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RESEARCH ARTICLE

Applications from Paleoecology to Environmental Management and Restoration in a Dynamic Coastal Environment

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Abstract

Estuarine restoration is a major focus of coastal management. To set estuarine restoration targets, coastal managers need to understand natural baselines and human modifications. The goal of this study was to characterize baseline environmental conditions for the purposes of restoration planning at Elkhorn Slough, a regionally significant California estuary. We reconstructed baseline salinity, sediment sources, sediment accumulation rates, and wetland plant distribution by collecting and analyzing sediment cores from the upper and lower reaches of the estuary, and marsh extent by synthesizing previously published stratigraphic descriptions of sediment cores. The results of this study show strong contrasts between current and baseline conditions. Sediment accumulation rates have recently increased, whereas flood deposits have disappeared from marsh sediments. Representation by freshwater and brackish plants has also declined. Extent of marshes increased in the recent past, likely as a result of anthropogenic sediment loading from early Euro-American land use changes. Many of these marshes have degraded in past decades, but marsh extent today is still higher than in previous periods. Reconstruction of natural baselines and processes suggests that restoration strategies for the estuary should focus on increasing sediment supply and freshwater inputs to the marshes in order to restore the processes that naturally sustained marsh accretion and diversity. This study highlights the importance of revealing human modifications when designing restoration strategies for dynamic and highly altered systems such as estuaries.

Key words: coastal management, estuary, paleoecology, salt marsh restoration.

Introduction

Globally, estuaries are among the most anthropogenically modified ecosystems (Edgar et al. 2000), and estuarine restoration is a major focus of coastal management (Kennish 2002). In the United States, restoration plans are being developed for nearly all large estuarine systems, including San Francisco Bay, Chesapeake Bay, and the Mississippi Delta region (Simenstad et al. 2006). Although the development of most complex, region-wide restoration initiatives necessitates extensive compromise between diverse needs, restoration has been traditionally defined as the act of returning an altered or denigrated system to a better representation of pre-disturbance conditions or its historic trajectory (NRC 1992; Streever 1999). Concerted efforts at environmental restoration should identify—to the extent possible—historic conditions as a basis for developing locally appropriate restoration targets and guidelines for restoration design (Grossinger et al. 2007).

The reconstruction of historic conditions in estuarine environments is particularly challenging, as these environments are naturally dynamic across all temporal scales (Stive 2006), and were modified by human activities even during early historic times. Predictably, this raises questions about what might constitute natural baselines or ranges of natural variability in estuarine environments. In the past, paleoecological records were often considered too descriptive and imprecise to inform environmental conservation and management (Willis & Birks 2006). However, recent studies have shown valuable insights can be provided through applied paleoecological research (Birks 1996; Brown & Pasternack 2005), particularly in dynamic coastal settings (Cooper & Brush 1991; Brewster-Wingard & Ishman 1999).

Paleoecological analyses have been used to establish pre-Anthropocene physical, chemical, and biological baselines (Willard & Cronin 2007), determine the timing and scope of diverse anthropogenic impacts (Richerson et al. 2008), suggest

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Table 2. Comparison of recent, historic, and late prehistoric stratrigraphic indicators: average (±SD).

	Last 50 cal yr	*200–50 cal yr BP*	*1,000–200 cal yr BP*
	Azevedo: 0–17 cm	Azevedo: 17–35 cm	Azevedo: 35–105 cm
	Yampah: 0–28 cm	Yampah: 28–70 cm	Yampah: 70–192 cm
Habitat extent	Variable	65%	56 ± 6.1%
Pollen index	Az: 0.92 ± 0.05	Az: 0.67 ± 0.006	Az: 0.77 ± 0.09
(0 = fresh; 1 = marine)	Y: 0.90 ± 0.10	Y: 0.78 ± 0.29	Y: 0.76 ± 0.20
Sediment grain size	Az: 10.12 ± 6.99	Az: 3.01 ± 0.21	Az: 5.58 ± 5.82
Mode (μm)	Y: 13.03 ± 6.08	Y: 8.20 ± 5.60	Y: 4.74 ± 4.11
Sediment grain size	Az: 8.28 ± 0.097	Az: 8.35 ± 0.032	Az: 8.39 ± 0.40
Mean (ϕ)	Y: 8.09 ± 0.16	Y: 8.20 ± 0.18	Y: 8.24 ± 0.25
Sediment sorting	Az: 1.89 ± 0.06	Az: 1.67 ± 0.023	Az: 1.63 ± 0.21
SD (ϕ)	Y: 1.71 ± 0.046	Y: 1.69 ± 0.050	Y: 1.62 ± 0.064
Sediment organic	Az: 24.90 ± 5.49	Az: 43.96 ± 5.27	Az: 35.03 ± 8.10
Content (%)	Y: 21.23 ± 6.86	Y: 32.04 ± 27.27.68	Y: 10.46 ± 6.83
Sediment accumulation	Az: 3.5 mm/yr	Az: 1.05 mm/yr	Az: 0.93 ± 0.17 mm/yr
Rates*	Y: 5.4 mm/yr	Y: 2.46 mm/yr	Y: 1.41 ± 1.48 mm/yr
Pb concentration (ppm)	Az: 22 ± 2.4	Az: 13.5 ± 0.71	Az: 12.5 ± 3.62
	Y: 25.4 ± 15.3	Y: 11.5 ± 2.07	Y: 14 ± 1.5
Flood/episodic	Az: 3 ± 3%	Az: 6%	Az: 18.3 ± 10.0%
Deposition (%)	Y: 7.5 ± 10.6%	Y: 24 ± 14%	Y: 21.8 ± 15.1%

Habitat extent denotes percentage of maximum wetland habitat. Grain size measures include inclusive graphic mean, a robust measure of central tendency (calculated as $M_Z = (\phi_{16} + \phi_{50} + \phi_{84})/3$) and inclusive graphic deviation, a robust measure of spread or degree of sorting (calculated as $\sigma_I = (\phi_{84} - \phi_{16})/4 + (\phi_{95} - \phi_5)/6.6$).
* For recent period, from maximum depth of radiocesium.

Detailed chronologies were produced for these sediment cores using radiometric dating techniques. For greater depths, organic material (e.g. seeds, plant rhizomes) was dated using Accelerator Mass Spectrometry (AMS) radiocarbon dating. For near-surface depths, sediments were analyzed for excess Pb-210 and Cs-137 using low-energy, germanium gamma ray detectors (Canberra, Meriden, CT, U.S.A.; Wheatcroft & Sommerfield 2005). Detector efficiency and self-absorption corrections were made using National Institutes of Standards and Technology (NIST) standards (Gilmore & Hemingway 1995), and samples were decay-corrected to the date of core collection. Age–depth models were produced for each core using linear interpolation of median ages reported by CALIB, version 6, for the radiocarbon dates (except in the case of reversals) and the assigned age of 1954 for the maximum depth of detectable radiocesium.

Data Analysis

To determine whether recent accumulation rates fell outside of the longer-term mean, confidence intervals (using a 99% confidence level) were developed for the slope of a linear regression equation (forced through the origin) describing change in depth as a function of change in age (dx/dt) for all levels dated using radiocarbon determinations.

To facilitate formal comparisons of salinity, a pollen salinity index[1] developed for central California coastal wetlands (Goman et al. 2008) was employed. Pollen has been used as paleosalinity proxy in previous studies (Davis 1992), with good agreement found between pollen assemblages and other measures of paleosalinity (diatoms, Byrne et al. 2001; modern analogs, Willard et al. 2001). In central California wetlands, marsh composition varies along salinity gradients, with saline marshes dominated predominantly by *Salicornia virginicia* (perennial pickleweed; Chenopodiaceae family) and brackish to fresh marshes dominated predominantly by species of sedge (Cyperaceae family; Watson & Byrne 2009). Thus, changes in the ratio of the relative abundance of the Chenopodiaceae and Cyperaceae pollen types typically are a function of average salinity.

In order to compare recent environmental conditions with those up to 1,000 years before present (BP), proxy values were formally and informally (Table 2) compared for the following intervals: 50 years BP to present, 200–50 years BP, and 1,000–200 years BP. Formal comparisons (of pollen index, sediment grain size, sediment sorting, and sediment lead concentration) used t tests to compare 0–50 and 50–1,000-year intervals. To detect overall vegetation change, MANOVA was used to detect a shift in the relative abundance of the 12 most common pollen types (*Pinus, Sequoia, Quercus,* Rhamnaceae, Asteraceae, Poaceae, *Salix, Alnus*, Chenopodiaceae, *Ruppia*, Cyperaceae, and *Typha*) over the past five decades.

