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The paleoecological record of human disturbance in wetlands of the Lake Tahoe Basin

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Abstract

Increased human activities since discovery of gold in northern California have changed the structure and function of many ecosystems. To reconstruct the changes in watershed environmental conditions, sediment cores were collected from three montane marshes in northern Sierra Nevada, CA. Pollen analysis was conducted, and water content, bulk density, ash, carbon, nitrogen, phosphorus, major cations, and lead concentrations of sediments were determined. Cores were dated by the ^{210}Pb method. Pollen analyses showed changes in plant communities in this region due to severe logging in the late-1800s and moderate logging in the 1900s. The local changes were more clearly recorded in small marsh pollen profiles than regional changes. The water milfoil (*Myriophyllum spicatum* L.) introduction into Tahoe Basin was inferred from the pollen record and ^{210}Pb dating. Road construction and maintenance activities were recorded in physical and chemical characteristics, such as increases in sodium, calcium, and magnesium concentrations. Pollen and physical and chemical records also documented the time line of the expansion of dry meadow, and the decrease of pine forest in one of the watersheds. This study showed that sediments in small marshes were especially useful to reconstruct local disturbance by human activities.

Introduction

Human activities since the Industrial Revolution have changed the structure and function of many ecosystems (Schlesinger, 1997), including wetlands. A prominent anthropogenic impact on wetlands has been an increase in transport of soluble and particulate forms of nutrients and heavy metals from watersheds and the atmosphere (Boynton et al., 1995; Billen & Garnier, 1997; Carpenter et al., 1998; MacKenzie et al., 1998). To understand the cause-response relationship of watershed and wetland ecosystem changes, it is important to know the historical record of watershed and wetland change. However, monitoring data are scarce for many ecosystems and, if they are available, it is only for a few decades (Bradbury & Van Metre, 1997). Records in sediments, combined with human activity history, comprise retrospective studies on human impacts on wetlands beyond the time scale of any existing monitoring program (Wieder et al., 1994; Bartow et al., 1996; Bradbury & Van Metre, 1997).

In this study, we investigated the cause of changes in sediment characteristics by comparing human history and sediment records in the Lake Tahoe region of the northern Sierra Nevada, California. We studied pollen, organic and mineral element content, sedimentation/accumulation rate, and total lead as indicators of past watershed environmental condition. Pollen analysis was used to reconstruct landscape changes of wetland and watershed plant communities according to water level change in wetlands and disturbances such as logging, recreation, and residences in the watershed. The increase of ash content and accumulation rate was the expected response to the increased input of mineral components due to logging and construction of roads

and housing. Road maintenance and road salt application in the winter season led us to expect an increase of sodium and calcium in marshes near heavily used roads. Also, total lead content was expected to increase during the last 60 yrs because of the use of leaded gasoline, and then a decline with the ban of leaded gasoline since the 1980s.

The specific objectives of this study were (1) to reveal changes in plant communities for the recent few hundred years in the Tahoe region and wetlands through pollen analysis, (2) to determine physical and chemical characteristics of the sediments, and (3) to assess the effects of human activities on sediment characteristics.

Human activities in study area

The structure and function of many ecosystems in Sierra Nevada have been changed due to anthropogenic impacts, which escalated since the mid-19th century discovery of gold in California. These changes have been particularly significant in the Lake Tahoe Basin and immediately adjacent areas. Most of the pine and fir forests surrounding Lake Tahoe have been logged, with the heaviest cutting occurring between 1860 and 1900 (Smith, 1969). Tahoe Dam construction was completed in 1913 and the water level of Lake Tahoe has been regulated. Tahoe Keys were constructed by dredging and filling over 300 ha of the central part of original Truckee Marsh for a housing development and a boat dock at the south end of Lake Tahoe in 1971 (Goldman, 1989). This activity divided original Truckee Marsh into what is now called Pope Marsh and the remaining Truckee Marsh. New roads have been constructed and modern snow removal equipment and chemicals have been used to keep highways open in winter. Permanent residents in this region increased about 20-fold during 25 yrs: from 2,859 in 1956 to 48,071 in 1980. The seasonal peak of visitors increased from 98,836 in 1970 to 223,320 in 1980 (Ingram & Sabatier, 1987). Byron et al. (1991) reported the increase of precipitation acidity and nitrate concentration from 1979–1986. As the result of increased leaded gasoline usage in automobiles, lead content in Lake Tahoe sediment drastically increased over the interval from about 1920 and 1980 (Heyvaert, 1998).

Methods

Sampling sites

Sampling was conducted in November 1995 in three montane marshes: Pope Marsh, Kyburz Flat, and Meyers Grade Marsh in northern Sierra Nevada, California (Figure 1). Characteristics of the three marshes are summarized in Table 1. Pope Marsh was once part of the large Truckee Marsh, but it was isolated by construction of the Tahoe Keys housing subdivision at the end of the 1960s. Water level in Pope Marsh is largely determined by the water level of Lake Tahoe and partly by the pumping of water into the Tahoe Keys (Green, 1998). This marsh is surrounded by a ponderosa pine (*Pinus ponderosa* Loudon) forest which is heavily used for recreational activities such as camping and bird watching. Two islands dominated by lodgepole pine (*Pinus contorta* Loudon) are surrounded by the marsh. Plant distribution in the marsh is determined primarily by water depth, with the deepest zone dominated by floating-leaved and submersed macrophytes such as water lily (*Nuphar luteum* L. ssp. *polysepalum* Engelman), horse tail (*Hippuris vulgaris* L.), pondweeds (*Potamogeton* spp.) and water milfoil (*Myriophyllum* spp.), and shallow areas occupied by tule (*Scirpus acutus* Bigelow), sedge (*Carex utriculata* Boott) and rush (*Juncus balticus* Willd) (Rejmankova et al., 1999).

Meyers Grade Marsh is adjacent to U.S. Highway 50 about 12 km south of Lake Tahoe (Figure 1, Table 1). On the west side is a steep slope upwards towards a wagon road that was improved and renamed Highway 50 in the 1930s. The slope is covered with small grasses and shrubs. The north and east sides are surrounded by tall ponderosa pine and huckleberry oak (*Quercus vaccinifolia* Kellogg). Quaking aspen (*Populus tremuloides* Michaux) grows on the north side of the marsh. Dominant species in this marsh are tule (*S. acutus*), rush (*Juncus ensifolius* Wikstrom), water lily (*N. luteum* ssp. *polysepalum*), and sedges (*C. utriculata* and *C. nebrascensis* Dewey). Water is colder than in the other two marshes because the water source is primarily from ground water (except in winter and spring from snow melt) and this marsh receives fewer hours of direct sunshine due to tree shadows.

Kyburz Flat is about 35 km north of Lake Tahoe. Towards the north is a dry meadow with grasses (*Festuca californica*, *Agrostis* spp., *Bromus japonicus*, etc.) and lupine (*Lupinus albicaulus*), and beyond this meadow is a small creek whose elevation is a little higher than Kyburz Flat. The other sides are surrounded by ponderosa pine forest. Dominant species in this marsh are sedge (*C. utriculata*), tule, and water lily. Water input to the marsh is from creek overflow and groundwater.

Precipitation (usually snow) in the study area is concentrated in winter, and the water level of all three marshes is usually highest in June and lowest in

