A 7500-YEAR PALEOLIMNOLOGICAL RECORD OF ENVIRONMENTAL CHANGE AND SALMON ABUNDANCE IN THE OREGON COAST RANGE

by

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THESIS ABSTRACT

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Title: A 7500-Year Paleolimnological Record of Environmental Change and Salmon Abundance in the Oregon Coast Range

Pacific salmon (*Oncohrynchus*) abundance has declined significantly over the last century. The lack of a long-term context of salmon abundance hinders restoration efforts. A ca. 6000-year record of coho salmon abundance in the Oregon Coast Range was developed using paleolimnological techniques ($\delta^{15}N$ and complimentary proxies) at Woahink Lake and compared to a control lake (Triangle Lake) that is inaccessible to salmon. Proxies of salmon abundance declined over the record, consistent with a reduction in coastal upwelling and marine forage caused by increasing Pacific sea-surface temperatures. The record suggests that salmon abundance was anomalously high at the time of early Euro-American settlement. The resolution of this study is limited by low sedimentation rates and additional factors influencing $\delta^{15}N$ concentrations. Visual stratigraphy, magnetic susceptibility, loss-on-ignition, organic carbon and nitrogen, bulk density, biogenic silica, $\delta^{15}N$, $\delta^{13}C$, and pollen were used to reconstruct vegetation, earthquake disturbances, and the dune-barrage origin of the lake.

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This thesis is dedicated to my wonderfully supportive husband, Ross Kusler, for encouraging my academic and profession endeavors, and to my parents, Richard and Victoria Reynolds, who taught me the value of commitment and education.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

Pacific salmon (most *Oncorhynchus* species) play a unique role in the environment, as they are anadromous and semelparous; these traits result in a transfer of nutrients from the marine to freshwater and terrestrial environments (Bilby et al., 1996, Schindler et al., 2003). Marine-derived nutrients (MDN) play an important role in the aquatic and riparian ecosystems, and may be traced using paleolimnological biogeochemical methods to reconstruct the abundance of anadromous fish over millennia (Gregory-Eaves et al., 2009). Such studies may also help distinguish the environmental factors that influence salmon abundance over time (Finney et al., 2000; Gregory-Eaves et al., 2009). Several reconstructions of sockeye salmon (*O. nerka*) abundance have been developed by analyzing the isotopic signature of sediments, in conjunction with other biological proxies, from nursery lakes in Alaska (Finney et al., 2002; Gregory-Eaves et al., 2003; Selbie et al., 2009). South of Alaska, however, studies have identified that paleolimnological reconstructions of anadromous salmon are hindered by high flushing rates, high nutrient contributions from the terrestrial environment, and low salmon-densities relative to Alaskan lakes (Hobbs et al., 2007; Hobbs et al., 2008; Selbie et al., 2009).

Paleolimnological approaches to salmon reconstruction have not yet been attempted in watersheds with dominant species other than sockeye salmon, such as coho salmon (*O. kisutch*). This has important implications, as sockeye salmon do not spawn in the southern portion of *Oncorhynchus* distribution, where historical declines of salmon have been most prominent (Lichatowich, 1999; Schindler et al., 2003; Selbie et al., 2007). We speculate that environmental setting rather than the species *per se* may be more important for the success of a paleolimnological approach to salmon population reconstruction. Though some behaviors and habitat preferences are different (e.g. the use of nursery lakes), all anadromous salmon species gain >95% of their biomass in the ocean (Brock et al., 2007) and therefore should contribute measurable isotopic signatures to lake sediments if environmental conditions are suitable. Reconstructions are likely possible if MDN from spawning salmon comprise a significant portion of the nutrient

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budget (affecting nitrogen isotope proxies) and hydrologic retention rates are high (>1 yr, allowing for nutrients the persist through the growing season; Holtham et al., 2004).

Our understanding of long-term salmon population dynamics in the Oregon Coast Range (OCR) has been limited to ethnographies and historical archives (e.g. cannery and escapement records) (Lichatowich, 1999; Meengs et al., 2005). Reliable harvest records of coho salmon in Oregon, which only extends back to 1923 AD, reflect a large range of annual catches (ca. 150,000-4,000,000) (Lichatowich, 1999). Dendrochronology reconstructions of Chinook salmon in this region have created a record back to 1750 AD (Drake et al., 2007). This lack of data provides little context in terms of variability in salmon abundance prior to widespread anthropogenic disturbance. Since the early 20th century, salmon have declined dramatically, resulting in numerous laws and policies to protect existing populations from anthropogenic threats and to restore degraded salmon habitat (Lawson, 1993; Schindler et al., 2008; Shaff et al., 2009).

In addition to habitat loss and exploitation, climate has been identified as an important control on salmon abundance (Mantua et al., 1997; Finney et al., 2000; Schindler et al., 2003; Drake et al., 2007). In particular, decadal-scale modes of variability of sea surface temperatures (SST) in the northern Pacific (i.e. the Pacific Decadal Oscillation) are manifested as major changes in salmon abundance (Mantua et al., 1997; Drake et al., 2007). When the Aleutian Low is strong, SSTs tend to be relatively warm and stratification of coastal waters is more pronounced (Mantua et al., 1997; Mueter et al., 2002). In the southern Pacific Northwest (PNW) these conditions lead to reduced upwelling, thereby reducing coastal nutrient availability and primary productivity, and thus reducing forage for salmon. Conversely, in the northern PNW, these conditions lead to increased coastal nutrient flux and stratification, which in this region increases primary productivity and thereby forage for salmon (Beamish et al., 1993; Finney et al., 2000). Whether such variability is strongest on interannual, decadal, centennial, or longer time scales remains unknown, though the long-term perspective over the last ca. 2200 years suggests strong variability over both multi-decadal and multi-centennial timescales (Finney et al., 2002).

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This study is the first to attempt to reconstruct salmon abundance in the Oregon Coast Range (OCR) using paleolimnological methods. Few lakes in the OCR are suitable for paleolimnological salmon reconstruction, due to the region's steep topography and high precipitation (ca. 200 cm/yr), low lake-water retention rates, and high inputs of terrestrial organic matter to lake sediments. We carefully selected sites to help overcome these issues. We compare sediment records of stable isotopes ($\delta^{15}N$ and $\delta^{13}C$), organic content and aquatic productivity (carbon, LOI, and biogenic silica), and pollen at two lakes: one downstream of coho salmon spawning grounds and, as a control, one upstream of a natural barrier to fish migration. We compare these records to existing Pacific SST reconstructions to assess centennial-to-millennial-scale climatic controls of salmon abundance in the OCR.

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CHAPTER II

STUDY SITE

The study site with salmon, Woahink Lake (43°54’33” N, 124°06’10” W), is an oligotrophic and deep (22.8 m) dune-barrage lake with a dendritic shape and a close proximity to the ocean (ca. 3.2 km, 13 m asl; Fig.1). It is one of the few lakes in the OCR that has a high water retention time (1.2 yr) due to its large size (299 ha) and relatively small watershed (1784 ha). The lake is monomictic with thermal stratification during the summer and mixing during the winter, which may increase biological recycling of nutrients (Johnson et al., 1985; Pfauth et al., 2005). Woahink Lake contains three major tributaries that are used by salmon for spawning and rearing. The most common tree species in the watershed are *Picea sitchensis* (Sitka spruce), *Alnus rubra* (red alder), *Tsuga heterophylla* (western hemlock), *Pseudotsuga menziesii* (Douglas-fir), and *Pinus contorta* var. *contorta* (shore pine).