Results

Marsh sediment core stratigraphy for 12 cores, collected as part of this study and 27 cores described in the literature, were reinterpreted. For all locations, the depth of "peaty deposits" or "marsh peat" varies, although in many locations marsh deposits are only 50 cm in depth, or less (Fig. 3). In cores

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[1] The ratio of the sum of Chenopodiaceae pollen to the sum of the Cyperaceae and Chenopodiaceae pollen types. Higher values of this index (approaching 1) denote more saline conditions, whereas minimum values (approaching 0) denote fresh conditions.

reference conditions beyond those provided by current and historical records (Feurdean & Willis 2008), and provide evidence for ecosystem–climate interactions on a range of time scales (Millar & Woolfenden 1999; Froyd & Willis 2008). Furthermore, such studies have helped conservation practitioners accept the notion that disturbance and change (due to climatic variability, fire, and geomorphic events like earthquakes and landslides) are natural, and in some cases, necessary parts of ecosystem function (Swetnam et al. 1999). Paleoecological analyses can also be used to determine the feasibility of returning ecosystems to historic states (Jackson & Hobbs 2009).

This study was undertaken to demonstrate the usefulness of translating paleoecological data into a form accessible to restoration practitioners, as such data is often not easily interpreted by nonspecialists (Davis 1994; Froyd & Willis 2008). Specifically, we sought to characterize natural baselines and environmental conditions for the purpose of detecting human modifications to natural estuarine processes. Elkhorn Slough, a moderately sized shallow estuarine embayment located in central California, provided an especially suitable case study for several reasons (Figs. 1 & 2). First, Elkhorn Slough is a regionally significant ecological unit: it is the site of one of the nation's first estuarine research reserves, is among the largest intact areas of tidal wetlands in California, and is the site of an ambitious ecosystem-based management initiative supported by NOAA and the David and Lucille Packard Foundation. Secondly, several research groups have collected, analyzed, and reported on sediment cores collected at Elkhorn Slough (Mudie & Byrne 1980; Schwartz et al. 1986; West 1988; Hornberger 1991); thus, there was an existing, although not exhaustive, pool of data to draw upon and to add to. Perhaps most importantly, environmental managers at Elkhorn Slough are explicitly considering historical and longer-term ecological conditions in setting future habitat goals and management regimes (ESTWP 2007). Although the specific paleoecological results and management implications of our study apply only to this estuary, our study serves as an example of the value of applied paleoecology for coastal restoration, underlining the importance of understanding the factors that promote sustainability of tidal wetlands across ecological and geological timescales. Moreover, our approach has broad relevance to the environmental management of all naturally dynamic systems.

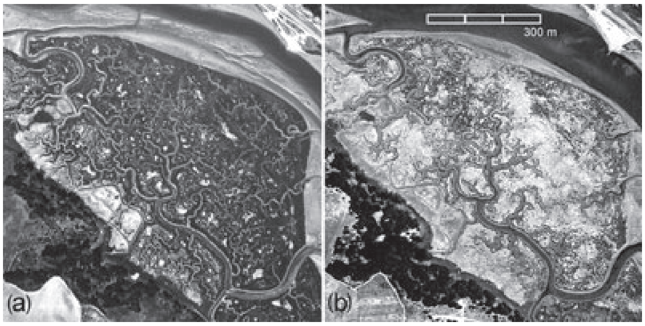

Figure 1. Evolution of salt marsh to mudflat at Elkhorn Slough. Dark areas are salt marsh, light areas are unvegetated. (a) Tidal creek network and growing interior pannes, 1980 aerial photo and (b) deteriorated marsh largely converted to open mudflat, 2001 aerial photo.

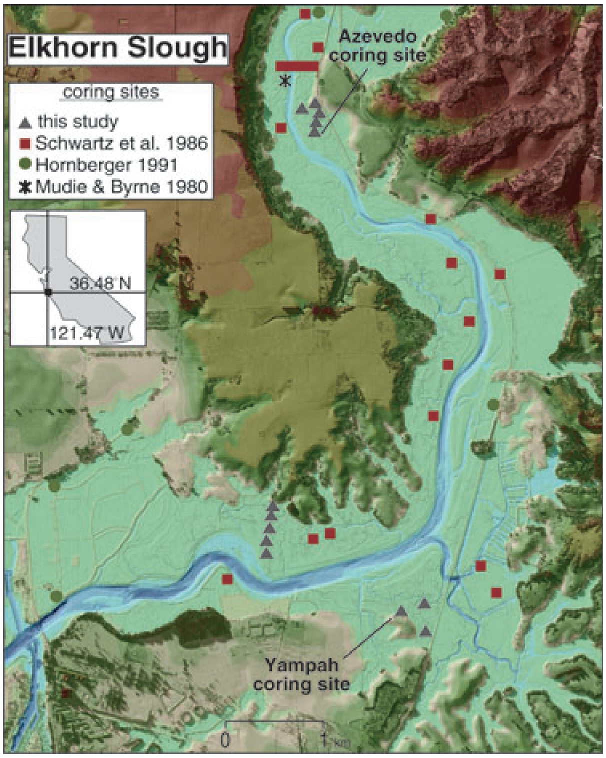

Figure 2. Map of Elkhorn Slough showing coring sites. This figure appears in color in the online version of the article (doi: 10.1111/j.1526-100X.2010.00722.x).

Methods

Study Site and Regional Context

The United States West Coast is an active margin characterized by a narrow continental shelf, heavy surf, mesotidal regime, coastal cliffs, sand beaches, and submarine canyons that accelerate the removal of coastal sediments from littoral cells (Grewell et al. 2007). Consequently, estuaries supporting tidal marsh in California are few in number and tend to be geographically limited. Elkhorn Slough supports close to 1,000 ha of tidal wetlands, which is among the largest tracts of intact tidal wetland in the state. However, tidal wetlands at Elkhorn Slough are degrading. During the period from 1870 to 1956, more than 60 km of dikes were constructed, greatly reducing the area of salt marsh habitat at Elkhorn Slough (Van Dyke & Wasson 2005). Although active wetland reclamation largely ended by the 1950s, tidal marsh deterioration has continued. Percent cover by salt marsh vegetation within regions of the slough that were never diked has declined from an average of 90% in 1931 to an average of 46% in 2003 (Fig. 1; Van Dyke & Wasson 2005). Current water salinity at Elkhorn Slough is generally similar to oceanic conditions: winter salinity in the lower part of the slough averages 32.1 psu and in the upper slough 30.7 psu. Summer salinity averages 33.6 psu in the lower slough and 34.7 psu in the upper slough (MBARI 2010). Over a tidal cycle, salinity varies by approximately 1 psu during neap tides and 2 psu during spring tides (MBARI 2010).

Paleoecological Methods

To provide a rough estimate of marsh extent through time, stratigraphic descriptions of Elkhorn Slough marsh sediments were compiled in order to produce a matrix showing marsh habitat (presence or absence) for each location plotted against depth at 25-cm intervals. Descriptions of 27 sediment cores previously taken at Elkhorn Slough were compiled (Mudie & Byrne 1980; Schwartz 1986; Hornberger 1991; P. Mudie 2007, Geological Survey of Canada, Dartmouth, NS, personal communication) and added to descriptions of the 12 sediment cores collected as part of this study. As most previously collected cores were not adequately dated, a depth-for-age substitution was performed using the average long-term accumulation rate calculated using a linear regression model derived from age–depth relationships of 15 calibrated radiocarbon dates.

Two reference cores, one each from the lower and upper reaches of the slough, were chosen for further study (referred to as the Azevedo and Yampah coring sites; Fig. 2). These sediment cores were scanned using a magnetic susceptibility sensor, x-rayed, and subsampled for loss on ignition determinations, lithic grain size analysis, bulk sedimentary geochemical analysis, and pollen analysis at intervals ranging from 1–10 cm. Magnetic susceptibility measurements were made using a Magnetic Susceptibility Sensor MS2C (Bartington Instruments, Oxon, U.K.); x-rays were taken using a cabinet x-ray system (Faxitron, Lincolnshire, IL, U.S.A). X-ray films were scanned and analyzed for the purpose of identifying laminations using the Matlab image processing toolbox. Sediments were analyzed for organic matter using the loss on ignition method (Dean 1974), and for mineral grain size by introducing approximately 0.25 cc of sediment (pre-treated with heated hydrogen peroxide to remove organic matter and disaggregated in a dilute sodium hexametaphosphate solution) into an LS-230 grain size analyzer (Beckman-Coulter, Brea, CA, U.S.A.). Sediments were analyzed for bulk geochemistry using ICP-AES, with pre-treatment by four-acid (hydrochloric, nitric, perchloric, and hydrofluoric) near-total digestion. Standard reference material (San Joaquin Soil) was analyzed in concert to determine dissolution efficiency and accuracy of bulk elemental measurements. For pollen analysis, tablets containing *Lycopodium* spores each were added to 1-cc subsamples as a control to determine fossil pollen concentration (Stockmarr 1971). Samples were then processed using standard techniques (Faegri & Iversen 1975). Pollen grains were identified with the aid of the University of California Museum of Paleontology pollen reference collection and published keys (Kapp et al. 2000). A minimum of 300 grains was counted per level. For the purpose of relating pollen assemblages to salinity, surface samples were collected from tidal freshwater, brackish, and saline wetlands in central California, and also analyzed for pollen spectra.