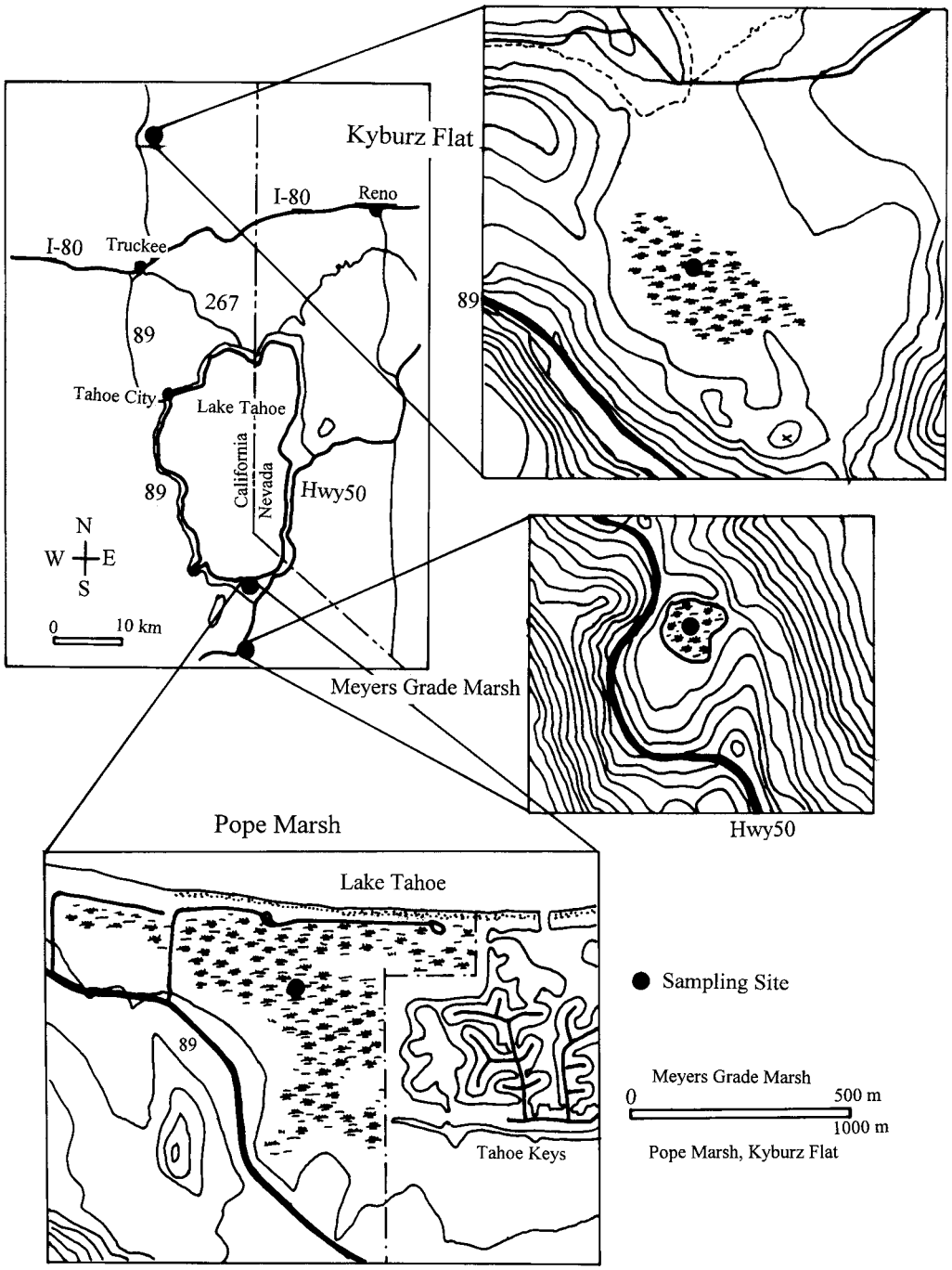

Figure 1. Location of study sites. (A): Pope Marsh, (B): Meyers Grade Marsh, (C): Kyburz Flat.

November. The three marshes usually do not dry during the dry season except during severe drought yrs. Average annual temperature and precipitation in Tahoe City are 5.7 °C and 747 mm. Figure 2 shows the variation of total annual precipitation at Tahoe City and Truckee. Truckee is a small town located about half way between Kyburz Flat and Tahoe City, and it has the longest record of climate data for this region. Annual precipitation pattern in Truckee is the same as

Table 1. Characterization of sampling sites

	Pope Marsh	Kyburz Flat	Myers Grade Marsh
Coordinates	38 °56′N,120 °02′ E	39 °29′ N,120 °14′ E	38 °50′ N,120 °02′ E
Elevation (m)	1,885	1,909	2,066
Size (ha)	70	40	2
Primary hydrology	Snow-melt in Spring, Ground water (Pumping)	Surface Flow in Spring, Ground water	Snow-melt in Spring, Ground water
Hydroperiod	rarely drying (severe drought year)	rarely drying (severe drought year)	Permanently flooded
Sediment Type	Dark and soft humic peat	Brown humic peat to peat-clay	Light brown fibric peat
Dominant Species	*N. luteum* ssp. *polysepalum*, *C. utriculata, Hippuris vulgaris, S. acutus*	*Carex utriculata*, *Scirpus acutus* *Nuphar luteum* ssp. *polysepalum*	*C. nebrascensis*, *C. utriculata, S. acutus* *N. luteum* ssp. *polysepalum*
Disturbance	Tahoe Keys construction (1971), camping site (since 1970s)	Logging (1926–1928)	Hwy 50 construction (1930s) and maintenance

that in Tahoe City and combined graph shows the changing pattern of annual precipitation since 1870. There was a prolonged drought period between 1987 and 1994.

Sample collection and analyses

Two sediment cores were taken in each wetland in early November 1995 by driving plastic open-end samplers (5.6 cm diameter) to a depth of 50 cm at the central part of Pope Marsh and Meyers Grade Marsh, and at the deepest part of Kyburz Flat (Figure 1). Water level is the lowest at this time, and the sampling sites were selected in the flooded area. The upper end of the corer was capped after the corer was pushed into the sediment, and the other end was capped after retrieval. Cores were transported to the lab in a cooler and then kept in a freezer. Frozen cores were later sectioned into 1-cm thick segments. About 1 g of a wet sub-sample was taken for pollen analysis because grinding of dry samples causes some damage to large pollen grains (Wieder et al., 1994) and then the samples were air-dried. Pollen analysis was done at 1 cm intervals in Pope Marsh and Meyers Grade Marsh and 2 cm intervals in Kyburz Flat by a modification of the standard method (Faegri & Iverson, 1989) including KOH treatment, sieving, $ZnCl_2$ flotation, and acetolysis. A minimum of 1000 pollen grains was counted under a light microscope (× 400) to verify any changes in minor pollen taxa (Birks & Birks, 1980). Identified pollen taxa were then divided into three groups: arboreal, herbs, aquatic/wetland taxa. A sum of all counted pollen for the aquatic/wetland taxa and a sum of arboreal and herbs for these types were used for calculation of pollen percentages (Faegri & Iverson, 1989).

Air-dried samples were ground in a mortar with a pestle and sieved with a standard #60 sieve (mesh size

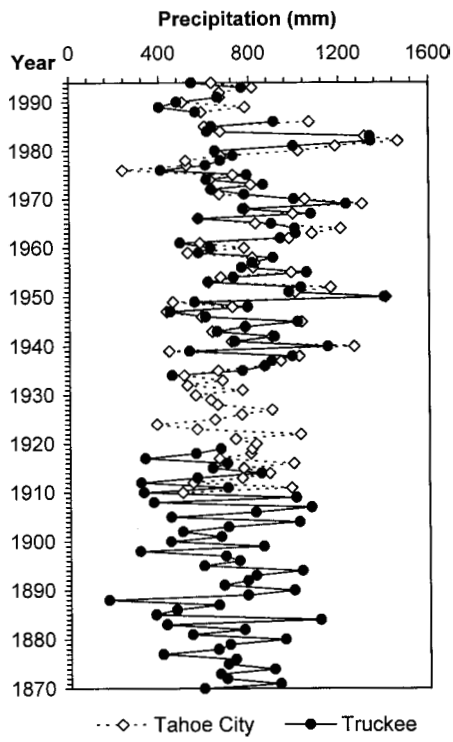

Figure 2. Annual precipitation at Tahoe City and Truckee.

250 μm). Dry weight was determined after drying at 105 °C for 24 h. Bulk density was calculated as dry weight per wet volume, and ash content was determined by combustion in a muffle furnace at 550 °C for 4 h (Dean, 1974). Total carbon and nitrogen were determined on a Carlo-Erba series 5000 CHN-S analyzer. Inorganic carbon concentration was determined for a subset of samples. Concentrations of inorganic carbon were less than 1% of total carbon, hence total and organic carbon concentrations were considered equivalent (Belyea & Warner, 1996). Total phosphorus and lead were determined by ICP-AES (Inductively Coupled Plasma spectroscopy, Thermo Jarrell Ash Corporation, model Atom Scan 25) after microwave acid digestion (Sah & Miller, 1992). The digested solution was used to determine total sodium, potassium, calcium and magnesium with a Perkin-Elmer 2380 Atomic Absorption Spectroscopy following the methods described in Allen (1989).

Cores were dated using ^{210}Pb (Appleby & Oldfield, 1986; Binford, 1990). One g of an air-dried sample was digested in 50 ml 8 N nitric acid after adding about 1 dpm of ^{209}Po to determine the chemical yield of ^{210}Po. The supernatant was evaporated to dryness and the remnant was digested again in 50 ml 6 N hydrochloric acid. The supernatant was combined with the dried residue of the nitric acid digestion supernatant and dried. The dried residue was dissolved in 50 ml 0.5 N hydrochloric acid, and then 500 mg ascorbic acid was added. The ^{209}Po and ^{210}Po (granddaughter of ^{210}Pb in decay series) were deposited on a silver planchet (9 mm diameter) at 70–80 °C. The silver planchet was put on a holder on a magnetic stirrer and stirred at 400 rpm (Smith & Hamilton, 1984). The activities of ^{209}Po and ^{210}Po were measured with silicon-ion-implanted α-counters (Oxford Instruments Inc.) in the Lawrence Livermore Nuclear Laboratory. Supported ^{210}Pb was estimated from total ^{210}Pb by assuming the background activity of total ^{210}Pb in the bottom portion of cores represented supported ^{210}Pb (Binford, 1990). Two models were used to determine dates based on ^{210}Pb counts: smoothed Constant Initial Concentration (CIC) and Constant Rate of Supply (CRS) (Robbins, 1978; Appleby & Oldfield, 1986; Binford, 1990).

