Coast Range. Fire-adapted taxa were prominent at all sites from ca. 11,000 to 7000 cal yr B.P. Closed forest of fire-sensitive taxa became plentiful throughout the ecoregion in the last ca. 6000 cal yr B.P. Fires were common throughout the early Holocene, and during shorter periods of the last ca. 6000 cal yr B.P. From ca. 4000 to 3000 cal yr B.P. and over the last 1000 years, fire histories from multiple sites suggest short periods of dry conditions were embedded within the overall moist conditions of the last ca. 6000 cal yr B.P.

The climate conditions that control fires generally operate on shorter temporal scales than those that govern vegetation growth in the seasonal rain forest. As global temperatures increase over the next several centuries (Houghton, 1999; IPCC, 2001), it is likely that fires will become more common within the seasonal rain forest. The evidence from the Oregon Coast Range and other seasonal rain forest sites suggests that the response to warmer-than-present conditions may not be uniform, with environmental gradients creating a heterogeneous mixture of young disturbance- and fire-adapted forest stands at southern locations, and more mature fire-sensitive forest stands at northern locations.

CHAPTER IV

THE RELEVANCE OF PALAEOECOLOGICAL DATA FROM THE OREGON COAST
RANGE FOR THE MANAGEMENT OF SEASONAL TEMPERATE RAIN FORESTSIntroduction

Among the most productive forests in the world, the rain forests of the Pacific Northwest (PNW) are home to a variety of endemic and endangered species (Hayes and Hagar, 2002; Spies et al., 2002). When Euro-Americans first arrived in the PNW in the 1800s, the western slopes of the Cascade Range and the Coast Range of Oregon had extensive forests stands of *Pseudotsuga menziesii* (Douglas-fir), *Tsuga heterophylla* (western hemlock), *Thuja plicata* (western red cedar), and *Picea sitchensis* (Sitka spruce) was abundant along the coast (Franklin and Dyrness, 1988). The U.S.D.A. Forest Service and Bureau of Land Management oversee 3.2 million ha of federal lands west of the Cascade crest in Oregon (Loy et al., 2001). From the early 1900s to the 1960s, the management of these forests for timber production was their primary objective (FEMAT, 1993).

Beginning with the passage by Congress of the Multiple-Use-Sustained Yield Act in 1960, and the Wilderness Act in 1964, management of forest lands has become a balance between preserving specific forest stand types and providing timber resources. Recent legislation has made it more difficult to sustain timber harvest at historically high levels. For example, the National Forest Management Act of 1976 requires each national

forest administration to generate management plans to preserve biological diversity, defined as the complex of species, communities, and ecological functions within the forest (National Forest Management Act, 1976). The Endangered Species Act of 1972 established federal procedures for identifying and protecting threatened and endangered species on federal lands. The Forest Ecosystem Management Assessment Team report (FEMAT) in 1993 and the subsequent Northwest Forest Plan placed further restrictions on forest harvest activities by setting a priority on the management of ecosystems rather than protection of individual species (FEMAT, 1993; Tuchmann et al., 1996). The Northwest Forest Plan emphasizes ecosystem integrity, i.e., "developing management plans that maintain an ecosystem within the range of conditions, or seral stages that allow processes of succession to operate toward a pre-disturbance condition" (Kimmings, 1997). FEMAT and the Northwest Forest Plan seek to ensure the preservation of threatened, or at-risk species through a system of forest reserves. One type of reserve conserves late-successional/old growth (LS/OG) forests, which consist of stands in mature (80+ years) and old-growth seral stages (FEMAT, 1993). These reserves represent the range of variation found in different types of old-growth forests (Wells et al., 1998). The definition of old growth is debated in the forest science community (Wells et al., 1998), but for management purposes it is considered to be stands with 175-250 year old trees (i.e., undisturbed) and a patchy multilayered canopy with trees of several age classes and the presence of large living trees, snags, downed woody debris, and understory vegetation dominated by shade-tolerant species. The presence of species and functional processes in these forests are representative of the potential natural

community that existed prior to extensive Euro-American activity (Franklin et al., 1981; FEMAT, 1993).

Although small-scale disturbances, such as gaps created by individual trees falling down during wind storms (Lertzman et al., 1996), are common in LS/OG stands, the

absence of widespread disturbances, such as wildfire, is critical for LS/OG development (Matlack, 1994; Spies, 1997). However, historical and tree-ring data indicate that fires are part of these ecosystems. For example, old-growth stands of ca. 500 years in age in the forests of Washington and Oregon are attributed to a series of large fires between ca. 1400 and 1575 (Weisberg and Swanson, 2003). The desire to preserve these types of forest stands and to identify the conditions that maintain and create them has generated interest in understanding disturbance processes that are important within temperate

Lertzman and Fall, 1998; Gavin et al., 2003).

Forest fires are relatively discrete events in time that disrupt ecosystems and

population structures, as well as change resource and substrate variability and the physical environment (White and Pickett, 1985). Several terms are used to describe fire characteristics and effects. "Large" implies the spatial extent of a fire, but indicates

nothing about its effects. "Intensity" refers to energy release rates of a fire and does not imply any physical damage to vegetation. "Severity" refers to the ecological effects of a fire on the dominant vegetation (Agee, 1993). Interactions with other disturbances, such as insects and disease, also affect size, frequency, intensity and severity of fires with the net result expressed as a "fire regime" (Agee, 1997a).

In order to be successful at managing forests for biological diversity and ecological integrity, FEMAT and the Northwest Forest Plan considered the fire regime to be part of the dynamic processes that occur in temperate coniferous forest ecosystems (FEMAT, 1993; Tuchmann et al., 1996). However, in the short term, management strategies to perpetuate particular forest conditions, such as LS/OG, have focused on protection against fire. For example, active suppression of wildfires has been a government policy since the early 1900s on all forest lands in the PNW (FEMAT, 1993). Where fire return intervals span several centuries, such as in the Oregon Coast Range, fire suppression has been the preferred strategy for preserving multi-layered LS/OG forest stands (Agee, 1997b). However, in drier forests, such as those dominated by ponderosa and lodgepole pine in eastern Oregon, suppression policies are thought to have altered the natural fire regime of frequent low-intensity fires and led to extensive undergrowth development (Sampson and Adams, 1995). Forest managers are now using prescribed burns in an attempt to reinstate a historical fire regime in such forests (Agee, 1997b).

