AN ABSTRACT OF THE THESIS OF

Anna Pakenham for the degree of Master of Science in Marine Resource Management presented on June 4, 2009.

Title: Patterns of Sediment Accumulation in the Siletz River Estuary, Oregon

Abstract approved:

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Anecdotal evidence suggests many Pacific Northwest estuaries are filling with sediment due to historical logging activities in upstream watersheds. Using the Siletz River estuary as a case study, this research began by analyzing timber harvest and discharge records of the Siletz River watershed, and found that increased timber harvest coincides with a period of higher discharge. Based on these findings, sediment flux from the Siletz watershed was expected to have increased and resulted in higher sediment accumulation rates (SARs) in the estuary. To test these assumptions, SARs were estimated using down-core profiles of excess ^{210}Pb and ^{137}Cs from thirty-three cores taken within the estuary. Digital x-radiographs and grain size distributions of cores were used to provide a timeframe for flood deposits and provided further information on retention-related functions of the system. Results indicate minimal evidence for changes in SARs with only two ^{210}Pb profiles and six ^{137}Cs profiles that indicate an increase in deposition attributable to land use and hydroclimatic changes. Calculated SARs (0.18cm/y) were comparable to the rate of local sea level rise (0.19 cm/y), which indicates that retention in the estuary is influenced by the available accommodation space. This finding helps explain the distinct difference in sediment supplied (5.91 x 10^7 kg/y) to, and retained (8.42 x 10^6 kg/y) in, the estuary. Overall, this study illuminates the complexity of the forces that influence sediment flux from a watershed and retention within an estuary.

Patterns of Sediment Accumulation in the Siletz River Estuary, Oregon

by

Anna Pakenham

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 4, 2009
Commencement June 2010

Master of Science thesis of Anna Pakenham
presented on June 4, 2009.

APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Anna Pakenham, Author

ACKNOWLEDGEMENTS

seeker of truth

follow no path
all paths lead where

truth is here

-E.E. Cummings

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1. Introduction

Estuaries are critical interfaces between terrestrial and marine systems, where fresh water from rivers and salt water from the ocean mix, making them one of the most productive ecosystems in the world. They are biological 'hotspots' (Good 2000) that provide resources and services potentially affecting the entire coastal marine food web. Important functions of estuaries include habitat and nursery grounds, pollution absorption, flood control, and nutrient retention (Good et al. 1999). The high biodiversity and function of estuaries makes them economically and socially important.

Estuaries in Oregon and the greater Pacific Northwest (PNW) are relatively pristine compared to those in other parts of the United States (Emmett et al. 2000; Borde et al. 2003). Oregon estuaries are home to many commercially important species at various points in their life cycle, such as salmon (Magnusson and Hilborn 2003), Dungeness crab (Armstrong et al. 2003; Holsman et al. 2003), and Pacific oysters (Ruesink et al. 2003). In addition, more than seventy species of juvenile fish and migrating waterfowl are known to forage in Oregon estuaries (Good et al. 1999), making them useful for natural resource extraction (aquaculture, fishing, clamming, and waterfowl hunting) and, increasingly, for tourism and recreation (birding, boating, sailing, sightseeing, and simple enjoyment of nature) (Huppert et al. 2003).

These natural resources were are for more than recreation, and like other Oregon estuaries, the Siletz was once an area of commercial opportunity for clam, salmon, and a log export industries. However, an increase in sediment load has caused clam beds to be covered, and the filling in the estuary bar preventing ship crossing, which lead to their decline and eventual failure (Starr 1979). Findings from an Oregon Department of Fish and Wildlife report explain the increased sediment load as a result of diking and filling of wetlands and logging in the watershed (Starr 1979); however, more recent literature indicates the need to address additional considerations in this complex system.

Other factors influencing sediment flux to the coastal zone include: geomorphology, tectonic activity, geography (location and climate), geology, and human activity within of a drainage basin (Milliman and Syvitski 1992; Syvitski and Milliman 2007). Specifically, increased sediment load can reduce the flow of water through the wetland and allow more time for deposition, which then creates a positive feedback loop for further deposition (Callaway and Zedler 1999; Lee et al. 2006). Alterations in water flow caused by sedimentation can also lead to changes in water salinity, temperature, and oxygen concentrations, and may also contribute to eutrophic conditions (Fong and Zedler 2000; Lee et al. 2006). Physical and chemical alterations in the ecosystem can cause changes in species composition and survivability, ultimately impacting the aesthetic, commercial, and economic value of these estuaries. Cumulatively, these factors in the watershed can influence sediment supply to the estuary and adversely affect its ecological functions.

The recognized threat of sedimentation to estuarine ecosystems has lead several studies to investigate possible explanations for changes in sediment load, accumulation, depositional patterns, and sources in Oregon estuaries (e.g., Kulm and Byrne 1966; Rauw 1974; Rea 1974; Peterson et al. 1984; Komar 1997a; McManus et al. 1998; Styllas 2001; Komar et al. 2004; Wilson et al. 2007). These studies show that sediments are delivered to Oregon's estuaries by rivers, shore erosion, and the sea (Rauw 1974; Styllas 2001). General depositional patterns within estuaries have also been identified and indicate that the marine sediment component is primarily in tidal inlet area, while the fluvial component is primarily located in the upper reaches of the estuary near the river mouth, with a mixed zone comprising the portion in between these areas (Kulm and Byrne 1966; Peterson et al. 1982; Peterson et al. 1984; Styllas 2001; Komar et al. 2004). These different sources of sediment are relevant because they can control the grain-size distributions found within Oregon estuaries (Peterson et al. 1982; Styllas 2001; Komar et al. 2004). For example, during peak river discharges in the winter months, terrestrial sand, silt, and gravel are transported into the estuary, while beach sand is transported up estuary during the low fluvial discharge in summer months (Peterson et al. 1984). While studies have identified logging as a primary cause for an increase in fluvial sediment load (Rea 1974; Komar 1975; Komar 1997a; Styllas 2001), none have been able to quantify the specific effect of logging on sediment accumulation. For example, Komar et al. (2004) demonstrated an increase in river discharge as a result of intensive logging and fire in the nearby Tillamook estuary, but was unable to demonstrate a change in shoaling in the estuary.

The objective of this study was to first establish whether factors that affect sediment supply to the estuary might have changed in the recent past by evaluating timber harvest records for Lincoln and Polk Counties, and discharge data from the Siletz River. Second, this work sought to determine if there has been a change in sediment accumulation rates and patterns in the estuary using excess 210Pb, 137Cs, and 14C geochronologies, supported by digital x-radiography and grain-size analysis. Then, based on these findings, establish if changes in sediment accumulation can be related to known influences that affect supply (changes in hydroclimatology and land use) and retention (sea level rise and accommodation space).

2. Study area

The Siletz estuary is one of Oregon's smallest twenty-two major estuaries. It is a bar built, drowned river-mouth estuary located on the central Oregon coast (Fig. 1). Habitat types within the ~4.8 km^2 (mean high water) estuary include tidal marshes, seagrass beds, rock bottoms, and mud and sand flats (Percy et al. 1974). The Siletz estuary is designated a conservation estuary under the Oregon Estuary Classification system, which means it lacks maintained jetties or channels, but has altered shorelines (Bottom et al. 1979). Previously, the Siletz estuary was a site of commercial enterprise, but alterations in the estuary and watershed caused these industries to decline. The Siletz is now managed for long-term uses of renewable resources that do not require major alterations of the estuary — primarily recreation (Starr 1979).

The mountainous terrain of Siletz watershed is primarily located within Lincoln (85%) and Polk (13%) Counties in the Oregon Coast Range (Fig.1). The county is home to 44,479 people, and has a population density of 18 people/km^2. The watershed contains steeply incised ridges and low gradient stream valleys, with the highest peak in the Upper Siletz watershed being Laurel Mountain at 1.1 km elevation (Monthey et al. 1996). Like most of the Coast Range, the Siletz watershed is primarily composed of Eocene sedimentary bedrock (45-55 million years old) (Monthey et al. 1996; Roering and Gerber 2005) and has alluvial deposits of sand and gravel that overlay Eocene deposits in the low gradient stream valleys (Monthey et al. 1996).

There are seasonal fluctuations in the river discharge of the Siletz River that reflect temporal precipitation patterns of the region. The precipitation data collected at a nearby station in the Salmon estuary (Otis-356366) from 1971-1990 (Oregon Climate Service) indicate highest rainfall occurs during the winter months, with a historic monthly mean high in the winter (40 cm), and the low (4 cm) during the summer. High-intensity precipitation exceeding 2.5 cm/d for more than 4 days/month only occurs from November to January. Three freshwater sources contribute to the Siletz estuary: the Siletz River, Drift Creek, and Schooner Creek (Fig.1). The Siletz River discharge was evaluated using data collected at USGS river gage 14305500, located 2.9 km downstream from Baker Creek, 31.2 m above sea level (Fig. 1). Due to its location, this gage drains 523 km^2 of the 966 km^2 total watershed, with daily discharge data available from 1905 to present, continuous starting in 1920. The highest discharge occurs during the winter months and lowest during the summer; the highest monthly average of 95 m^3/s occurs in December and lowest (4 m^3/s) in August (Fig. 2). The annual peak discharge over the period of record always occurred between November and April with the highest yearly high on record (1523 m^3/s) occurring in November 1999. The daily mean discharge during the period of record is 42 m^3/s.

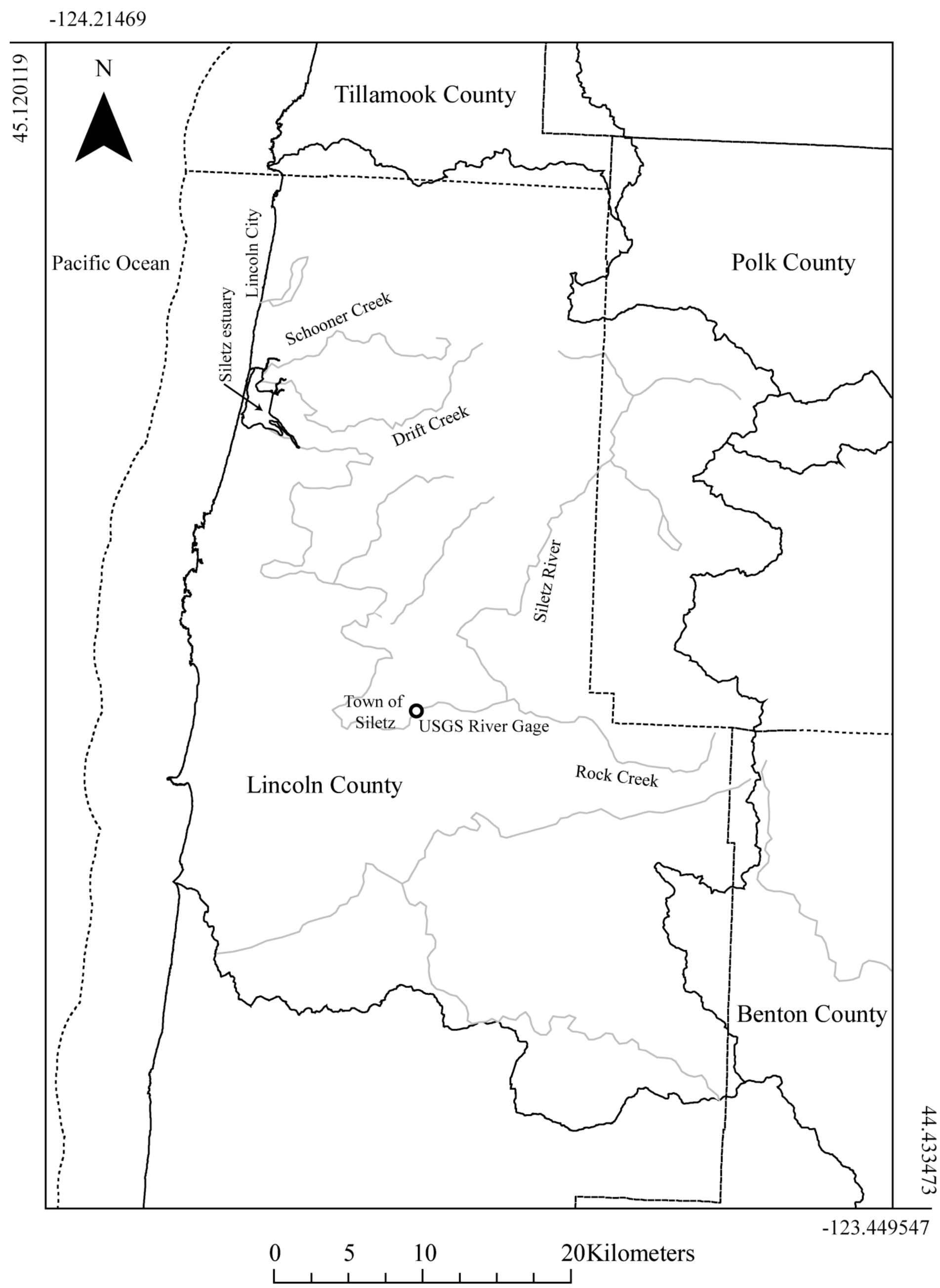

Figure 1: The Siletz River estuary, watershed, and the surrounding county lines (dashed). Location of the USGS river gage station indicated.

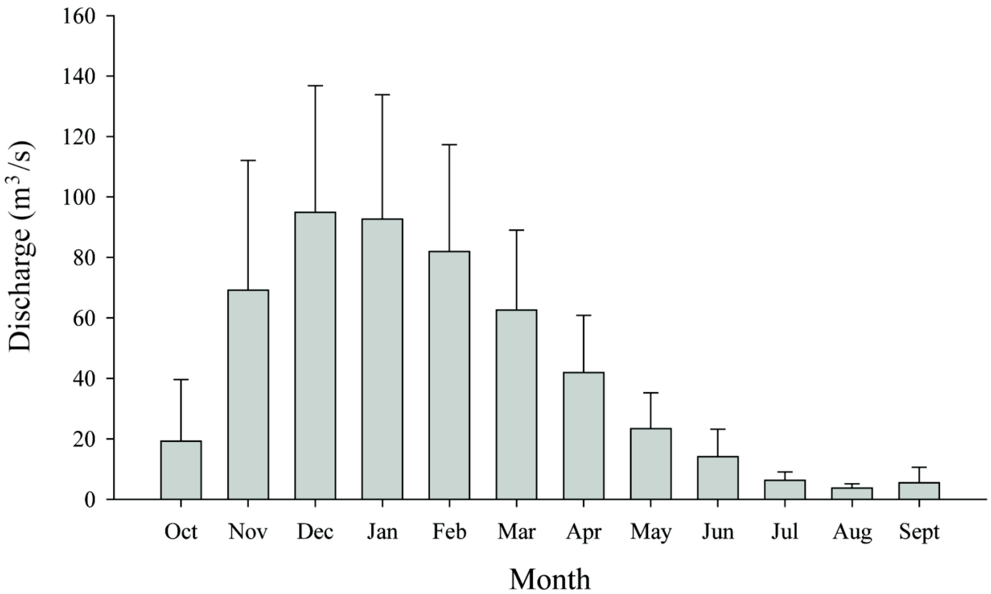

Figure 2: Mean monthly discharge of the Siletz River from 1920-2007. Error bars represent standard error.

2.1. Changes in the hydroclimate of the Siletz River watershed

To determine the effect of the hydroclimatic changes on the Siletz River watershed, trends of increasing discharge and flood occurrence were assessed in several ways. The first approach focuses on the long-term trends in discharge based on an analysis of cumulative residual discharge. The cumulative residual discharge, Q_n, is defined as

$$Q_n = \sum_{i=0}^{n} (Q_i - \overline{Q}),$$

where n is the sequential value in the time series, Q_i is the yearly discharge, and $\overline{Q}$ is the mean discharge over the period of record (Hurst 1957; Inman and Jenkins 1999; Wheatcroft and Sommerfield 2005). A time series of the cumulative residual has a positive trend during periods of above-average discharge and a negative trend during below-average discharge periods. From 1947 to 1975 there is an increasing trend in discharge in the Siletz record that is consistent with other studies in the PNW (Wheatcroft and Sommerfield 2005), and from 1976 to 1992 there is a general decreasing trend (Fig. 3).