Elemental lead is a widely cited sedimentary marker of industrialization, particularly due to its use in automobile fuels from the 1920s until the early 1980s (Murray & Gottgens, 1997). Since the improvement of Hwy 50, visitors have increased and the usage of leaded gasoline might increase the lead content in marsh sediments. Lead content started to increase from the 1920s until the early-1980s in Lake Tahoe (Heyvaert, 1998), and the increasing or peak depth of lead content was used to confirm our ^{210}Pb dating as the late-1930s or late-1970s, respectively. Dates were assigned to sediment intervals based on smoothed CIC and CRS models by considering ash content increase due to Tahoe Keys construction (1971) for Pope Marsh and road construction (1930s) for Meyers Grade Marsh, and grass pollen increase due to logging activity (1928) in Kyburz Flat. Uncertainties of ^{210}Pb dates were calculated with Binford's CRS program (Binford, 1990) for the CRS model and with a log-linear model fit for the CIC model. Uncertainties of pollen dates and lead dates were based on ^{210}Pb dating results and the depth of sample slices. Dates for the deeper part of the cores that cannot be dated with these models were extrapolated.

Results and discussion

Sediment dating, age models, and sediment accumulation rates

The ^{210}Pb activity below the 26 cm depth in Pope Marsh and the 22 cm depth in Meyers Grade Marsh was too low to provide reliable dates. Log-linear models were used to estimate average accumulation rates ($R^2 > 0.96$) (Figure 3). The total ^{210}Pb activity of the lower part in Kyburz Flat fluctuated and the average of those activities was used as a supported activity. The ^{210}Pb flux was 0.49 dpm cm^{-2} yr^{-1} at Pope Marsh, 0.38 dpm cm^{-2} yr^{-1} at Meyers Grade Marsh, and 0.21 dpm cm^{-2} yr^{-1} at Kyburz Flat. The estimated dates using the CIC model were younger than those from the CRS model but the difference was not significant (Table 2). Overall accumulation rates were 0.0174 g cm^{-2} yr^{-1}at Pope Marsh, 0.0307 g cm^{-2} yr^{-1} at Kyburz Flat, and 0.0104 g cm^{-2} yr^{-1} at Meyers Grade Marsh.

The main assumption of the CIC model is the constant accumulation rate. This model excludes the possibility of dilution due to accumulation rate change or mixing, while the CRS model does not assume the constant accumulation rate (i.e. the CRS model is useful to calculate dates of a sediment core which has accumulation rate changes: Binford, 1990). Both the CIC and CRS models can be used if the accumulation rate did not change. The ^{210}Pb activity in all three marshes showed an exponential decrease with depth even though there were slight changes of slope along depth, therefore both smoothed CIC and CRS models were used to calculate dates. We determined the initial specific

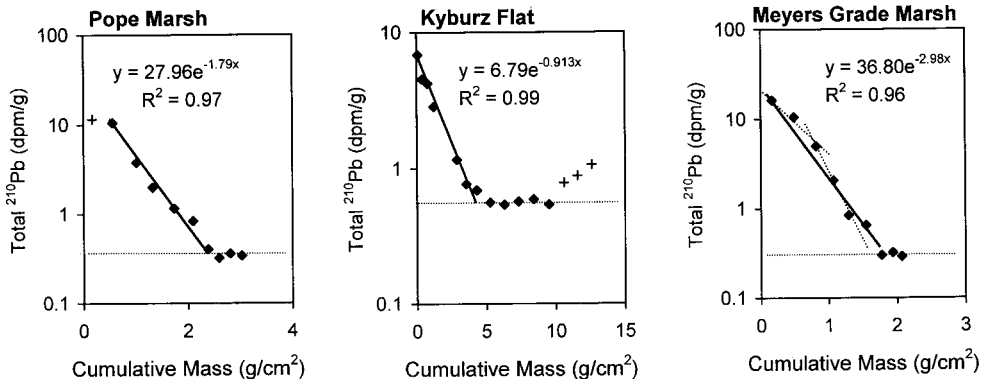

Figure 3. Total ^{210}Pb stratigraphic profiles for three montane marsh cores. A log-linear model was used for the calculation of overall sedimentation rates: + data points were excluded for analysis, dotted bottom line indicates supported ^{210}Pb, and regression equations were calculated from unsupported ^{210}Pb stratigraphic profiles. Dotted lines, except bottom line, in Meyers Grade Marsh infer the change of accumulation rates.

Table 2. ^{210}Pb age dates calculated from the CIC model and the CRS model. Bold dates were used for other analyses

Depth	Pope Marsh				Kyburz Flat				Meyers Grade Marsh			
cm	CIC	±	CRS	±	CIC	±	CRS	±	CIC	±	CRS	±
0	1994	6	1994	5	1994	3	1994	4	1994	10	1994	5
1	*1993	6	**1993		1991	2	1991	4	*1990	10	**1992	
2	*1990	6	1990	6	1987	2			1985	9	1990	7
3	1984	5	1987	6	1982	2	1985	5	1978	9	1980	7
4	1979	5	**1982		1976	2			1969	8	**1973	
5	1973	5	**1976		1970	2	1974	5	1959	7	1965	6
6	1967	4	1972	8	1964	1			1947	6	1956	7
7	1961	4	1964	9	1958	1	1962	7	1936	6	**1942	
8	1953	3	**1955		1952	1			1926	5	1934	7
9	1946	3	**1947		1944	1			1916	4	1921	11
10	1941	3	1941	7	1936	1			1907	4	**1903	
11	1935	2	1932	9	1927	1			1899	3	1897	14
12	1929	2			1917	1			1891	3	1885	29
13	1923	2	1920	9	1909	1	1883	18	1878	3		
14	1917	2	1913	12	1899	2			1870	3	1856	32
15	1912	2			1889	2	1845	44	1862	3	1852	> 32
16	1907	2	1888	19	1879	3			1854	3		
17	1901	2	1880	21	1867	3			*1846	3		
18	1894	3			*1854	4			*1838	4		
19	1887	3			*1839	4			*1832	4		
20	1883	3			*1826	5			*1824	4		
21	1878	3			*1809	6			*1816	5		
22	1873	4			*1795	6			*1808	5		
23	*1867	4			*1780	7			*1800	7		
24	*1861	4			*1763	8			*1796	7		
25	*1856	5			*1747	9						
26	*1850	5			*1729	9						
27	*1844	6			*1714	10						
28	*1839	6			*1699	11						
29	*1832	7			*1683	12						
30	*1825	7			*1668	12						
31	*1819	7			*1655	13						

*indicates extrapolation, **indicates interpolation. Errors of CIC dates were calculated from log-linear model fit of Figure 3.

^{210}Pb activity from a log-linear model fit of ^{210}Pb data. Calculated initial specific ^{210}Pb activities were much higher than measured values at surface samples. The problem with estimating supported ^{210}Pb is that the estimate can differ depending on the number and value of included points in the bottom portion of the cores. Relative differences of unsupported ^{210}Pb activity in the lower part due to different estimates of supported ^{210}Pb activity is much larger than in the upper part. Estimated ages in the lower sediment were affected much more by the different level of supported ^{210}Pb activity than in the upper part (Heyvaert, 1998). Heyvaert (1998) suggested a decision method for supported ^{210}Pb after trying several different supported ^{210}Pb values to calculate dates: slightly under its true value. ^{226}Ra is the grandmother of ^{210}Pb in the soil and ^{226}Ra activity is measured to avoid this problem (Binford et al., 1993; Brenner et al., 1996). Unfortunately, we did not have the option of measuring ^{226}Ra. The low activity in the upper sediments may be attributed to mixing or to increased sedimentation rate. However, Binford et al. (1993) showed that under most circumstances ^{210}Pb dates calculated by the CRS model are robust enough that the mixing zone can be as much as 15% of the depth of the ^{210}Pb profile. When a ^{210}Pb profile indicates a recent change of accumulation rate and dates for the deep part need to be extrapolated, it is reasonable to use the CRS model during the accumulation rate changing period (upper part) and the CIC model for the lower part, which might have relatively constant accumulation rate (P. Appleby, personal communication). Therefore, we calculated dates for the bottom part from the slope of the least squares fit to the log unsupported ^{210}Pb activity versus cumulative mass total. This method can reduce the error of bottom dates and is reliable to extrapolate dates older than 150 yrs.