Loss on ignition was used to determine the extent to which allochthonous mineral sediment derived from coastal watersheds and organic sediment derived from in situ peat growth has contributed to marsh accretion over recent and prehistoric time scales. X-radiography was used to distinguish laminations and their relative volume in order to identify the role of infrequent flood events in marsh accretion. Pollen analyses were conducted on the two reference sediment cores to characterize past plant communities, and by extension, salinity regimes, over historic and prehistoric time scales. In particular, wetland pollen types (*Ruppia*, Chenopodiaceae, Cyperaceae, and Typhaceae) were considered bioindicators for tidal exchange and/or salinity (Table 1). Magnetic susceptibility measurements and geochemical and grain size analyses were used to determine the extent of past and ongoing changes in depositional patterns.

Table 1. Pollen types as bioindicators.

Pollen Type	*Species*	*Environment*
Ruppia	*Ruppia maritima*	Permanently flooded mesohaline soils with sluggish currents (Kantrud 1991), in California represented primarily by tidal lagoons with restricted tidal exchange, or by permanently flooded salt ponds which often have hyposaline rainy season and hypersaline dry season conditions
Chenopodiaceae	*Salicornia virginica* (syn. *Sarcocornia pacifica)*	The most salt-tolerant plant species found in northern California wetlands (Barbour & Davis 1970; Watson 2006). Because this plant species is largely limited in distribution to areas with some salinity, its presence many miles from the oceanic inlet infers influence of marine conditions
Cyperaceae Typhaceae	Sedges *Typha latifolia* *Typha angustifolia*	These taxa require brackish or fresh soil conditions. Some representation (<20% of pollen abundance) at a site can occur due to freshwater inputs leading to reduced soil salinities in the high marsh, even in fully tidal conditions where pickleweed still dominates the marsh plain. Dominance by these taxa (>60% of pollen) suggests soil salinities are low in all parts of the wetland, indicative of lack of full salinity (Byrne et al. 2001; surface sample analysis; Table 4)

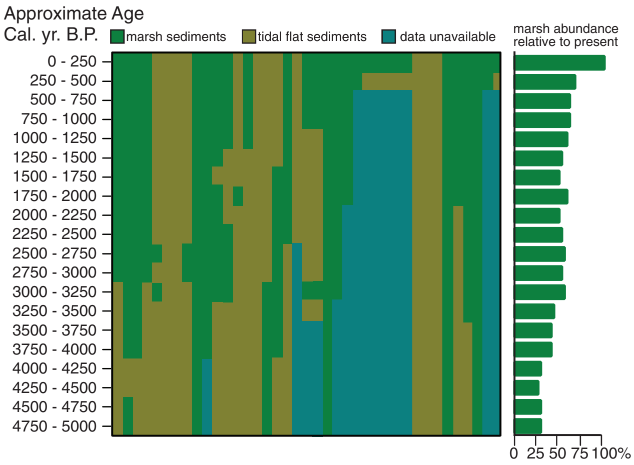

Figure 3. Matrix showing proportion of marsh versus tidal flat sediments during recent geological times. Each column represents one core. This figure appears in color in the online version of the article (doi: 10.1111/j.1526-100X.2010.00722.x).

collected as part of this study, marsh deposits were also commonly found at depths of approximately 250 cm. Overall, these results show a recent expansion in marsh extent.

On the basis of a linear regression for all AMS radiocarbon dates, overall accumulation rates average 0.87 mm/year for the Azevedo core and 1.05 mm/year for the Yampah core (Table 3; Fig. 4). Using linear regression for dates from both cores and a 99% confidence level, average accumulation (±SE) was 0.91 ± 0.33 mm/year. However, variability in rates of accumulation was noted. Specifically, accumulation rates appear to have been high during the twentieth century and during an interval corresponding roughly to 3,000 calendar years BP. Recent accumulation rates reconstructed from Pb-210 dating averaged 2.5 mm/year at Azevedo and 3.2 mm/year at Yampah for approximately the last 85 years (Supporting Information, Appendix S1). Accumulation rates reconstructed from the basal depth of detectable radiocesium indicate sedimentation rates of 3.0 mm/year for Azevedo and 5.4 mm/year for Yampah since 1954 (Supporting Information, Appendix S1). These recent accumulation rates fall substantially outside of the long-term mean calculated for both cores (0.58–1.2 mm/year). There is no decrease in density in near-surface sediments to explain this increase in near-surface accumulation.

Table 3. Radiocarbon dates from Azevedo and Yampah sediment cores, calibrated using CALIB (Stuiver et al. 2009).

Core	*Depth (cm)*	*Calibrated Age (2σ)*	*Lab Number*
		Cal. yr BP	
Yampah	75	232 (352–55)	CAMS-132991
Yampah	180	658 (723–597)	CAMS-132992
Yampah	275	3366 (3459–3226)	CAMS-125886
Yampah	325	3269 (3417–3103)	CAMS-132989
Yampah	370	3331 (3426–3143)	CAMS-125885
Yampah	425	4028 (4147–3824)	CAMS-132990
Yampah	510	4592 (4856–4483)	CAMS-125884
Azevedo	70	561 (679–381)	CAMS-132995
Azevedo	135	1363 (1435–1253)	CAMS-132994
Azevedo	192	2393 (2517–2218)	CAMS-125887
Azevedo	245	3340 (3422–3223)	CAMS-132993
Azevedo	295	2677 (2807–2548)	CAMS-125888

Detailed stratigraphic profiles of reference cores taken from the upper and lower reaches of Elkhorn show variations in sediment lithology (Fig. 5). X-radiographs show laminations, tentatively assumed to represent flood deposits. Dry density of marsh sediments is low: highest values are at depths with no evidence of marsh deposits (approximately 1.0–1.5 g/cc); density of marsh deposits is often half those values, and varies inversely with organic content. Organic content of marsh sediments varies with depth. At Yampah, values typically vary between 8 and 30%, with an average value of 14.92% by weight; however, some levels are over 80% organic by weight. Values at Azevedo are similar, averaging 16.04% by weight, with values typically between 10 and 30%, with a few very peaty layers. Peaty layers are found consistently at five depths at both Yampah and Azevedo, which appear to roughly correspond in age. These peaty layers are possibly indicative of brief episodes of inlet closure (Clark 1986), particularly in light of their rough association with pollen assemblages dominated by salt-intolerant taxa, although this association cannot be identified precisely as many peaty layers do not coincide with levels analyzed for fossil pollen. Nonmarsh organic contents are less than 5% by weight for Azevedo, and 8 to 9% organic for Yampah.

A near-surface peak in magnetic susceptibility, which was found to increase at a depth of 37 cm and peak at 33 cm, was present in the Yampah core. This peak may possibly reflect early historic period landscape change (weathered sediments, high in oxidized iron, eroded from slopes with the introduction of grazing), and was also found in cores taken from Santa Clara Valley tidal marshes (Watson 2004, 2006). This peak is not apparent in the Azevedo core, although this peak was found in most other cores collected from Elkhorn Slough as part of this study, including from other Azevedo coring sites.

Average particle size composition for both cores is approximately 67% silt. Azevedo had a few levels with abundant clay, and basal sediments were found to be sand (resembling the underlying hill slope). Both sediment cores reflect a shift to coarser particle size and more poorly sorted sediments near the surface. Grain size distributions for both cores tend to display multimodal peaks at approximately 3 and 15 μm. Near the surface, and occasionally at depth, the prominent peak shifts from 3–15 μm. Flood—or episodic—deposition appears to account for up to 40% of sediment deposition for both cores, although there is some variability with depth. Pollen concentration varies for both cores between 25,000 and 600,000 grains/cc.