Because our knowledge of the relationship between forest development and fire is generally limited to the last ca. 500 years (Agee, 1991), suppression or reintroduction of fire in particular forest types characterized by long periods without fire may not maintain the range of forest types that existed prior to Euro-American settlement. The motivation for maintaining historic forest types (i.e., forests-types that existed prior to Euro-American settlement) is that most of the native species that depend on these habitats will be preserved (Wimberly et al., 2000; Cissel et al., 1999). Paleoeccological data, such as

pollen and charcoal found in lake and wetland sediments, offer information on vegetation and fire history beyond the dendrochronological record. This long-term perspective can be an important resource for forest managers by providing information on the antiquity of present-day forest composition and fire regimes, as well as the sensitivity of forests to changes in climate, both past and future.

Information about vegetation changes in the PNW are known from a network of pollen records, and on millennial time scales these variations have been explained as a response to large-scale changes in the climate system (Whitlock, 1992; Thompson et al., 1993; Hebda and Whitlock, 1997). For example, from ca. 11,000 to 6000 years ago warmer-than-present summer temperatures and summer drought are attributed to greater-than-present summer insolation in the northern hemisphere. (Years in this chapter refer to calendar years, obtained by converting ^{14}C years to calendar years using the calibration of Stuiver et al. (1998)). The decrease in summer insolation has been used to explain the onset of cool wet conditions beginning ca. 6000 years ago and continuing to the present-day. The relation between climate, vegetation, and fire on regional spatial scales, such as the PNW, and shorter temporal scales (submillennial: 10^1 to 10^3 years) are not completely understood.

This chapter presents a case study to illustrate the value of long-term fire history data for understanding the natural fire regime of the Oregon Coast Range. Specifically, I address the following questions: 1) how representative of the past are present-day fire regimes; 2) how can paleoecological data be used to test assumptions about the historic variability of forest types, such as LS/OG on the landscape; and 3) how can

paleoecological data contribute to an understanding of future fire responses in the face of projected climatic changes arising from the increase in greenhouse gases in the atmosphere? Several recommendations for future forest management are also discussed.

Case Study: Long-Term Fire Variations in the Oregon Coast Range

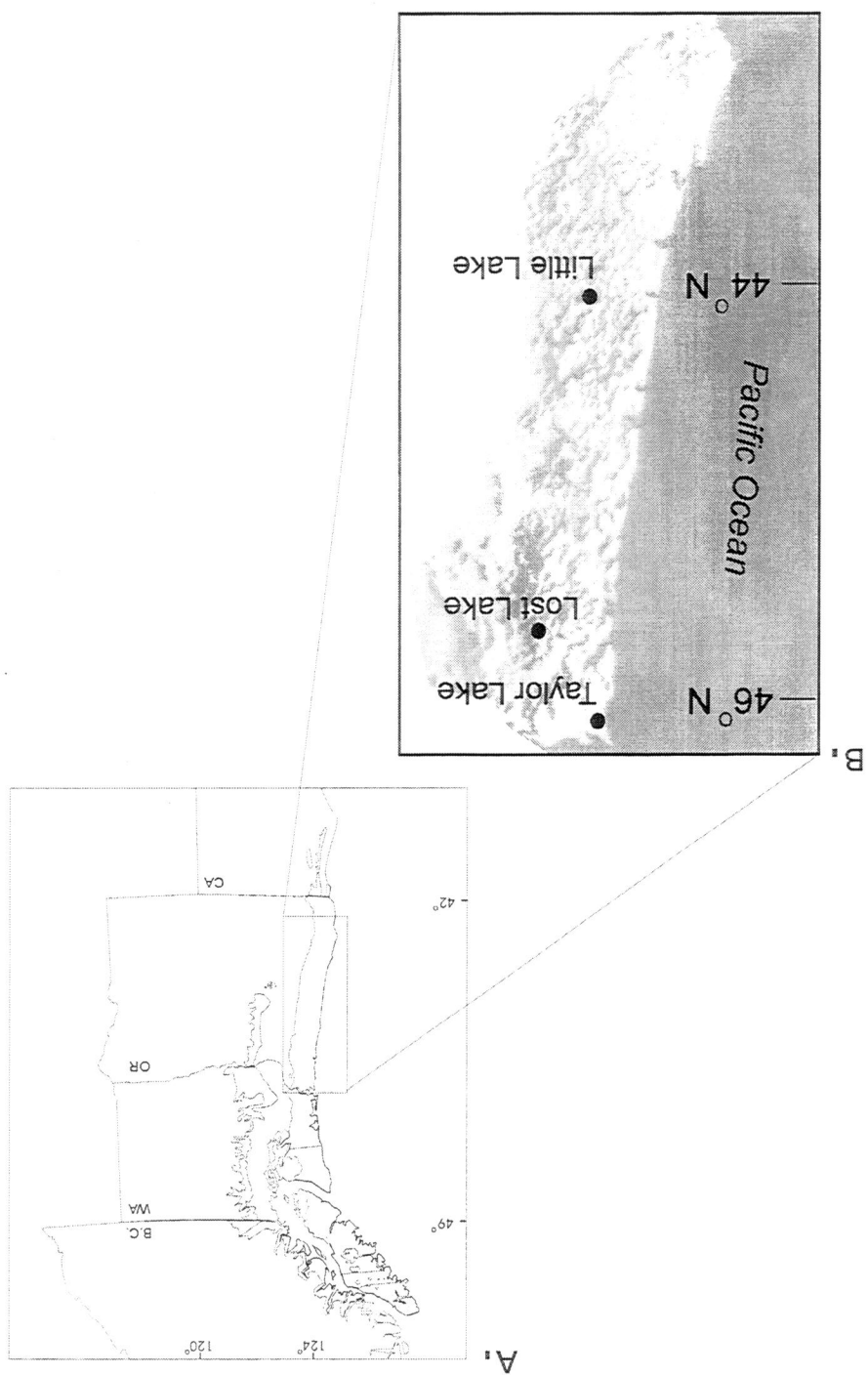
Study sites

Fire and vegetation history from three sites in the Oregon Coast Range is based on an examination of charcoal and pollen data from lake-sediment records. Taylor Lake (46° 06' 02"N, 123° 54' 24"W, 4 m elevation), Lost Lake (45° 49' 30"N, 123° 34' 40"W, 460 m elevation), and Little Lake (44° 10' 00"N, 123° 35' 00"W, 210 m elevation) experience a climate of relatively warm dry summers and cool wet winters with ca. 90% of

precipitation falling between October and May (Hemstrom and Logan, 1986). Taylor Lake is located 8 km south of the mouth of the Columbia River on the Clatsop Plain, an area of sand aggradation (Orr et al., 1992), Lost Lake is located 30 km inland in the northern Coast Range, and Little Lake is located 45 km inland in the central Coast Range (Fig. 4.1).