The ^{210}Pb profile of Kyburz Flat showed a monotonic decrease and the smoothed CIC model was used (Figure 3). The pine forest around Kyburz Flat was logged in the late-1920s and became a dry meadow (M. Baldrica & Darry-Schweyer, personal communication, Tahoe National Forest). This apparently caused the increase of grass pollen in Kyburz Flat (Figure 5). Pollen results showed a slightly later occurrence of grass pollen than expected from the ^{210}Pb dates and this difference might be the result of the pollen analysis being conducted at 2 cm intervals (about 16 yrs). The upper two points of Pope Marsh and the upper three points of Meyers Grade Marsh had a lower slope than the deeper parts of both cores (Figure 3). This indicates a slight change of sedimentation rate in Pope Marsh and Meyers Grade Marsh. Construction activities often disturb watersheds and wetlands, and increased input of mineral soil particles can be seen in sediments (Bunting et al., 1997; Miller et al., 1997). Tahoe Keys construction was finished in the early 1970s and Hwy 50 was improved in the 1930s. It seems reasonable to expect an increased ash content in Pope Marsh and Meyers Grade Marsh (Figures 7 & 9). The dates calculated by the CRS model in Pope Marsh and Meyers Grade Marsh were closer to this historical indicator, and the peak time or increase of total lead content (late 1970s and late 1930s for Pope Marsh and Meyers Grade marsh, respectively). The difficulty to determine supported ^{210}Pb levels and these indicators led us to use the dates calculated by the CRS model in upper sediment (above 10 cm in Pope Marsh and 12 cm in Meyers Grade Marsh) and by the CIC model in lower sediment (Table 2).

The ^{210}Pb flux (max. 0.4 dpm cm^{-2} yr^{-1}) in these three marshes is lower than 0.84–1.44 dpm cm^{-2} yr^{-1} in Lake Tahoe (Heyvaert, 1998). About 90% of all ^{210}Pb fallout is delivered by wet deposition, with the remainder in dry deposition. The residence time of water determines the sedimentation of ^{210}Pb (Turekian et al., 1977; Binford et al., 1993). The water residence time (~ 700 yrs: Jassby, 1998) in Lake Tahoe is much longer than in small marshes (less than 10 yrs), and small mineral particles combined with ^{210}Pb in water column are preferentially focused into the deeper part of the basin during this residence time (Turekian et al., 1977). The ^{210}Pb flux in small and shallow marshes may be expected to be lower than in a deep area of Lake Tahoe. Also, the ^{210}Pb flux is much lower in the western United States than in the eastern United States because it is determined by the land-based source of ^{210}Pb (Brenner et al., 1996; Binford et al., 1993). The Lake Tahoe area has a primarily north-west wind direction so the source of ^{210}Pb is mostly limited to California and southern Oregon. The peak of total lead occurs at 8 cm depth at Pope Marsh (Figure 7), at 4–8 cm depths at Kyburz Flat (Figure 8), and at 4 cm depth at Meyers Grade Marsh (Figure 9). Even though leaded gasoline had been used until the early 1980s, total lead content started to decrease in the late 1960s and early 1970 in Pope Marsh and Meyers Grade Marsh, respectively. The total lead content was not useful to confirm the dating result, but indicated the increase in the 1960s and 1970s, and a decrease in recent yrs.

The sampled cores were compacted and the accumulation rate was accordingly calculated on a dry weight basis to reduce the compaction effect (Haflidason et al., 1992). The overall accumulation rate of 0.01–0.03 g cm^{-2} yr^{-1} in these montane marshes is in the low-range of accumulation rates for North America (Table 3). There

Table 3. Comparison of sedimentation/sediment accumulation rates of various freshwater wetlands in northern America and Iceland

Type	Region	cm yr^{-1}	g cm^{-2} yr^{-1}	Source
Montane marsh	California	0.12–0.18	0.01–0.03	This study
Boreal subarctic peatland		0.05		Gorham (1991)
Bog	Thingvallavatan (Iceland)		0.03–0.06	Haflidason et al. (1992)
	Ontario (Canada)		0.006	Belyea & Warner (1996)
	Massachusetts	0.43		Hemond (1980), (1983)
	Maryland, Pennsylvania, West Virginia	0.14–0.31		Wieder et al. (1994)
	Minnesota	0.24		Wieder et al. (1994)
Fen	Michigan	0.09		Craft & Richardson (1998)
Pocosins	North Carolina	0.26		Craft & Richardson (1998)
Freshwater marsh	Everglades	0.48–1.13		Reddy et al. (1993)
	Everglades	0.14–0.67		Craft & Richardson (1998)
	Anderson Marsh (California)	0.457	0.126	J. Kim, unpublished data
Freshwater tidal marsh	Maryland	0.07–0.15	0.09–0.52	Khan & Brush (1994)

are many records of sedimentation rates in wetlands and lake sediments all over the world, but it is not reasonable to compare the sedimentation rate calculated by ^{210}Pb dating with those based on radiocarbon dating that overestimates the age of the upper core. Radiocarbon dating is usually limited to material older than about 350 yrs (Heyvaert, 1998) and typically used to date long cores for a time span of hundreds to a few tens of thousands of yrs.

The accumulation rate in Kyburz Flat is the highest among the three marshes, and the rate in Meyers Grade Marsh is the lowest (0.031 g cm^{-2} yr^{-1}at Kyburz Flat, 0.017 g cm^{-2} yr^{-1} at Pope Marsh, and 0.010 g cm^{-2} yr^{-1} at Meyers Grade Marsh). These differences can be explained by different primary production and decomposition rates in individual marshes. Cores were collected in the *Nuphar-Hippuris* community in Pope Marsh, the *C. utriculata* community in Kyburz Flat, and the *Carex nebrascensis* community in Meyers Grade Marsh. Corresponding above-ground biomass values for these communities were 90, 110, and 30 g dry weight m^{-2} for Kyburz Flat, Pope Marsh and Meyers Grade Marsh, respectively (H. Spanglet for Kyburz Flat and Myers Grade Marsh, unpublished data, University of California, Davis; Rejmankova et al., 1999 for Pope Marsh). *Carex* leaves and *Nuphar* leaves and petioles decomposed by 78.5% and 96.6% in the water-soil interface, respectively during 1 yr (1997) in Pope Marsh (J. Kim, unpublished data). When we consider 1-yr production and decomposition in these marshes, the ratio of accumulation rates in Kyburz Flat, Pope Marsh and Meyers Grade Marsh should be 3:0.6:1. This analysis explains the difference of accumulation rates between Kyburz Flat and Meyers Grade Marsh. Water lily is a dominant species in Pope Marsh making it difficult to decide net primary productivity because an entire leaf or a portion of the water lily dies and decays in a single growing season. This problem should be investigated to understand the relationship among production, decomposition, and accumulation. Also, we have to consider historical changes of communities and allochthonous input. For example, in the dry yr, 1989, the decomposition rates measured at Pope Marsh were much lower (*Carex* leaves < 50% per yr, E. Rejmankova, unpublished data). Historically, plant communities of these montane marshes are related to changes in water level (Rejmankova et al., 1999). High ash content of Kyburz Flat sediments can serve as an example of allochthonous input of silt or clay particles with overflowing water into the marsh.

Vegetation history

The montane zone of northern Sierra Nevada is dominated by conifers (mostly *Pinus ponderosa*, *P. jeffreyi*, and *Abies magnifica*, TRPA and USDAFS 1971) and the pine pollen percentage (> 80% of terrestrial pollen sum) reflects this well (Figures 4, 5 & 6). Different percentages of arboreal pollen among the three marshes can be a result of the different marsh sizes (Table 1). Ideally, pollen rain decreases exponentially with distance from the pollen source (Janssen, 1966) and pollen representation at the center of marshes depends on basin size (Prentice, 1985).