Pollen assemblages were dominated by wetland pollen, specifically the Chenopodiaceae and Cyperaceae pollen types. Pollen index comparisons show current salinity conditions at Elkhorn Slough and pollen ratios at the high end of the range for regional estuaries (Table 4). Significant variations in wetland pollen assemblages were noted (Fig. 6), reflecting

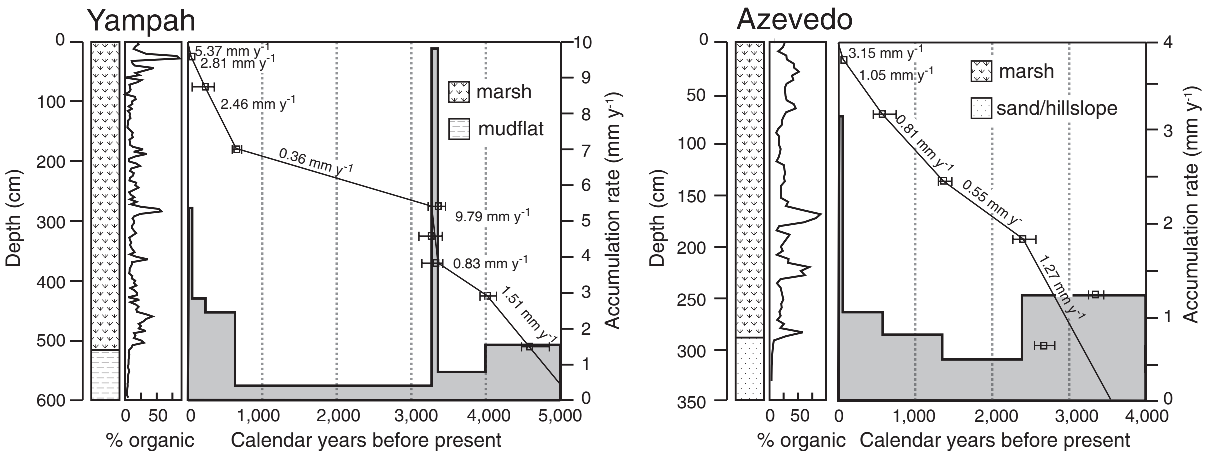

Figure 4. Chronology of reference sediment cores collected from the lower (Yampah) and upper (Azevedo) reaches of Elkhorn Slough. Gray shading denotes accumulation rates (which are also labeled between slope breaks). For the purposes of producing an age-model, two-σ median ages were used, except in the case of reversals. For the Yampah core, the low end of the two-σ range was used for the 275-cm date; the 325-cm date was ignored, and the upper end of the two-σ range was used for the 370-cm date. For the Azevedo core, the bottom two depths and ages were averaged. The maximum depth of detectable radiocesium was assigned a calendar date of 1954.

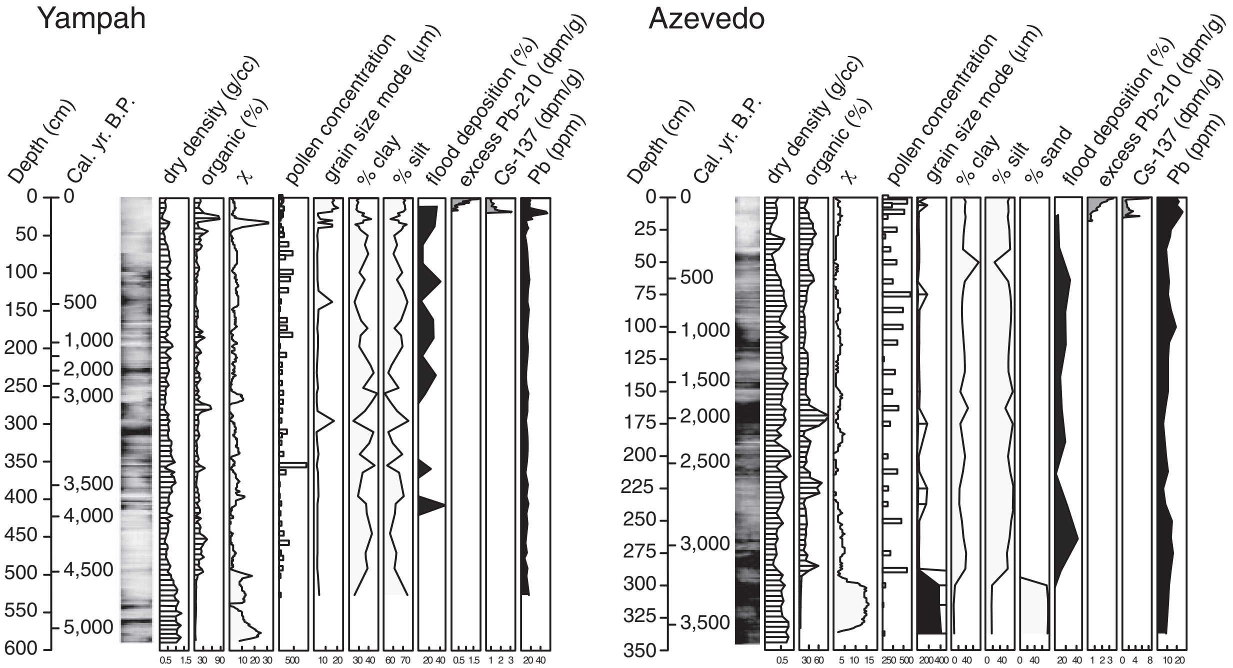

Figure 5. Core lithology of reference sediments collected from the lower (Yampah) and upper (Azevedo) reaches of Elkhorn Slough. Pollen concentration is in thousands of grains/cc; χ is magnetic susceptibility; grain size mode for Azevedo is shown in concert at an exaggerated scale (10×). The percentage of deposition derived from floods was calculated by summing the measurements of the widths of individual high-density laminations, and dividing this sum by a 25-cm interval wide sediment thickness.

variability in the relative abundance of halophytic and salt-intolerant taxa through time, and by extension marine versus freshwater influence. A formal comparison of pollen assemblages deposited over the past 50 years with assemblages deposited from 1,000 to 50 years BP indicated that the pollen index was higher (indicating more saline conditions; $t = 2.43$, $p = 0.021$) during recent decades and pollen assemblages were significantly different (MANOVA; $\chi^2 = 33.443$, $p < 0.001$) between the two periods. Further discussion of pollen composition changes may be found in the Supporting Information (Appendix S2).

In addition to pollen assemblage change in near-surface sediments, we found a contrast between sediment lithology for recently deposited sediments (0–50 years BP) in comparison with sediments deposited 1,000–50 years BP (Table 2). Qualitatively, the extent of the salt marsh habitat

Table 4. Surface samples analyzed for pollen relative abundance.

Marsh	*Location*		*Salinity (psu)*	*Mean Tidal Range (m)*	*Dominant Plant Cover*	*Grains Counted*	*Pollen Grains/cc*	*Pollen Ratio*
Browns Island, SFB	38°2′	121°52′	3.3	0.92	*Juncus* spp. *T. maritima* *S. virginica*	304	97,400	0.085
Tembladero, MB	36°46′	121°47′	6.5	minimal	*D. spicata*	320	69,550	0.28
Hill Slough, SFB	38°13′	122°00′	7.2	1.27	*D. spicata*	342	205,012	0.14
Grey Goose, SFB	38°13′	122°03′	7.2	1.27	*S. americanus*	358	158,398	0.22
Peytonia Slough, SFB	38°14′	122°02′	7.2	1.27	*S. americanus*	327	173,618	0.27
Rush Ranch, SFB	38°12′	122°02′	7.2	1.27	*T. maritima*	327	109,484	0.31
Peyton Slough, SFB	38°14′	122°06′	7.7	1.12	*S. americanus* *S. virginica*	492	360,000	0.69
Southampton Bay, SFB	38°4′	122°12′	7.7	1.20	*S. virginica* *D. spicata*	374	183,000	0.67
Napa River, SFB	38°7′	122°17′	17.0	1.63	*S. virginica*	333	108,000	0.95
Petaluma Marsh, SFB	38°11′	122°34′	21.3	1.49	*S. virginica*	313	67,900	0.98
Point Pinole, SFB	38°00′	122°21′	20.2	1.34	*S. virginica*	312	117,000	0.97
Moro Cojo, MB	36°47′	121°45′	25.3	minimal	*S. virginica*	524	1,024,999	0.91
Wildcat Slough, SFB	37°58′	122°23′	27.5	1.31	*S. virginica*	419	131,000	0.95
Point Isabel, SFB	37°55′	122°19′	27.5	1.28	*S. virginica*	481	239,000	0.99
Emeryville, SFB	37°50′	122°18′	27.5	1.28	*S. virginica*	348	177,000	0.99
Yampah, MB	36°49′	121°45′	32.7	1.08	*S. virginica*	323	179,730	0.95
Azevedo, MB	36°50′	121°46′	32.3	1.14	*S. virginica*	314	218,403	0.99

Surface samples were collected from tidal wetlands in San Francisco Bay (SFB) and Monterey Bay (MB). Plant cover (*Distichlis spicata*, *Juncus* spp., *Salicornia virginica, Scirpus americanus, Triglochin maritima*) is reported from field notes. Data sources for salinity and tidal range: Knowles (2000); Ritter et al. (2008); UCSC (2008); NOAA (2010); MBARI (2010). The "pollen ratio" is defined as the ratio of the sum of Chenopodiaceae pollen to the sum of the Cyperaceae and Chenopodiaceae pollen types. Higher values of this index (approaching one) denote more saline conditions, whereas minimum values (approaching zero) denote fresh conditions ($r^2 = 0.92$).

was greatest and flood deposition lower during recent times (0–50 years BP). The results of statistical tests indicated that the sediment grain size was greater ($t = -1.98,\ p = 0.05$), sediment sorting was lower ($t = 2.55,\ p = 0.02$), and sediment lead concentrations were higher ($t = 5.08,\ p < 0.001$) for sediments deposited over the past 50 years.

Discussion

Our paleoecological analyses at Elkhorn Slough reveal that marsh communities and the environmental processes that sustain them currently fall outside the range of conditions that occurred over the past millennia at this central Californian estuary. Below, we review the likely causes and management implications for changes to sediment accumulation, salinity, and marsh communities at the estuary, and explore the broader lessons of this case study for restoration of dynamic ecosystems.