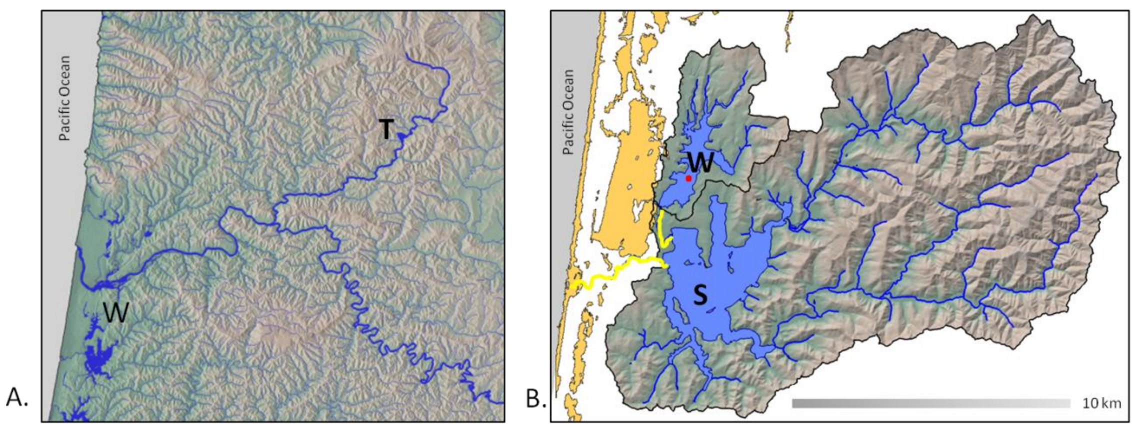

Figure 1. Maps of study sites. A. Study sites: Woahink Lake (W), Triangle Lake (T) in the central OCR. B. Topography and streams of the Woahink Lake (W) and Siltcoos Lake (S) watersheds. Currently, salmon must enter Siltcoos Lake to access spawning streams in the Woahink Lake watershed, as shown by yellow streams. Streams that are used for coho spawning and rearing (streamnet.org) are depicted in blue. Beach and unvegetated dunes are portrayed in orange, and watersheds are delineated with brown outlining. The red dot denotes the coring site at Woahink Lake

Escapement records beginning in1960 are available from the adjacent Siltcoos Lake, which salmon must currently pass through to access the spawning grounds upstream from Woahink Lake. Coho salmon have used these systems historically, with counts ranging from 555 to 10,212 spawners per year between 1960 and 2010 AD

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(Buckman, R., personal communication, 2011), which is much less than in the highest relative production of Alaskan sockeye lakes, though sockeye salmon are generally much smaller (average weight =2.7 kg; Finney et al., 2000) than coho salmon (average weight =4.5 kg; Bilby et al., 1996). Low densities of salmon can result in low contributions of MDN to nutrient budgets, which is problematic for paleolimnological reconstructions. However, post-1960 escapement records almost certainly do not represent earlier abundance. Cannery and escapement records (since 1860 AD and 1960 AD, respectively) indicate that salmon abundance in the OCR peaked in 1911, and has declined drastically since then (Lichatowich, 1999). Salmon abundance at Woahink Lake is also thought to have declined significantly prior to escapement records due to the introduction of the warm water game species *Micropterus salmoides* (largemouth bass), *Lepomis macrochirus* (bluegill), and *Perca flavescenes* (yellow perch) at ca.1930 AD (Buckman, R., personal communication, 2011).

The control site, Triangle Lake (44°10’19” N, 123°34’20” W) is an oligotrophic and deep (29 m) lake located 50 km from Woahink Lake, and 44 km from the Pacific Ocean, at 212 m asl (Fig. 1; Johnson et al., 1985). It was formed by a landslide ca. 44 ka (thousands of years before present) at the headwaters of Lake Creek in the Siuslaw River watershed (Worona and Whitlock., 1995). The water retention time of Triangle Lake (1 month) is shorter than that of Woahink Lake (Johnson et al., 1985). Triangle Lake is likely monomictic, though lake survey data are sparse. Triangle Lake was inaccessible to salmon until a fish ladder was constructed ca. 1990 AD, and the lake has intermittently been stocked with salmon and steelhead trout since ca. 1960 AD (Buckman, R., personal communication, 2011). Modern forests are primarily composed of *T. heterophylla*, *P. menziesii*, and *Thuja plicata* (western red cedar). Multi-millennial reconstructions of forest and fire history have been developed from Little Lake, located ca. 0.4 km west of Triangle Lake (Worona and Whitlock, 1995; Long et al., 1998; Long et al., 2007).

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CHAPTER III

METHODS

Sediment cores were collected from both lakes in 2010 AD. Surface cores (<1 m) were recovered from both lakes using a clear acrylic tube attached to drive rods and fitted with a piston. Long cores were collected using a modified Livingstone piston corer guided by rigid steel casing between the raft platform and the sediment surface. A single core was collected from the deepest location (22.5 m) at Woahink Lake, and two cores were collected from a broad level area (24.7 m depth) at Triangle Lake. The Livingstone cores were extruded in the field, wrapped in plastic wrap, and stored in PVC piping. Short-cores were subsampled at 1-cm intervals at the University of Oregon, and stored in polyacrylic vials. Aside from transport, the cores were stored in a refrigeration unit in the Paleoecology Lab at the University of Oregon.

Initial Core Description (ICD) began at the University of Minnesota Limnological Research Center (LacCore). The cores were split and photographed using a high-resolution line-scan camera. Lithologic and biogenic components were identified using smear-slides and scanning electron microscopy (SEM). The presence of vivianite was confirmed by SEM, and contiguous 1 cm^3 samples of the Woahink Lake cores were visually inspected for its presence. Measurements of magnetic susceptibility (MS) were taken every 0.5 cm using a Geotek multi-sensor core logger. At the University of Oregon Paleoecology Lab, loss-on-ignition at 550°C (LOI) and bulk density (BD) were measured every 1-5 cm following standard methods (Heiri et al., 2001). Samples of $1cm^3$ were dried and weighed to determine BD, then combusted at 550°C for four hours and weighed again to determine LOI.

Stable isotopes, carbon and nitrogen were measured at <5 cm intervals. Sediment samples were freeze-dried to minimize fractionation caused by volatilization during the dehydration process. Percent organic carbon and percent organic nitrogen were measured at Idaho State University using a Costech Elemental Analyzer. Stable isotopes (^{15}N and ^{13}C) of homogenized bulk sediment were measured using a Finnigan Delta Plus mass spectrometer. Nitrogen and carbon isotopes are reported in standard delta notation

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relative to atmospheric N_2 or Vienna PeeDee Belemnite (VPDB), respectively, and analytical precision is within ± 0.2‰.

Five and three AMS radiocarbon dates on identifiable plant macrofossils or charcoal were obtained from Woahink and Triangle lakes, respectively. The age-depth relationship at each lake was constructed by fitting spline curves to calibrated radiocarbon dates. Zones were assigned to each sediment core subjectively based on the means and variability of organic content, magnetic susceptibility, $\delta^{15}N$ and $\delta^{13}C$.