January temperatures at Taylor and Lost lakes are 4.7°C and 2.9°C respectively, and July temperatures at both lakes average 15°C. The watersheds receive ca. 2000 mm of precipitation yearly (Oregon Climate Service, 2002; P. J. Bartlein, unpublished data

Figure 4.1. A. Location of seasonal rain forest along the northwest coast of North America (Alaback and Pojar, 1997). B. The location of Taylor, Lost, and Little lakes within the Oregon Coast Range province (Franklin and Dyrness, 1988; Spies et al., 2002).



2002), whereas Taylor Lake experiences frequent summer fog that helps maintain high effective moisture during the summer months (Alaback and Pojar, 1997; Chapter 2). By contrast, Little Lake experiences January and July mean monthly temperatures averaging 4.5°C and 16.9°C and annual precipitation of ca. 1600 mm (P. J. Bartlein, unpublished data 2002).

Taylor Lake lies in the *Picea sitchensis* forest zone (Franklin and Dyrness, 1988). The lake is surrounded by a forest of *Tsuga heterophylla*, *Picea sitchensis*, and *Thuja plicata* (western red cedar) with some *Pseudotsuga menziesii* and scattered

Chamaecyparis nootkatensis (Alaska cedar). *Alnus rubra* is the most abundant deciduous tree, growing in recently disturbed sites and riparian areas. The charcoal record from Taylor Lake suggests fires in 1911 and 1973 (Chapter 2). The 1911 event may be from an undocumented fire or nearby fires in 1910 in western Oregon (Morris 1934, Juday 1977). The 1973 fire is likely associated with a debris burn following logging on the eastern side of the watershed.

Lost and Little lakes are located within the *Tsuga heterophylla* forest zone (Franklin and Dyrness, 1988). The forest in the Lost Lake watershed consists of *Tsuga heterophylla*, *Thuja plicata*, *Pseudotsuga menziesii*, with *Alnus rubra* growing on recently disturbed slopes. The watershed also supports minor amounts of *Picea sitchensis*, *Abies grandis* (grand fir), and *Abies procera* (noble fir). The watershed burned in 1933 as part of the Tillamook fire complex (Oregon Department of Forestry, 1975), and evidence from charcoal analysis indicates that the Tillamook fire of 1868 (Morris, 1934) also burned in the vicinity of Lost Lake (Chapter 3).

Forests growing in the Little Lake watershed reflect the drier conditions found at this site and consist of *Pseudotsuga menziesii*, *Tsuga heterophylla*, and *Thuja plicata*, with some *Abies grandis* and *Pinus monticola* (western white pine). Deciduous species include *Alnus rubra* and *Acer macrophyllum* (big leaf maple), which are found in riparian areas and newly disturbed sites. Archival records and charcoal analysis indicate fires occurred in 1910, 1929, 1967, and 1982 in or near the Little Lake watershed (Long et al., 1998).

Mean fire interval (MFI, or average time between fire episodes) estimates for present-day *Picea sitchensis* forests ranges between 300 and 1100 years (Fahnestock and Agee, 1983; Agee, 1993; Gavin et al., 2003), whereas it ranges from 150 to 350 years in drier *Tsuga heterophylla* forests (Juday, 1977; Teensma et al., 1991; Agee, 1993). The fire season in the Oregon Coast Range occurs during the dry summer and early autumn months (July to mid October). Recent fires are associated with the presence of east winds that dry fuels to critical moisture-content levels (Schroeder and Buck, 1970; Agee and Flewelling, 1983; Chandler et al., 1983).

Reconstructing Oregon Coast Range fire and vegetation history

Information on past fire regimes is gained in two ways. The first approach is to examine fire-scarred tree-rings and forest stand ages to estimate the time of stand establishment following fire. The second is by examining charcoal particles found in lake and wetland sediments and calculating charcoal accumulation rates (CHAR) from particle concentrations. Peaks (i.e., high CHAR) are then identified and assumed to represent fires. Tree-ring and stand-age data are temporally and spatially explicit, but

only extend back to the age of the oldest tree (Agee and Flewelling, 1983; Teensma, 1987; Agee, 1990; Morrison and Swanson, 1990; Agee, 1993; Impara, 1997; Weisberg and Swanson, 2003). Fire history gained by examining charcoal in lake or wetland records have the advantage of spanning long periods of time and providing information on the frequency of past fires when climate was different than today (Whitlock and Larson, 2001; Whitlock and Anderson, 2002). The paleoecological records presented here from Taylor, Lost, and Little lakes span the last ca. 4600, 8400, and 9000 years respectively.

Fire history reconstructions followed the methods outlined in Whitlock and Larson (2001) and Whitlock and Anderson (2002). By sampling charcoal particles > 125 μm , which do not travel far from a fire, the spatial resolution was assumed to be that of the watershed (Whitlock and Millsbaugh, 1996). The charcoal data from each core, sampled at 1-cm intervals, were converted to concentration values and then interpolated to pseudo-annual values. These were then averaged at 10-year intervals and charcoal accumulation rates (CHAR ; particles $\text{cm}^{-2} \text{yr}^{-1}$) were calculated by dividing charcoal concentration by the deposition time represented in each 1-cm sediment sample.