We have demonstrated significant and abrupt shifts in sediment accumulation rates in Elkhorn Slough salt marshes over the past 3,000 years. In particular, sediment accretion over the past 50 years appears to be greater than 3 mm/year, in contrast to a rate of around 1 mm/year for the previous millennium. This rate shift indicates that either sediment inputs have increased greatly due to anthropogenic land use changes (agricultural practices; Silberstein et al. 2002) or the marsh plain has declined in elevation relative to tidal datums (as sediment accumulation tracks relative sea level rise; Orson et al. 1998). Because marsh elevations at Elkhorn Slough are demonstrably lower relative to tidal datums in comparison to other nearby marshes, this shift in accumulation rates suggests a drowning marsh plain, and (based on the timing of the increase) furthermore implicates anthropogenic activities as a key trigger for increased rates of deposition.

However, comparing deposition rates over different time intervals is somewhat problematic. Previous work in mid-Atlantic tidal marshes has demonstrated a decrease in sediment accumulation rates with increasing time interval (Kearney et al. 1994; Neubauer et al. 2002), a phenomenon that has been attributed to a combination of factors, including a twentieth century increase in the rate of relative sea level rise (Kearney & Ward 1986), and carbon mineralization and sediment compaction in buried sediments (Neubauer et al. 2002). However, shallow stratigraphic profiles at Elkhorn Slough do not reveal a decline in organic matter or water content or an increase in density with depth in cores thus examined, indicating that this apparent increase in accumulation rates is probably not a function of auto-compaction at depth, but rather represents an authentic rate shift.

Some of this increase may be due to marsh response to eustatic sea level rise, which has increased globally over this period (IPCC 2007). However, analyses of sea level data from

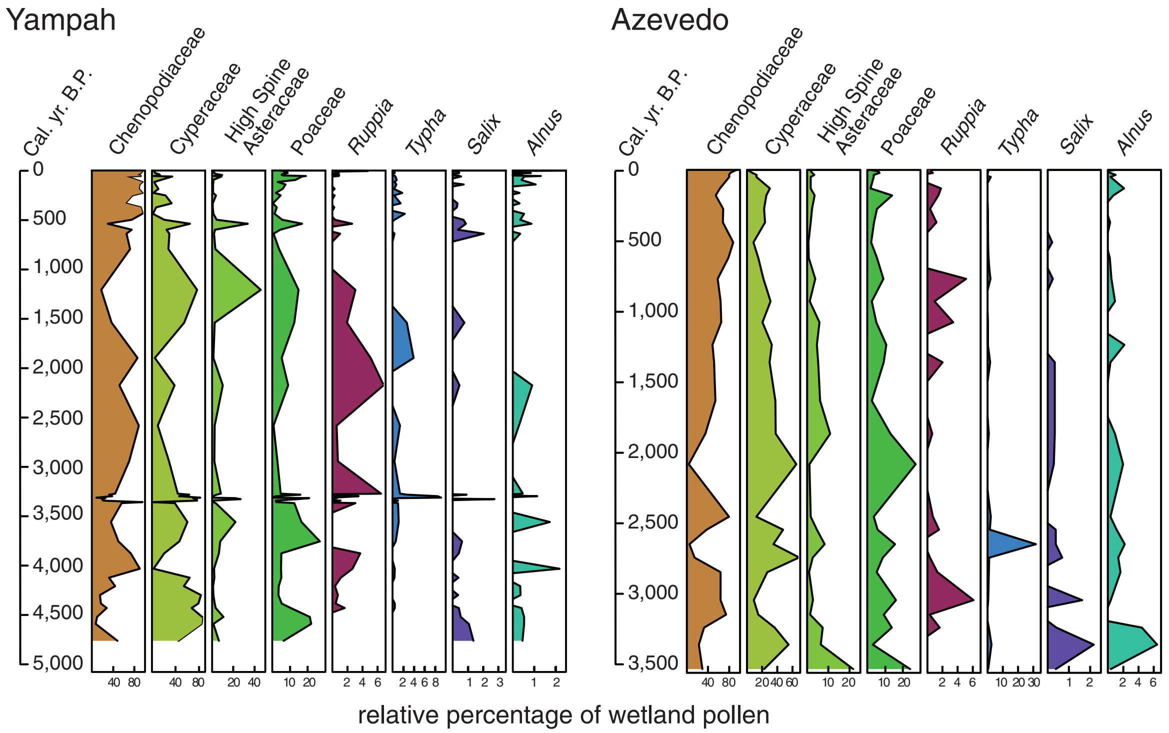

Figure 6. Relative abundance of selected wetland pollen types found in Elkhorn Slough sediment cores. This figure appears in color in the online version of the article (doi: 10.1111/j.1526-100X.2010.00722.x).

San Francisco Bay, 125 km to the north of Elkhorn, suggest that sea level rise in this region has remained relatively constant over the past century (Ryan & Noble 2007), and should therefore not be sufficient to account for this increased deposition rate. More likely explanations for a recent increase in the rate of relative sea level rise at Elkhorn Slough include local processes such as the 1947 Moss Landing harbor mouth construction, or subsidence due to ecological or geological processes, or due to groundwater overdraft. The construction of the harbor and jetty system increased the maximum tidal height by about 30 cm at Elkhorn Slough (PWA et al. 2008), whereas recent reports have found evidence for co-seismic subsidence associated with the 1989 earthquake on the San Andreas Fault, and quantified marsh plain shallow subsidence at approximately 5 mm/year, and subsidence of deep benchmarks at approximately 3 mm/year (Spear 2009). On the basis of data from San Francisco Bay, where groundwater overdraft led to profound subsidence during the early twentieth century, sediment accumulation rates increase with sea level as a function of tidal height (Patrick & Delaune 1990; Watson 2004). Although there is some uncertainty about the specific process driving subsidence at Elkhorn Slough, the sediment demand for marsh plain sustainability has increased during recent times, and is likely to continue increasing with projected sea level rise (Temmerman et al. 2004).

Although sediment demand is increasing, sediment supply to the estuary has likely decreased due to river diversion. Our analyses revealed that considered over the past millennia, flood deposition appeared to account for a significant portion of sediment deposition, but these deposits (laminations) were rarely present in near-surface sediments, representing the last 100 years. Although the frequency and intensity of flood-derived deposition has varied during the past (avg. interval 40–70 years; avg. vol. 20–30%), the absence of recent flood deposition combined with marsh degradation suggests that marsh conservation and restoration efforts at the estuary will need to address sediment supply issues. In the long term, the estuary's marshes are unlikely to be sustainable without the riverine sediments that formerly supplemented organic accretion and littoral inputs.

Paleoecological analyses thus can uncover the physical processes required to sustain biological restoration targets (Davis 2001). Current measurements of sediment deposition rates would have provided an insufficient snapshot. Deposition rates of 3–5 mm/year are not in themselves alarming, but they raise concern against the backdrop of much lower baseline rates. Moreover, identification of likely sediment sources through disappearance of flood deposits suggests a potential mechanism for restoration success—restoration of connections between the estuary and tributary rivers. For naturally dynamic systems such as estuaries, restoration strategies must include consideration of episodic events such as flooding. Perhaps the best use of historical and paleoecological analyses is not to rigidly prescribe restoration targets, but to inform practitioners about what is possible within the context of certain ecological systems and temporal scales, and place current conditions into those contexts (Swetnam et al. 1999). Estuaries are highly open and complex systems, so there is no single constrained restoration endpoint, but rather a range of more or less dynamic domains depending on how inputs and boundaries are manipulated.

Representation of halophytic marsh plants (pickleweed and allies, represented by the Chenopodiaceae pollen type) has increased relative to freshwater and brackish marsh plants (cattails, sedges, represented by the Cyperaceae and Typhaceae pollen types) and brackish lagoonal plants (*Ruppia*) in the past 50 years at Elkhorn. Our pollen index calculations reveal that current marsh plant communities at Yampah and Azevedo (the sites of the two reference cores) are at the saline end of the natural range for the past millennia. In the past (over the past 50–200 years), the pollen index at Elkhorn Slough was consistent with Californian estuaries with substantial freshwater as well as tidal influence (Table 4). Freshwater inputs to Elkhorn Slough have decreased through time due to groundwater overdraft (Caffrey & Broenkow 2002), and through loss of freshwater flow from tributary rivers. In order to return Elkhorn Slough marsh communities to a more historically and regionally natural range of composition, management strategies to increase freshwater inputs would need to be developed. Although management concerns about altered marine influences due to harbor mouth construction originally motivated our paleoecological analyses, the distinctive signatures of altered freshwater influences we uncovered suggest that changing freshwater influences may be at least as important for understanding ecosystem changes in this estuary.