The difference between $\delta^{15}N$ values at Woahink Lake and Triangle Lake was calculated to attempt to control for non-MDN impacts to the $\delta^{15}N$ signal at Woahink Lake. To account for the higher resolution of sampling at Triangle Lake, and the error in the age models, the Triangle Lake $\delta^{15}N$ values were smoothed using a 100-year moving average before subtracting from the values of the Woahink Lake samples of corresponding age.

A mixing-model was developed to estimate the number of salmon required to produce a given value of $\delta^{15}N$ in the Woahink Lake sediment. The mixing model uses three levels of watershed N input and three levels of salmon N input. The presence of *Alnus*, a species that has a symbiotic relationship with N-fixing bacteria, can greatly increase soil N and the cycling of N in an ecosystem (Scott et al., 2008). As a result, productivity within the watershed and the measured $\delta^{15}N$ record is influenced by the abundance of *Alnus* (Perakis et al., 2011). Concentrations of stream-water DIN (dissolved inorganic nitrogen) reflect *Alnus* cover and stream nitrate concentrations found nearby (Compton et al., 2003). We used *Alnus* percent covers of 5, 15, and 25% that correspond to nitrate levels of 47, 85, and 122 μg/L. These values are consistent with an observed lake-water DIN measurement of 114 μg/L, which was >99% nitrate (Vaga et al., 2005). Watershed DIN input is then based on an estimate of stream discharge from mean precipitation (2.74×10^6 m^3/yr; Johnson et al., 1985), which is diluted by direct precipitation onto the lake surface (16% of the watershed). The $\delta^{15}N$ value assigned for watershed DIN (2‰) is based on the mean value at Triangle Lake, and is within the range of soil organic matter components measured at various locations in the central OCR (which are always less than 3.75‰ and average 2.2‰; Scott et al., 2008). Salmon input

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for the model is based on historical escapements as a minimum and 2000 adults as a maximum. We assume a $\delta^{15}N$ signature of salmon N to be 13.5‰ (Johnson et al, 2009; Bilby et al., 1996), and a salmon mass of 4.5 kg that is composed of 3% N.

To assess changes in primary productivity at Woahink Lake, the percent dry weight of amorphous silica, or biogenic silica (BSi) was measured every <10 cm using a modified wet-alkaline extraction method (Mortlock and Froelich, 1989). Each sample consisted of approximately 60 mg of freeze-dried sediment that was digested in a 10% Na_2CO_3 solution while heated in a water bath at 80°C. Due to the high silt and clay content of the sediment which may contribute to the measured silica concentration, aliquots were collected at 200, 300, 400, and, 500 minutes for the first several batches. Silica concentrations were measured using a molybdate-blue reaction followed by an absorbance reading in a GENESYS 8 spectrophotometer. A time-series correction was used to account for the dissolution of mineral silica in the timed extractions (Mortlock et al., 1989).

Pollen analysis was performed at <10 cm intervals on the Woahink Lake core (increments of <300 yrs). Samples were processed according to standard methods, mounted on slides in silicon oil, and scanned at a magnification power of 400X (Faegri et al., 1989). A minimum of 350 grains was identified to the lowest taxonomic unit possible. Based on the modern presence of these species, *Alnus* is attributed to *A. rubra*, *Picea* is attributed to *P. sitchensis*, *Pinus* is attributed to *P. contorta* var. *contorta*, and *Pseudotsuga*-type pollen is attributed to *P. menziesii.*

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CHAPTER IV

RESULTS

Woahink Lake

We recovered 722 cm of sediment before reaching an impenetrable layer. The core is composed of fine silt- with low organic content (LOI mean=20%), visible color changes throughout, deposits of sand and shells in lower 422 cm, and formations of vivianite throughout the lowest 611 cm (Fig. 2). The basal radiocarbon date indicates that the record extends back to 7.45 ka (Table 1). Organic matter increases over the record (LOI: 16 to 33%, C: 6 to11%), whereas declines were observed in $\delta^{15}N$ (ca. 7 to 4.5‰) and $\delta^{13}C$ (ca. -21 to -29).

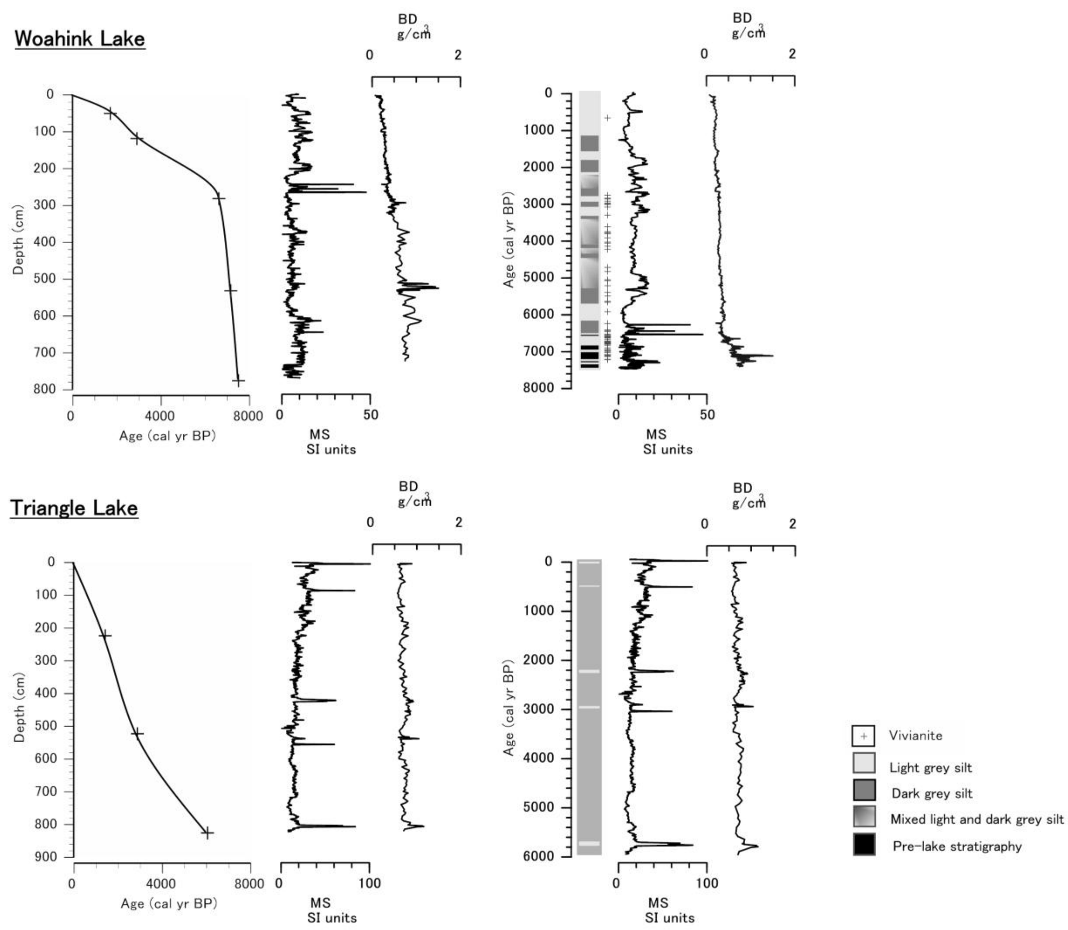

Figure 2. Chronology, magnetic susceptibility, bulk density and general lithology of sediment cores from Woahink and Triangle lakes, Oregon. Data are presented on both depth (left) and age (right) axes. See Table 1 for details regarding radiocarbon dates.