Comparing recent peaks in charcoal accumulation with times of known fires in the specific watershed enabled a decomposition of the longer record into background CHAR and CHAR peaks. Background CHAR is the general amount of charcoal deposited into the lake over time. CHAR peaks are identified as positive deviations (peaks) above background and inferred to represent a fire episode. Peaks in CHAR may represent one

or more closely timed fires within the watershed (fire episode), and the number of peaks per 1000 years is considered an index of fire-episode frequency. The peaks and number per 1000 years identified in this analysis represent a conservative estimate of fire episodes and fire-episode rates. (For more detailed discussion of the methods used and analyses of the charcoal records see Long et al., 1998; Chapter 2; and Chapter 3).

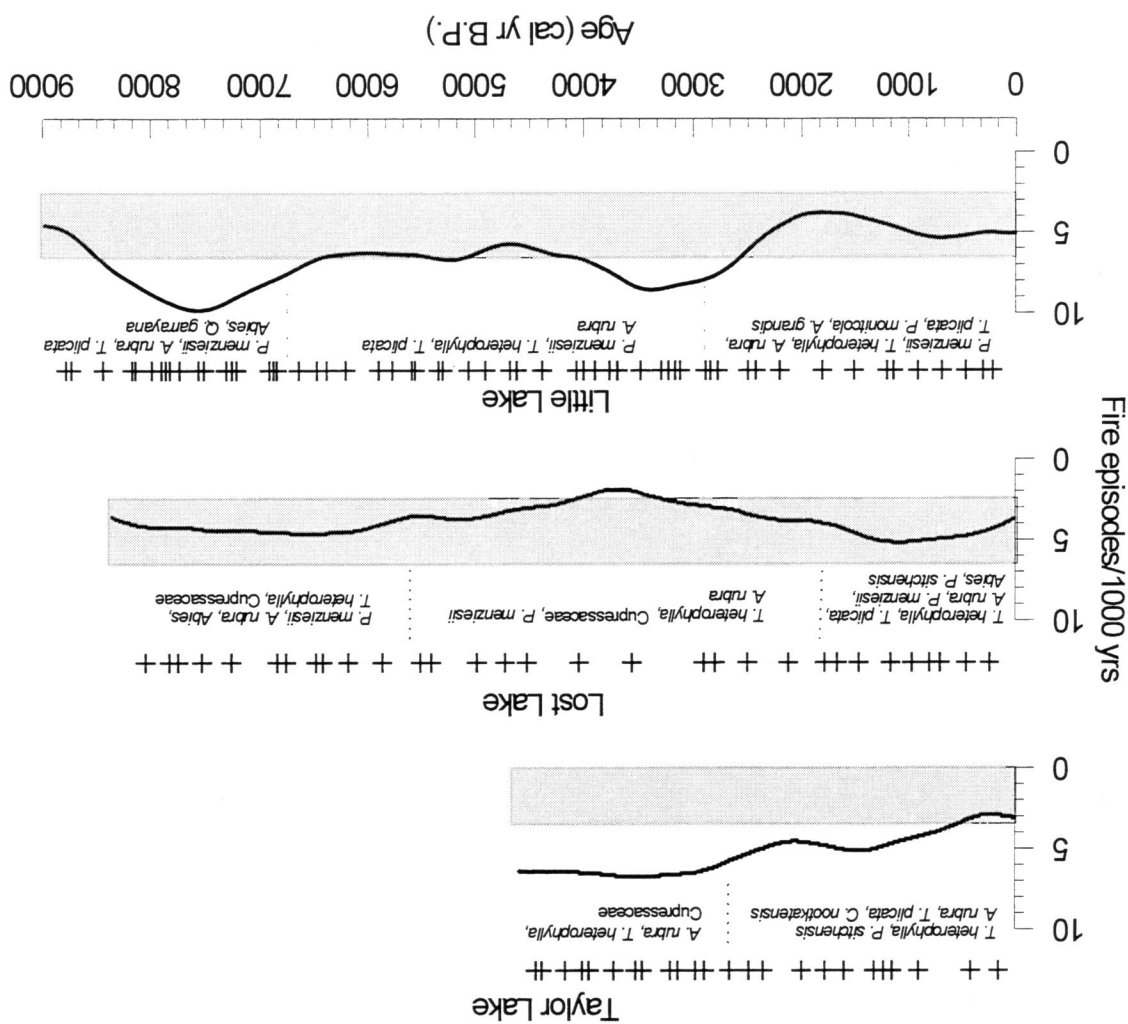
Pollen and spores found in the cores were the basis for the vegetation reconstruction (Faegri et al., 1989). The pollen data were sampled at 10-cm intervals from Taylor and Lost lakes for a resolution of one sample every ca. 130 years for Taylor Lake, and every ca. 200 years for Lost Lake. The pollen record from Little Lake was described in Worona and Whitlock (1995) and had a sampling interval of 20 to 40 centimeters, resulting in a resolution of ca. 160-600 years between samples. Haploxydon-type and Diploxydon-type *Pinus* grains were assigned to *P. monticola* (western white pine) and *P. contorta* (lodgepole pine) respectively, based on their present coastal distribution. *Pseudotsuga*-type pollen was attributed to *P. menziesii*, and *Picea* pollen was assumed to represent *P. sitchensis*. *Abies* pollen was inferred to be from *A. grandis* and *A. amabilis*, both of which grow above 1000 m elevation in the northern Oregon Coast Range. Cupressaceae pollen was assigned to *Thuja plicata* and *Chamaecyparis nootkatensis*, which is also a possible contributor. Like the charcoal data, the spatial resolution for the pollen records was considered to be primarily the watershed and surrounding area, based on studies of pollen source area in other regions (Jacobson and Bradshaw, 1981; Sugita, 1993). Pollen was identified to the lowest taxonomic level

possible based on the modern pollen collection at the University of Oregon paleoecology lab and published atlases (e.g., Bassett et al., 1978; Moore et al., 1991).

How representative of the past are present-day fire regimes?