At Pope Marsh, the ranges of arboreal, aquatic/wetland taxa, and herb pollen were 64.0–94.3, 4.4–18.0 and 1.3–11.6% of the total pollen, respectively. Pine pollen composed about 83% of the terrestrial pollen. Pine pollen percentages fluctuated between 14 and 21 cm depths; at depths above 13 cm, it decreased (Figure 4). The relative decrease of pine pollen above 6 cm

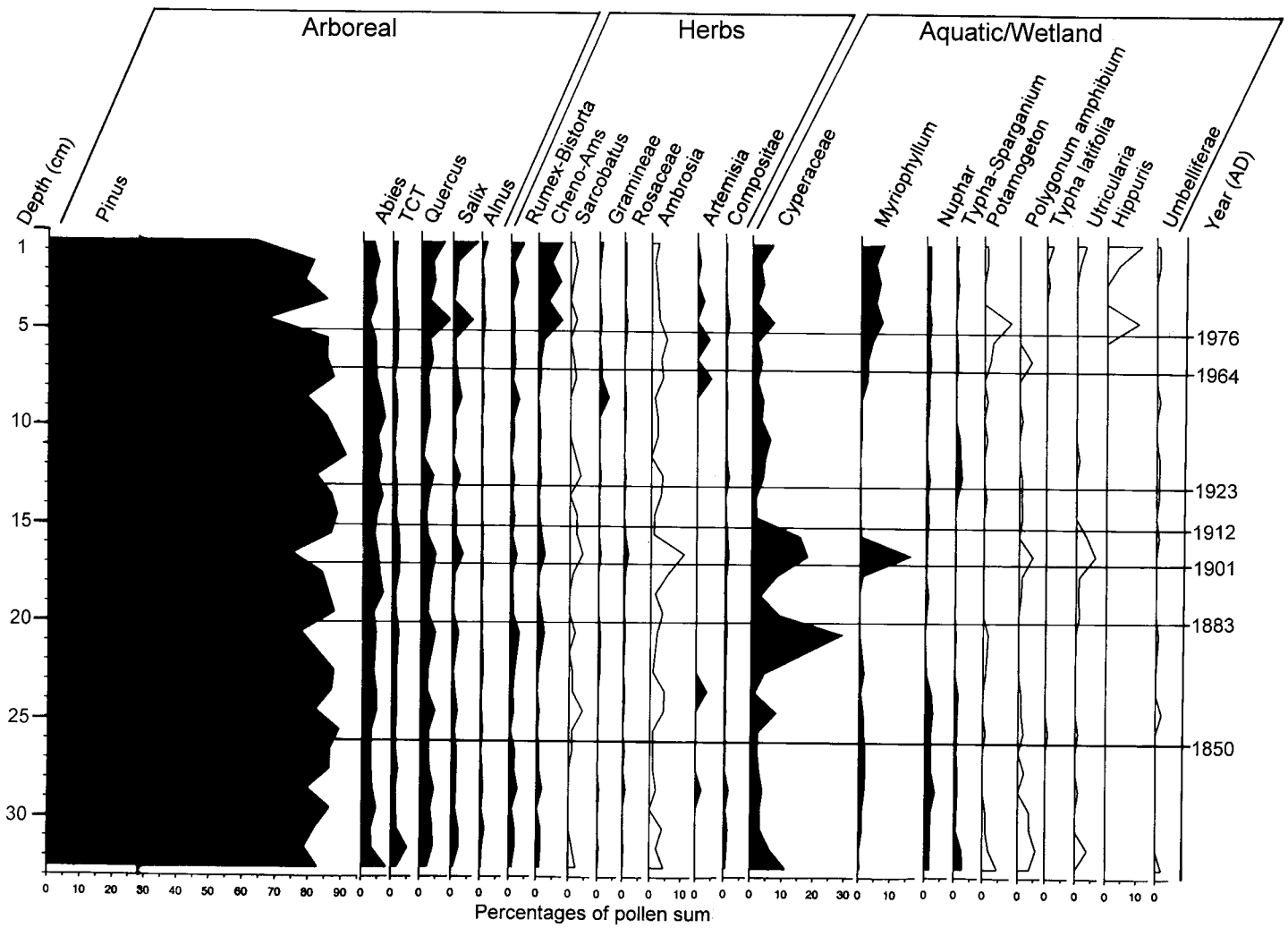

Figure 4. Pollen percentage diagram for Pope Marsh. Unshaded curves are 10-fold exaggerations. Horizontal lines are ^{210}Pb-derived sediment dates. TCT – Taxodiaceae, Cupressaceae, and Taxaceae.

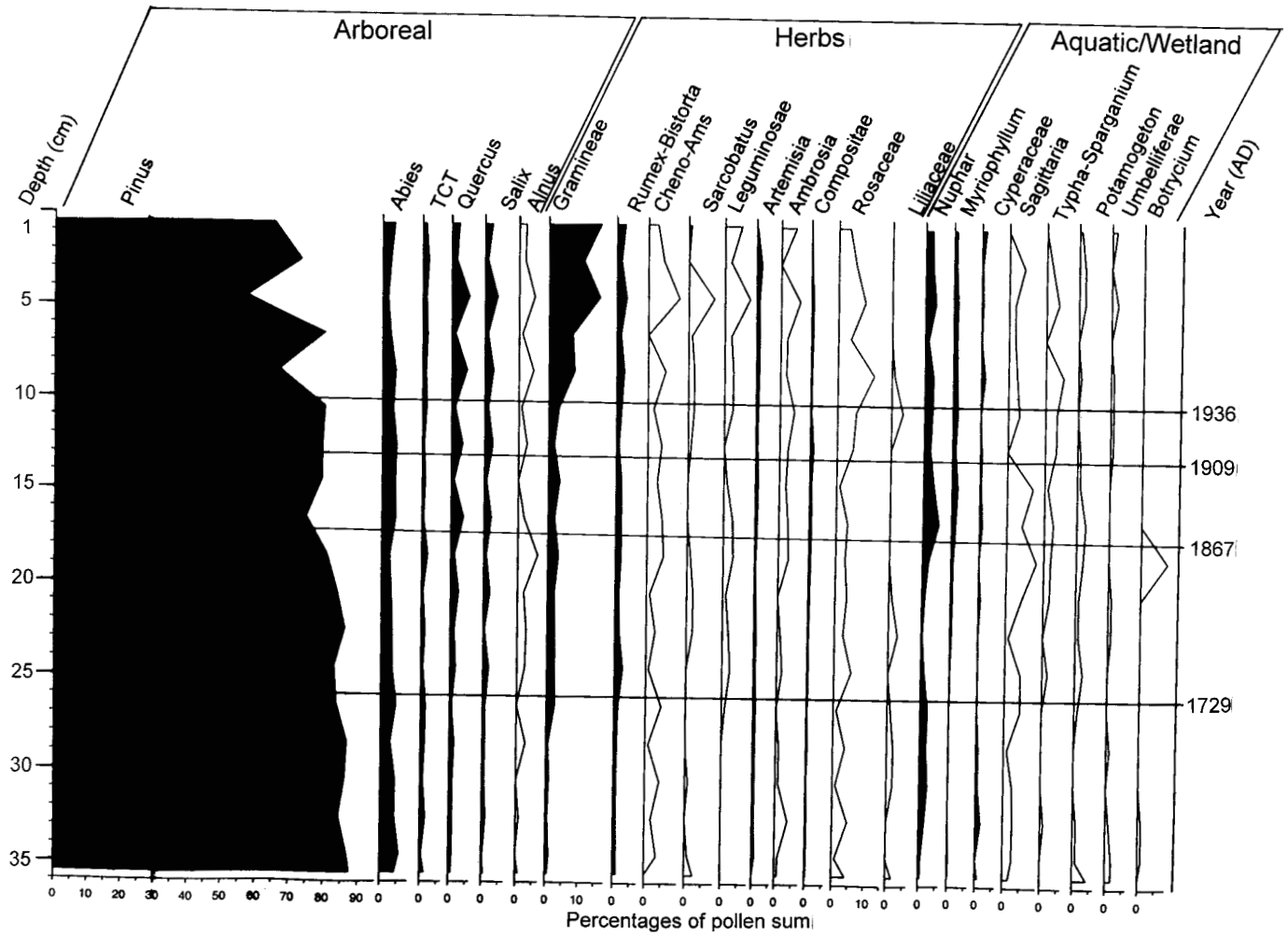

Figure 5. Pollen percentage diagram for Kyburz Flat. Unshaded curves are 10-fold exaggerations. Horizontal lines are ^{210}Pb-derived sediment dates. TCT – Taxodiaceae, Cupressaceae, and Taxaceae.