Table 1. AMS (Accelerator Mass Spectrometry) radiocarbon dates and calibrated ages (Reimer et al., 2009). Lab codes refer to the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory (CAMS) or Woods Hole Oceanographic Institute (OS).

Depth (cm)	Material dated	Lab code	Radiocarbon age (± 1σ)	Calibrated age 2σ (median) 2σ
Woahink Lake				
40-44	charcoal	CAMS-155163	1665± 45	1420 (1570) 1690
111-112	wood	CAMS-155164	2865± 35	2870 (2990) 3140
274-275	wood	CAMS-151038	5775± 30	6500 (6580) 6650
523-525	wood	CAMS-151039	6220± 35	7010 (7115) 7249
771	charcoal	OS-82618	7450± 40	7422 (7470) 7560
Triangle Lake				
218-219	wood	CAMS-151040	1375± 35	1190 (1300) 1350
517-518	wood	CAMS-151041	2635± 30	2720 (2760) 2840
821	wood	OS-83224	6930± 40	5660 (5930) 6190

Zone W1 (7.45 – 5.4 ka)

This zone is marked by a high sedimentation rate (0.35 cm/yr), the presence of shells below 521 cm (7.1 ka), sand facies below 300 cm (6.67 ka), and three major reversals in most sediment properties (Fig. 2 and 3). First, from 6.67 to 6.3 ka, the organic matter in the sediments increases substantially (8 to 20% LOI, and 2 to 7% C) following a pulse of high MS and above a layer of sand. These changes co-occurred with a slight decrease and stabilization of BD at 0.4 g/cm^3, an increase in N (0.2 to 0.4%), a slight increase of C:N (10 to 12), and a decrease in δ^{15}N (from 7 to 3‰). Second, from 6.3 to 5.9 ka, decreases are observed in LOI (20 to 12%), C (7 to 4%), and N (0.75 to 0.4%). At the same time, δ^{15}N (3 to 6‰) and δ^{13}C (-29 to -22‰) increase. The third reversal occurs at 5.9 ka, as LOI, C, and N increase, and δ^{15}N decreases.

Zone W2 (5.4 – 2.75 ka)

This zone is marked by stability in most sediment properties following the onset of a much slower sedimentation rate relative to zone W1 (0.35 to 0.04 cm/yr; Fig. 2). MS varies from 6.2 to 17.5 SI. BD decreases slightly (0.35 to 0.25 g/cm^3) and LOI increased

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slightly (18 to 20%; Fig. 4). N increases from 0.49 to 0.62%, C:N remains between 12.8 and 14.3, and BSi is low (1.3 to 9.8%). $\delta^{13}C$ increases slightly from -29.6 to -28.5‰ and $\delta^{15}N$ decreases steadily from 4.4 to 3.5‰.

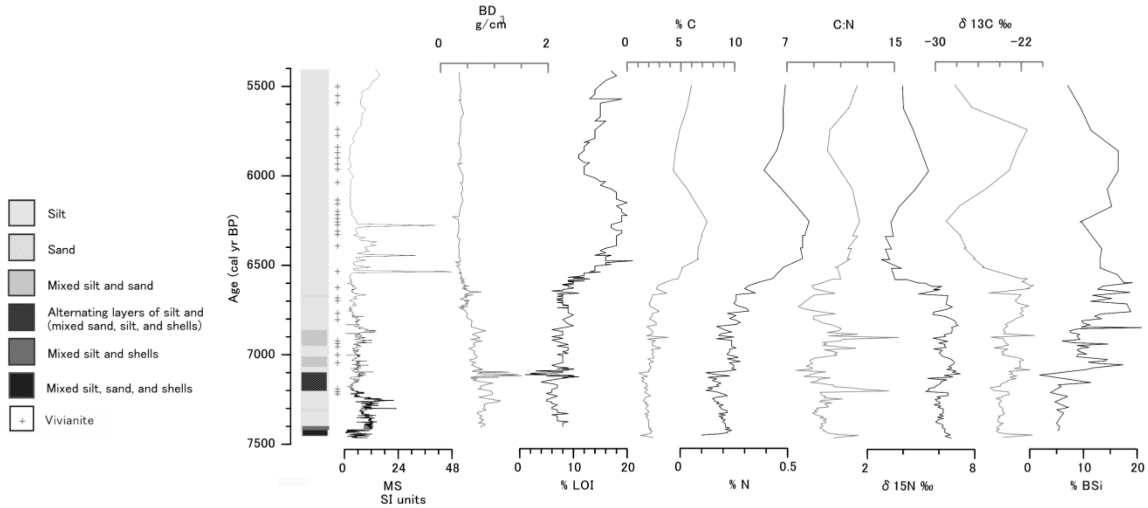

Figure 3. Zone W1 at Woahink Lake, encompassing the high-sedimentation rate period of the transition from a marine-estuarine to a freshwater environment.

Zone W3 (2.75 – 1.6 ka)

Zone W3 is characterized by increases in variability in organic matter properties and an increase in the sedimentation rate (0.04 to 0.06 cm/yr). Directional shifts of MS, LOI, and N occur at ca. 200-year intervals; with positive (increasing) phases beginning at 2.4, 2.1, and 1.6 ka, and negative (decreasing) phases beginning at 2.6, 2.2, and 1.8 ka (Figs. 2, 4). MS ranges from 4.1 to 17.2 SI. BD decreases (0.31 to 0.17 g/cm^3) and the mean LOI increases slightly (from 19 to 21%). N ranges from 0.49 to 0.67%, C:N decreases slightly (14 to 12.8), and BSi increases from 4.6-14.1%. $\delta^{13}C$ decreases from -29.7 to -28.4‰, and $\delta^{15}N$ declines from 4.1‰ to 3‰.

Zone W4 (1.6 ka – 1400 AD)

This zone is distinguished by stability among most sediment properties and a decrease in the sedimentation rate (0.06 to 0.03 cm/yr). MS varies from 0.2 to 8 SI and BD ranges from 0.16-0.28 g/cm^3. LOI peaks at 1.5 ka and then declined (from 25 to 18%). N ranges from 0.51 to 0.72%, and peaks from 1.2–1.0 ka. C:N follows a similar

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trend, peaking at 1.35 ka and ranges from 13.9 to 11.8). BSi ranges from 6.9 to 11.6%. $\delta^{13}C$ increases slightly (-29.4 to -28‰), whereas $\delta^{15}N$ declines from 3.5 to 2.6‰.