Our case study thus illustrates how paleoecological analyses provide a powerful and holistic approach for identifying the key processes sustaining valued ecosystems, sometimes leading to unexpected findings (Chambers et al. 1999; Froyd & Willis 2008). For understanding marsh community changes, we also found it helpful to examine a regional as well as an historical context. For dynamic ecosystems, restoration planners may want to consider not only the range of variation natural for a particular site but also the range of natural variation within similar ecosystems in the region (Landres et al. 1999).

On the basis of the cores collected to date, the extent of salt marsh at Elkhorn Slough appears to have been greatest during recent times (i.e. 1900 A.D.). The increase in salt marsh extent appears to have occurred gradually over the past few thousand years, but seems to have accelerated during the past few hundred years. The most likely cause of salt marsh expansion is increased sediment input from changed land use coincident with the early years of Euro-American settlement, particularly from cattle grazing and land clearing for agriculture. Such increased sedimentation and subsequent lateral expansion of marshlands has been well documented for locations on the east coast of the United States (Pasternack et al. 2001; Hilgartner & Brush 2006) and also locally in South San Francisco Bay, the Sacramento-San Joaquin Delta, Bolinas Lagoon, and Goleta Slough in central California (Baker 2003; Brown & Pasternack 2005; Watson 2006).

Current restoration planning efforts at Elkhorn Slough were largely motivated out of concern for marsh degradation; in particular, the decrease from 90–45% vegetated cover in the estuary's marshes documented in a 70-year time series of aerial photographs (Van Dyke & Wasson 2005). Being able to compare recent with longer-term changes in marsh extent has allowed us to put current changes in perspective. The rapid rates of marsh conversion to mudflat recently observed at Elkhorn Slough may be unprecedented. The stratigraphic evidence suggests there were few examples of marsh conversion to mudflats, although such events have occurred during the past. However, our analysis led to the novel and surprising conclusion that loss of marsh extent per se may not be a conservation concern, because marsh extent, though reduced, is still larger than in the prehistoric past. Many of the marshes that are now degrading may be ones that resulted from anthropogenic sediment inputs that have now ceased. Although historic growth and increasing density of land use have destroyed large extents of tidal wetlands regionally (Goals Project 1999), attempting to sustain recently formed marshes may not be feasible, because such high sediment inputs will not recur, and may not be desirable from the perspective of restoring conditions to fall within the natural range of past variation. Rather than restoring recently lost marsh extent, restoration efforts at the estuary should perhaps focus on improving long-term sustainability of the ancient marshes in the system, by ensuring an adequate sediment supply, and focus on restoring the formerly greater community diversity of these marshes by increasing freshwater inputs.

Paleoecological analyses can thus reveal that human modifications may have been extensive during early historic times (Hilgartner & Brush 2006). At Elkhorn Slough, using the earliest maps to reconstruct baseline conditions (which show extensive marshes that have more recently been lost) would have led to the setting of inappropriate restoration targets. Examination of a natural range of variation over a long time frame rather than a single historical snapshot can thus more productively support restoration planning. Moreover, deeper historical analyses can powerfully reveal pendulum swings in human modifications. In our case study, human activities appear first to have accelerated marsh expansion over natural rates, due to high sediment inputs, and then accelerated marsh deterioration, due to decreased sediment budgets, increased tidal range, and other stressors. The extent of human modification can be masked by such opposing directional changes, and may only be uncovered by an examination of environmental processes over a longer time scale.

Implications for Practice

- Stratigraphic data provide a useful framework for understanding ecological change in the context of restoration, as reference conditions constructed from such analyses provide insight into how ecosystems have responded to

both natural and anthropogenically driven environmental change.
- Episodic phenomena, such as riverine flooding, appear to be vital for sustaining community diversity in dynamic estuarine ecosystems.
- Assessment of long-term baselines may lead to different conservation priorities than those arrived at from the assessment of current conditions or recent changes.

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LITERATURE CITED

Baker, G. 2003. Santa Barbara. Harbor Town Histories. Santa Barbara, California.

Barbour, M. G., and C. B. Davis. 1970. Salt tolerance of five California salt marsh plants. American Midlands Naturalist **84:**262–265.

Birks, H. J. B. 1996. Contributions of Quaternary palaeoecology to nature conservation. Journal of Vegetation Science **7:**89–98.

Brewster-Wingard, G. L., and S. E. Ishman. 1999. Historical trends in salinity and substrate in central Florida Bay: a paleoecological reconstruction using modern analogue data. Estuaries **22:**369–383.

Brown, K. J., and G. B. Pasternack. 2005. A paleoenvironmental reconstruction to aid in the restoration of floodplain and wetland habitat on an upper deltaic plain, California, USA. Environmental Conservation **32:**1–14.

Byrne, R, B. L. Ingram, S. Starratt, F. Malamud-Roam, J. N. Collins, and M. E. Conrad. 2001. Carbon-isotope, diatom, and pollen evidence for Late Holocene salinity change in a brackish marsh in the San Francisco Estuary. Quaternary Research **55:**66–76.

Caffrey, J., and W. Broenkow. 2002. Hydrography. Pages 29–42 in J. Caffrey, M. Brown, W.B. Tyler, and M. Silbersten, editors. Changes in a Californian Estuary: a profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, California.

Chambers, F. M., D. Mauquoy, and P. A. Todd. 1999. Recent rise to dominance of *Molinia caerulea* in environmentally sensitive areas: new perspectives from paleoecological data. Journal of Applied Ecology **36:**719–733.

Clark, J. S. 1986. Late-Holocene vegetation and coastal processes at a Long Island tidal marsh. Journal of Ecology **74:**561–578.

Cooper, S. R., and G. S. Brush. 1991. Long-term history of Chesapeake Bay anoxia. Science **254:**992–996.

Davis, M. B. 1994. Ecology and paleoecology begin to merge. Trends in Ecology and Evolution **9:**357–358.

Davis, O. K. 1992. Rapid climate change in coastal southern California inferred from pollen analysis of San Joaquin marsh. Quaternary Research **37:**89–100.

Davis, O. K. 2001. Palynology: an important tool for discovering historic ecosystems. Pages 229–256 in D. Egan and E. Howell, editors. The historical ecology handbook: a restorationist's guide to reference ecosystems. Island Press, Washington, D.C.

Dean, W. E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Petrology **44:**242–248.

Edgar, G. J., N. S. Barrett, D. J. Graddon, and P. R. Last. 2000. The conservation significance of estuaries: a classification of Tasmanian estuaries using ecological, physical and demographic attributes as a case study. Biological Conservation **92:**383–397.

Elkhorn Slough Tidal Wetland Project Team. 2007. Elkhorn Slough Tidal Wetland Strategic Plan: a report describing Elkhorn Slough's estuarine habitats, main impacts and broad conservation and restoration recommendations, http://www.elkhornslough.org/tidalwetland/ strategic_plan.htm (accessed February 1, 2009).

Faegri, K., and J. Iversen. 1975. Textbook of pollen analysis. Hafner Press, New York.

Feurdean, A., and K. J. Willis. 2008. The usefulness of a long-term perspective in assessing current forest conservation management in the Apuseni Natural Park, Romania. Forest Ecology and Management **256:**421–430.

Froyd, C. A., and K. J. Willis. 2008. Emerging issues in biodiversity and conservation management: the need for a palaeoecological perspective. Quaternary Science Reviews **27:**1723–1732.

Gilmore, G., and J. D. Hemingway. 1995. Practical gamma-ray spectrometry. Wiley, New York.

Goals Project. 1999. Baylands Ecosystem Habitat Goals. A report of habitat recommendations prepared by the San Francisco Bay Area Wetlands Ecosytem Goals Project. U.S. Environmental Protection Agency, San Francisco, California, and the San Francisco Bay Regional Water Quality Control Board, Oakland, California.

Goman, M., F. Malamud-Roam, and B. L. Ingram. 2008. Holocene environmental history and evolution of a tidal salt marsh in San Francisco Bay, California. Journal of Coastal Research **24:**1126–1137.

Grewell, B. J., J. C. Callaway, and W. R. Ferren. 2007. Estuarine wetlands. Pages 124–154 in M. G. Barbour, T. Keeler-Wolf, and A. A. Schoenherr, editors. Terrestrial vegetation of California, 3rd edition. University of California Press, Berkeley.

Grossinger, R. M., C. J. Striplen, R. A. Askevold, E. Brewster, and E. E. Beller. 2007. Historical landscape ecology of an urbanized California valley: wetlands and woodlands in the Santa Clara Valley. Landscape Ecology **22:**103–120.

Hilgartner, W. B., and G. S. Brush. 2006. Prehistoric habitat stability and post-settlement habitat change in a Chesapeake Bay freshwater tidal wetland, USA. Holocene **16:**479–494.

Hornberger, M. I. 1991. Paleoenvironments of Elkhorn Slough and surrounding wetland habitats: a geologic study using an ecological approach. M.S. thesis, Moss Landing Marine Laboratories, San Jose State University, California.

IPCC. 2007. Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, R. K. Pachauri, and A. Reisinger, editors. IPCC, Geneva, Switzerland.