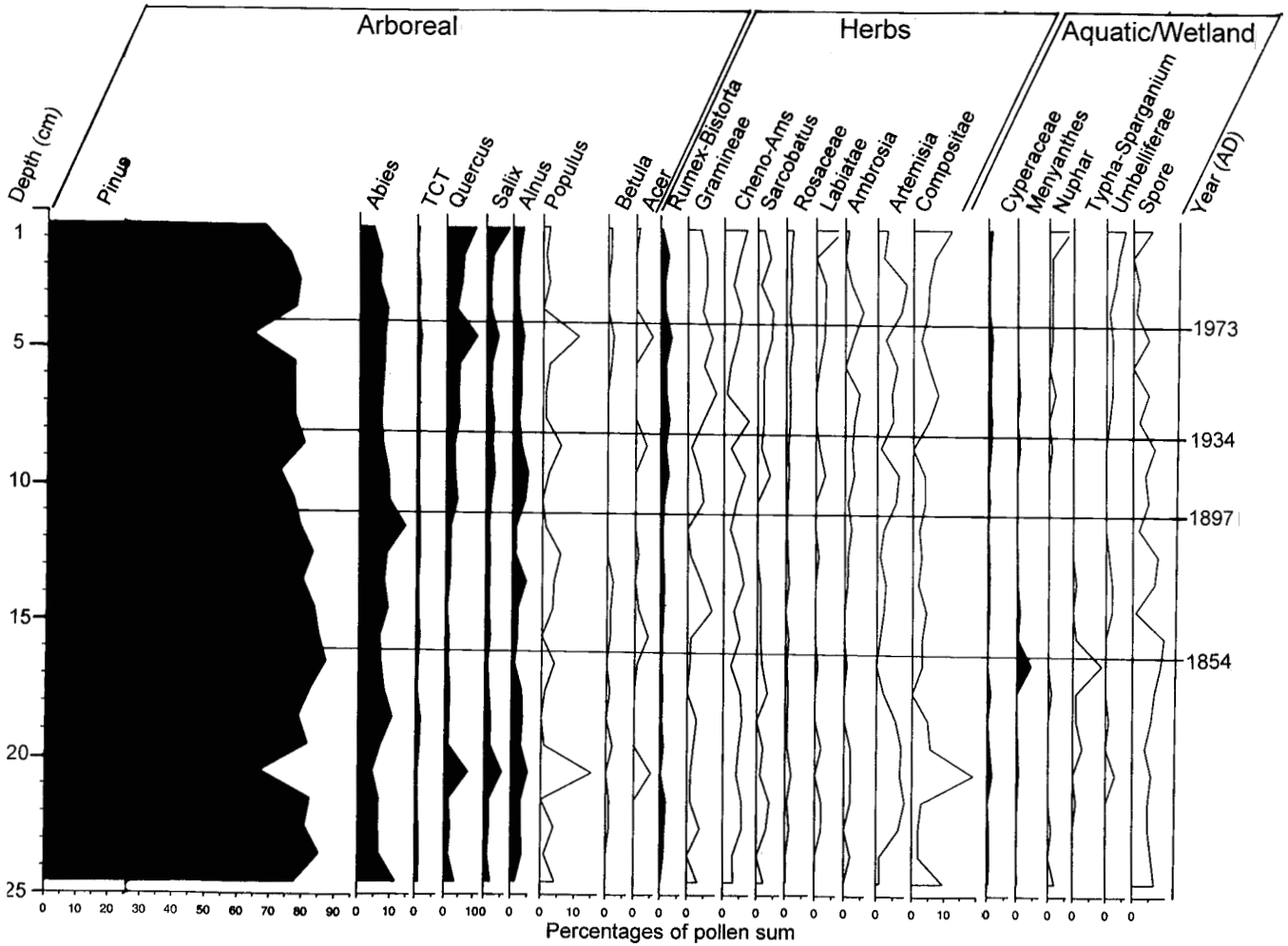

Figure 6. Pollen percentage diagram for Meyers Grade Marsh. Unshaded curves are 10-fold exaggerations. Horizontal lines are ^{210}Pb-derived sediment dates. TCT – Taxodiaceae, Cupressaceae, and Taxaceae.

corresponded to an increase of *Quercus*, *Salix*, *Rumex-Bistorta*, Cheno-Am (Chenopodiaceae and *Amaranthus*) pollen. Logging related to gold mining started in the late-1850s in the Lake Tahoe basin and occurred in the early-1900s around Pope Marsh (Smith, 1969). The pollen diagram did not show the regional scale change of *Pinus* pollen percentages but did show a local scale change above 13 cm (1923 ± 8). Decrease of pine pollen above the 6 cm might be the effect of recreation around Pope Marsh.

Cheno-Am pollen increased in the top 5 cm (1976 ± 6) of the core. The population in South Lake Tahoe has increased with the completion of Tahoe Keys since the 1970s (Ingram & Sabatier, 1987). The disturbance of natural vegetation by increased camping around Pope Marsh and the increased input of nutrients from the Tahoe Keys residential area are apparently responsible for the increased abundance of Cheno-Am pollen types. These plants were reported as indicators of human activities or water level drawdown in other regions by many authors (e.g., Watts & Winter, 1966; Behre, 1981; Jacobson & Engstrom, 1989). There was a severe drought period (1987–1993) in the Tahoe region (Figure 2), but Cheno-Am pollen did not increase during this period, suggesting that Cheno-Am pollen abundance was not related to water level drawdown in Pope Marsh.

Myriophyllum pollen increased in the top 7 cm (1964 ± 9) of the core. In the Lake Tahoe region, introduced water milfoil (*Myriophyllum spicatum*) is proliferating and becoming a concern for ecologists and limnologists. However, it is uncertain when the plant was introduced. The pollen profile for Pope Marsh (Figure 5) shows the increase of *Myriophyllum* pollen (except one spike at 16 cm depth) just before the increase of Cheno-Am pollen. We tried to distinguish *Myriophyllum* pollen to the species level according to Aiken (1978) and Mathewes (1978), but could not because they did not include *M. sibiricum*, which is a native species. They used pollen length and electron microscopic details of the pollen surface sculpture as criteria, but the pollen length criteria overlapped and the surface sculpture criteria were too detailed to use in fossil pollen. Even though it is reasonable to estimate the introduction time of water milfoil at the time of the Tahoe Keys construction in the late-1960's, this has to remain a speculation because we could not discriminate *Myriophyllum spicatum* pollen from other native species such as *M. sibiricum*. Cyperaceae increased between 21–14 cm depths (between 1878 ± 8 and 1917 ± 8) with two peaks, and these are coincident with the decrease of *Nuphar* pollen at the 21 cm depth. We interpret the decrease of *Nuphar* pollen and the increase of Cyperaceae pollen as a result of a decrease in water level. The Cyperaceae pollen decreased at the 14 cm depth, and this is coincident with the completion of the Tahoe Dam (1913), at which time the water level of Lake Tahoe was probably low because of the construction. The Cyperaceae pollen assemblage declined above 14 cm depth, and was replaced by a *Typha* dominated assemblage until the 9 cm depth (1947 ± 8).

Figure 5 shows the pollen percentage diagram for Kyburz Flat. The ranges of arboreal, wetland taxa, and herb were 84.9–95.4, 1.4–8.2, and 2.4–8.6% of total identified pollen, respectively. Pine pollen decreased steadily above the 26 cm, with more rapid decreases between 10 cm and 4 cm depths. The *Pine* decrease corresponds to the increase of grass pollen from the 26 cm (1729 ± 24) and 10 cm depth (1936 ± 9). The north side of Kyburz Flat is a dry meadow with many grass species. The pollen profile suggests that this area was originally a pine forest. Historical records support this interpretation (e.g. there was logging around Kyburz Flat between 1926 and 1928, and there has been no record of forest fire since 1909 in the Kyburz region (M. Baldrica & Darry-Schweyer, personal communication, Tahoe National Forest)). The increase of grass pollen at 1936 (± 9) is coincident with the increase of rainfall after a drought yr (Figure 2). The rainfall after logging might wash the ash, soil and organic particles from the watershed to the plain area, north of Kyburz Flat, and form a base for dry meadows.

Figure 6 shows the pollen percentage diagram for Meyers Grade Marsh. The ranges of arboreal, wetland taxa, and herb pollen were 89.6–97.7, 0.4–4.9, and 1.8–7.7% of total pollen, respectively. Pine pollen decreased at the 15 cm depth (1862 ± 11) and oak pollen increased at the 11 cm depth (1899 ± 11). This indicates that logging of big pine trees opened the canopy and allowed huckleberry oak to proliferate. There is no obvious changing pattern in pollen from other species.

Pollen profiles for all three montane marshes in the Tahoe region showed a slight or no decrease of pine trees even though severe logging has occurred in the Lake Tahoe region in the late-1800s and moderate logging since 1900, as reported by Smith (1969). The effect of logging, as shown in pollen profiles for Pope Marsh and Meyers Grade Marsh, is not as obvious as for Kyburz Flat, because forests surrounding these two marshes have been preserved relatively well (forests around Pope Marsh were not clear-cut). Pollen results showed that activities within a relatively short distance were better recorded in the pollen profiles than those at further distance.

Biogeochemical responses

The sediment in Pope Marsh could be characterized as a sapric peat. There was little variation in water content and bulk density along the length of the core (Figure 7). Ash content declined from the bottom, but increased from the 10 cm depth, with two peaks at 18 and 25 cm. The changing pattern of total carbon was similar to that of total nitrogen. Calcium concentration fluctuated between 20 cm (1883 ± 3) and 15 cm (1912 ± 2) and decreased from 15 cm to the core top. Magnesium increased between 20–15 cm. Concentrations of sodium and potassium were highest at the sediment surface. Total lead peaked at 8 cm.