In the PNW, climate is driven in part by phases of the Pacific Decadal Oscillation (PDO) (Bowling et al. 2000), with cold and wet winters associated with the negative phase (Mantua et al. 1997; Hamlet and Lettenmaier 1999). The residual discharge values show a negative relationship to the phases of the PDO, showing a period of higher discharge from 1945 to 1976 associated with the negative phase of the PDO (Fig. 3).

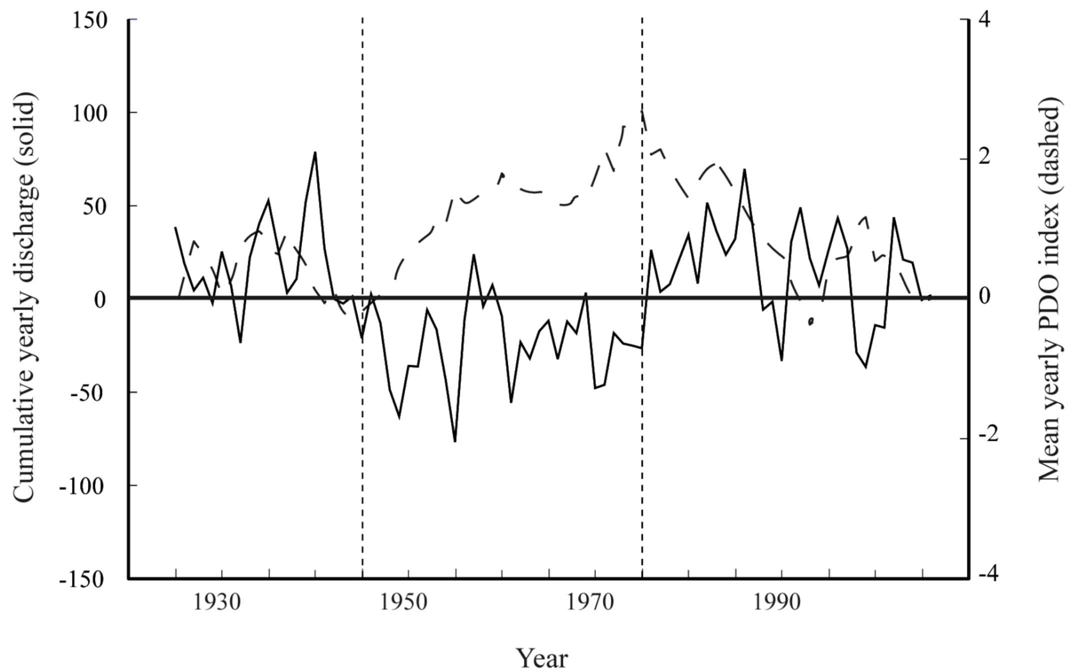

Figure 3: Cumulative residual discharge from the Siletz River gauging station and mean yearly PDO index. Positive trends in the cumulative residual discharge indicate periods of higher discharge, which corresponds to the cold phase of the PDO from 1945 to 1975 indicated by the dashed lines. PDO data were from (http://jisao.washington.edu/pdo/PDO.latest).

In addition to decadal variability, such as the PDO, there is a trend of increasing precipitation, including intensity and frequency, in the United States since the early portion of the 20th century (Kunkel et al. 1999; Groisman et al. 2001; Mote 2003). In the PNW, increases in winter precipitation are expected to cause higher winter river flow (Mote 2003). To determine if there has been an increase in discharge over the period of record, the Siletz River daily discharge was analyzed in two ways. First, the number of floods above a given threshold was evaluated over time. All rivers gauged by the USGS have a predetermined base discharge (recurrence interval of 1.1 years) that is used in flood frequency analysis; this value for the Siletz River is ~400 m^3/s.

The number of flood days/y ranged from 0 to 7, with no evidence for a trend in the number of floods over time (Fig. 4a). Second, the annual peak discharge was analyzed to see if there is a trend over time. Magnitude of annual peak discharge does not exhibit a statistically significant relationship with time (Fig. 4b). However, the four largest discharge values during the period of record have occurred since 1996: 1999 (1523 m^3/s), 1998 (1147 m^3/s), 2006 (1028 m^3/s), and 1996 (982 m^3/s). The 1999 discharge was more than four standard deviations from the mean, and 1998 and 2006 discharge values were both more than two standard deviations from the mean.

Because high flows can lead to an increase in sediment yield (Ambers 2001; Vellidis et al. 2003), changes in suspended sediment load over time were evaluated. River sediment concentration data were not available for the Siletz River, therefore a rating curve from the Alsea River, which has a similar average annual discharge and watershed size as the Siletz River, was used (Wheatcroft and Sommerfield 2005). Daily discharge from the Siletz River and the estimated sediment concentration generated from an Alsea River rating curve were used to compute daily load estimates, and these were summed for each water year to generate a time series of annual load (kg/y) (Wheatcroft and Sommerfield 2005). The calculated average annual sediment load of $5.9 \pm 3.5 \times 10^7$ kg/y is comparable to what has been found in other studies of the Siletz River (Roden 1967; Karlin 1980). An inter-annual variability in the annual load is evident, with two orders of magnitude difference between the high of 1.7×10^8 kg in 1999, and a low of 3.8×10^6 kg in 2001 (Fig.4c).

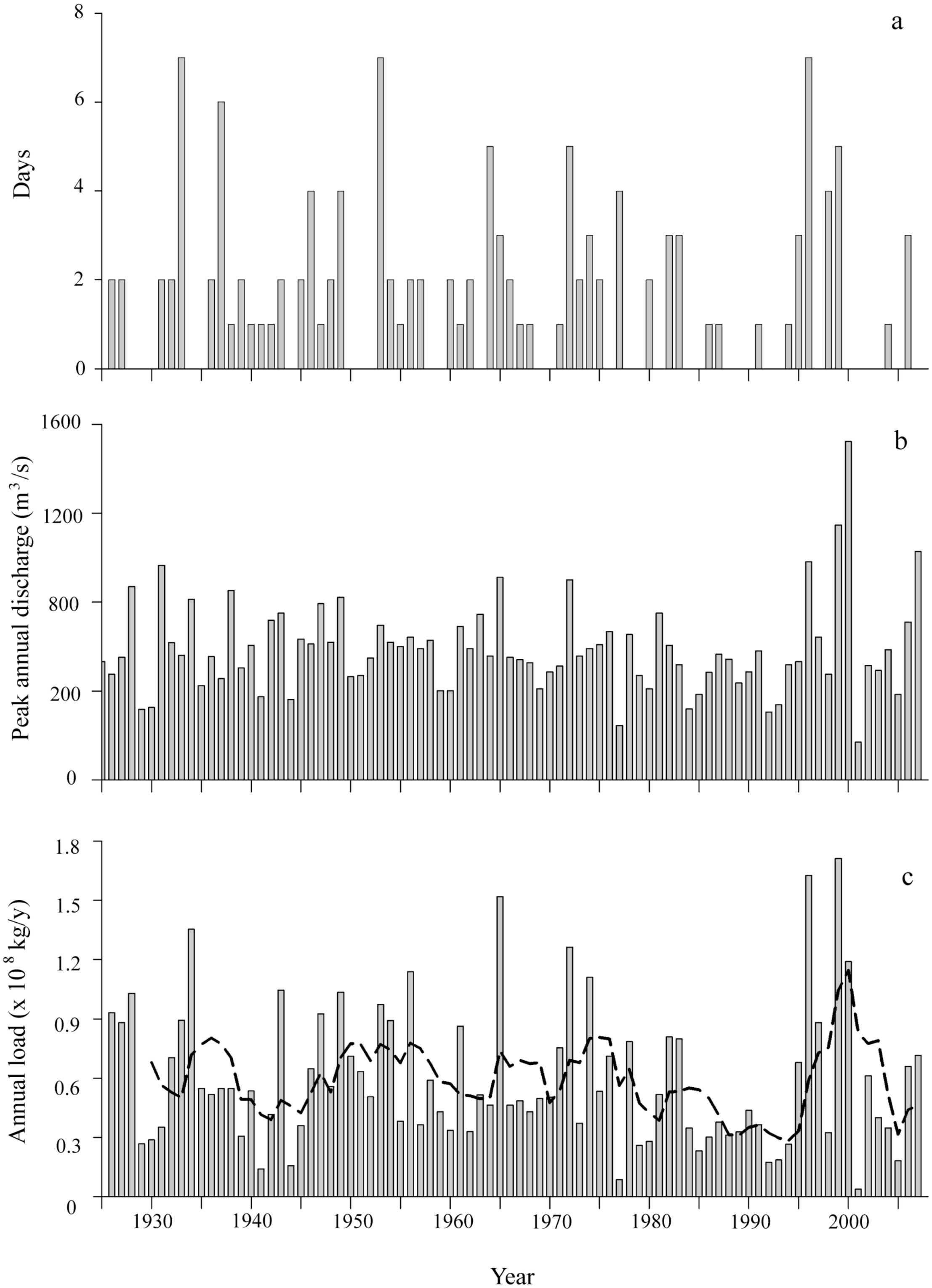

Figure 4: Discharge and sediment yield for Siletz River. (a) Number of days above base discharge per year for the Siletz River from 1920 to 2007. (b) Time series of peak annual discharge for the Siletz River. (c) Bars representing time series of estimated annual load (x 10^8 kg/y) and dashed-line representing 5-year running average.

2.2. Logging

The preceding analysis of discharge and sediment load for the Siletz River was based on the assumption that land use has been constant through time; however, this assumption is not accurate. In the early 1900s, the Siletz estuary supported a large commercial log export industry. Extensive logging in the conifer forests of the Siletz basin began about 1918 (Monthey et al. 1996). Harvests consisted primarily of the long-lived Douglas-Fir that rapidly regenerated after historic wildfires (Agee 1993; Monthey et al. 1996). This land use is thought to have an important effect on sediment erosion.

Natural forest conditions have the ability to buffer increased rainfall, storm events, and other climatic variability that may impact sediment flux from the watershed. Consequently, numerous studies have been conducted in the PNW to evaluate the relationships between logging, streamflow, road construction, and sedimentation (Beschta 1978; Jones and Grant 1996; Beschta et al. 2000; Bowling et al. 2000; McIver and McNeil 2006). In some Oregon watersheds it has been shown that the loss of vegetation can increase peak river flow (Jones and Grant 1996) and thus cause an increase sediment production (Beschta 1978; Grant and Wolff 1991). In addition to the loss of vegetation, the roads constructed to access harvest sites can alter overland water velocities, impact soil infiltration capacity (Wempel 1994; Jones and Grant 1996), and have been linked to increased sediment production (Beschta 1978). Fire, logging, and road construction also have the potential to increase the frequency of landslides in the Oregon Coast Range (Swanston and Swanson 1976; Swanson et al. 1977; Ketchenson and Froehlich 1978; Gresswell et al. 1979; Swanson et al. 1981; Schmidt et al. 2001; Roering and Gerber 2005). These landslides have been identified as a key factor in controlling the timing and magnitude of sediment yield from small, steep watersheds (Grant and Wolff 1991).

To assess this human impact, historic records of timber harvest in Lincoln County and Polk County measured in board feet (Andrews and Kutara 2005) were used as an estimator of logging. Board feet is a timber management term and it refers to the amount of wood contained in an unfinished board 1 inch think, 12 inches long, and 12 inches wide. This estimator was used because to calculate actual area harvested required georeferencing and area calculations from aerial photographs, which were difficult to obtain. The timber harvest record for each county was multiplied by the percent of the county that the Siletz watershed occupies (54% Lincoln and 13% Polk) to estimate the timber harvested. This method assumed that the counties were uniformly harvested by area, and did not take into account road construction and changes in harvest technique over time. There was a period of increased timber harvest from 1940 to 1975 (Fig. 5). During this time there were 22 years that the board feet harvested from the Siletz watershed was greater than 2 x 10^8 board feet/y, with highest yearly harvest in 1955 (3.3 x 10^8 board feet).

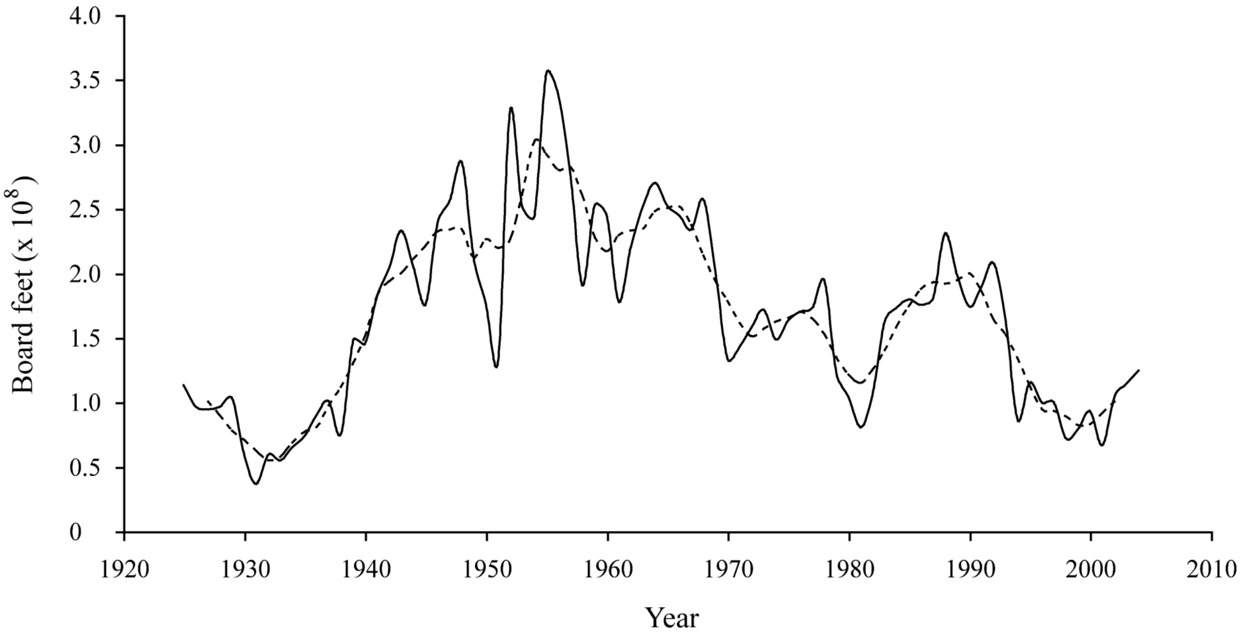

Figure 5: Annual timber harvest for the Siletz watershed within Lincoln and Polk Counties. Solid line represents yearly harvest and dashed line represents a five-year running average.

As the primary land use in the Pacific Northwest in the last 100 years (Grant and Wolff 1991), the impact of timber harvest on the surrounding environment, specifically sediment production, makes it one of the most debated issues in the PNW today (Ambers 2001). While these land-use changes have been attributed to a decline in commercial industries in the Siletz estuary (Starr 1979), they have been shown to coincide with periods of discharge. In recognition of the complexity of factors that influence sediment supply, this study used a variety of laboratory techniques on estuarine sediment cores to clarify how sediment is supplied to and retained within the estuary.

3. Methodology

3.1. Field methods

To assess the impact of logging and hydroclimatic changes on sediment accumulation in the Siletz estuary a total of twenty-three short cores and ten long cores were taken in the southern part of the Siletz estuary between June 2007 and June 2008 (Fig. 6) (Appendix A). The estuary was subdivided into six areas based on vegetative cover, tidal height, radioisotope profiles, and grain size distributions. The areas included are the vegetated 'Marsh Area' (MA), non-vegetated 'Marsh Edge' (ME) adjacent to the MA, the non-vegetated mud-flat of the 'South Bay' (SB), an area northeast of where the Siletz River enters the bay that is known as 'Snag Alley' (SA), and a low intertidal region of sand flats referred to as the 'Center Bay' (CB). Short-core tube dimensions were 50-cm long with a 9.5-cm inner diameter. The short cores were hammered or pushed into the sediment, capped on the top end, dug out, and capped on the bottom end. The long-cores tubes were made of schedule 40 PVC pipe and measured 300-cm long with a 10.2-cm inner diameter. The penetrating end of the long core was beveled and contained a stainless steel core catcher to help retain sediment during extraction. Long cores were pounded into the sediment with a sledgehammer, sealed with a test plug, extracted using a mechanical jack, and end caps were attached to both ends. Once capped, both long and short cores were transported to Oregon State University labs for processing.