Jackson, S. T., and R. J. Hobbs. 2009. Ecological restoration in light of ecological history. Science **325:**567–569.

Kantrud, H. A. 1991. Wigeongrass (*Ruppia maritima* L.): a literature review. U.S. Fish and Wildlife Service, U.S. Department of Interior, Washington, D.C.

Kapp, R. O., O. K. Davis, and J. E. King. 2000. Pollen and spores. American Association of Stratigraphic Palynologists, Dallas, Texas.

Kennish, M. J. 2002. Environmental threats and environmental future of estuaries. Environmental Conservation **29:**78–107.

Kearney, M. S., J. C. Stevenson, and L. G. Ward. 1994. Spatial and temporal changes in marsh vertical accretion rates at Monie Bay implications for sea-level rise. Journal of Coastal Research **10:**1010–1020.

Kearney, M. S., and L. G. Ward. 1986. Accretion rates in brackish marshes of a Chesapeake Bay estuarine tributary. Geo-marine Letters **6:**41–49.

Knowles, N. 2000. Modeling the hydroclimatology of the San Francisco Bay-Delta estuary and watershed. Ph.D. dissertation. University of California, San Diego.

Landres, P. B., P. Morgon, and F.J. Swanson. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications **9:**1179–1188.

Millar, C. I., and W. B. Woolfenden. 1999. The role of climate change in interpreting historical variability. Ecological Applications **9:**1207–1216.

MBARI (Monterey Bay Aquarium Research Institute). 2010. LOBOViz 3.0—LOBO Network Data Visualization, http://www.mbari.org/lobo/loboviz.htm (accessed March 15, 2010).

Mudie, P. J., and R. Byrne. 1980. Pollen evidence for historic sedimentation rates in Californian coastal marshes. Estuarine and Coastal Marine Science **10:**305–316.

Neubauer, S. C., I. C. Anderson, J. A. Constantine, and S. A. Kuehl. 2002. Sediment deposition and accretion in a Mid-Atlantic (U.S.A.) tidal freshwater marsh. Estuarine Coastal and Shelf Science **54:**713–727.

NOAA (National Oceanic and Atmospheric Administration). 2010. Tide station locations and ranges, http://tidesandcurrents.noaa.gov/tides09/tpred2.html (accessed January 25, 2010).

NRC (National Research Council). 1992. Restoration of aquatic ecosystems: science, technology, and public policy. National Academy Press, Washington D.C.

Orson, R. A., R. S. Warren, and W. A. Niering. 1998. Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuarine Coastal and Shelf Science **47:**419–429.

Pasternack, G. B., G. S. Brush, and W. B. Hilgartner. 2001. Impact of historic land-use change on sediment delivery to an estuarine delta. Earth Surface Processes and Landforms **26:**409–427.

Patrick, W. H., and R. D. Delaune. 1990. Subsidence, accretion, and sea level-rise in South San Francisco Bay marshes. Limnology and Oceanography **35:**1389–1395.

PWA (Phil Williams and Associates), H. T. Harvey and Associates, E. Thornton, and S. Monismith. 2008. Hydrodynamic modeling and morphologic projections of large-scale restoration actions, final report. Prepared for the Elkhorn Slough tidal wetland project, Moss Landing, CA, http://www.elkhornslough.org/tidalwetland/williams_final_report/index.htm (accessed February 1, 2009).

Richerson, P. J., T. H. Suchanek, R. A. Zierenberg, D. G. Slotton, C. A. Eagles-Smith, and C. E. Vaughn. 2008. Anthropogenic stressors and changes in the Clear Lake ecosystem as recorded in sediment cores. Ecological Applications **18:**A257–A283.

Ritter, A. F., K. Wasson, S. I. Lonhart, R. K. Preisler, A. Woolfolk, K. A. Griffith, S. Connors, and K. W. Heiman. 2008. Ecological signatures of anthropogenicaly altered tidal exchange in estuarine ecosystems. Estuaries and Coasts **31:**554–571.

Ryan, H. F., and M. A. Noble. 2007. Sea level fluctuations in central California at subtidal to decadal and longer time scales with implications for San Francisco Bay, California. Estuarine Coastal and Shelf Science **73:**538–550.

Schwartz, D. L., H. T. Mullins, and D. F. Belknap. 1986. Holocene geologic history of a transform margin estuary: Elkhorn Slough, Central California. Estuarine, Coastal and Shelf Science **22:**285–302.

Silberstein, M, C. Zabin, L. Newberry, D. Mountjoy, L. Strnad, and J. Caffrey. 2002. History of land use. Pages 93–115 in J. Caffrey, M. Brown, W.B. Tyler, and M. Silbersten, editors. Changes in a Californian Estuary: a profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, California.

Simenstad, C., D. Reed, and M. Ford. 2006. When is restoration not? Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration. Ecological Engineering **26:**27–39.

Spear, B. 2009. Twenty-nine years of geomorphic change at Elkhorn Slough, California. M.S. thesis, California State University at Monterey Bay, Monterey.

Stive, M. J. F. 2006. Morphodynamics of coastal inlets and tidal lagoons. Journal of Coastal Research **39:**28–34.

Stockmarr, W. 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores **13**: 615–621.

Streever, W. 1999. An international perspective on wetland rehabilitation. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Stuiver, M., P. J. Reimer, and R. Reimer. 2009. CALIB 6.0. www program and documentation, http://intcal.qub.ac.uk/calib (accessed February 10, 2009)

Swetnam, T. W., C. D. Allen, and J. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications **9:**1189–1206.

Temmerman, S., G. Govers, S. Wartel, and S. Meire. 2004. Modeling estuarine variations in tidal marsh sedimentation: response to changing sea level and suspended sediment concentrations. Marine Geology **212:**1–19.

UCSC (University of California, Santa Cruz). 2008. Statistical analysis of sixteen years of water quality data project: report to the Elkhorn Slough Foundation and the Community Foundation for Monterey County, http://www.elkhornslough.org/research/PDF/ESNERR_WQ_Statistical_Analyses.pdf (accessed March 16, 2010).

Van Dyke, E., and K. Wasson. 2005. Historical ecology of a Central California estuary: 150 years of habitat change. Estuaries **28:**173–189.

Watson, E. B. 2004. Changes in elevation, accretion, and tidal marsh plant assemblages in a South San Francisco Bay tidal marsh. Estuaries **27:**684–698.

Watson, E. B. 2006. Environmental change in San Francisco Estuary tidal marshes. Ph.D. dissertation. University of California, Berkeley.

Watson, E. B., and R. Byrne. 2009. Diversity and abundance of San Francisco Estuary tidal marsh plants: implications for global change ecology. Plant Ecology **205:**113–128.

West, G. J. 1988. Exploratory pollen analysis of sediments from Elkhorn Slough. Pages 25–39 in S. A. Dietz, W. Hildebrandt, and T. L. Jones, editors. Archaeological investigations at Elkhorn Slough: CA-MNT-229, a Middle Period Site on the Central California Coast. Northern California Anthropological Research Group, Berkeley, California.

Wheatcroft, R. A., and C. K. Sommerfield. 2005. River sediment flux and shelf sediment accumulation rates on the Pacific northwest margin. Continental Shelf Research **25:**311–332.

Willard, D. A., and T. M. Cronin. 2007. Paleoecology and ecosystem restoration: case studies from Chesapeake Bay and the Florida Everglades. Frontiers in Ecology and the Environment **5:**591–498.

Willard, D.A., L. M. Weimer, and W. L. Riegel. 2001. Pollen assemblages as paleoenvironmental proxies in the Florida Everglades. Review of Paleobotany and Palynology **113:**213–235.

Willis, K. J., and H. J. B. Birks. 2006. What is natural? The need for a long-term perspective in biodiversity conservation. Science **314:**1261–1265.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Values for Yampah sediment samples.
Appendix S2. Pollen zonation.