The reconstructed fire histories for Taylor, Lost, and Little lakes show variations in fire episodes over time (Fig. 4.2). At Taylor lake from ca. 4600 to 2700 years ago the MFI was 140 ± 40 years (mean $\pm$ standard error of the mean), (about six to seven fire episodes per 1000 years), and *Tsuga heterophylla* and *Picea sitchensis* were less prominent in the forest than at present. Beginning at ca. 2700 years ago fire-episode frequency declined from six episodes per 1000 years at ca. 2700 years ago, to three episodes per 1000 years by ca. 750 years ago (Fig. 4.2). The MFI for the last 2700 years was 220 ± 30 years, although only three fire episodes are registered in the last ca. 750 years. The pollen record indicates the presence of forests with *Tsuga heterophylla*, *Picea sitchensis*, *Alnus rubra*, and some *Thuja plicata* and *Pseudotsuga menziesii* for the last ca. 2700 years (Chapter 2). The fire history indicates that fire episodes were more frequent than present-day estimates of 300 to 1100 years would suggest (Agee 1993). In contrast, the Lost Lake record shows that present-day MFI estimates of 150 to 350 years (Teensma et al., 1991; Agee, 1993) have persisted for millennia. From ca. 8400 to 5600 years ago, the charcoal data suggest a MFI was 230 ± 50 years (about four to five episodes per 1000 years), and the area supported forests of *Pseudotsuga menziesii*, *Alnus rubra*, *Abies* spp., and some *Tsuga heterophylla* and *Thuja plicata* (or possibly *Chamaecyparis nootkatensis*) (Fig. 4.2) (Chapter 3). From ca. 5600 to 1800 years ago, the MFI increased to 300 ± 50 years, (about two to four episodes per 1000 years). At

Figure 4.2. Comparison of fire and vegetation history at Taylor Lake, Lost Lake, and Little Lake, based on pollen and charcoal records described in Chapters 2 and 3 and in Long et al. (1998). Plus marks (+) indicate fire episodes inferred from the charcoal accumulation rates at each site. Fire episodes/1000 yrs are calculated from a 2000-year locally weighted average of fire episodes. Gray boxes identify the range of present-day MFI estimates at each site. The present MFI for Taylor Lake, surrounded by a *Picea sitchensis* forest is 300 to 1000 years (Agee and Flewelling, 1983; Agee, 1993). The present MFI for Lost and Little lakes surrounded by *Tsuga heterophylla* forests is 150 to 350 years (Teensma et al., 1991; Agee, 1993). Taxa indicate dominant forest taxa for different periods based on the pollen records.



times when the MFI increased, for example from ca. 4500 to 3000 years ago, a concurrent decline in *Alnus rubra* pollen suggests an increase in LS/OG character of the forests. The charcoal record of the last ca. 1800 years indicates that MFI increased slightly to 150 ± 20 years (about five to six episodes per 1000 years) (Fig. 4.2) (Chapter 3). Forests of the last 1800 years have included *Tsuga heterophylla*, *Thuja plicata*, *Alnus rubra*, *Pseudotsuga menziesii* and some *Abies grandis* and *Picea sitchensis*.

The fire history at Little Lake shows a greater range of variability over the last 9000 years than that at Taylor or Lost lakes, but it also indicates that the present fire regime has been in place for the last ca. 2800 years (Fig. 4.2). From ca. 9000 to 6800 years ago the MFI was 110 ± 20 years, (about six to ten fire episodes per 1000 year). Forests in the watershed were composed of *Pseudotsuga menziesii*, *Alnus rubra*, and *Thuja plicata*, with some *Abies* spp. and *Quercus garryana* (Oregon white oak) also present (Worona and Whitlock, 1995). From ca. 6800 to 2800 years ago, the MFI was 150 ± 20 years (about five to eight fire episodes per 1000 years). Increases in shade-tolerant species, such as *Tsuga heterophylla* and *Thuja plicata*, along with the continued presence of *Pseudotsuga heterophylla* and *Alnus rubra*, suggest a mixture of closed forests in wetter areas, and more open or younger stands on drier slopes. Over the last ca. 2800 years, the MFI has been 210 ± 30 years, (about four to six fire episodes per 1000 years) and is similar to present-day values in the central Oregon Coast Range (Teensma et al., 1991; Impara, 1997) (Fig. 4.2). *Pseudotsuga menziesii* and *Alnus rubra* have remained major constituents of the forest, but increases in more-mesic species, such as *Picea sitchensis* and *Abies grandis*, indicate undisturbed mesophytic forest stands.

The fire histories from these three sites suggest that the local environmental gradient found in the Oregon Coast Range is an important factor in determining fire occurrence from site to site. Also, the history of fire activity leading to present-day conditions is highly variable across the landscape. The present-day fire regime was established about 750 years ago at Taylor Lake, the wettest site, and several millennia ago in the coastal interior locations of Lost and Little lakes. However, the trends leading to the present-day fire regime are different at all three sites. The Taylor Lake fire history suggests that the last 750 years is part of a declining trend in fire occurrence that began ca. 2700 years ago. I suggest in Chapter 2 that increases in effective moisture were a result of increased summer fog. At Lost Lake, the fire history indicates that over the last ca. 8400 years the occurrence of fires fell within the range of variability suggested by present-day estimates of Oregon Coast Range forests (Agee and Flewelling, 1983; Impara, 1997). The Lost Lake fire history also suggests that despite variations in climate that have taken place over the last ca 8400 years, the local environmental conditions were not altered enough to cause a significant change in the frequency of fire episodes for an extended period of time. At Little Lake, the most xeric site, fire activity was more sensitive to changes in regional climate over the last 9000 years (Long et al., 1998), and the present fire regime is quite different from most of the record. For example, the fire-episode frequency from ca. 9000 to 6800 years ago, and from ca. 4500 to 2500 years ago, was higher than today.

How much LS/OG forest has historically been present on the Oregon Coast Range landscape?