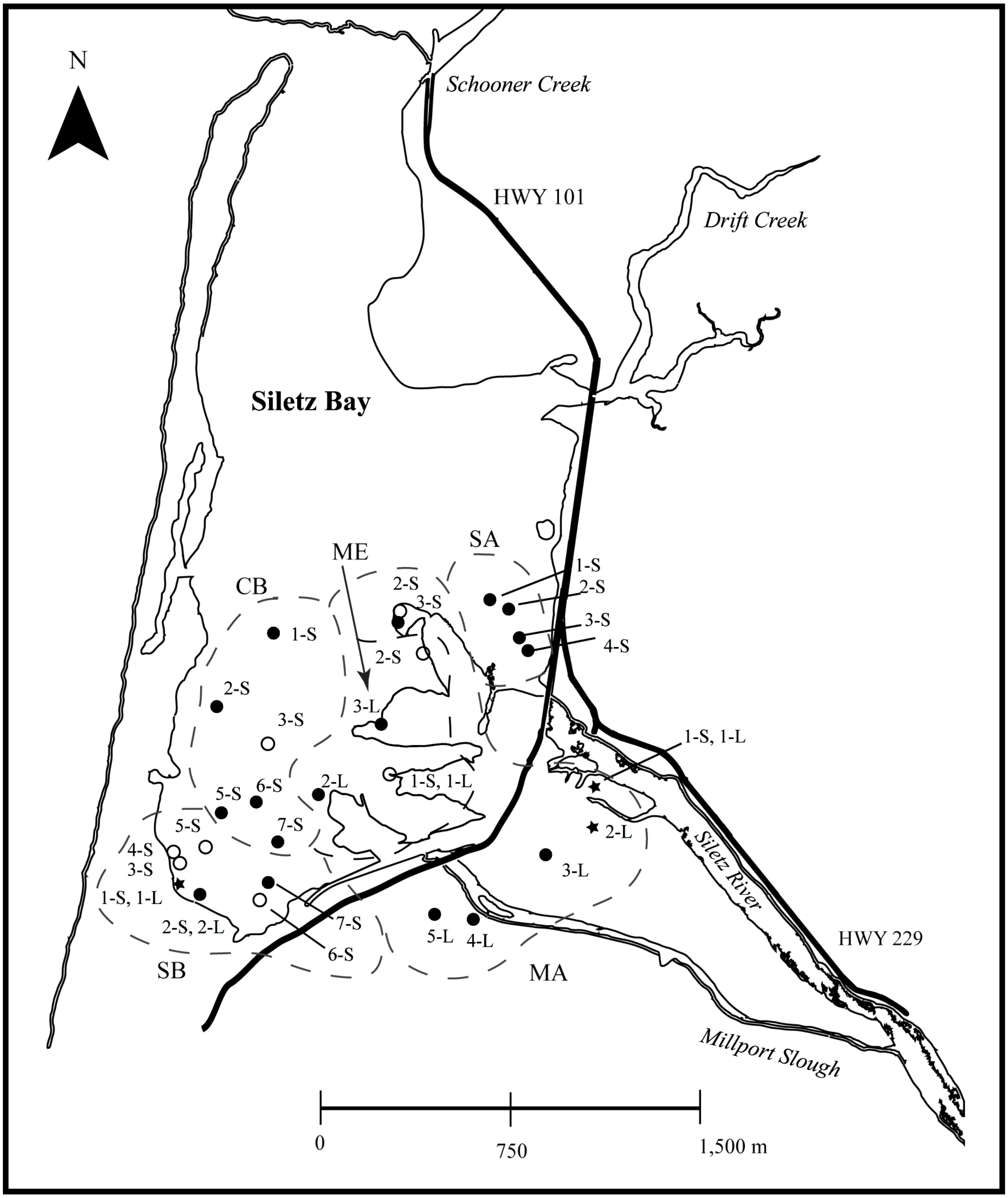

Figure 6: Location of cores taken in the Siletz River estuary. Analyses include radionuclides (closed-circle), radionuclides and grain size (open-circle), and radionuclides, grain size, and ^{14}C (star).

3.2. Laboratory methods

Short cores, which ranged in length from 20 to 35 cm, were sectioned in 1-cm increments and subsampled for radionuclide and grain size analyses. The long cores, which ranged from 104 to 256 cm, were split lengthwise with a core splitter. One half of the core was sectioned into 2-cm increments and used for radionuclide and grain size analyses, while the remaining half was used for the x-radiographs, ^{14}C analysis, and then archived. Porosity was calculated by the difference between the wet and dry weight of the sampled material, with a correction for salt content assuming a salinity of 35 ppt.

3.2.1. Radionuclide geochronology

Linear sediment accumulation rates (SARs) were calculated based on activity-depth profiles of excess ^{210}Pb and ^{137}Cs. Samples were dried at 60°C for 3-4 days and then ground to a consistent texture by mortar and pestle. Large organic material (e.g., roots and shell fragments) was removed prior to grinding. Activities of excess ^{210}Pb and ^{137}Cs were determined using γ–ray spectroscopy (e.g., Gilmore and Hemingway 1995; Wheatcroft and Sommerfield 2005). Approximately 30 g of dried, ground sediment was counted for >24 hrs using two identical Canberra GL2020RS LEGe planar (2000 mm^{2}window) γ–ray detectors. The 46.5, 352.0, and 661.6-keV photopeaks were used to measure activities of ^{210}Pb, ^{214}Pb (used to calculate supported ^{210}Pb), and ^{137}Cs, respectively (Wheatcroft and Sommerfield 2005).

Standard techniques were used to determine SARs from excess ^{210}Pb (e.g.,Nittrouer et al. 1979; Anderson et al. 1988; Wheatcroft and Sommerfield 2005). Namely, it is assumed that the system is in steady state, the input of ^{210}Pb is constant, and that bioturbation does not exist below a certain depth within the core. Bioturbation depth was typically 10 to 12 cm, thus only samples below this depth were used to estimate sedimentation rates. At the CB sites burrowing shrimp (*Neotrypaea californiensis* and *Upogebia pugettensis*) and their burrows were found through the entire length of the cores, causing bioturbation; therefore, SARs were not estimated at CB sites.

Based on the assumptions mentioned above, there is a balance between sediment accumulation and decay (e.g., Wheatcroft and Sommerfield 2005):

$$\omega \frac{\partial A}{\partial z} = -\lambda A$$

where ω is the sediment accumulation rate (cm/y), A is excess ^{210}Pb (dpm/g), z is depth (cm) within the sediment column, and λ is the ^{210}Pb decay constant (0.0311/y). The SAR is proportional to the slope of an unweighted, least-squares fit of a plot of the natural logarithm of excess ^{210}Pb activity versus depth. Mass accumulation rates (MARs) (g/cm^2/y) were calculated by converting linear-depth (cm/y) into mass-depth using porosity data, assuming a sediment density of 2.55 g/cm^3, and then regressing the natural logarithm of excess ^{210}Pb activity versus cumulative mass depth (Appendix C &D).

SARs were independently determined by measuring the maximal penetration depth of ^{137}Cs. In this approach, it is assumed that the ^{137}Cs supply to the environment began in 1954 as a product of nuclear bomb testing. Therefore, the depth of penetration of ^{137}Cs minus the depth of bioturbation, divided by the difference in time between 1954 and the year of core collection, provides another SAR estimate (Wheatcroft and Sommerfield 2005). Some ^{137}Cs profiles contain a pronounced peak that is taken to represent 1963, the year of maximum ^{137}Cs fallout, thereby providing another date to calculate SARs. Herein, a peak is defined as the point with the highest subsurface activity that has two points above and below it that are statistically different (i.e., outside the counting error of that point) from the original point and from each other (Fig. 7).

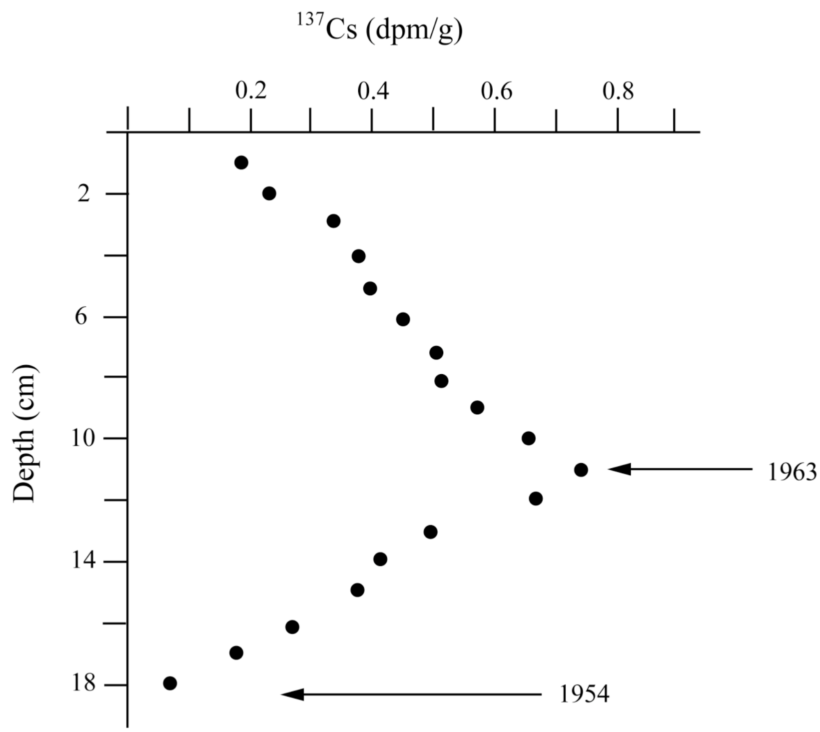

Figure 7: Example of how ^{137}Cs profiles were analyzed. 1954 is the last measured sample with activity, and 1963 is the peak. The greatest penetration depth of Cs-137 is taken to represent 1954, whereas the peak is considered to be 1963.

3.2.2. Grain size

Sediment grain size distributions were measured in select cores using a laser diffraction particle size analyzer (Coulter LS 100Q). Sediment subsamples (5-20 g) had 40 ml of 30% hydrogen peroxide and 160 ml of distilled water added to them to remove organic matter. A week after the addition of the peroxide solution, 10 ml of dispersant composed of Na_2CO_3 and $NaPO_3$ was added. After 24 hours samples were run on the laser diffraction particle size analyzer. Grain-size distributions were summarized as percent clay (<2 µm), silt (2-63 µm), and sand (64 µm-2 mm).

3.2.3. X-radiography

X-radiographs were taken of sediment slabs collected in aluminum and plexi-glass trays (2 cm x 7 cm x 30 cm, thickness, width, length) (Fig. 8). Core material was extracted by pressing the aluminum-back, plexi-glass sided slabs into the surface of the halved long cores. Once the three sides were filled with sediment, the plexi-glass face was slid into grooves on the plexi-glass sides to seal the sediment on four sides to allow removal from the core. Then the foam-lined plexi-glass sealers were taped onto both ends, creating a 6-sided chamber full of sediment. The slabs were then cleaned to remove sediment on the surface and loaded into the x-radiograph chamber.

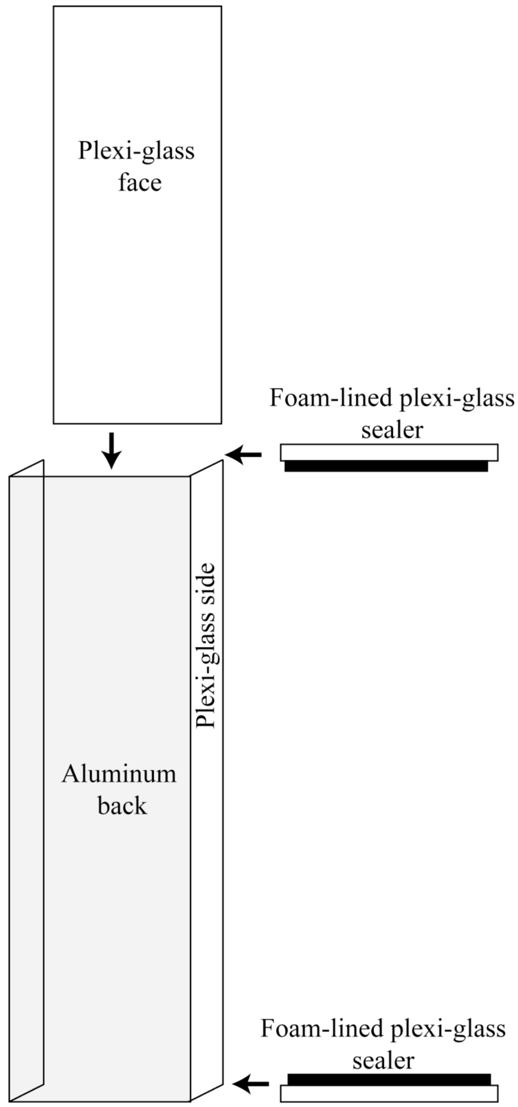

Figure 8: Schematic diagram of x-ray slabs with aluminum back and plexi-glass sides.

The digital x-radiography system consists of an x-ray source, a Lorad LPX-160 industrial X-ray generator that comprises a tube head, liquid cooling unit, control unit, and a detector - a dpiX Flashscan 30 imager (Wheatcroft et al. 2006). X-radiography detects changes in the sample attenuation, which is in part a function of bulk density of the material, and can be used to identify flood deposits, changes in grain size, and presence of large organic material within the collected cores. Flood deposits generally have a lower bulk density (higher porosity), which is often due to the higher fine grain content of the flood sediments (Wheatcroft et al. 2006). Detection of layering within the x-radiographs was conducted using image-processing software (IPLab and

Adobe Photoshop), which was used to alter brightness and contrast to enhance the layering image. The layers were then outlined and simplified as a binary image that allowed for easier comparison between cores.

3.2.4. ^{14}C dating

Samples for ^{14}C dating were collected from three cores (SB-1-L, MA-1-L, and MA-2-L) (Fig. 6). Cores were chosen based on available organic material to sample, contained identifiable layers in x-radiographs, and were representative of the areas with active sediment accumulation. From the identified horizons, material was collected, washed with deionized water on 1 mm and 250-µm sieves, agitated, decanted to remove sediment, and dried to produce 5-10 mg of material (needles, seeds, and roots). Radiocarbon dating was via Accelerator Mass Spectrometry performed at the Center for Accelerator Mass Spectroscopy at Lawrence Livermore National Laboratory. Radiocarbon ages were calibrated using CALIB, Version 4 (Stuiver et al. 1998; Stuiver et al. 2005).

4. Results

4.1. Short core sediment accumulation rates and grain size

With the exception of the Center Bay cores, most cores have measurable activities of excess ^{210}Pb and ^{137}Cs at the surface (Appendix B). ^{210}Pb surface activities ranged from 0.12 to 9.87 dpm/g. ^{137}Cs peak activities were extremely high in the Marsh Areas (2.4 to 10.2 dpm/g) (Fig. 9). The depth of sub-surface activity maxima (peaks) ranged from 8.5 to 31.0-cm depth.

There were three types of ^{210}Pb profiles determined from the thirty-three cores taken in the Siletz estuary. In the first type, ^{210}Pb activity has a monotonic logarithmic decrease with depth beneath a region of uniform activity (bioturbation) that implies steady-state accumulation (Fig. 10 a & b). In the second type of profile, there is more than one region with a monotonic logarithmic decrease in ^{210}Pb activity; therefore, more than one best-fit linear regression line is applied (Fig. 10 c & d). The third profile type, ^{210}Pb activity is highly variable with low ^{210}Pb surface activities (Fig. 10 e & f); these profiles were not evaluated further.