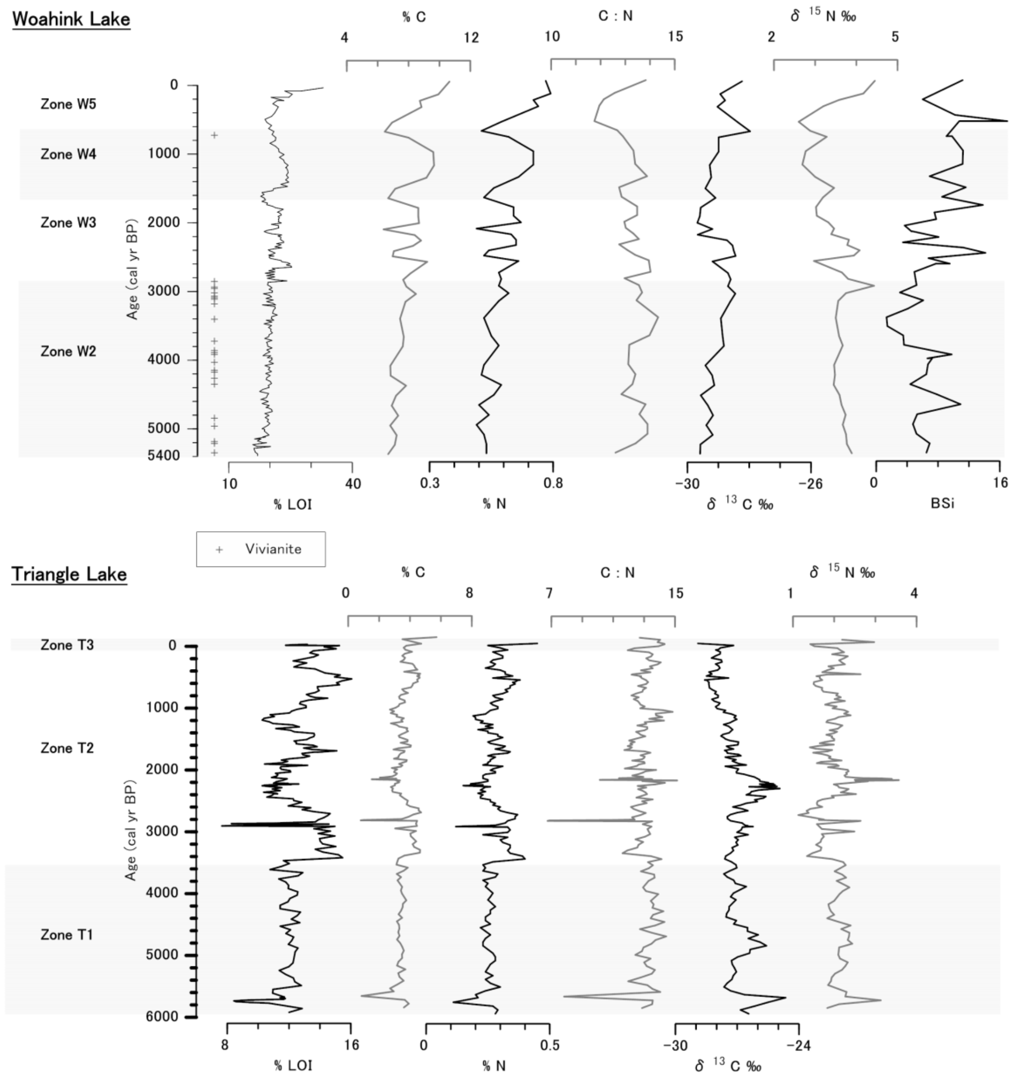

Figure 4. Organic matter properties of sediment cores from Woahink and Triangle lakes, Oregon.

Zone W5 (1400 AD – 2010 AD)

This zone is marked by an increase in most organic sediment properties. MS ranges from 2.4 to 13.3 SI, and BD ranges from 0.07 to 0.24 g/cm^3. LOI increases from 19 to 33%. N increases from 1400 – 1800 AD (0.72 to 0.79%), then decreases slightly (0.02%), though C:N is marked by a steady increase over the zone (11.5 to 13.8). BSi changes slightly (10.2 to 11.9%) after a distinct peak of 16%. $\delta^{15}N$ has the greatest change over

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the past 5,500 years (increasing from 3.2 to 4.5‰). $\delta^{13}C$ continues the gradual trend from the previous zone, increasing from -29.03 to -28.23‰. The uppermost (surface) sediments had low BD (0.07 g/cm^3) and high LOI (33%).

Pollen record

Alnus, *Picea*, and *T. heterophylla* are the dominant pollen taxa for most of the record (means= 31%, 24%, and 16%, respectively; Fig. 5). *Pinus*, *P. menziesii* and *Cupressaceae* are also present throughout the record (means =13%, 10%, and 4%, respectively). *Alnus* and *Picea* vary inversely at 7.0, 6.0, 3.5, 1.7 ka, and 1400 AD. *Alnus* has the highest variability (range: 10-69%) and mean values decrease by ~15% over the record. *Picea* also decreases (~10%) over the record. At 1.2 ka, *T. heterophylla* reached its highest values (35%). At 1400 AD, *Pinus* and *Alnus* increased as *T. heterophylla* decreased.

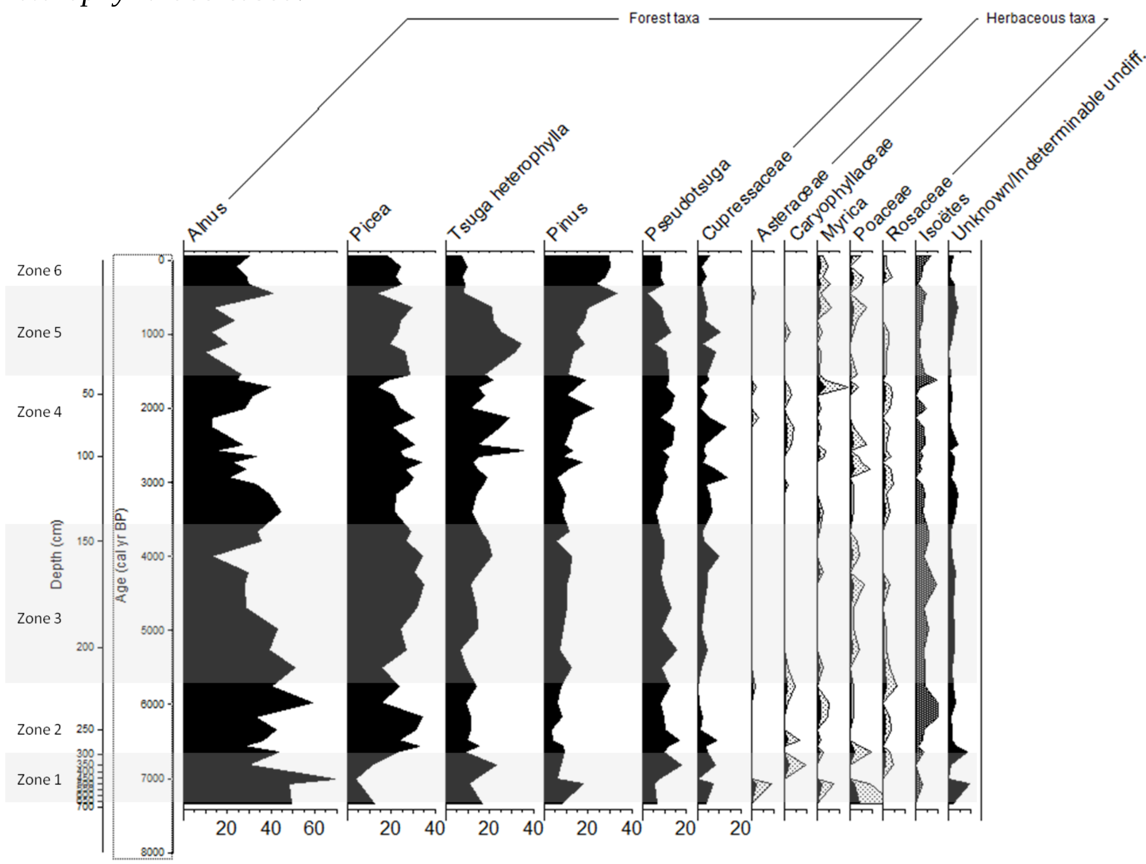

Figure 5. Pollen-percentage diagram for forest, herbaceous, and aquatic taxa at Woahink Lake, Oregon.