After the gold discovery in the mid-19th century, major logging in this region began to support gold mining (Smith, 1969). Water flow through disturbed watersheds carried more organic and inorganic material, and resulted in increased deposition of mineral material in Pope Marsh between the 1880s and 1910s. The construction of the Tahoe Keys seemed to influence only the ash content, not any other measured chemical components of sediment. If there was a free water flow between Pope Marsh and the construction site, contents of organic material and major cations could be increased. However, our results suggest that Pope Marsh was not directly connected to the construction site and was influenced by only airborne material.

The sediment in Kyburz Flat was composed of brown humic peat in the upper part above 18 cm, and a light brown clay-peat below 18 cm (1854 ± 4). Water content increased continuously, and bulk density and ash content decreased continuously with a more abrupt change at the 18 cm depth (Figure 8). The pattern of carbon, nitrogen and phosphorus corresponded to that of water content. All changes at 18 cm (1854 ± 4) were

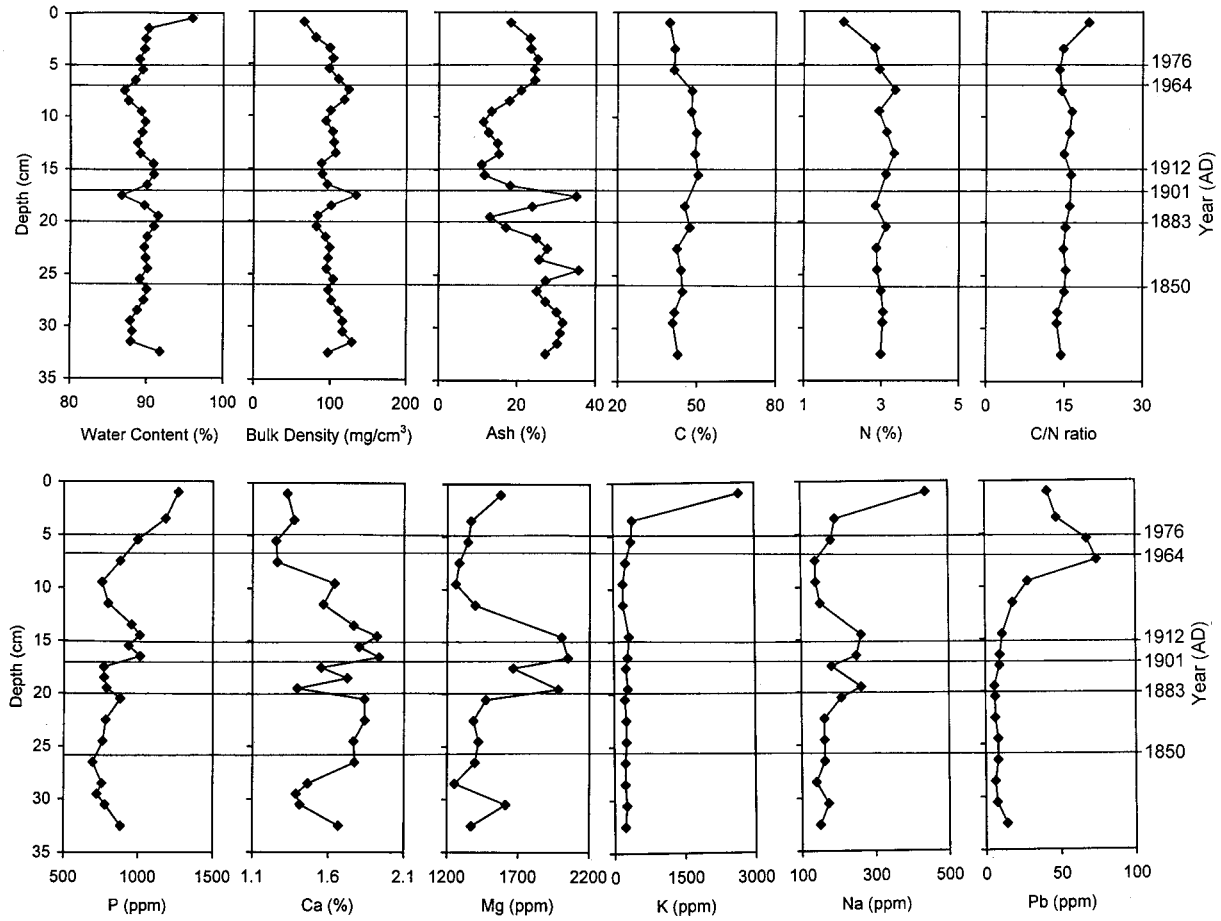

Figure 7. Depth distribution of physical and chemical variables in the soil core collected from Pope Marsh. Horizontal lines are ^{210}Pb-derived sediment dates.

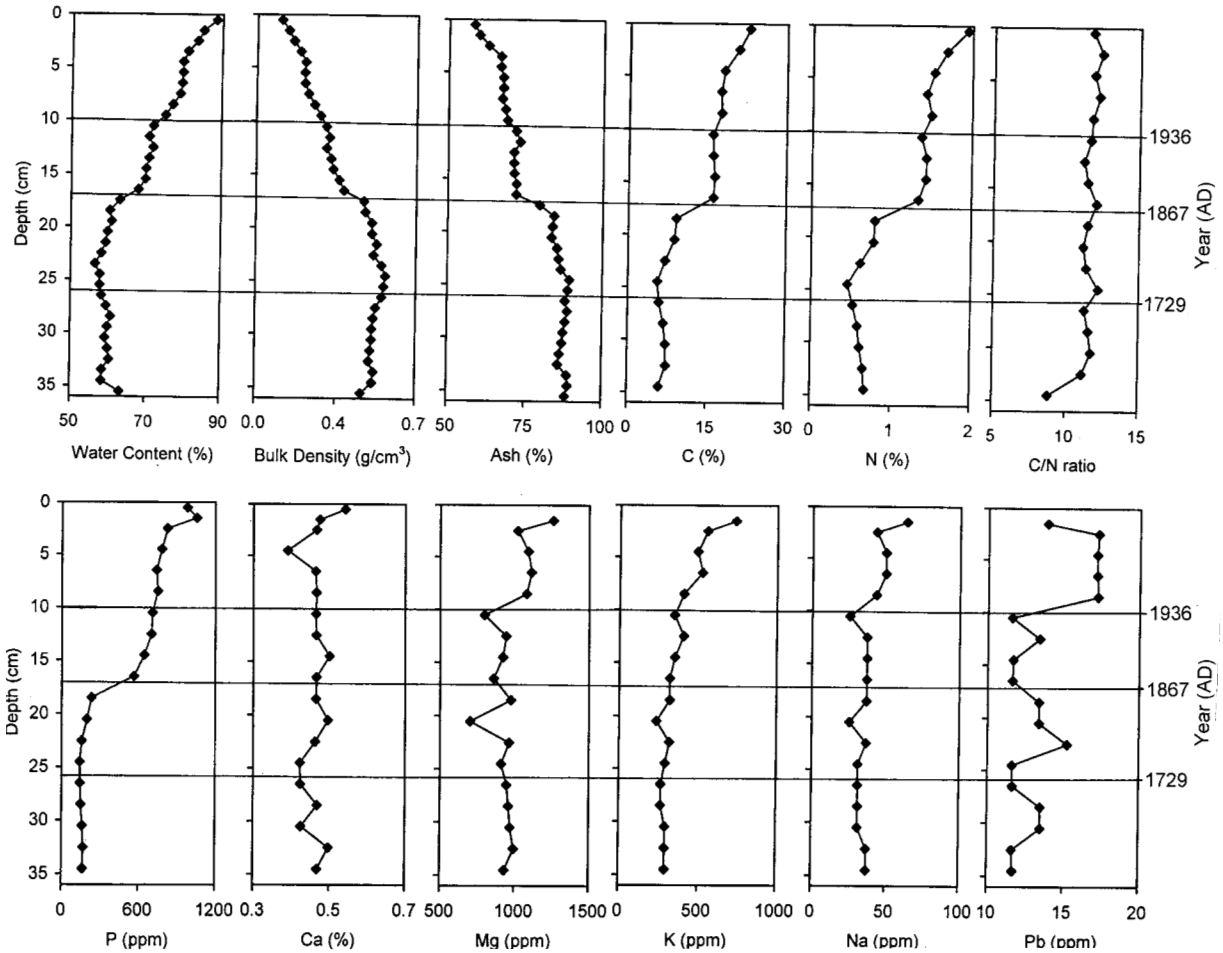

Figure 8. Depth distribution of physical and chemical variables in the soil core collected from Kyburz Flat. Horizontal lines are ^{210}Pb-derived sediment dates.

correlated with organic content. The pollen diagram showed the increase of *Nuphar* pollen and continuous decrease of *Pinus* pollen above 18 cm. These results suggest that the water level increased since ~1860s because of watershed changes due to logging. Moor (1993) and Alcala-Herrera et al. (1994) suggested a mechanistic explanation of water level change due to logging: logging in the uplands resulted in decreased evapotranspiration, with consequently increased runoff and locally increased water tables. Cations did not show any particular pattern. The early-1900s logging might affect the slight increase of ash content between 12–14 cm depths. The concentration of total lead increased above 9 cm, but increased concentration corresponds to the background level in the other two marshes.