SARs determined by both ^{210}Pb and ^{137}Cs show the highest accumulation rates occurring in the Marsh Area and lowest in the South Bay (Fig. 11). The ^{210}Pb SARs varied by areas and ranged from 0.05 to 0.37 cm/y (Table 1). ^{210}Pb SARs in the Marsh Area were 0.13 to 0.37 cm/y and in the South Bay 0.05 to 0.21 cm/y (Table 1). SARs determined from ^{137}Cs penetration depth (dated as 1954) ranged from 0.06 to 0.5 cm/y (Table 1). When a ^{137}Cs peak activity could be deciphered within the core, SARs were calculated from 1954 to 1963, these SARS were higher than in any other time period in the core (0.28 to 2.44 cm/y). There is a positive correlation between the SARs calculated from ^{137}Cs and ^{210}Pb (0.58 correlation coefficient). The ^{137}Cs SARs were slightly higher than ^{210}Pb SARs (Fig. 12 and Table 1). The range of SARs calculated from ^{137}Cs was 0.12 to 1.32 cm/y, and from 0.08 to 0.23 cm/y for ^{210}Pb. The average ^{210}Pb SAR for all cores was 0.17 cm/y, 0.21 cm/y for ^{137}Cs calculated by 1954 penetration depth, 1.44 cm/y for ^{137}Cs calculated between 1954 and 1963, and 0.10 cm/y for ^{137}Cs calculated from 1963 to present.

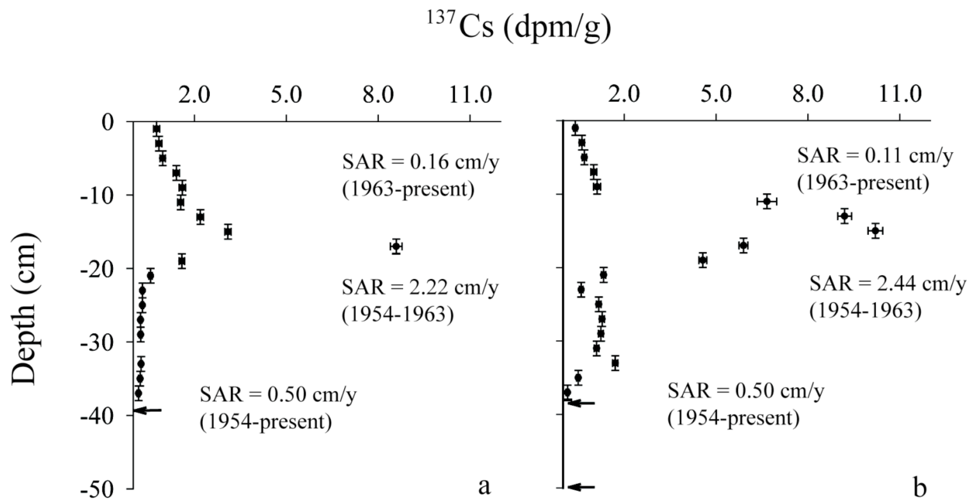

Figure 9: ^{37}Cs profiles from cores MA-2-L (a) and MA-5-L (b) illustrating high activity peaks. Arrows indicate where activity was measured below detection limit (~0.15 dpm/g), x-axis error bars represent counting errors, and y-axis error bars represent depth intervals.

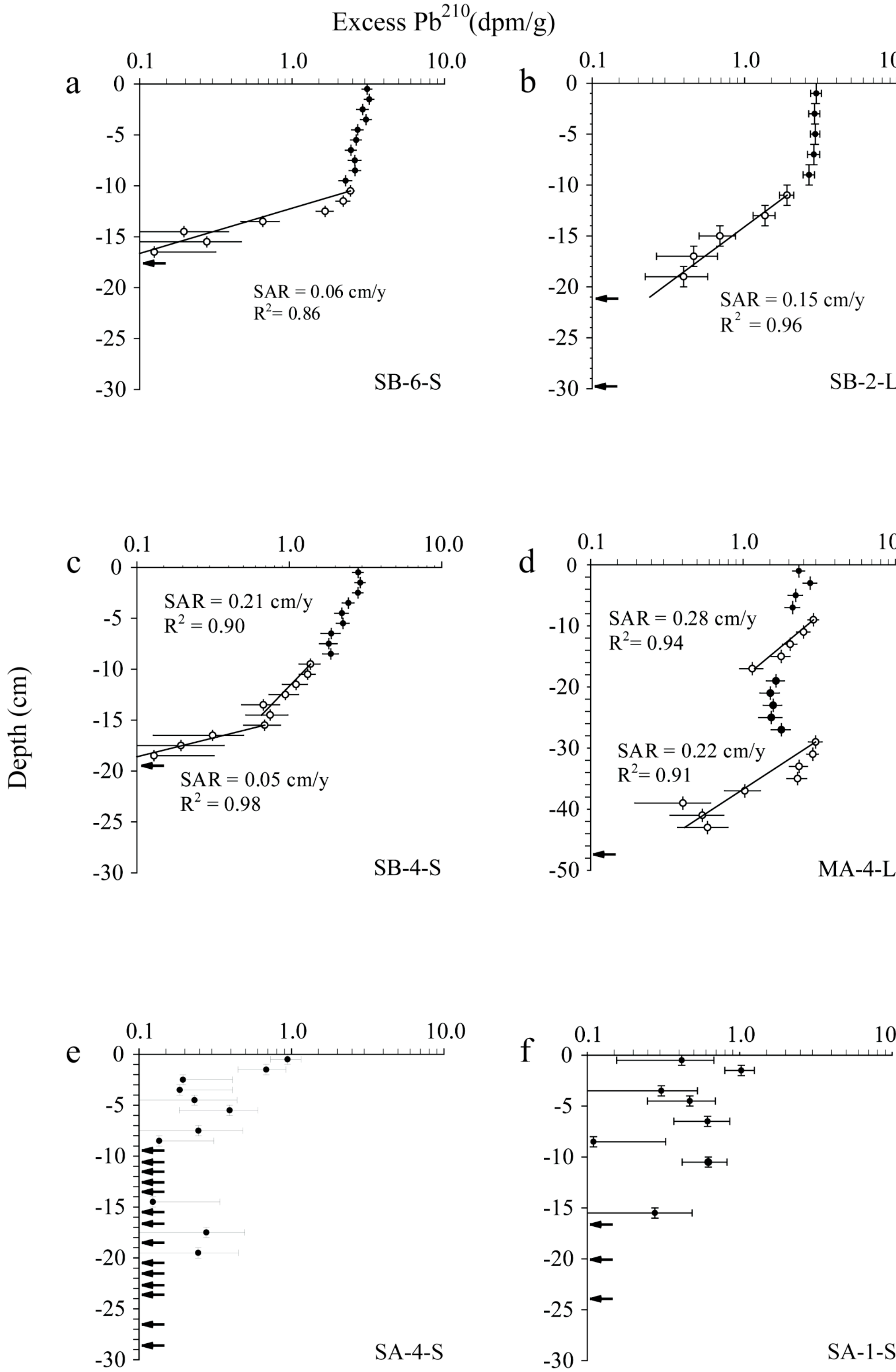

Figure 10: Selected ^{210}Pb profiles. Profile types include steady-state accumulation (a & b), variable accumulation (c & d), and non-steady state (e & f). Arrows indicate samples counted that were below detection limit (~0.1 dpm/g). Open symbols indicate points used to calculate SARs, x-axis error bars represent counting errors, and y-axis 'error' bars represent depth intervals.

Core	^{210}Pb SAR (cm/y)	^{137}Cs SAR (cm/y) 1954-P	1954-1963	1963-P
Marsh Edge				
ME-1-L				
ME-2-L		0.09		
ME-3-L				
ME-1-S		0.17		
ME-2-S				
Average		0.13		
St. dev.		0.06		
South Bay				
SB-1-L		0.09		
SB-2-L	0.15	0.09		
SB-1-S	0.07	0.13		
SB-2-S	0.09	0.09		
SB-3-S	0.06			
SB-4-S	0.05	0.10		
	0.21			
SB-5-S		0.27		
SB-6-S	0.06	0.08		
SB-7-S		0.07		
Average	0.10	0.12		
St. dev.	0.06	0.07		
Marsh Area				
MA-1-L	0.21	0.35		
MA-2-L	0.27	0.50	2.22	0.16
MA-3-L		0.20	0.67	0.11
MA-4-L	0.22	0.50		
	0.28			
MA-5-L	0.13	0.50	2.44	0.11
MA-1-S	0.37	0.31*		
MA-2-S	0.18	0.10	0.78	
MA-3-S		0.22	1.11	0.03
Average	0.24	0.34	1.44	0.10
St. dev.	0.08	0.16	0.83	0.05
Snag Alley				
SA-1-S		0.27*		
SA-2-S		0.22*		
SA-3-S		0.27*		
SA-4-S		0.25		
Average		0.25		
St. dev		0.02		
Overall average	0.17	0.21		
St. dev	0.01	0.06		

Table 1: SARs (cm/y) by area within the Siletz estuary derived from ^{210}Pb and ^{137}Cs. Asterisk indicates when the ^{137}Cs activity did not reach the minimum detection limit (~0.1 dpm/g) at the bottom of the core, therefore, these SARs represent minimal estimates.

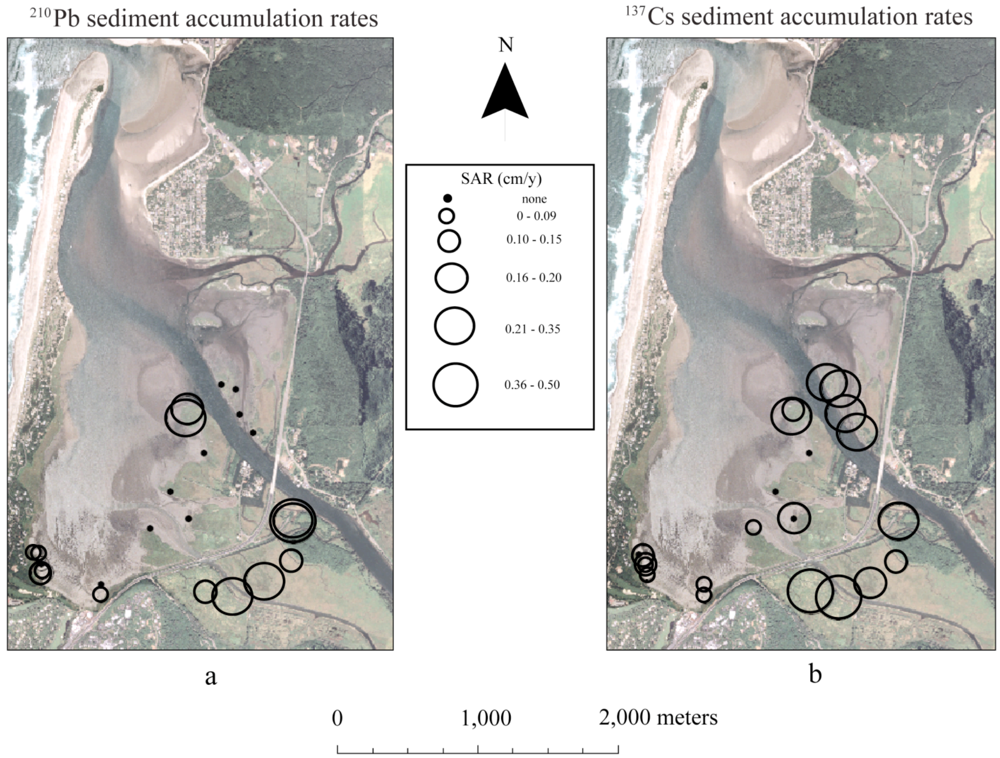

Figure 11: ^{210}Pb (a) and ^{137}Cs (b) sediment accumulation rates (cm/y).

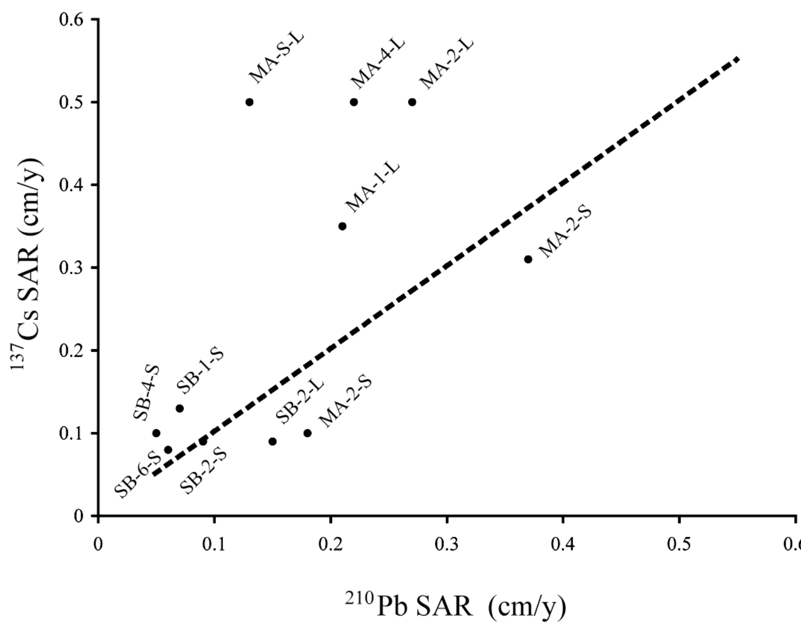

Figure 12: ^{137}Cs SAR (cm/y) vs. ^{210}Pb SAR (cm/y). Dashed-straight line is a one-to-one relationship.

The grain-size distributions determined from the cores in Siletz estuary varied by location within the estuary (Fig. 13 and Table 2). With the exception of Snag Alley, the top 0-5 cm (representing ~25 y assuming a constant SAR of 0.2 cm/y) showed no difference to 15-20 cm (representing ~75-100 y) in terms of the dominant grain-size, however, in all locations the percent clay increased in the upper portion of the cores. Snag Alley has the most variability in grain-size distribution with sand and silt alternating dominance in the cores. The Marsh Edge dominant grain-size was sand (54.5% from 0-5 cm and 65.4% 15-20 cm). The Marsh Area and the South Bay dominant grain-size was silt, but the Marsh Area had the highest clay content of all the areas (24.0% from 0-5 cm and 20.3% from 15-20 cm).

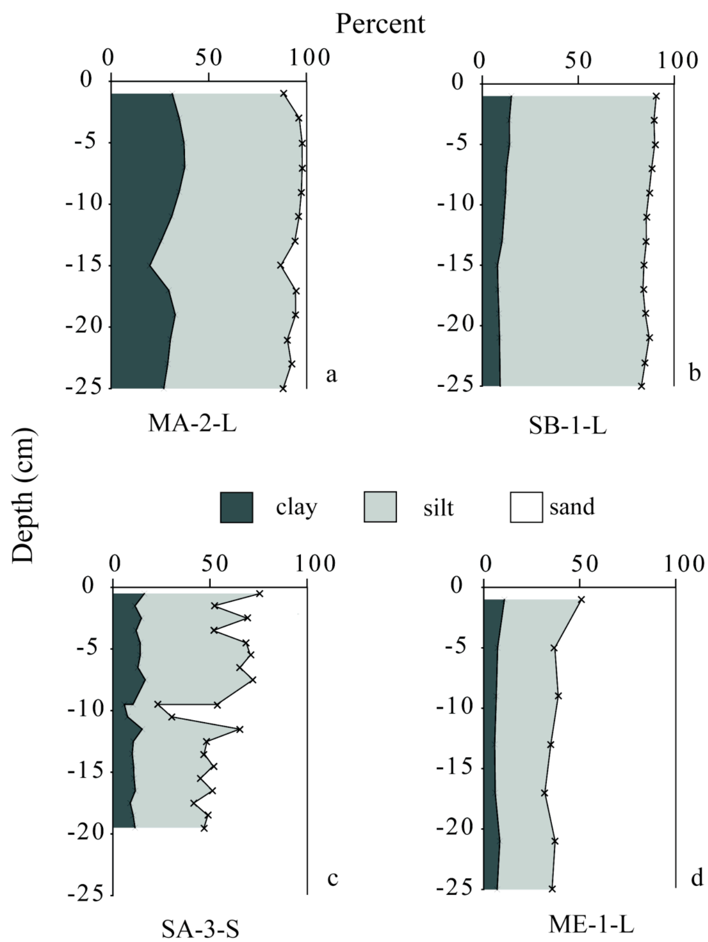

Figure 13: Grain size distributions of select cores from each area within the estuary. Percent of clay, silt, and sand in each sample taken (x) is identified.