Herbaceous and shrub taxa (*Asteraceae, Caryophyllaceae, Myrica, Poaceae*, and *Rosaceae*) were minor components of the pollen record (<1%). Herbaceous taxa are lowest from 5.9 – 3.5 ka. *Isoetes* pollen was found in low percentages (mean =3.08%) and declined over the record, with peaks at 6.0, 4.5, and 2.5 ka.

Triangle Lake

We recovered 824 cm of sediment before practical limitations in the length of the drive rods (31 m) and sediment stiffness prevented us from reaching additional depths. The sediments are low in organic material (mean=12%) and are composed of brown silt with five distinct narrow bands of light-grey silt. Radiocarbon dating of basal sediments indicated that the record extends to 5.93 ka. $\delta^{15}N$ was relatively stable, with a mean of 2.04‰. $\delta^{13}C$ was the only proxy to experience notable change over the record; it decreased from -23.68‰ in the basal sediments to -28.23‰ in the surface sediments.

Zone T1 (6.0 – 3.5 ka)

This zone is characterized by low variability across most sediment properties, and the lowest sedimentation rate of the record (0.09 cm/yr). MS is relatively low (mean =15.21 SI), BD ranged from 0.64 to 1.16 g/cm^3, LOI varied from 11 to 13%, and N ranged from 0.1-0.3%. $\delta^{13}C$ varied from -27.7 to -24.7‰ and $\delta^{15}N$ ranged from 1.8 to 3.1‰. A 5.5 cm light-grey layer with high MS (84 SI) and BD values (0.11 g/cm^3) is present at 5.75 ka.

Zone T2 (3.5 ka – ca. 1900 AD)

This zone is marked by increased variability across most sediment properties and an increased sedimentation rate (0.09 to 0.17 cm/yr). MS increased (mean=20.32 SI), and BD became less variable (range =0.74 to 0.63 g/cm^3). LOI, N, and C:N experienced greater variability (ranges: 7-16%; 0.12-0.4%, and 6.75-15.15, respectively). At 2.9 ka, a 2.5-cm thick, light-grey layer of silt coincides with sharp minimums in LOI (7.65%), N (0.12%), and C:N (6.75). At 2.25 ka, a peak in C:N (15.14), $\delta^{13}C$ (-24.93‰) and $\delta^{15}N$ (1.99‰) corresponds with a 4-cm layer of light-grey silt. At 1500 AD, a 0.4 cm-thick deposit of light-grey silt corresponds with peaks in LOI (16.06%), N (0.38%) and $\delta^{15}N$ (2.64‰).

Zone T3 (ca. 1900 AD- 2010 AD)

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This zone, covering roughly the last century, is marked by distinct changes across most sediment properties and a slight increase in sedimentation rate (0.17 to 0.21 cm/yr). A 1-cm layer of light-grey silt dates to 1925 AD, and has corresponding peaks in MS (100.9 SI), BD (0.89 g/cm^3), and decreases in LOI (11.78%) and N (0.25%). $\delta^{15}N$ also peaks at this time (2.97‰). The uppermost (surface) sediments have low LOI (13.19%), $\delta^{13}C$ (-27.18‰), and N (0.25%).

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CHAPTER V

DISCUSSION

Transition from estuary to lake at the Woahink site

From 7.45 to 5.4 ka (Zone W1), the site was in a transition from a marine-estuary to a freshwater lake, and would not have reliably recorded an isotopic signature of salmon abundance. Periods of high $\delta^{15}N$ (>7‰) and the shell content of the sediment core are consistent with estuarine sediments. This landscape transition occurred through several geomorphic events, as evidenced by the $\delta^{13}C$ to C:N ratios and changes in stratigraphy (Figs. 1, 6). Peterson et al (2007) documented nearby (<5 km north of Woahink Lake) Holocene dune emplacement at 7.3 ka that corresponds to a 4-cm thick layer of sand and a peak in MS in the Woahink Lake sediments, supporting local dunal activity. At this time, increasing eustatic sea level and the latitudinal placement of the NE Pacific storm track promoted strong onshore winds, causing the transportation and deposition of sand along the Oregon coast (Peterson et al., 2007). The event at 7.3 ka also correlates with a tsunami record from Bradley Lake (Kelsey et al., 2005), located 98 km south of Woahink Lake), and may be attributed to seismic activity or extreme wave runup. Sand deposits persist until 6.8 ka during the period of high sedimentation rate, while C:N indicates pulsed inputs of terrestrial and aquatic organic matter. C:N ratios are primarily in the range of aquatic productivity, but fluctuate greatly as would be expected in an estuary. These inputs of terrestrial organic matter could be the result of mass wasting events, or the accumulation of material in an enclosing hydrologic system as dunes blocked the outlet of the lake.

Freshwater conditions were induced at 6.55 ka, maintained until 6.1 ka, and then transitioned to marine-estuary conditions until 5.75 ka, as inferred by $\delta^{13}C$, $\delta^{15}N$, and C:N ratios (Lamb et al., 2006). The reversion to estuary may be the result of the erosion or loss of the dune dam caused by a large, well-documented Cascadia earthquake that occurred at 5.93 ka (Morey et al., 2012). Sediment records also captured an event at this time that caused rapid deposition of inorganic material at Triangle Lake, and the adjacent Little Lake (Long et al., 1998). It is unlikely that fire was the causal mechanism of increased inorganic sedimentation at Triangle Lake, as the charcoal record at nearby Little Lake does not increase significantly at this time (Long et al, 1998). An increase in precipitation in the Pacific Northwest at 5.7 ka (Starratt, 2012) may have facilitated the observed transition from estuarine to freshwater conditions at the Woahink Lake site at

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ca. 5.75 ka through greater moisture and increased fluvial sediment delivery.

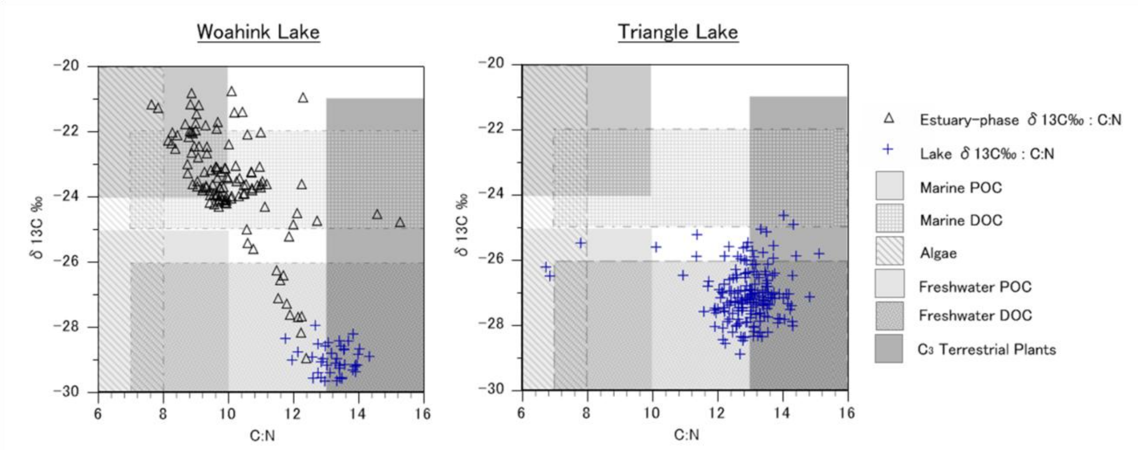

Figure 6. Feature space for C:N : δ^{13}C (modified from Lamb et al., 2006) indicate the origin of organic matter over time in Woahink and Triangle lakes. Estuary-phase samples are those in Zone 1, and Lake samples include those in Zones 2-5.