Fire histories that span long time periods also encompass short-term forest processes, including multiple successional cycles. Wimberly et al. (2000) simulated the proportion of LS/OG in an Oregon Coast Range landscape over the past 3000 years using a time-series of fire frequencies derived from the charcoal data analysis at Little Lake (Long et al., 1998). The simulation was done using the landscape age-class simulator (LADS), which is a stochastic simulation model that estimates the temporal variability in the proportions of forest-age classes by tracking stand age and time since last high-severity fire in two-dimensional 100 ha grid cells. In the experiment described by Wimberly et al. (2000), the fire history of three landscape sizes, province (2,250,000 ha), national forest (302,500 ha), and late-successional reserves (40,000 ha), were simulated to examine the effect of changing fire regimes at different spatial scales. The fire history from Little Lake was converted to MFI, and the assumption was made that the Little Lake record was equivalent to the natural fire rotation (NFR, time for an area the size of the study area to burn) at all spatial scales. A mean fire size of 70,600 ha was used in the experiment, based on the size of historic Oregon Coast Range fires of the nineteenth century (Loy et al., 1976). The NFR was varied, based on the Little Lake reconstruction, in order to determine the sensitivity of landscape-age classes to changes in fire frequency. The results of the model simulations indicate that old-growth percentages were between 25 and 75% at the provincial scale, 10 and 80% at the national forest scale, and 0 to 100% at the late-successional reserve scale. The differences in old-growth

percentages reflect the spatial scale of observation relative to the mean fire size. The mean fire size of the analysis increased as the spatial scale of the analysis decreased, so that when fires occurred they burned larger portions of the smaller scale plots (Wimberly et al., 2000). The results suggest that the present percentages of old-growth forest are below what would be expected using the prehistoric (i.e., > 400 years) fire regime. Paleoeecological studies provide a good source of fire-episode frequency data for long-term fire modeling because they offer a better sense of the temporal variability in fire regimes (Wimberly et al., 2000).

In a subsequent study, Wimberly (2002) used published data from a ca. 366-year-long dendrochronological study of fire history in the central Oregon Coast Range (Impara, 1997) to compute a NFR of 200 years for the coastal portion and 100 years for the interior portion of a 23,000 km² the study area. These NFR estimates were assumed to be representative of the last 1000 years based on the relatively stable fire return intervals of the Little Lake charcoal record for the last 1000 years. As with Wimberly et al. (2000), the NFR was varied to determine the sensitivity of forest age classes to changes in fire frequency. Wimberly (2002) incorporated fire size and severity into the LADS model based on the dendrochronological record (Impara, 1997), and used an age-based model of forest structure development to simulate early successional, young, mature, and old-growth stands. Stand-age classes were determined by time since last fire. The simulated landscape showed that old-growth structure was most common with a median of 42%, and young forest was the next most common with a median of 21%. Early successional forests and mature forests had median landscape coverage of 17 and

16% respectively. As with the Wimberly et al. (2000) landscape simulations, the percentages of forest age class responded strongly to changes in the NFR and simulated area.

Charcoal-based fire histories have intrinsic limitations when used in landscape simulations. They lack information on the spatial extent of fires and fire severity, and the chronology to compare records is relatively poor. Fire size was a critical factor in estimating percentages of old growth forest among spatial scales of observation. Also, the assumption that the Little Lake fire history was representative of the entire Coast Range is now known to be false (Chapter 3). With the additional long-term fire history information provided by Taylor and Lost lakes, the differences in fire regimes across environmental gradients in the Coast Range are more clearly identified and should help improve simulations of past forest age classes within a complex region.

How can paleoecological data contribute to an understanding of future fire responses in the face of global climatic changes?

Developing a better understanding of the relations between fire regimes and climate in the past can aid in understanding potential fire-climate relations under future climate conditions. Long-term paleoenvironmental records of fire are important because they provide evidence of the rates and magnitude of changes in fire regimes in response to past climate variability, as well as an idea of the complexity of fire-climate relations within a given forest type (Clark, 1990; Hallet and Walker, 2000; Millspaugh et al., 2000; Turner et al., 2003; Whitlock et al., 2003). For example, the fire history based on the Oregon Coast Range sites indicates that fire frequencies in the past changed in

conjunction with changes in forest composition. At Little Lake, the time between fires increased from ca. 7500 to 6000 years ago, when the vegetation experienced an increased in the abundance of fire-sensitive species, such as *Tsuga heterophylla* and *Thuja plicata* (Minore, 1979; Agee, 1993) (Fig. 4.2). A similar increase in the time between fires and shift in forest composition also occurred from ca. 6500 to 4000 at Lost Lake and Taylor Lake where increases in *Tsuga heterophylla* and fire-sensitive *Picea sitchensis* accompanied longer fire-free intervals from ca. 2700 years ago to the present (Fig. 4.2) (Long et al., 1998; Chapter 2; Chapter 3).

Whitlock et al. (2003) outlined ways in which paleoecological data can be compared with model simulations of past climates to explore the response of vegetation and fire regimes to past and future climate variability. Simulations of past climate have been made using coupled atmospheric-ocean general circulation models (AOGCMs), which are mathematical models based on nonlinear flow equations and the principles of mass and energy conservation (COHMAP, 1988; Kutzbach et al., 1993a). Whitlock et al. (2003) note that although AOGCM simulations have a coarse resolution of several degrees of latitude and longitude, they demonstrate the potential effects of variations in the large-scale controls of climate, such as variations in seasonal insolation, growth and decay of ice sheets, and topography. The variables used in AOGCMs, such as seasonal insolation values, ice-sheet size, surface albedo, sea surface temperature and atmospheric CO₂ content, allow climate to be simulated for particular time periods when paleoenvironmental data, such as pollen, lake levels and ice-core data, document the scope and nature of past climatic variations (Kutzbach et al., 1993a; Bartlein et al., 1998).

For example, AOGCM simulations for 11,000 and 6000 years ago in the PNW indicate that summers were warmer and drier than present as a result of increased summer insolation (Bartlein et al., 1998).

How much the fire regime of the Oregon Coast Range may be altered by future climate changes is difficult to determine. AOGCM simulations of potential future climate changes indicate warmer wetter winters and warmer slightly drier summers in western North America during the next century with increased greenhouse gas and sulfate aerosol concentrations in the atmosphere (Giorgi et al., 2001). Whitlock et al. (2003) suggest that increased summer temperatures could increase summer drought stress on vegetation and lead to an increase in vegetation conditions conducive for fires. They also note that increased summer temperatures could lead to a longer fire season (Flannigan et al., 2000), and simulations of future climate indicate the potential for increased atmospheric circulation patterns that promote thunderstorms and lightning-caused fires (Price and Rind, 1994; Whitlock et al., 2003).