South Bay		% Sand	% Silt	% Clay
	Max	16.9	81.2	20.9
	Min	4.6	55.1	8.0
0-5	Average	8.1	76.7	15.1
	St. dev.	2.8	1.6	3.3
15-20	Average	13.8	76.9	9.2
	St. dev.	2.8	1.8	1.1
Marsh Edge				
	Max	68.2	43.0	11.6
	Min	49.1	25.8	5.7
0-5	Average	54.5	36.3	9.2
	St. dev.	6.9	6.0	2.0
15-20	Average	65.4	27.9	6.7
	St. dev	2.7	1.8	1.5
Marsh Area				
	Max	39.0	77.1	37.8
	Min	2.1	47.2	12.0
0-5	Average	14.9	61.0	24.0
	St. dev	12.8	7.9	9.1
15-20	Average	20.2	59.5	20.3
	St. dev	12.0	5.1	8.4
Snag Alley				
	Max	76.8	59.5	16.7
	Min	24.3	17.3	5.9
0-5	Average	35.3	50.9	13.7
	St. dev	10.2	8.5	1.8
15-20	Average	53.2	36.1	10.7
	St. dev	3.7	2.9	1.0

Table 2: Table of percent sand, silt, and clay for areas of the estuary. Table includes maximum and minimum values for the cores, and average and standard deviation of 0-5 cm and 15-20 cm depth intervals.

4.2. Long core grain size, x-radiographs, and sediment accumulation rates

The grain-size distributions for the long cores taken in the estuary show changes in the ratio of clay, silt, and sand by depth. In the South Bay, SB-1-L is characterized by an abrupt change in grain size from ~105 cm to the top of the core that consists of a reduction in the clay fraction and an increase in the sand fraction. Additionally, in the top 20 cm there is another smaller change with a decrease in the sand content and an increase in the clay content (Fig. 13 & 14). Within the Marsh Area (core MA-1-L), the fraction of clay is relatively uniform over the depth of the core (average 10.6% ± 3.8); however, the sand and silt fractions are more variable (47.7% ± 18.2 and 41.7% ± 14.64, respectively).

The stratigraphic sequence from x-radiographs shows an alternation of fine-grained layers (x-ray transparent) and coarse-grained material (x-ray opaque) that varies depth (Fig. 14 & 15). The x-ray transparent regions are comprised of plant material (root hairs, peat-marsh vegetation, and large woody material) and finer-grained sediment. In two of the Marsh Edge cores (ME-2-L and ME-3-L) there are no layers present, while in the other Marsh Edge core (ME-1-L) layering is between ~40 cm and ~130 cm. In the South Bay cores, there is no layering in the top 90 cm of the cores; however, below 90 cm in one of the South Bay long cores (SB-1-L) there are three layering groups of ~30 cm each. In the other South Bay core (SB-2-L) layering is only found between 112 cm and 136 cm. The overall pattern in all of the Marsh Area long cores is a section of finer-grained or plant material in the top ~20 cm (dark bands), a section of no layering ~30 cm, and another layering section of variable width (45 cm to 60 cm in MA-1-l, MA-5-L, and MA-2-L) (~15 cm in MA-4-L and MA-3-L), underlain by a long section of no layering.

The SARs calculated from ^{14}C dates are comparable to the SARs calculated from ^{210}Pb short cores (Fig. 16 & Table 1). The Marsh Area core (MA-2-L) calculated SAR between 417 and 1490 B.P. is 0.10 cm/y and tripled between 287 and 417 B.P. to 0.28 cm/y. The average ^{210}Pb SAR is 0.23 cm/y. The South Bay core only had one calculated SAR between the ^{14}C dates (0.10 cm/y), which is similar to the SAR calculated from ^{210}Pb (0.08cm/y).

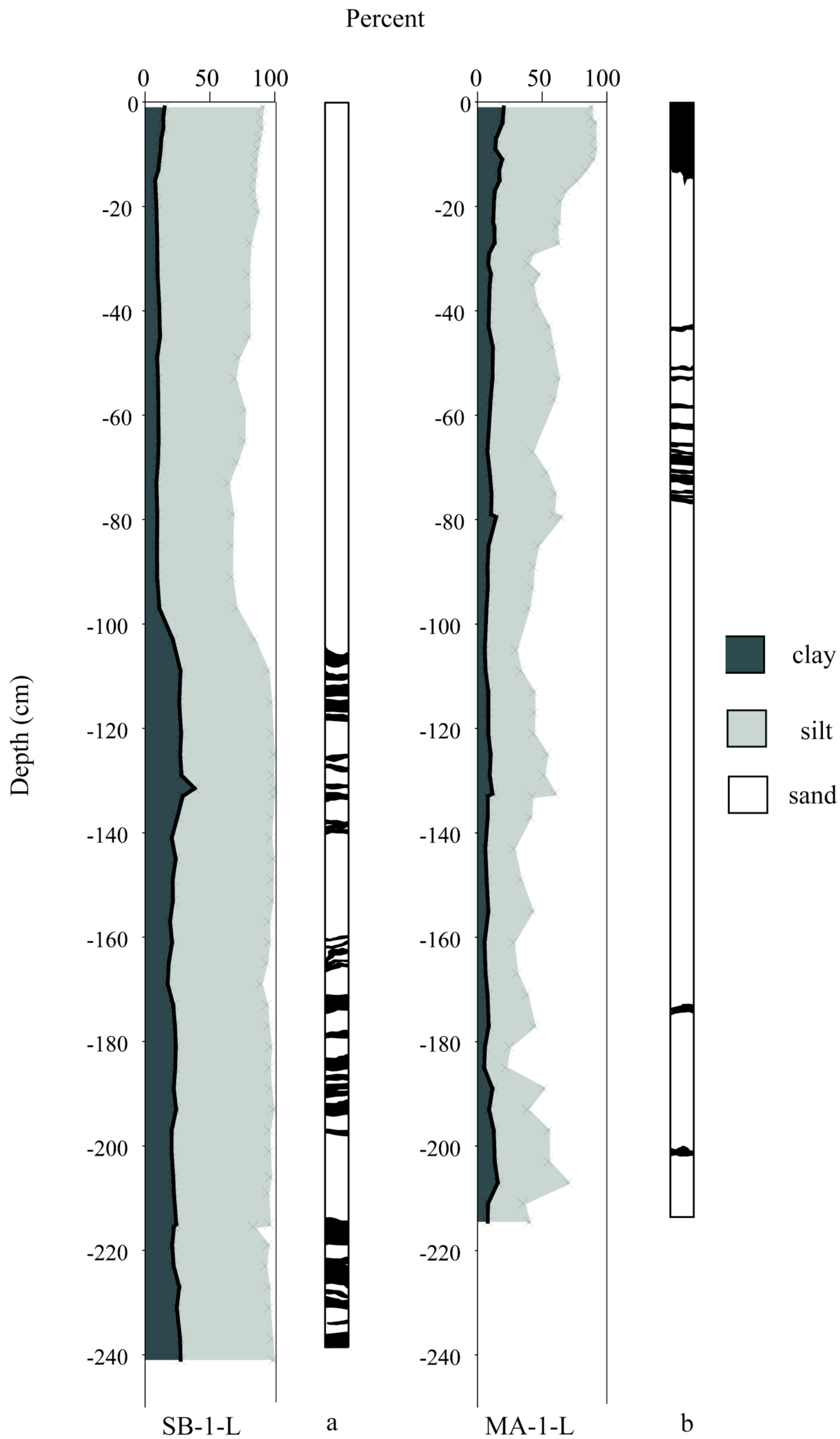

Figure 14: Figure of select long cores SB-1-L (a) and MA-1-L (b). Grain size distribution (left) percent clay, silt, and sand with X indicating where samples were taken. Black and white display of layering in cores based on digital x-radiographs (right); Dark bands represent finer-grained sediment; no banding represents coarser-grained sediment.

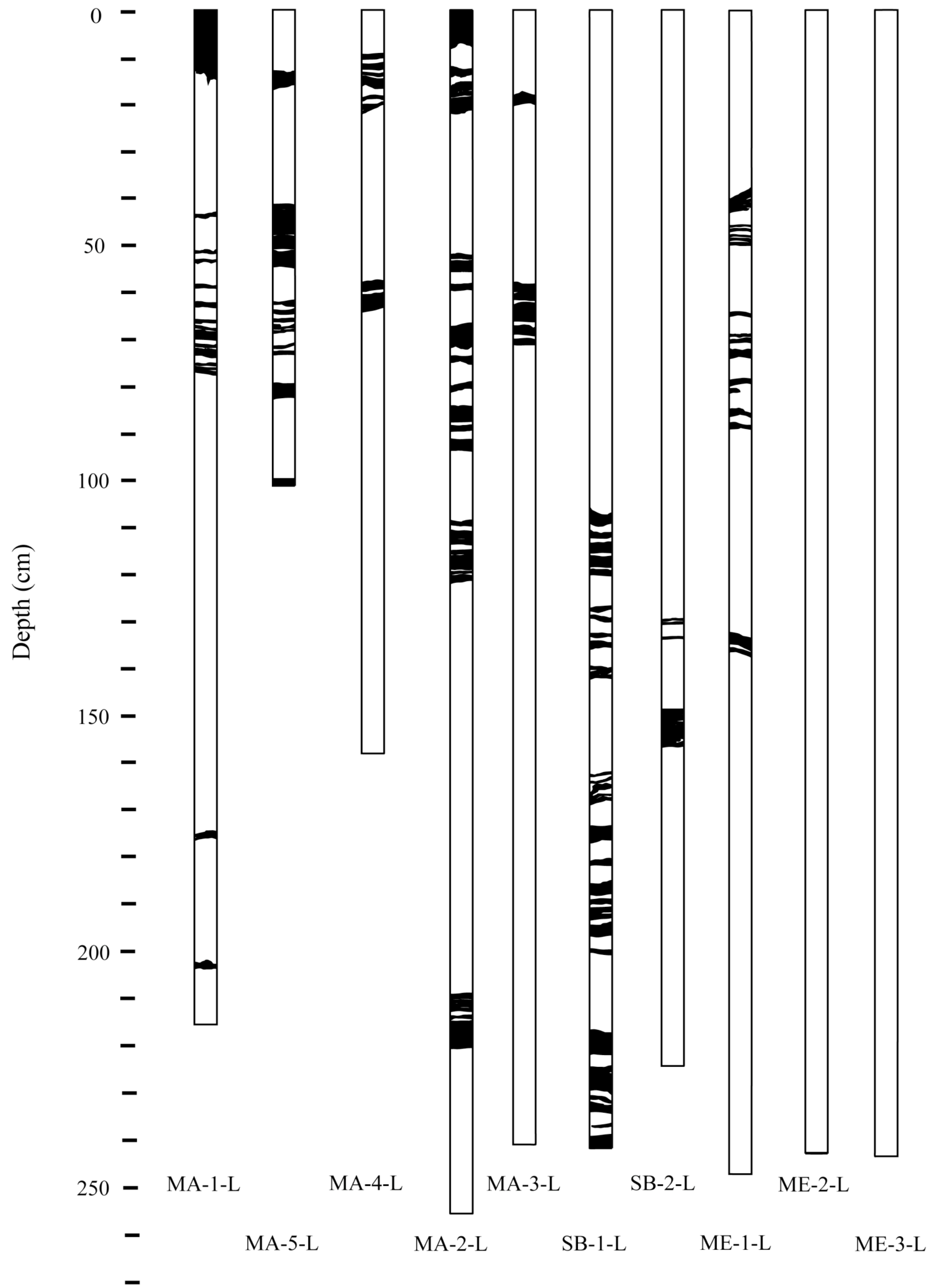

Figure 15: A binary representation of core stratigraphy based on digital x-radiographs. Dark bands represent finer-grained sediment; white represents regions of coarser-grained, unlayered sediment.

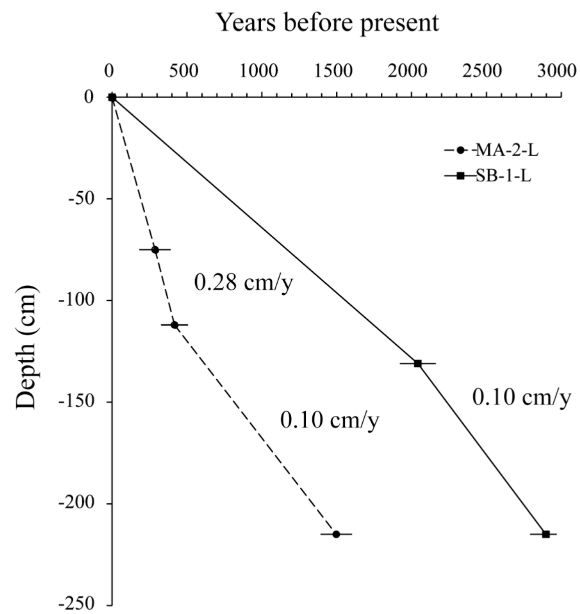

Figure 16: ^{14}C age before present with error bars at various depths and calculated SARs (cm/y).

5. Discussion

When hydroclimatic variability and logging are evaluated in the Siletz watershed, increased timber harvest is found to coincide with a period of higher than average discharge that is related to the negative phase of the PDO. It is expected that these coincident changes would result in increased sediment delivery to the estuary, and therefore increase estuarine SARs. However, with the exception of two cores (SB-4-S) and (MA-4-L), ^{210}Pb profiles show either non-varying accumulation over time with an average accumulation rate of 0.17 cm/y or non steady-state accumulation. Similar to the ^{210}Pb data, the ^{137}Cs data provides weak evidence that a change in accumulation may have occurred over the last 100 years. The Marsh Area cores represent the only increase in ^{137}Cs SARs during the 1954-1963 timeframe (Table 1). In all core locations there is an increase in clay content in the upper 0-5cm, representing the past 25 years, but this is the only evidence in the grain size data to suggest a change in sediment delivery. As a whole, there is little evidence that hydroclimatic and land-use changes have altered the estuary's SAR; therefore, other reasons why this potential increase in sediment flux is not accounted for in the estuary has to be evaluated. The following sections assess methodological issues to determine if techniques used in this study are adequate to detect changes in the watershed, and then evaluate various factors affecting the balance between sources and sinks of sediments. This will be followed by section that provides a long-term perspective of sediment accumulation patterns, before closing with discussion of this study's limitations and lessons learned.

5.1. Methodological issues

Estuaries accumulate sediment unevenly as a result of variation in topography, vegetation, and hydrodynamics of the system (Kulm and Byrne 1966; Peterson et al. 1982; Peterson et al. 1984; Styllas 2001). In the Siletz estuary, similar to other Oregon estuaries, coarse-grained sediment accumulates in the center of the bay, closest to the ocean inlet (Rauw 1974; Rea 1974; Peterson et al. 1984; Styllas 2001; Komar et al. 2004). In one Oregon study that attempted to evaluated human impact on sediment accumulation, calculation of SARs was difficult because fine-grained sediment was not found in the areas cored (Komar et al. 2004). In an effort to sample where sediment was in fact accumulating, distribution of the sampling cores was widespread and represented various tidal inundation levels, grain size distributions, and vegetation types throughout the estuary (Fig. 6). This widespread distribution allowed for a range of SARs and grain-size distributions to be calculated, with the highest clay content in the Marsh Area, which corresponded to the highest ^{210}Pb and ^{137}Cs SARs. This is because vegetation has the ability to reduce the shear velocity and turbulence in the canopy (Friedricks and Perry 2001; Leonard and Reed 2002), creating favorable conditions for rapid sediment settling and preventing further sediment re-suspension (Frey and Basan 1985; Pethick et al. 1992; Leonard and Luther 1995; Christiansen et al. 2000; Leonard and Reed 2002).