Disturbance events after the formation of Woahink Lake (ca. 5.4 ka)

Both sites contain records of disturbance events that correlate with previously identified seismic activity in the region. At 2.9 ka and 2.2 ka, disturbance events in the Triangle Lake watershed were identified by a sharp increase in MS decrease in organic matter (LOI, C, N, C:N) and an increase in δ^{15}N. The timing of these events correlate well with Cascadia-earthquake induced turbidites in the Hydrate Ridge Basin at 2.96 ka and 2.2 ka (Morey et al., 2012). At 1400 AD (0.55 ka), changes among many sediment properties, including MS, at both sites coincides with a peak in MS at Sanger Lake (ca. 200 km southeast of Woahink Lake; Briles et al., 2008) that was attributed to seismic activity (Morey et al., 2012). We did not see strong evidence of the well-documented, m-9 earthquake that spanned the entire Cascadia Margin in 1700 AD, and induced onshore tsunamis from northern California to BC, and subsidence of some coastal locations in the OCR (Kelsey et al., 1998; Peterson et al., 2007).

We expected to see changes caused by Euro-American activities (e.g. logging, urban development, etc.) after ca. 1850 AD. However, at Woahink Lake, any signal of recent anthropogenic activity is muted by already-increasing trends of organic matter and a very slow sedimentation rate. A land-use signal at Triangle Lake is more pronounced, with an increasing trend in organic content until ca. 1970 AD. At this time, LOI and C:N

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decrease suddenly, which may reflect increased erosion from accelerated road building and logging in the 1970s and 1980s.

Reconstruction of salmon abundance at Woahink Lake

We examined several lines of evidence regarding the possibility that a signature of MDN was recorded in the sediments at Woahink Lake. Some factors, including low sedimentation rates, low salmon abundance, and other influences on $\delta^{15}N$ levels hindered the temporal resolution of the record and precluded the possibility of calibrating the $\delta^{15}N$ records against historical trends, the existing data support the hypothesis that $\delta^{15}N$ primarily reflects changes in salmon abundance.

The first line of support for salmon influence on $\delta^{15}N$ is that the $\delta^{15}N$ values at Woahink Lake (mean =3.5‰, since 5.4 ka) are higher than at the control lake (mean =2.2‰) (Fig. 7). The difference between the values (the "adjusted $\delta^{15}N$") is always positive and ranges from 0.5-2.8‰. The $\delta^{15}N$ values at Woahink Lake are also higher than the average $\delta^{15}N$ values reported from organic matter found in soils of pure *Alnus* stands in the central OCR (ca. 2.2‰ Scott et al., 2008), which indicates that leaching from *Alnus* cannot account for the observed values at Woahink Lake. The peak in $\delta^{15}N$ in the modern sediments at Triangle Lake could possibly be attributed to the ability for spawning salmon to access the Triangle Lake watershed after the construction of a fish-ladder in 1989 (Buckman, R., personal communication, 2011).

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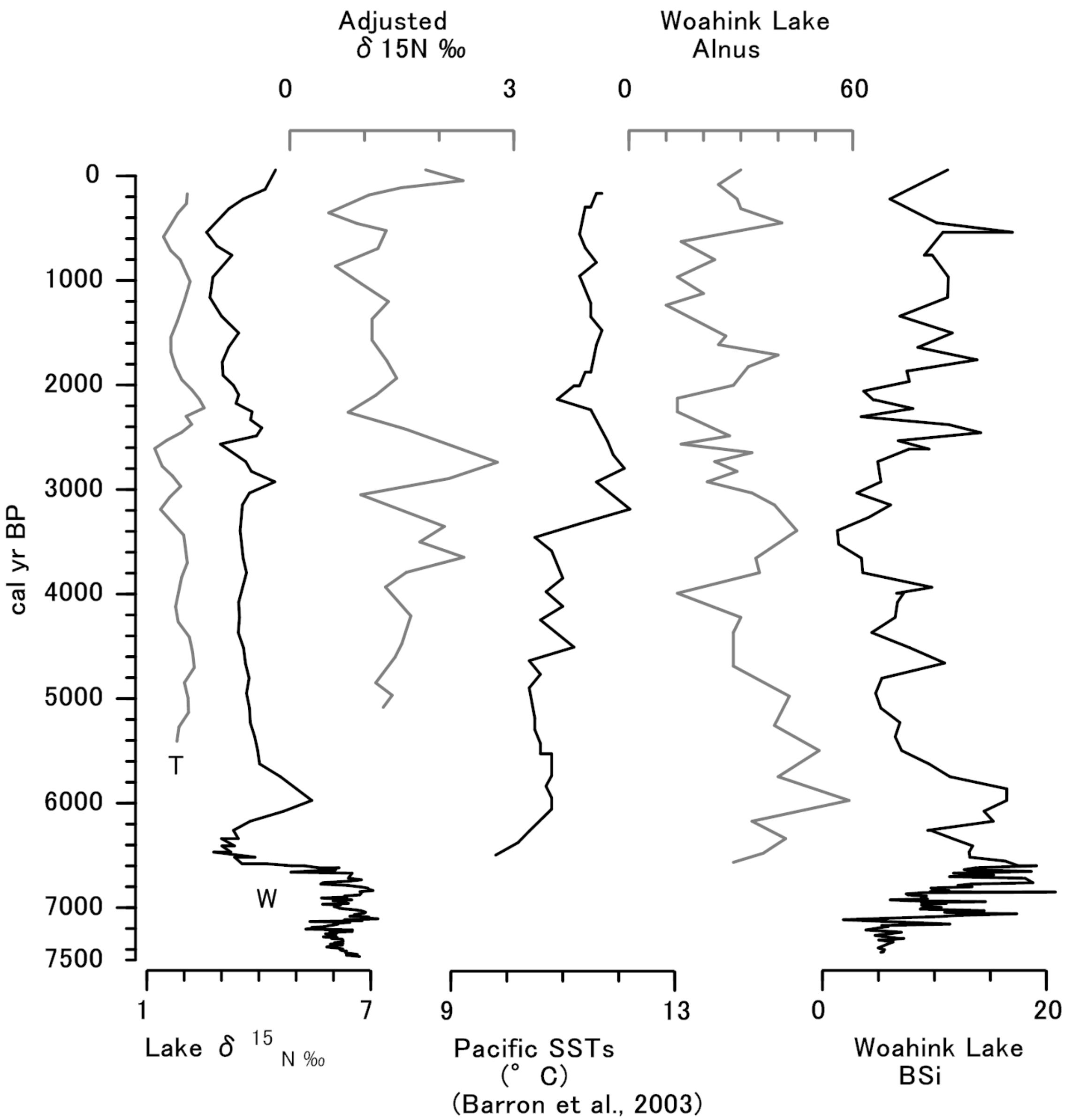

Figure 7. The $\delta^{15}N$ records at Triangle Lake (T) and Woahink Lake (W), $\delta^{15}N$ at Woahink adjusted by the Triangle Lake record, reconstructed sea-surface temperature from a site near northern California (Barron et al. 2003), and other proxies at Woahink Lake that are potentially related to nutrient status (BSi and *Alnus* pollen).