The temporal variability seen in fire reconstructions at Taylor, Lost and Little lakes also suggests no consistent long-term fire interval; rather that fire occurrence likely changed continually in response to changes in temperature and precipitation on centennial-to-millennial scales (Long et al., 1998; Chapter 2; Chapter 3). The fire history at Taylor, Lost, and Little lakes suggests that fire episodes were more frequent ca. 4500 to 3000 years ago than present rates as a result of intensified seasonal drought (Long et al., 1998; Chapter 2), which implies that short-term changes in future climate could affect fire regimes. The paleoenvironmental record from the Oregon Coast Range describes the

complexity of fire-vegetation-climate interactions through time. For example, fire frequency changes were not concurrent at Taylor, Lost, and Little lakes despite all sites being under the influence of the same large-scale climate conditions (Fig. 4.2) (Chapter 3). Local environmental conditions apparently gave rise to inter-site differences in the past (Chapter 3) and suggest that the response of fire regimes to future climate change will also not be uniform across the Oregon Coast Range. Although past response cannot be used to accurately forecast the future, paleoecological records are an important source of information on the variability of fire regimes and the complexity of fire-climate relations through time.

Recommendations for Future Forest Management

Several recommendations for management of future forests can be made based on the paleoecological evidence presented here. The first is that management plans should consider disturbance by fire as an important process in forest development and take into account the possibility of changes in the historical fire regime. Cissel et al. (1999)

designed a management plan for the *Tsuga heterophylla* forests of the Blue River watershed in the western Cascades of Oregon based on a historic fire record of 44 fire

episodes over the last ca. 500 years. The plan reapportioned areas from those assigned by the guidelines of the National Forest Plan to blocks of land that more accurately depicted the landscape pattern created by historic fire events. The general prescriptions for timber harvest were also based on historic fire regime patterns in order to try to maintain the size and distribution of different forest stand ages created in prehistoric times. Blocks of land were assigned a schedule of timber harvest, prescribed burns, and forest regeneration in

both management scenarios at 20-year intervals for 200 years. The plan based on the historic fire regime lengthens the timber harvest rotations by 20-40 years in order to more accurately mimic the timing of fires in the area. The results suggest that the reapportioned landscape plan produced more late-successional habitat, larger patch sizes, and less border between young and old forests than the present National Forest Plan. These simulations indicate that incorporating historic fire regimes into future management plans may produce landscapes with a wider range of habitats than current management plans (Cissel et al., 1999). However, this new management plan was based on a 500-year record of fire and forest development. The evidence from the Oregon Coast Range suggests that changes in the frequency of fire have occurred through time and have been associated with changes in climate. It would be prudent to recognize the range of variability in fire regimes, as demonstrated by paleoecological data, in assigning management plans to forest lands.

The second is to acknowledge that changes in future fire regime may not be uniform across the seasonal temperature rain forest. Therefore, recognition and identification of subregional differences in fire regime will be necessary to develop local management plans that incorporate the spatial variability of fire regimes. Changes in climate in the past have not resulted in uniform or unidirectional adjustments in fire regimes in the Oregon Coast Range. For example, over the last 2000 years fire frequency has decreased at Taylor Lake while fires became more frequent at Lost Lake (Fig 4.2), despite both being mesic northern Coast Range sites. At Little Lake, fire intervals have been consistent over the last ca. 1000 years, but this trend is not representative of the

Holocene fire history at this central Coast Range site (Fig. 4.2). The trends in fire history as recorded in paleoecological data suggest that differences in future fire frequencies at the three sites will also be dissimilar.

The third recommendation is that using prescribed burning or thinning of forest stands to prevent future fires may not be practical in forests with long fire-return intervals, such as the seasonal temperate rain forest. In response to future changes in fire regimes Noss (2001) suggests that a strategy incorporating prescribed burning and understory thinning in some areas to reduce the risk of high-intensity fires, but in other areas fires should be allowed to burn with minimal suppression. The fire histories from Taylor, Lost, and Little lakes suggests that the use of prescribed burning and thinning in regions where fires have long return intervals may not be useful. Currently, prescribed burning or thinning to reduce fuel loads is not practiced in the Oregon Coast Range because the low number of fires and their small spatial extent does not make the practice cost-effective (C. West, personal communication). Given the prospect of changes in fire regimes, the drier southern areas of the Coast Range may see increases in fire frequency greater than those areas in the mesic northern Coast Range. However, the shortest return intervals of the Holocene, ca. 110 years at Little Lake, a drier southern site, indicate that future fire return intervals may still be long enough to make prescribed burning or thinning to reduce fuel loads impractical. Given the fact that the present-day forest developed in conjunction with infrequent, high-severity, widespread fires (Chapter 2 and 3), Noss's (2001) suggestion to let such forests burn is sensible. A policy of non-

suppression may be the most ecologically sound approach to Oregon Coast Range fires in the future.

Finally, current forest management policies must recognize the dynamic nature of fire regimes in seasonal temperate rain forests. FEMAT (1993) and the Northwest Forest Plan (Tuchmann et al., 1996) recognize fire as an important disturbance process, but do not address the possibility of changes in fire regimes. Both consider the rate of fire occurrence as stationary, and express concern about the possibility of high-severity fires placing current stands reserved as LS/OG at risk (FEMAT, 1993). However, LS/OG forest stands are the product, in part, of past fire regimes (Millar and Woolfenden, 1999; Weisberg and Swanson, 2002; Chapter 3). Recognition that fire regimes could very likely change in the next several centuries (IPCC, 2001) should provide motivation for new management plans (e.g., Cissel et al., 1999) that allow for the wider range of disturbance conditions evident in the paleoecological record.

Conclusions

The focus of forest management in the PNW has changed over the last decades to incorporate protection of biological diversity and preserve ecosystem integrity. This objective requires knowledge of the natural disturbances, such as fire. Paleoecological data can provide a valuable perspective by furnishing information that spans millennia and incorporates periods when climate was different from today. Charcoal data from Taylor, Lost, and Little lakes were used to reconstruct fire histories from each site. The Taylor Lake record suggests that the long fire return intervals usually associated with wet *Picea sitchensis* forest were not present until ca. 750 years ago. In contrast, the Lost

Lake fire history suggests that the present fire return intervals for the mesic *Tsuga heterophylla* forests have been part of the fire regime for millennia. The Little Lake record indicates that, although the present fire return intervals for *Tsuga heterophylla* forest have persisted for the last ca. 2800 years, the xeric forests have experienced large variations in fire intervals through the Holocene.