While there are areas in the estuary where sediment is accumulating, there are also areas in the estuary where accumulation cannot be calculated because of biological activity that influences sediment retention and depositional patterns. For example, burrowing thalassinidean shrimp (*Neotrypaea californiensis* and *Upogebia pugettensis*) inhabit tidal flats and are a source of bioturbation and sediment destabilization. In the Marsh Edge and the Center Bay regions, there is a high abundance of these burrowing shrimp. Along the Marsh Edge there is 10-14% fine-grained sediment (Table 2); however, the shrimp displace sediment in the sediment column, thereby making the radioisotope profiles impossible to interpret and prevent SARs from being calculated in this region.

The SARs determined from this study were comparable to other estuarine studies (Bricker-Urso et al. 1989; Brush 1989; Goodman et al. 2007), were wide ranging (0.02 to 2.44 cm/y), and vary by location within the estuary. If there were a vast change in sediment flux from the watershed, thereby causing a change in sediment accumulation in the estuary over the past 100 years, the techniques used in this study would have detected it. Therefore other factors within the basin and estuary were evaluated to assess the source and sink of sediment in the Siletz.

5.2. Factors within the source basin

In the Siletz watershed there was a period of higher timber harvest that occurred between 1940 and 1975; however, because there was not a change in sediment accumulation within the estuary, the relative impact of that harvest on sediment production was evaluated. To determine effects of logging on the sediment yield in the Siletz basin relative to natural conditions, board feet harvested was first converted into area harvested using yield estimates from the Treelab model - 33,014 board feet/acre harvested (McArdle et al. 1961; Curtis 1992; Miller et al. 1993; Pittman and Turnblom 2003; Marshall and Turnblom 2005). This model was developed to represent current management levels for Douglas-Fir plantations; however, using this model did not account for differences in yield based on tree age or changes in forest-planting practices over time.

To account for long-lasting impacts that logging can have on sediment production after harvest has occurred, sediment load from the Siletz River (calculated in section 2.1) was augmented. It has been shown that suspended sediment loads can increase by over 200% following logging events out to 6 years following harvest (Lewis and Keppeler 2007). Using this example as a template, a multiplier was applied to the sediment load of the Siletz River to account for an estimated 200% increase in sediment production over a 6-year recovery time, post logging. When the cumulative augmented sediment load is compared to the non-augmented, “native” load of the Siletz River there is only a 13% increase that can be attributed to logging (Fig. 17).

In small Oregon watersheds, sediment production has been shown to increase following clear cutting and associated road construction (Swanston and Swanson 1976; Beschta 1978; Grant and Wolff 1991). While these studies did find a change is sediment production, it should also be noted that they were small watersheds. Grant and Wolff (1991) evaluated watersheds that were approximately 1 km^2, relative to the larger 966 km^2 Siletz watershed. In larger basins, the increase in sediment storage can cause small localized land use effects to be averaged out over the entire basin (Ambers 2001). This buffering effect, indicated in the relatively small difference between the augmented and native sediment loads, is one reason the assumed sediment increase due to logging cannot be accounted for in the estuarine sediment accumulation rates.

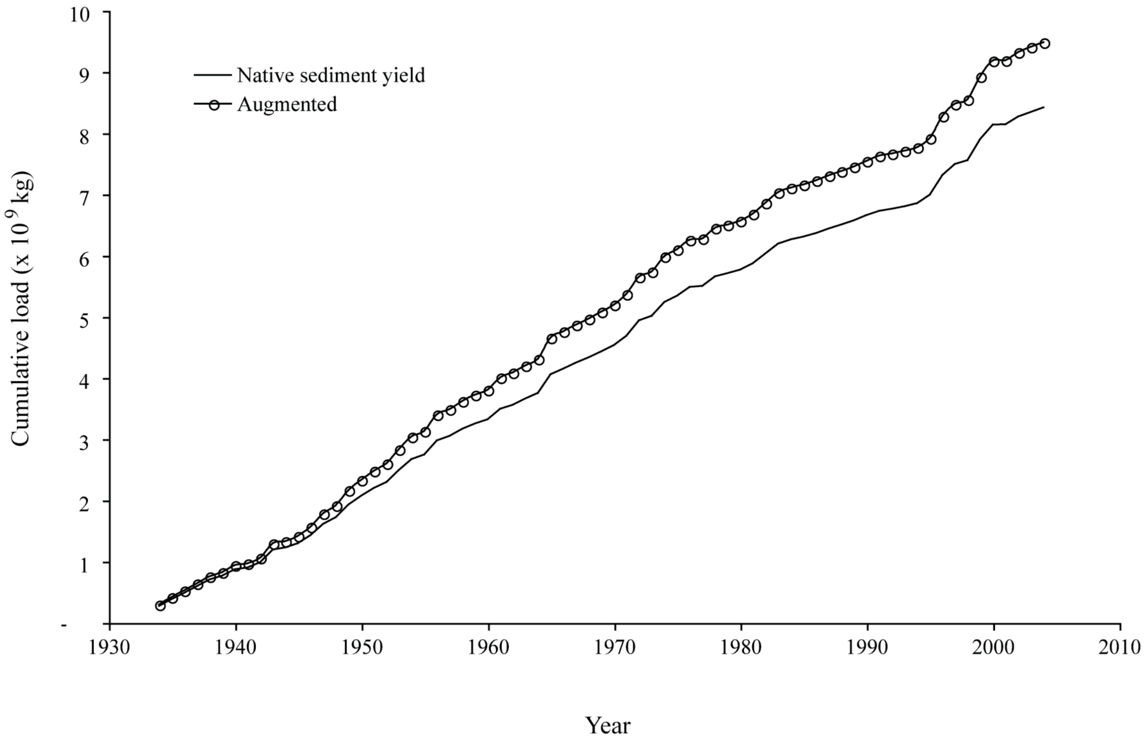

Figure 17: Cumulative load for the Siletz River watershed within Lincoln and Polk Counties. Black line represents an un-augmented cumulative load and black line with circles represents cumulative load augmented by logging.

5.3. Factors in the estuary

Sediment retention can be influenced by human changes to the estuary that prevent natural deposition. In the Siletz estuary, the placement of the Siletz Keys fill (1963-64) and the diking of Millport Slough (1951) blocked the natural flow of the Siletz River and Millport Slough through the southern part of the estuary (Rea 1974; Komar 1975) (Fig.18). This closure might have allowed for increased siltation in the South Bay by the reduction of the stream current needed to remove the sediment, causing marsh expansion in the South Bay (Rauw 1974; Rea 1974; Peterson et al. 1984). Increased siltation is evident in the South Bay cores where the grain-size distribution becomes less coarse with increased clay content in the top 20 cm of the core (Fig 12). The average SAR in the South Bay (0.10 cm/y) is still lower than that of the Marsh Area (0.24 cm/y). However, if cores were taken in the marsh adjacent to the South Bay, the described increase in siltation and marsh expansion might be accounted for.

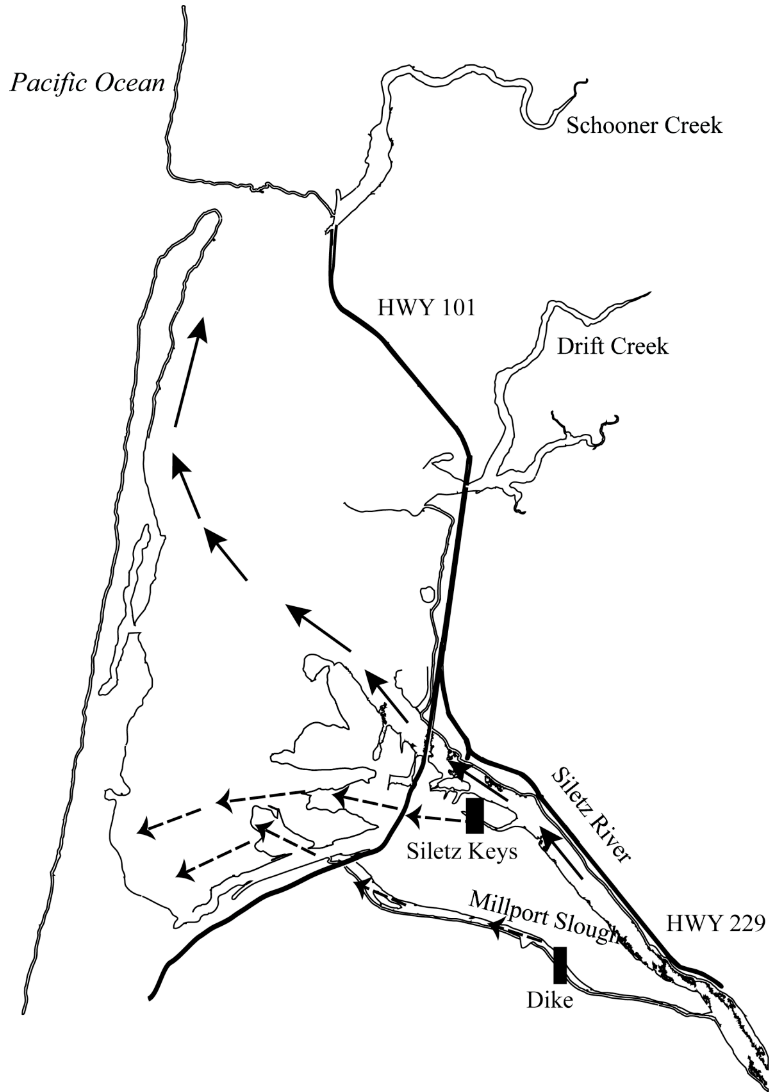

Figure 18: Siletz River flow through the estuary. Dashed arrows show how floodwaters formerly spilled into the South Bay. Solid arrows show current water flow through the main channel (based on Komar 1975).

While human induced alterations can account for some depositional patterns in the estuary, in general the SARs from the cores cannot account for changes in sediment yield through time; therefore, the balance between the source and sink of sediment needs to be evaluated. To determine if there is a discrepancy between what is supplied to the estuary and what is retained, the annual sediment load of the Siletz River (5.91×10^7 kg/y) is compared to the estuary's mass accumulation. If only considering areas where sediment accumulation could be calculated (South Bay and Marsh Area), the mass accumulation is 1.57×10^6 kg/y, which is significantly less than the annual load of the Siletz River. If the areas in the estuary (Marsh Edge) where fine-grained sediment was present, but accumulation could not be calculated, are included, then the mass accumulation is slightly higher (1.68 x 10^6 kg/y) but still significantly less than what is supplied. If the Center Bay and Snag Alley are also added into the calculated mass accumulation, despite their grain-size composition being primarily composed coarse-grained sediment (Peterson et al. 1984), and therefore unlikely accumulating fluvial sediment, the estuary's mass accumulation (3.87 x 10^6 kg/y) is still less than the annual load. Even if the entire estuary (4.8 km^2 at mean high water) was assumed to be accumulating fluvial sediment, what is being supplied to the estuary (5.91 x 10^7 kg/y) is still an order of magnitude different than would be retained (8.42 x 10^6 kg/y). The difference in annual load (supply) and the mass accumulation in the estuary (retained) would suggest that the sediment is not being preserved in the estuary and therefore is bypassing the system, possibly delivered offshore.

	MAR ($g/cm^2/y$)	Area (km^2)	Estuary mass accumulation (kg/y)	Total estuary mass accumulation (kg/y)	
SB-1-S	0.07				
SB-2-S	0.08				
SB-2-L	0.13				
SB-3-S	0.10				
SB-6-S	0.10				
SB-4-S	0.09				
	0.38				
Average	0.14	0.15	1.96E+05		
MA-5-L	0.07				
MA-4-L	0.26				
	0.10				
MA-2-L	0.14				
MA-1-L	0.20				
MA-1-S	0.50				
Average	0.21	0.65	1.38E+06	1.57E+06	SB & MA
ME	0.17	0.06	1.09E+05	1.68E+06	SB, MA, ME
CB	0.17	1.26	2.19E+06	3.87E+06	SB, MA, ME, CE
	0.17	2.68	4.55E+06	8.42E+06	the entire estuary

Table 3: MARs for the various areas of the estuary.

Other PNW studies provide some evidence of estuarine bypass. In the nearby Tillamook estuary, it was noted that higher river flow allows for accumulation of river-derived sand and gravel in the estuary, while finer sediment remains in suspension and is carried further before deposited or flushed to the ocean (McManus et al. 1998). The presence of fine-grained sediment or variable SARs on the shelf are further evidence for estuarine bypass. On the Californian Eel shelf ^{210}Pb and textural data suggest that there is an acceleration in SARs likely due to hydroclimatic and land use changes (Sommerfield and Nittrouer 1999; Sommerfield et al. 2002; Wheatcroft and Sommerfield 2005). While these SAR changes are not seen along all PNW shelves, likely due to the infrequency of larger floods, it has been shown that sediment does accumulate in these areas (Wheatcroft and Sommerfield 2005). The presence of fine-grained sediment along the Oregon continental shelf is, in part, controlled by periodic peak river discharges (Karlin 1980). This is not conclusive evidence of sediment bypass of the estuary, but it does suggest another sink for the sediment that is not retained in the estuary.

Limited accommodation space may help explain why sediment bypasses the estuary. Accommodation space, resulting from the balance between sea level rise and tectonic subsidence/uplift, plays an important role in estuarine sediment distribution and character (Mount and Twiss 2005). Over a given time interval, space is *created* by sea level rise and tectonic subsidence, whereas space is *lost* with falling sea level or crustal uplift (Mount and Twiss 2005). Numerous studies in Oregon have demonstrated gradual and episodic changes in accommodation space that preserve the stratigraphic record in estuarine systems (Darienzo et al. 1994; Nelson et al. 1996a; Nelson et al. 1996b; Witter et al. 2003; Nelson et al. 2004; Nelson et al. 2008).

Twentieth century eustasic sea level rise is estimated between 0.1- 0.2 cm/y (Church et al. 2004). However, because the Oregon Coast is situated on an active tectonic margin with variable uplift, the amount of accommodation space created by sea level rise varies. In the northern part of the state, land is submerged at a rate of ~0.25 cm/y by rising sea level while to the south, uplift causes the land to rise faster than sea level rise at a rate of ~0.10 cm/y (Komar 1997b). The relative sea level rise at the Siletz estuary is 0.19 cm/y, which is comparable to the average SAR for cores taken throughout the estuary (0.18 cm/y), and suggests that the estuary is being maintained relative to sea level rise. If only considering sea level rise and sediment flux, it would be expected that an increase in sea level that was not accompanied with an increased flux would result in a transition from marsh vegetation to open water. Conversely, an increase in sediment flux not accompanied with an increase in sea level would result in an infilling of the estuary.

5.4. Long-term perspective

While sea level rise creates relatively small-scale changes in accommodation space through time, coseismic subsidence, somewhat infrequent, can create large amounts of accommodation space. By examining the long-core data, a long-term perspective on sediment accumulation patterns can be obtained. Along the plate boundary of Cascadia, great subduction earthquakes (magnitude 8-9) have resulted in coseismic land subsidence followed by gradual uplift. The reoccurrence of these events has been estimated in Oregon to be ~600 years (Witter et al. 2003). Evidence of this activity is demonstrated in estuary cores as peat-mud couplets with abrupt contacts (Atwater 1987; Atwater and Yamaguchi 1991; Atwater 1992; Nelson et al. 1996a; Nelson et al. 1996b; Shennan et al. 1998; Atwater et al. 2001; Leonard et al. 2004). In Siletz Bay the estimated subsidence ranged from 0.4 to 0.9 m during the 1700 earthquake (Leonard et al. 2004).

A comparison of cores from this study with those from other studies in the Siletz that provide evidence of Holocene great subduction-zone earthquakes (Darienzo et al. 1994) was conducted to determine if similar patterns exist. The ^{14}C dates from MA-2-L were aligned with the Darienzo et al. "Milliport 1" core (1994) in a similar area of the Siletz (Fig. 18). MA-2-L is broadly consistent with the marsh core composition and event identification. Similar to the Darienzo study, MA-2-L shows distinct sandy horizons often above buried peat (old submerged salt marshes) and below fluvial sediment deposits, with plant macrofossil transitions. In MA-2-L one distinct sandy horizon occurs between 100-115 cm, which is ^{14}C dated between 1590 and 1720. Also during this time there is an anomalously high SAR that averages out to 0.28 cm/y. This sandy deposit, high SAR, ^{14}C age is consistent with the sand deposit resulting from the tsunami following the great 1700 earthquake that impacted this region (e.g., Atwater and Yamaguchi 1991; Witter et al. 2003; Komar et al. 2004; Leonard et al. 2004; Nelson et al. 2008).