Second, Woahink Lake is oligotrophic, so even small contributions of MDN are likely to affect the measured sediment $\delta^{15}N$. Organic matter is generally low throughout the record, indicating that the lake has probably always been oligotrophic. However, C:N ratios are relatively low at Woahink Lake, suggesting a major contribution from aquatic rather than terrestrial sources. C:N ratios of 4-10 are common for algae and ratios of 20+ are often attributed to vascular land plants (Fig. 7; Peterson et al 1987; Meyers, 1994).

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The range of C:N ratios at Woahink Lake (11.75–14.33) are likely influenced by a combination of aquatic productivity, nutrient availability, and inputs of terrestrial matter. We suggest there was very limited input of terrestrial organic matter at Woahink Lake because of the small drainage-basin to lake-size ratio and the location of the coring site, which is in a deep location far from the inlets. Thus, the addition of MDN to the hydrologic system could measurably affect δ^{15}N at the core site.

Our third line of support is derived from the mixing model of estimated dissolved inorganic N (DIN) and salmon abundance. It indicates that a reasonable salmon spawner population (ca. 2000 fish per year) can elevate the lake-water δ^{15}N from an estimated 2‰ from the watershed to the observed ca. 4‰ (Table 2). However, this estimate is very sensitive to the watershed contribution to lake DIN, which may change considerably under earlier climates with a different abundance of *Alnus* and stream discharge (Perakis et al, 2011). We suspect that the geological materials around the lake (mostly Pleistocene sand dunes; Peterson et al., 2007) are rapidly drained and contributes little N to stream-flow, and thus the lower estimate of watershed DIN levels may be more realistic (Table 2).

Table 2. Mixing-model of nitrogen inputs to Woahink Lake. The table shows the expected δ^{15}N (‰) of DIN in Woahink Lake: calculated using a mixing model with three levels of watershed N input and three levels of salmon spawner returns, bracketed using estimates of stream discharge, direct rainfall on the lake, *Alnus* cover effects on stream-water DIN, and salmon escapement records. See the text for details.

Salmon N Input		Watershed DIN Input (µg/L)		
	# of Salmon	*Low (10)*	*Medium (50)*	*High (114)*
Low Salmon Input	100	2.12	2.07	2.05
Medium Salmon Input	1000	3.09	2.63	2.45
High Salmon Input	2000	3.99	3.19	2.86

Finally, large-scale trends in proxies of salmon abundance at Woahink Lake are consistent with current theories of climate and salmon relationships. The millennial-scale decline in δ^{15}N (and inferred salmon abundance) is the expected response to changes in SSTs and coastal upwelling, and thus the availability of nutrients and forage for salmon.

During the mid-Holocene, the southward flow of the California Current was stronger than today, resulting in cooler SSTs and strong upwelling until ca. 5.0 ka (Barron et al., 2007). These conditions are known to favor high salmon abundance (Rupp et al., 2012). Along the southern coast of Oregon, the influence of the California Current declined between 4.8 – 3.6 ka (Barron et al., 2007), in parallel with a slight decrease in $\delta^{15}N$ at Woahink Lake. However, this millennial-scale relationship was not apparent form 3.5-3.0 ka when SSTs increased likely due to an increase in the influence of the El Niño Southern Oscillation (ENSO) (Barron et al., 2007). While marine conditions are assumed to be the primary control on coho abundance (Rupp et al., 2012), we note that these same conditions (warmer SSTs) may also be associated with higher stream-flow that positively affects migration, spawning, and juvenile survival (Chatters et al., 1995).

It is more difficult to interpret the record at shorter time-scales, as the temporal resolution is low and there are other factors influencing the N-record. *Alnus* individuals have short (<100 years) lifespans, and can influence $\delta^{15}N$ levels for decades following mortality (Scott et al., 2008). Though *Alnus* pollen follows an overall decreasing trend similar to the $\delta^{15}N$ record (r =0.29), century-scale variability in the *Alnus* pollen record does not match that of the $\delta^{15}N$ record. Therefore, we believe that factors in addition to *Alnus* control the $\delta^{15}N$ record at Woahink Lake.

We assume that that the nutrients provided by salmon should be important to biological productivity, particularly given the low availability of nutrients in Woahink Lake. Primary aquatic productivity has been strongly correlated with salmon abundance in several Alaskan sockeye lakes, and substantial increases of riparian forest growth have also been noted in salmon-spawning watersheds (Helfield et al., 2001; Hu et al., 2001; Gregory-Eaves et al., 2003; Brock et al., 2007). This makes BSi a suitable complementary proxy to $\delta^{15}N$ (assuming BSi reliably records diatom and chrysophyte abundance). However, BSi is not strongly correlated with the $\delta^{15}N$ at Woahink Lake (r=-0.28), which indicates that diatom and chrysophyte production is controlled by factors in addition to salmon-derived N. Alternatively, BSi may not be accurately reflecting total aquatic productivity. Identification of diatom taxa would likely improve our understanding of the BSi record, and may be performed in the future.

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CHAPTER VI

CONCLUSIONS

MDN and other lake-sediment proxies were analyzed to develop the first reconstruction of salmon in the OCR, as well as the first paleolimnological record from a coho-salmon spawning watershed. We infer that a signal of MDN was recorded in the sediments at Woahink Lake, though the robustness of the record was hindered by low sedimentation rates, low salmon abundance, and other factors influencing $\delta^{15}N$ budgets.

Most lakes in the OCR are likely not suitable for paleolimnological reconstructions of salmon abundance. Steep topography, heavy rainfall, and high organic productivity are common. High inputs of terrestrial matter can mask signals of MDN (Gregory-Eaves et al., 2009). In addition, salmon escapements are generally small, and hydrologic retention rates tend to be low (mean= <0.6 yr), which would prevent MDN from remaining in the lake long enough to leave a signature in the sediments. Woahink Lake was chosen to overcome these limitations, especially with respect to long retention times and low terrestrial organic matter contribution. Based on these factors, it is likely that only a few other lakes in the OCR are suitable candidates for paleolimnological salmon reconstructions.

Proxies of salmon abundance at Woahink Lake generally decrease as Pacific SSTs increase, presumably a result of the reduced availability of nutrients and forage for marine-phase salmon. However, the increases in proxies of salmon abundance that occurred from 3.8 to 2.2 ka coincide with high SSTs, increased ENSO activity, and the onset of the southern placement and modern regimes of coastal upwelling associated with the California Current (Barron et al., 2007). The relationship between SSTs and proxies of salmon abundance decouple again at 1600 AD, as both $\delta^{15}N$ and SSTs increase. The mixing model of DIN (Table 2) in combination with the observed $\delta^{15}N$ near the sediment surface suggests that modern salmon populations were anomalously high. However, it is likely the record did not have the resolution in the surface sediments to capture a decline in salmon over the past 50 years.

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The sediment records from Woahink and Triangle lakes also capture several geomorphic events, including the transition of the Woahink site from a marine estuary to a freshwater lake at 7.45-5.4 ka and corresponding events of dune-building and seismic activity, as well as additinoal records of disturbance events at both lakes that correlated with previously identified earthquakes in the region (Morey et al., 2012).

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