Appendix S1

Values for Yampah sediment samples

	46.5 KeV Pb-210				**352 KeV Pb-214**		**477.6 KeV Be-7**		**661.6 KeV Cs-137**	
Depth interval (cm)	Pb-210 dpm at time of collection	error dpm/g	**excess Pb-210 (dpm/g)**	error dpm/g	**supported Pb-210 (dpm/g)**	error dpm/g	**Be-7 (dpm/g) at time of collection**	error dpm/g	**Cs-137 (dpm/g) at time of collection**	error dpm/g
1-2	3.45	0.27	1.87	0.43	1.58	0.16	0.00	0.82	1.23	0.14
2-3	3.51	0.22	1.85	0.34	1.66	0.12	0.00	0.54	1.03	0.10
3-4	2.84	0.20	1.23	0.32	1.61	0.12	0.00	1.22	0.91	0.09
4-5	3.10	0.19	1.31	0.31	1.79	0.12	0.00	1.06	1.01	0.09
5-6	2.54	0.17	0.78	0.28	1.76	0.11	0.00	1.50	1.00	0.08
6-7	2.61	0.14	0.78	0.23	1.83	0.09	0.00	2.26	1.03	0.07
7-8	2.79	0.19	1.22	0.31	1.57	0.12	0.00	1.07	1.08	0.09
8-9	2.31	0.14	0.52	0.23	1.79	0.09	0.00	2.75	1.31	0.08
9-10	2.63	0.21	0.90	0.34	1.73	0.13	0.00	3.00	1.24	0.11
10-11	2.18	0.17	0.35	0.28	1.83	0.11	0.00	2.62	1.13	0.09
11-12	2.10	0.18	0.22	0.30	1.88	0.12	0.00	1.12	1.08	0.10
12-13	2.33	0.19	0.32	0.32	2.01	0.13	0.00	0.78	1.04	0.09
13-14	3.01	0.20	0.43	0.34	2.58	0.14	0.00	0.81	1.54	0.11
14-15	2.17	0.18	0.29	0.30	1.87	0.12	0.00	0.98	1.36	0.10
15-16	2.16	0.18	0.15	0.30	2.01	0.12	0.00	1.91	1.46	0.10
16-17	2.06	0.15	0.18	0.25	1.88	0.10	0.00	2.53	1.41	0.08
17-18	2.13	0.18	0.45	0.31	1.68	0.12	0.00	2.47	1.75	0.11
18-19	1.90	0.18	0.09	0.30	1.81	0.13	0.00	2.43	1.96	0.12
19-20	2.63	0.25	0.00	0.43	2.67	0.18	0.00	4.09	3.11	0.18
20-21	1.52	0.18	0.00	0.30	1.76	0.12	0.00	3.89	3.01	0.14
21-22	1.85	0.14	0.42	0.24	1.43	0.10	0.00	9.35	3.19	0.11
22-23	1.48	0.19	0.21	0.31	1.27	0.12	0.00	8.61	3.16	0.16
23-24	1.50	0.16	0.11	0.26	1.38	0.10	0.00	9.54	3.60	0.13
24-25	1.68	0.20	0.38	0.33	1.30	0.13	0.00	9.88	3.28	0.17
25-26	1.51	0.23	0.00	0.38	1.55	0.16	0.00	8.09	2.04	0.16
26-27	1.46	0.17	0.17	0.28	1.29	0.11	0.00	8.30	0.73	0.09
27-28	1.55	0.16	0.00	0.26	1.59	0.11	0.00	14.55	0.35	0.07
28-29	1.41	0.19	0.00	0.33	1.70	0.14	0.00	12.96	0.00	0.04

Appendix S2

These sediment cores were divided into zones based on chronological age.

Es-5 5000-3500 cal. Yrs. B.P. (Yampah 381-600 cm)

Zone ES-5 is characterized by variable brackish conditions. The Chenopodiaceae pollen type accounts for as much as 90% and little as 10% of the relative abundance of wetland pollen in this zone. The Cyperaceae, Typhaceae, High Spine Asteraceae, and Poaceae pollen types largely co-vary in this zone, indicating alternating dominance by halophytic species and salt intolerant and/or upland species.

ES-4 3500-1000 cal. yrs. B.P. (Yampah 192-381 cm, Azevedo 105-344cm)

In Zone ES-4, conditions continued to be brackish but variable, with notable "freshening" events at approximately 1,200 and 2,200 y B.P. An additional, major, freshening event and/or environmental shift appears to have occurred sometime between 2,500 and 3,500 cal y before present. Although the exact timing and duration of this event is somewhat uncertain (as the radiocarbon dates are poorly resolved during this time period), the depth appears to be constrained to 225-300 cm of depth at Yampah, Azevedo and Hudson's Landing (West 1988). A drop-off of the Chenopodiaceae pollen type to near zero occurred for a brief interval, while increases in salt-intolerant pollen types occurred, including and especially the *Salix* (willow) type, *Alnus* (alder), and *Typha* (cattails). These plants are today common in some of the wetlands of the estuary that are managed for greatly reduced tidal exchange with water control structures. This depth is also consistent with narrow bands of peat recovered from various locations in the lower reach of the slough, generally found at 250-300 cm of depth. Possible causes for this shift include increased river and/or groundwater flow, co-seismic uplift, or complete loss of a tidal inlet to Elkhorn Slough.

In both cores, the *Ruppia* pollen type appears to be common around 3500-3000 calendar y before present (and in West 1988), although at other times, increases or declines in the *Ruppia* pollen type are not synchronous (e.g., high *Ruppia* from 2,500-1,000 cal. yrs. B.P.). *Ruppia* pollen may either represent local and/or abundant salt ponds or sluggish estuarine circulation, during times of synchronicity (e.g., 3,500-3,000 cal. yr. B.P.), sluggish estuarine circulation may be implicated, and at other times local abundant ponds may have generated the site-specific patterns.

ES-3 1000-200 cal. yrs B.P. (Yampah 70-192 cm, Azevedo 35-105 cm)

In Zone ES-3, the Chenopodiaceae pollen type is increasingly common at the expense of the Cyperaceae pollen type. *Ruppia* and *Typha* are both less than three percent of wetland pollen; relative percent of Chenopodiaceae ranges from 40-85% at Yampah, and 30-95% at Azevedo. Relative percent of Cyperaceae ranges from 0-50% at Yampah to 15-30% at Azevedo.

ES-2 200-50 cal. yrs B.P. (Yampah 28-70 cm, Azevedo 17-35 cm)

Increasingly saline and less variable pollen assemblages, relative percent of Chenopodiaceae ranges from 65-95% at Yampah, and 55-68% at Azevedo characterize zone ES-2. Relative percent of Cyperaceae ranges from 1-33% at Yampah to 22-30% at Azevedo. During this interval, salt-intolerant taxa appear more common at Azevedo than at Yampah suggesting a salinity gradient along Elkhorn Slough, with more marine conditions at the mouth, and fresher conditions in the upper reach of the slough.

ES-1 Last 50 cal. yrs (Yampah 0-28 cm, Azevedo 0-17 cm)

Zone ES-1 is characterized by saline and less variable pollen assemblages. The relative percent of Chenopodiaceae ranges from 88-95% at Yampah, and 80-93% at Azevedo. Relative percent of Cyperaceae ranges from 2-11% at Yampah to 0-13% at Azevedo. Current pollen assemblages at Elkhorn Slough reflect more saline and less variable conditions than those found during recent times at for example, China Camp Marsh in the San Francisco Bay (Goman et al. 2008), a high elevation tidal marsh, where over 90% of plant cover is *Sarcocornia pacifica*.

Values for Azevedo sediment samples

	46.5 KeV Pb-210				**352 KeV Pb-214**		**477.6 KeV Be-7**		**661.6 KeV Cs-137**	
depth interval (cm)	Pb-210 dpm at time of collection	error (dpm/g)	**excess Pb-210 (dpm/g)**	error (dpm/g)	**supported Pb-210 (dpm/g)**	error (dpm/g)	**Be-7 (dpm/g) at time of collection**	error (dpm/g)	**Cs-137 (dpm/g) at time of collection**	error (dpm/g)
1-2	7.52	0.64	3.55	0.96	3.97	0.33	0.00	2.96	8.05	0.45
2-3	3.68	0.35	2.74	0.49	0.95	0.14	0.00	1.21	1.34	0.16
3-4	3.43	0.38	2.69	0.54	0.74	0.15	0.00	1.29	0.94	0.17
4-5	3.07	0.27	2.08	0.38	0.99	0.11	0.00	0.80	1.35	0.13
5-6	2.81	0.26	1.87	0.37	0.95	0.11	0.00	0.76	1.21	0.13
6-7	2.83	0.24	1.72	0.34	1.11	0.11	0.00	0.75	1.43	0.12
7-8	2.68	0.21	1.72	0.30	0.96	0.09	0.00	0.74	1.44	0.11
8-9	2.49	0.21	1.37	0.31	1.12	0.10	0.00	0.88	1.44	0.12
9-10	2.50	0.22	1.22	0.33	1.27	0.11	0.00	1.21	2.01	0.14
10-11	2.48	0.20	1.36	0.30	1.12	0.10	0.00	2.66	1.99	0.13
11-12	1.93	0.18	0.75	0.27	1.18	0.09	0.00	0.71	3.29	0.14
12-13	1.81	0.18	0.57	0.28	1.24	0.09	0.00	0.57	2.58	0.13
13-14	1.60	0.19	0.38	0.29	1.22	0.10	0.00	1.40	1.63	0.12
14-15	1.70	0.18	0.47	0.27	1.23	0.09	0.00	1.19	0.95	0.09
15-16	1.62	0.19	0.47	0.29	1.15	0.10	0.00	1.60	5.25	0.08
16-17	1.65	0.20	0.43	0.30	1.21	0.10	0.00	1.60	0.40	0.08
17-18	1.32	0.21	0.40	0.31	0.92	0.10	0.00	1.81	0.00	0.04
18-19	1.67	0.24	0.68	0.36	0.99	0.12	0.00	2.03	0.00	0.04