Overall, cores from this study provide evidence of coseismic subsidence and infilling following major earthquakes, which is consistent from other studies in this estuary (Darienzo et al. 1994; Leonard et al. 2004). Because of the accommodation space created and removed by subsidence and rapid infilling, and the tendency of sediment to move through or bypass areas of low available accommodation space (Mount and Twiss 2005), long-term sediment accumulation in the estuary might be permitted or restricted.

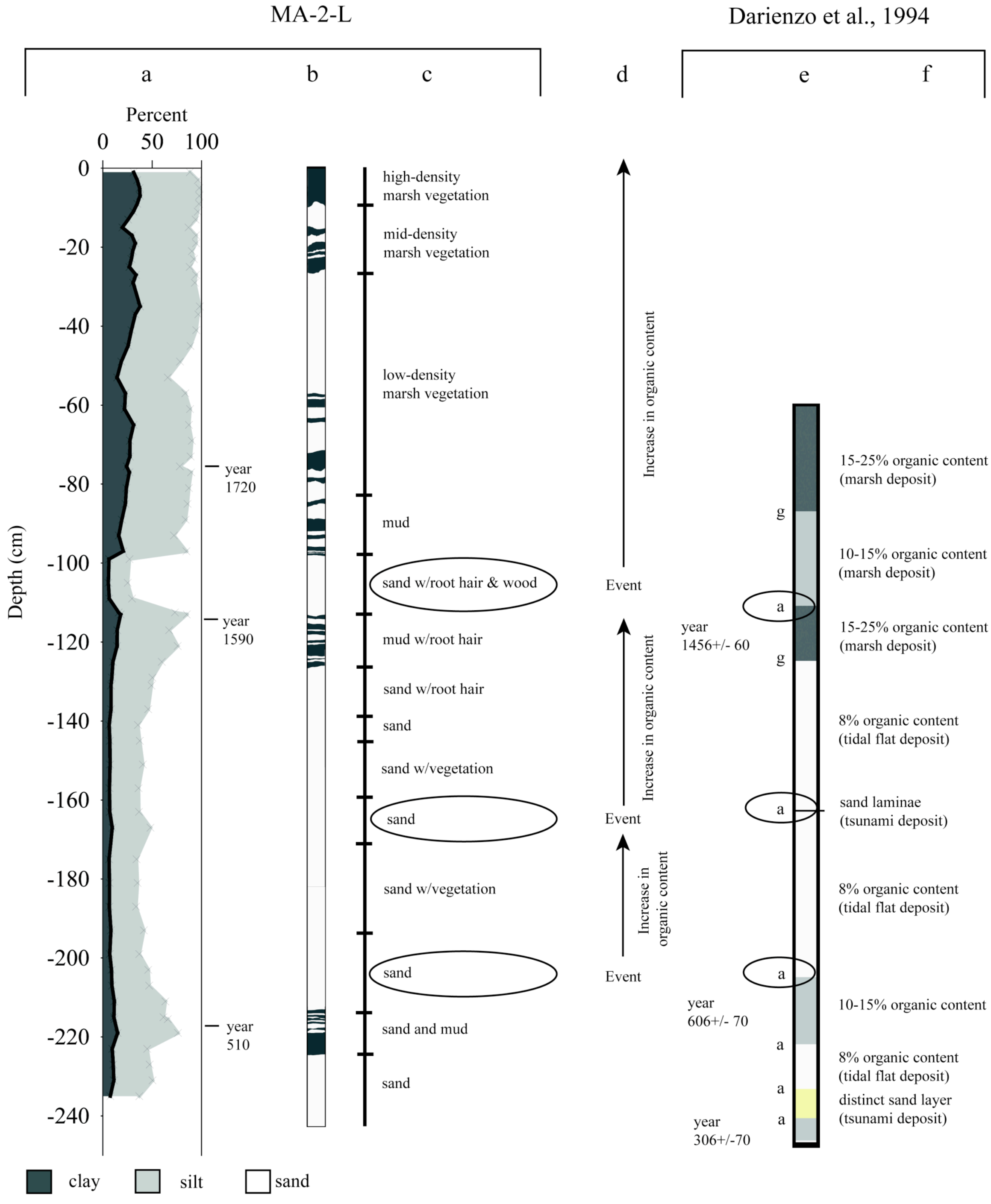

Figure 19: Long-term sediment accumulation patterns. Figure includes: percent clay, silt , and sand (a); X-radiograph: dark (fine-grained sediment), light (coarse-grained sediment) (b); core description (c); location of events (d); core schematic: a- abrupt contact g- gradual contact (e); core description (Darienzo et al. 1994) with subsidence events circled and ^{14}C dates from both cores noted (f).

5.5. Limitations and lessons learned

There are certain assumptions made in this study that limit these conclusions. In general, analysis was limited to one source of sediment load, the Siletz River. The Siletz River gage does not represent the entire drainage of the Siletz watershed, draining 523 km^2 of the 966 km^2 total watershed, causing the calculated sediment load from the watershed to be a minimum estimate. Additionally, the river gage is located 42 miles upriver; therefore, the estimated load represents sediment concentrations proportional to the discharge value at that location, not when it meets the estuary.

This study also does not take into account other sinks of sediment prior to reaching the estuary, such as floodplains, streambeds, or the tidal reaches of the river, which are major deposition centers of the sediment for small-mountainous streams (Trimble 1977; Ichim 1990; Milliman and Syvitski 1992; Mertes and Warrick 2001; Constantine et al. 2003). In the Siletz watershed, floodplains are extensive (Appendix E). Therefore, the calculated sediment load delivered to the estuary represents a maximum value by not accounting for other depositional regions before reaching the estuary. These other potential sinks might account for the difference between the sediment supply from the watershed and retention within the estuary.

The analysis of the effect of logging was premised on the assumption that a "native" condition could be compared to a post-logging condition. The augmented sediment load was compared to the native sediment load, but because the calculated native load was made using post-logging data from the 1970s, this study did not capture the actual pre-logging condition. If a true native condition could be obtained, the difference between augmented and native sediment load comparison might be greater. Additionally, the use of ^{210}Pb and ^{137}Cs geochronologies to calculate SARs are limited to the last ~125 years, therefore not able to capture a truly pristine condition.

These limitations provide the need for future work to further clarify the complex relationships between the factors that influence sediment supply and retention. They also illustrate how management decisions have to take into account the multiple factors that influence sediment dynamics in terrestrial and marine ecosystems. Often the most visually obvious cause of a problem (large clear-cuts increasing sediment loading) might only provide one piece of the picture.

6. Summary and future work

This study illuminates the complexity of the forces that influence sediment flux from a watershed and retention within an estuary. Sediment flux from the watershed was evaluated based on river discharge, hydroclimatic patterns, and harvest records in the basin. While previously logging has been assumed to have a great impact on sediment accumulation, and while there has been a change in the amount of harvest in the watershed, it appears that logging impacts are buffered within the watershed, minimizing their effect. Retention was evaluated based on ^{210}Pb and ^{137}Cs SARs, grain-size distribution, and digital x-radiographs. There was a distinct difference in what was being supplied to the estuary (the annual sediment load: 5.91×10^{7} kg/y) and what is retained (estuary's mass accumulation: 3.87×10^{6} kg/y), suggesting that sediment is bypassing the estuary. Bypassing can be attributed to available accommodation space that is created by sea level rise and tectonic subsidence. The relative sea level rise at the Siletz estuary is 0.19 cm/y, which is comparable to the average SAR for the cores taken throughout the estuary (0.18cm/y), suggesting the estuary is being maintained relative to sea level rise. In addition, SARs, ^{14}C dates, grain size, and layering in the long cores provide evidence for accommodation space change by coseismic subsidence and infilling following major earthquakes.

Other studies that may be conducted to clarify the relationship between flux from the watershed and retention include:

1. An evaluation of the spatial distribution of marsh vegetation migration to understand patterns of sediment accumulation.
2. Offshore coring to determine if sediment is bypassing the estuary and accumulating on the shelf.
3. Better characterization of the logging effect in the whole basin (i.e., hillslope data, actual area harvested, harvesting techniques, and suspended sediment data from rivers).
4. Sediment tracer study to clarify sediment transport through the estuary.

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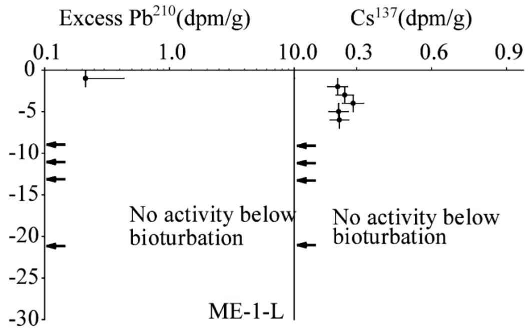
APPENDICES

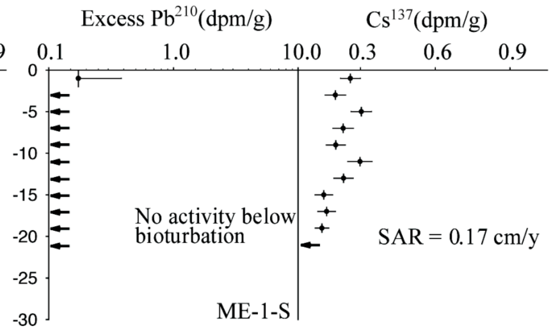
Appendix A: Core collection information

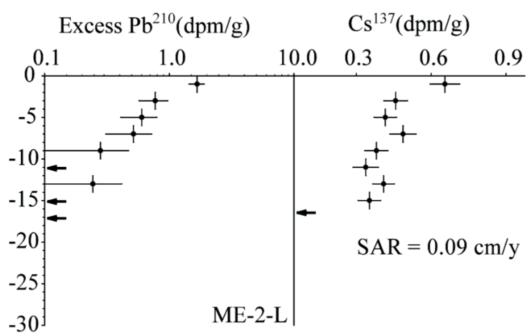
	Latitude	Longitude	Date taken	Core depth (cm)
Marsh Edge				
ME-1-L	-124.015447	44.896733	15-Jun-07	248
ME-2-L	-124.018934	44.896093	10-Jun-08	260
ME-3-L	-124.017118	44.898393	10-Jun-08	262
ME-1-S	-124.015447	44.896733	15-Jun-07	35
ME-2-S	-124.014164	44.900906	16-Aug-07	23
South Bay				
SB-1-L	-124.028744	44.893721	2-Jul-07	242
SB-2-L	-124.028664	44.893215	2-Jul-07	227
SB-1-S	-124.028744	44.893721	2-Jul-07	35
SB-2-S	-124.028664	44.893215	2-Jul-07	30
SB-3-S	-124.029328	44.894427	1-Aug-07	26
SB-4-S	-124.028894	44.894126	1-Aug-07	28
SB-5-S	-124.027757	44.894441	1-Aug-07	26
SB-6-S	-124.023354	44.89174	13-Aug-07	21
SB-7-S	-124.023297	44.892502	13-Aug-07	30
Marsh Area				
MA-1-L	-124.005948	44.896563	23-Aug-07	214
MA-2-L	-124.006262	44.894074	23-Apr-08	256
MA-3-L	-124.008453	44.892837	23-Apr-08	242
MA-4-L	-124.011289	44.891695	17-Dec-07	162
MA-5-L	-124.013865	44.892028	10-Sep-07	104
MA-1-S	-124.005948	44.896563	16-Aug-07	26
MA-2-S	-124.015566	44.903532	16-Aug-07	28
MA-3-S	-124.015775	44.903225	16-Aug-07	28
Snag Alley				
SA-1-S	-124.012602	44.905486	13-Aug-07	25
SA-2-S	-124.01131	44.905092	13-Aug-07	24
SA-3-S	-124.010923	44.903421	13-Aug-07	20
SA-4-S	-124.009761	44.902315	13-Aug-07	24
Center Bay				
CB-1-S	-124.022957	44.901538	9-Jun-08	26
CB-2-S	-124.026833	44.898661	9-Jun-08	30
CB-3-S	-124.023621	44.898182	9-Jun-08	29
CB-4-S	-124.020733	44.896889	9-Jun-08	27
CB-5-S	-124.023841	44.895034	9-Jun-08	27
CB-6-S	-124.02274	44.893319	9-Jun-08	29
CB-7-S	-124.025898	44.894254	9-Jun-08	28

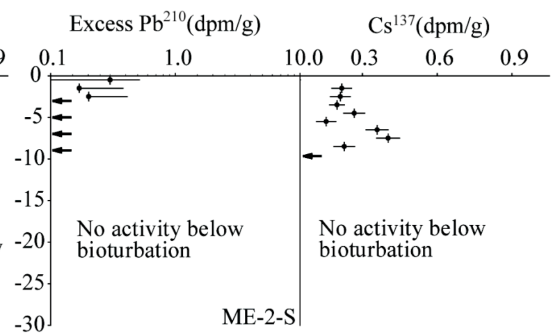
Appendix B: 210Pb and 137Cs Profiles

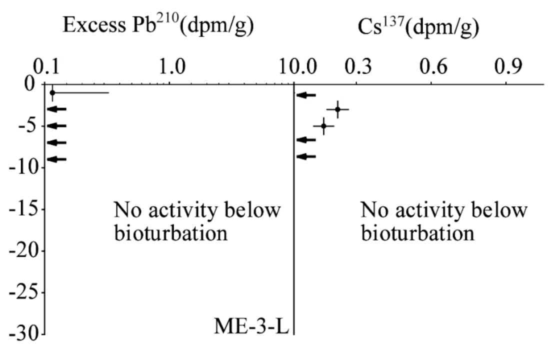
Marsh Edge (ME)