Long-term fire histories provide estimates and validation of parameters used in landscape analysis models that incorporate fire return intervals. These data can demonstrate the range of variability in fire regimes in response to past climate change. Estimates of future climate change, as a result of increases in carbon dioxide and other greenhouse-gases, indicate a 2° to 5°C increase in temperature over the next century at the global scale (IPCC, 2001). Increases in temperatures will affect plant growth and the distribution of plant species (Shafer et al., 2001) and will likely alter fire regimes (Franklin et al., 1992; Whitlock et al., 2003). Altered fire regimes in the Oregon Coast Range could force species to adjust to new conditions (Spies et al., 2002). Thus, managing forests for biological diversity and ecological integrity will require recognizing that forest ecosystems and fire regimes have dynamic relations, and will likely present site-specific challenges in the future.

CHAPTER V

SUMMARY

Pollen and high-resolution charcoal analyses of lake sediments were used to reconstruct the vegetation and fire histories from sites along a north-south environmental gradient in the Oregon Coast Range, a southern portion of the seasonal rain forest ecoregion of northwestern North America. These data provide information on the relations among vegetation, fire, and climate and suggest that forest composition and fire regimes have been affected by changes in climate at different temporal and spatial scales. The records from Taylor Lake, Lost Lake, and Little Lake also indicate the influence of local environmental conditions in shaping forest composition and fire regimes in the past. Over the course of the Holocene, forest vegetation and fire regimes responded to millennial-scale variations in seasonal insolation values. During the early Holocene (ca. 10,500 to 6700 cal yr B.P.), when summer insolation values were greater than present, forest were dominated by xerophytic, fire-adapted taxa, such as *Pseudotsuga menziesii* and *Alnus rubra*. Fire episodes were near present-day rates at Lost Lake and more frequent than present at Little Lake. During the mid Holocene (ca. 6700 to 2900 cal yr B.P.), as seasonal variability decreased, forests included more mesophytic, fire-sensitive taxa, such as *Tsuga heterophylla*, *Thuja plicata*, and *Picea sitchensis*, and fire-episode frequencies decreased. During the late Holocene, (ca. 2900 cal yr B.P. to present), present-day forests were established at Taylor, Lost and Little lakes, and fire-episode

frequencies decreased at Taylor Lake and increased at Lost and Little lake to attain present-day rates.

On centennial- to decadal-scales, variation in precipitation likely affected fire-episode occurrence. Fire episodes were coincident (within 50 years) among sites from ca. 8200 to 6900 cal yr B.P. and 4500 to 3000 cal yr B.P., suggesting that these were periods when drought conditions were severe enough to overcome environmental differences among sites. In contrast, from ca. 6100 to 4500 cal yr B.P. and ca. 2900 to 1000 cal yr B.P., sites burned asynchronously, suggesting periods when the environmental differences were stronger.

A comparison of the Coast Range data with other seasonal rain forest paleoecological records from Vancouver Island, the Washington Cascades, and the Klamath Mountains of California showed the same broad patterns found at the Coast Range sites. For example, fire-adapted taxa were prominent at all sites from ca. 11,000 to 7000 cal yr B.P., and fire-sensitive taxa became plentiful throughout the ecoregion in the last ca. 6000 cal yr B.P. This shift in composition implies a widespread response in the vegetation to variations in seasonal insolation occurring on millennial time scales. At the regional scale, sites also responded to increased summer drought brought about by higher-than-present summer insolation values in early Holocene with higher frequencies than present. Several sites featured high fire occurrence between ca. 4000 and 3000 cal yr B.P. and during the last 1000 years, suggesting centennial-scale droughts within the overall cool moist conditions of the mid and late Holocene.

The influence of anthropogenic activities on fire occurrence prior to the arrival of Euro-Americans ca. 150 years ago probably played a minor role in the fire episodes detected at Taylor, Lost and Little lakes. Vegetation reconstructions do not indicate a consistent presence of disturbance-adapted taxa, an indication of regular burning by Natives. Also, fire-episode frequency does not increase as Native populations increased. In contrast, the high number of fire-episodes recorded since the mid-1800s are associated with anthropogenic activity, primarily timber harvest activities.

The vegetation and fire histories from the Coast Range provide valuable information about the relations between vegetation and fire that should be considered in forest management planning. The fire histories demonstrate that rates at which fires occur are non-stationary because fire frequency varies continually with climate change. For example, the Taylor Lake record indicates that the range of fire return intervals, based on dendrochronological data is typical of the last 750 years. In contrast, the dendrochronological and charcoal records indicate little change in fire return intervals over the last 8400 years at Lost Lake. The frequency of past fires can also be used by forest landscape modelers to provide estimates of fire return intervals or validate dendrochronological-based fire return intervals used in the models. The outcome of such experiments offer information about the extent of important forest types, such as old growth, in the past.

The fire histories from Taylor, Lost, and Little lakes also suggest that the response to future climate change may not be uniform. Past climate change resulted in vegetation and climate responses that were broadly similar on millennial time scales, but more

spatially variable on centennial time scales because of local environmental influences. Predictions of future climate indicate that global temperatures will increase over the next several centuries (Houghton, 1999; IPCC, 2001). Based on the records at Taylor, Lost, and Little lakes, it is likely that warmer temperatures in the Oregon Coast Range will promote conditions conducive to fires and help shift forest composition toward fire-adapted species. In this way, the early Holocene may be a good analogue for future fire conditions in this summer-dry region (Whitlock et al., 2003). Despite such general projections, it is important to recognize that the evidence from Taylor, Lost, and Little lakes suggests that the response to past conditions was spatially variable. Just as in the past, environmental gradients in the Oregon Coast Range will likely create a heterogeneous mixture of young disturbance- and fire-adapted forest stands at xeric locations and more mature fire sensitive forest stands at more mesic locations.

The paleoecologic records presented here demonstrate the complex nature of ecosystem interactions. A critical component of that complexity is the variability of fire regimes that has occurred over time and space. How this complexity will play out in the future is unclear, but it is paramount that forest management plans consider the demonstrated interactions between fire, vegetation, and climate provided by paleoecologic records.

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