Ash content increased sharply at 8 cm, but bulk density above 5 cm decreased in Meyers Grade Marsh (Figure 9). Nitrogen and carbon content decreased above 9 cm, and calcium, magnesium, potassium, and sodium increased from 5, 9, 11, and 3 cm, respectively. Phosphorus content increased slightly above 10 cm. Total lead content peaked at 6 cm.

Highway 50 was constructed by renovating wagon roads through morainal debris and rock areas in the 1930s at the west side of Meyers Grade Marsh. The road cut through this moraine exposed fresh Tioga till resting on a deeply weathered till (Dorland, 1980). The composition of granite rock must have affected the chemical characteristics of water and sediment in Meyers Grade Marsh. This activity was recorded as the increase of ash content and magnesium content above 8 cm (1934 ± 7). Similar increases were recorded in lake-sediment cores following lakeside road construction at lakes in eastern North America (Leavitt et al., 1989; Stager et al., 1997). Sodium chloride has commonly been

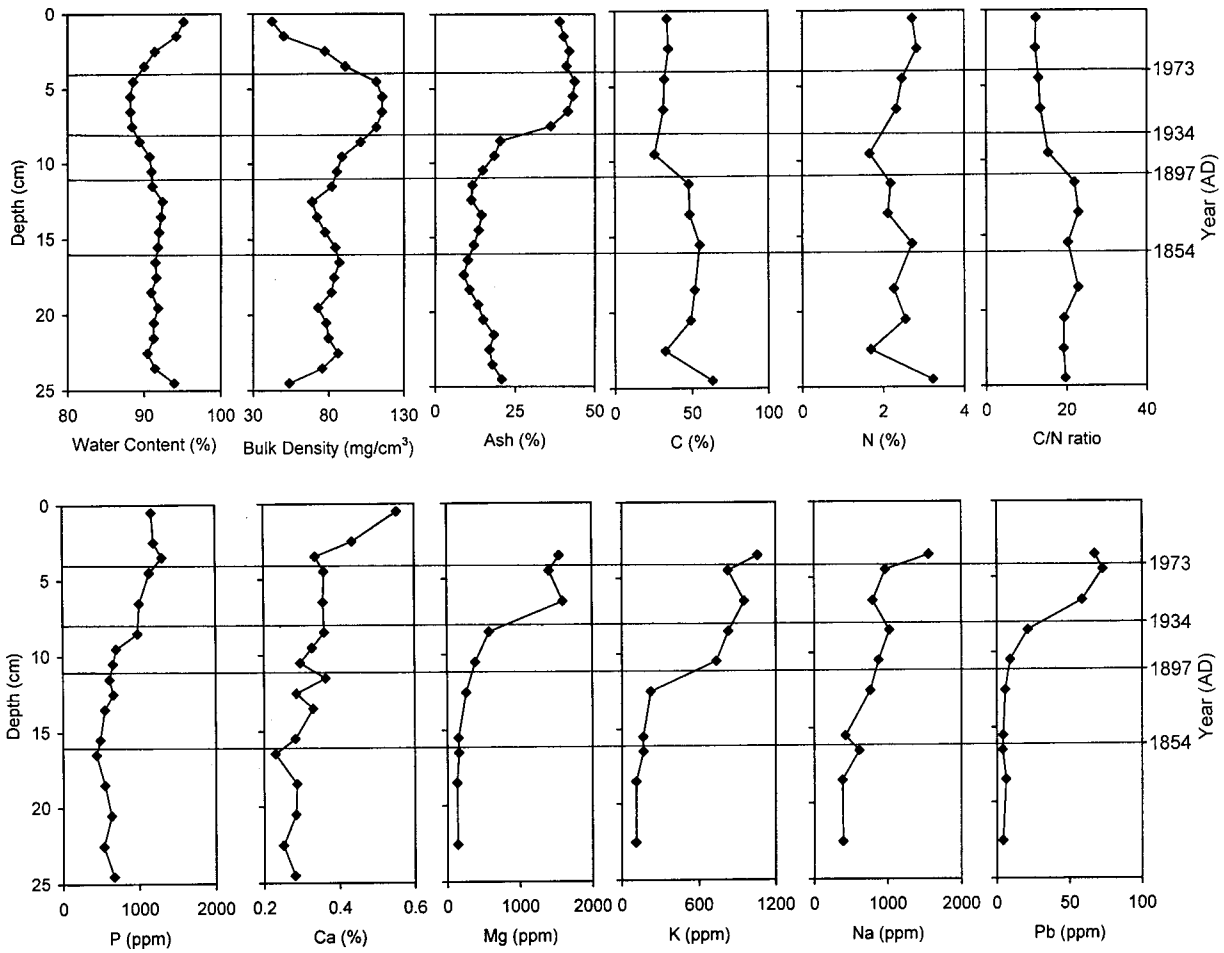

Figure 9. Depth distribution of physical and chemical variables in the soil core collected from Meyers Grade Marsh. Horizontal lines are ^{210}Pb-derived sediment dates.

used in California since 1945 as a snow melting agent, and calcium compounds have recently been used with sodium chloride in the studied area (Burke, 1987). Sodium and calcium in snowmelt water moved into Meyers Grade Marsh and accumulated in the sediment. The increase of sodium and calcium contents above 4 cm (Figure 9) is coincident with the heavy use of road salt for Hwy 50 opening in winter season. Smol et al. (1983) and Zeeb & Smol (1991) also suggested an increase of chloride content in sediments as a result of road salt treatment in central Canada and Fonda Lake, Michigan.

Even though nitrogen and carbon contents change with depth, the mass C/N ratio may be very similar in the same core if the sediment source has not changed (Reddy et al., 1993; Hassan et al., 1997). The average C/N ratios at Pope Marsh, Kyburz Flat, and Meyers Grade Marsh are 15.3, 11.5, and 17.8 respectively (Figures 7, 8 & 9). These ratios are similar to the values in the Everglades (Reddy et al., 1993), a southern Sweden Lake (Olsson et al., 1997), and planktonic organic matter (Wetzel, 1983): 14–16, 10–16, 6–12 respectively, but much lower than mangrove marshes (Middleburg et al., 1996) and sphagnum bogs (Belyea & Warner, 1996): 25.3, 20–120, respectively. A high C/N ratio is expected in nitrogen-limited marshes and our results indicate that the studied marshes are not limited by nitrogen.

Total phosphorus contents (200–1300 ppm) in the studied sites were correlated with organic content (Figures 7, 8 & 9), and concur with other reports (Middleburg et al., 1996; Craft & Richardson, 1998). Total phosphorus contents are similar to those in Lake Thonotosassa, Florida (600–900 ppm, Brenner et al., 1996), created and natural wetlands in the Atchafalaya Delta, LA (247–347 ppm, Poach & Faulkner, 1998), and a southern Sweden Lake (500–2500 ppm, Olssen

et al., 1997). Phosphorus content in phosphorus-limited ecosystems decreases abruptly with depth (Craft & Richardson, 1998), and this phenomenon was observed only in Kyburz Flat. Our results suggest that only Kyburz Flat may be a phosphorus-limited marsh.

Total lead content at Pope Marsh, Kyburz Flat, and Meyers Grade Marsh increased since 1941 ± 7, 1935 ± 2, and 1934 ± 7, respectively. This date is later than ~1886 in southern Quebec, ~1900 in Adirondack Mountains, N.Y. and the Northern Great Lake States, and ~1931 in northern Quebec, and earlier than ~1957 in northern Florida (Blais et al., 1995). Automobile leaded-gasoline increase is responsible for the increase of elemental lead in this region. Total lead results indicate the traffic increase since the late-1930s in this region.

Conclusions

Paleoecological records preserve the history of human activities and natural processes that affect the structure and function of ecosystems. ^{210}Pb dating results show that this is a suitable method to date short sediment cores in montane marshes in northern Sierra Nevada, California. Pollen analysis in the small wetlands showed the change of local watershed characteristics and human activities quite well. Aquatic/wetland taxa profiles were useful in reconstructing water level changes in the wetlands. However, the change of regional plant communities was not well recorded in arboreal pollen profiles of the small montane marshes. The physical and chemical characteristics of the sediment record the changes in watershed activities, such as road construction, maintenance, and other construction. Thus, paleoecological studies in the montane zone of California can record minor events in small watersheds as well as large-scale events in the northern Sierra Nevada. Paleoecological studies in small wetlands are very useful for reconstructing the history of local-scale disturbances and human activities in the watershed and wetlands.

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