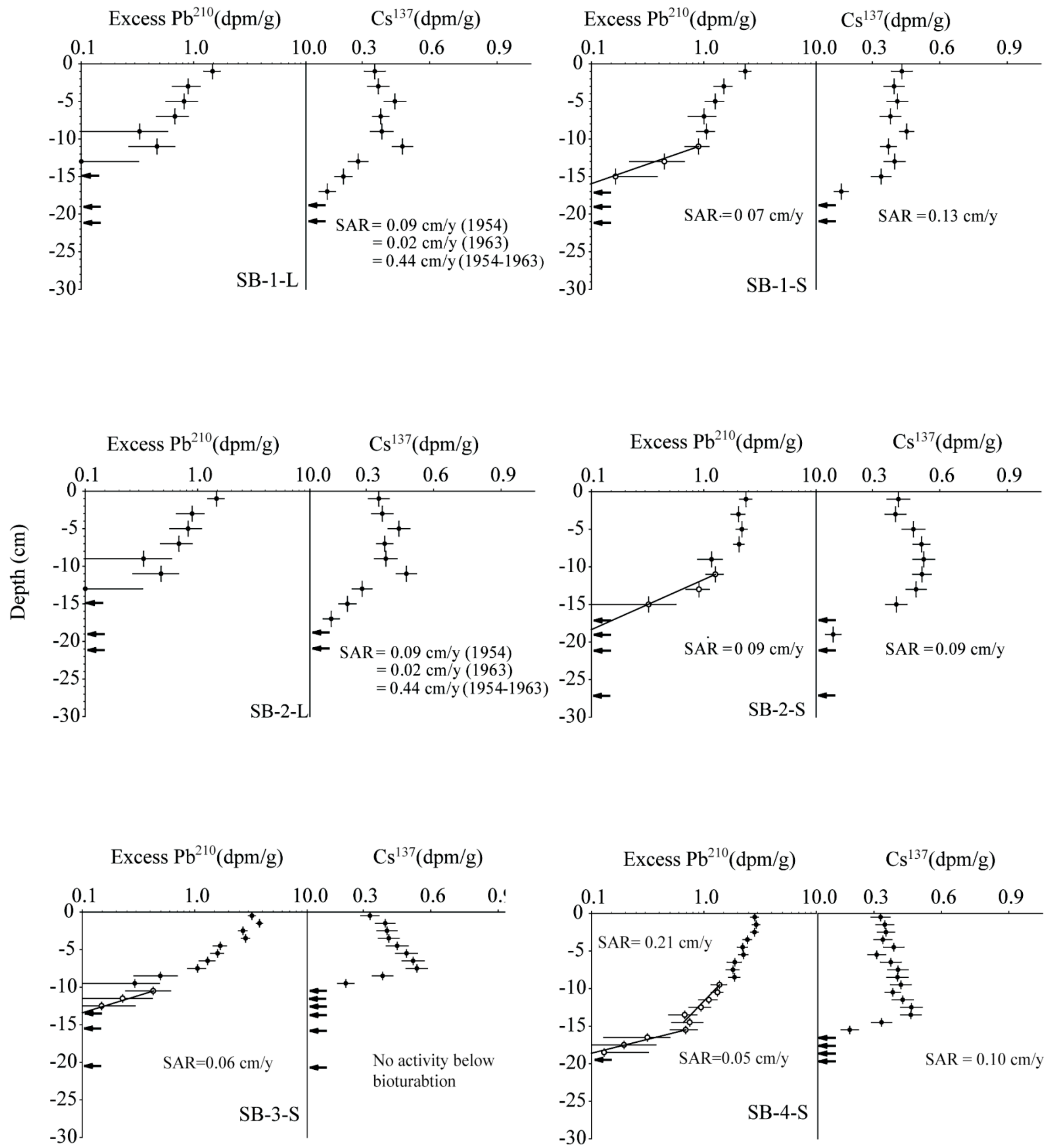




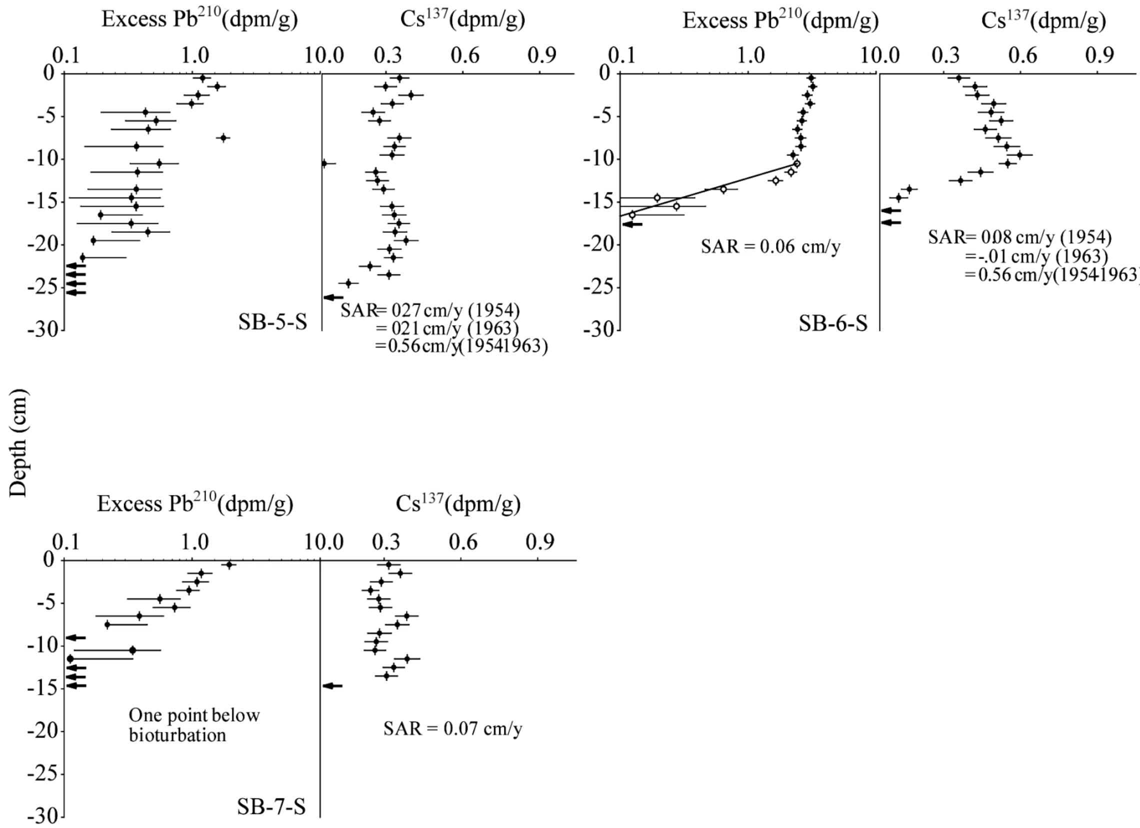




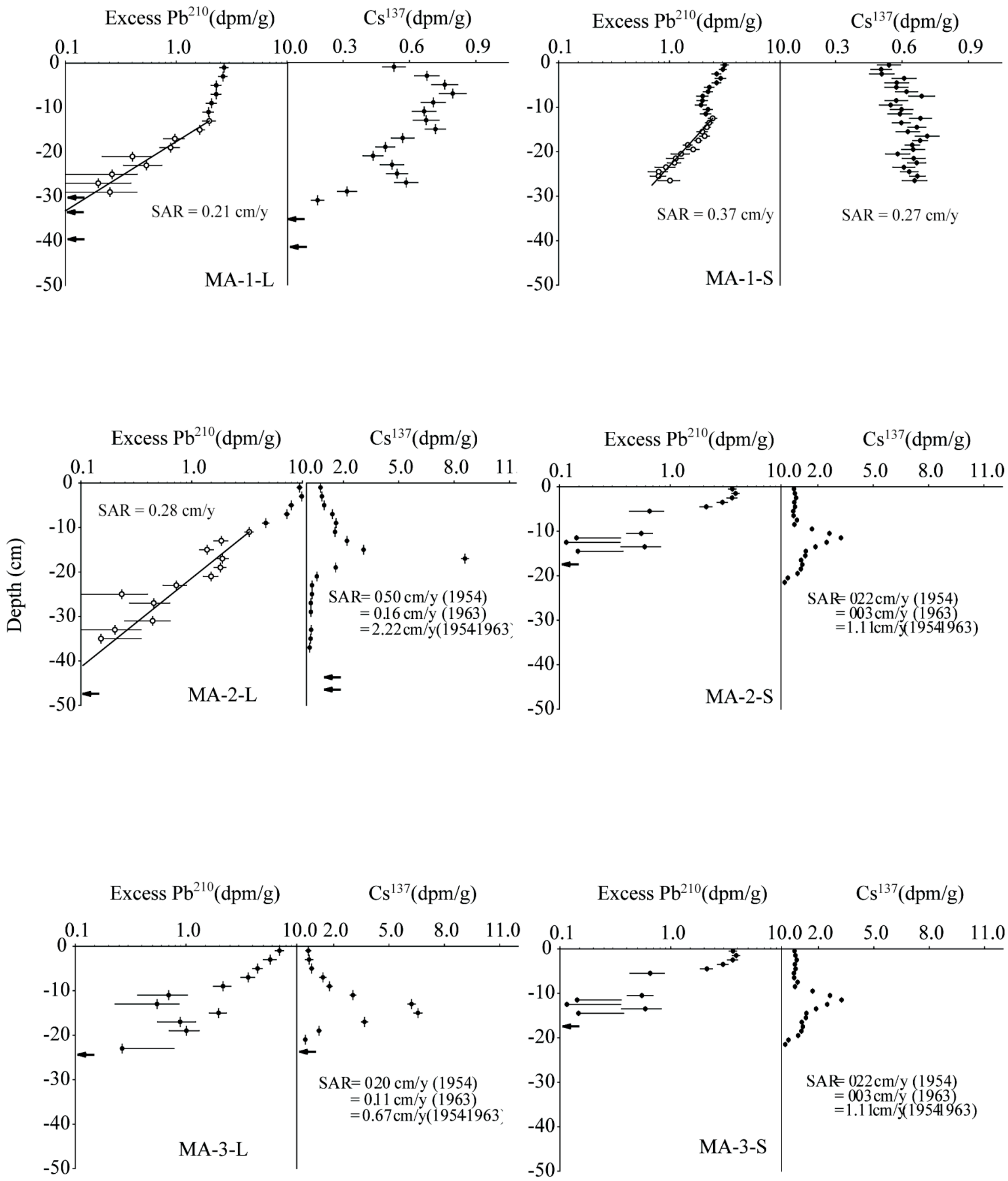
South Bay (SB)


Excess Pb210(dpm/g)
Cs137(dpm/g)
Depth (cm)
SAR = 0.09 cm/y (1954)
= 0.02 cm/y (1963)
= 0.44 cm/y (1954-1963)
SB-1-L
SAR = 0 07 cm/y
SAR = 0.13 cm/y
SB-1-S
SAR = 0.09 cm/y (1954)
= 0.02 cm/y (1963)
= 0.44 cm/y (1954-1963)
SB-2-L
SAR = 0 09 cm/y
SAR = 0.09 cm/y
SB-2-S
SAR=0.06 cm/y
No activity below
bioturabtion
SB-3-S
SAR= 0.21 cm/y
SAR=0.05 cm/y
SAR = 0.10 cm/y
SB-4-S

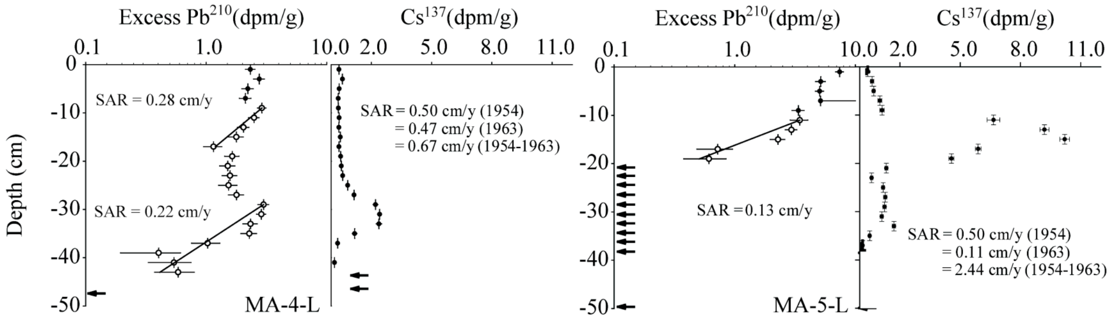
South Bay continued



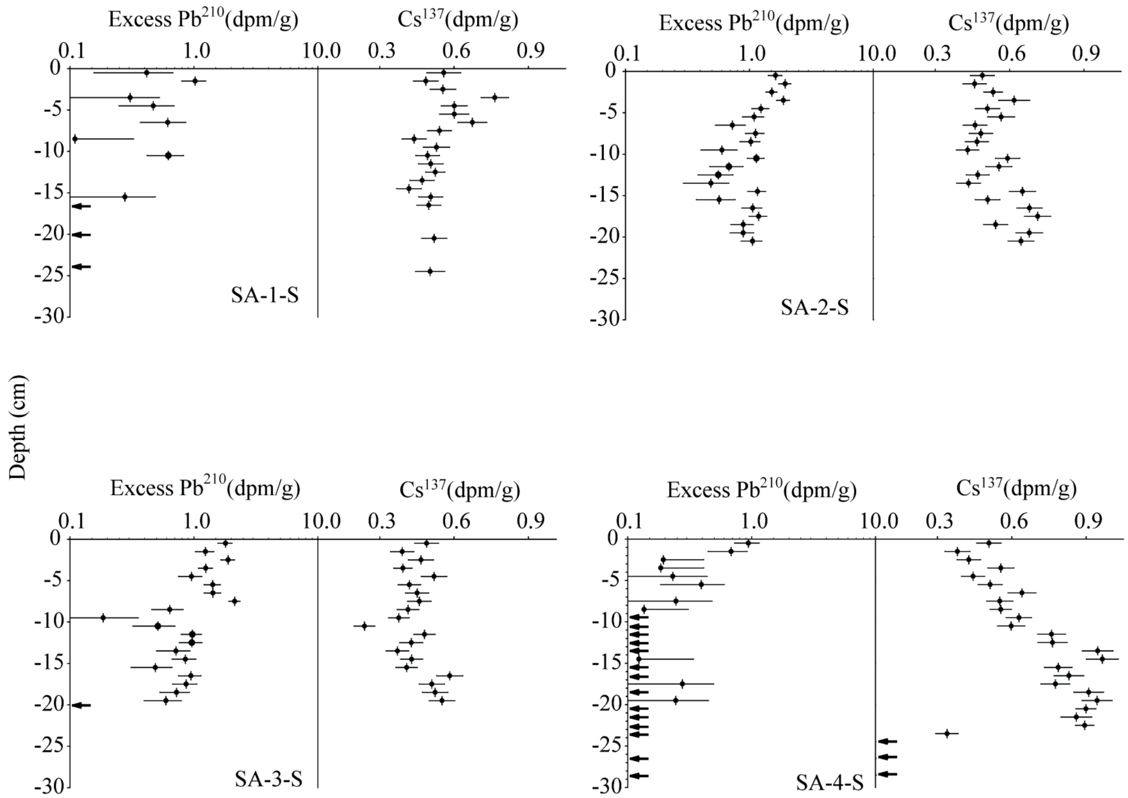
Marsh Area (MA)



Marsh Area (MA) continued



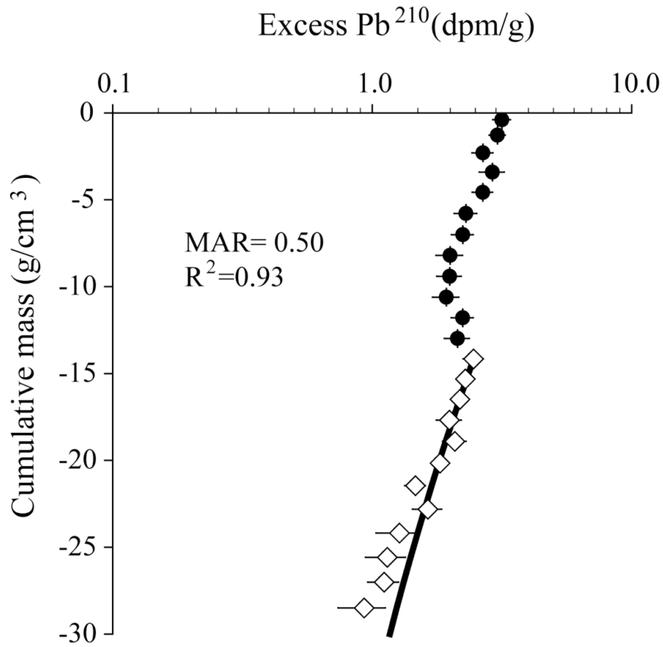
Snag Alley (SA)



Appendix C: MAR table

Depth (cm)	Porosity	Dry mass (g/cm3)	Cumulative dry mass	Excess Pb-210 (dpm/g)
0-1	0.847	0.390	0.390	3.161
1-2	0.806	0.495	1.275	3.041
2-3	0.793	0.527	2.297	2.671
3-4	0.772	0.582	3.406	2.906
4-5	0.772	0.583	4.571	2.668
5-6	0.752	0.633	5.786	2.299
6-7	0.769	0.590	7.009	2.235
7-8	0.763	0.606	8.204	1.996
8-9	0.764	0.602	9.412	1.988
9-10	0.767	0.593	10.607	1.931
10-11	0.767	0.594	11.794	2.232
11-12	0.764	0.601	12.988	2.131
12-13	0.774	0.576	14.165	2.460
13-14	0.773	0.578	15.320	2.287
14-15	0.768	0.592	16.490	2.178
15-16	0.761	0.609	17.691	1.986
16-17	0.759	0.615	18.914	2.084
17-18	0.752	0.634	20.162	1.827
18-19	0.738	0.667	21.463	1.468
19-20	0.731	0.686	22.816	1.640
20-21	0.730	0.690	24.191	1.275
21-22	0.722	0.708	25.588	1.143
22-23	0.718	0.720	27.016	1.113
23-24	0.699	0.768	28.504	0.932
24-25	0.699	0.768	30.040	0.801
25-26	0.709	0.741	31.548	0.798

Appendix D: MAR example plot



Appendix E: Flood plains of the Siletz watershed (Starr 1979)