Estuaries and Coasts
DOI 10.1007/s12237-011-9393-7

Peat Formation Processes Through the Millennia in Tidal Marshes of the Sacramento–San Joaquin Delta, California, USA

Judith Z. Drexler

Received: 20 April 2010 / Revised: 30 November 2010 / Accepted: 25 February 2011

Abstract The purpose of this study was to determine peat formation processes throughout the millennia in four tidal marshes in the Sacramento–San Joaquin Delta. Peat cores collected at each site were analyzed for bulk density, loss on ignition, and percent organic carbon. Core data and spline fit age–depth models were used to estimate inorganic sedimentation, organic accumulation, and carbon sequestration rates in the marshes. Bulk density and percent organic matter content of peat fluctuated through time at all sites, suggesting that peat formation processes are dynamic and responsive to watershed conditions. The balance between inorganic sedimentation and organic accumulation at the sites also varied through time, indicating that marshes may rely more strongly on either inorganic or organic matter for peat formation at particular times in their existence. Mean carbon sequestration rates found in this study (0.38–0.79 Mg C ha^{-1} $year^{-1}$) were similar to other long-term estimates for temperate peatlands.

Keywords Carbon sequestration · Inorganic sedimentation · Organic accumulation · Peat · Tidal marsh · Vertical accretion

Introduction

Tidal marsh peats contain both organic matter, which comes mainly from decaying plants in situ, and inorganic sediment, which is supplied through tidal and/or riverine inputs (Turner et al. 2001). There has been a long-standing debate concerning whether the deposition rate on a mass basis of inorganic matter (inorganic sedimentation in grams per square meter per year) or organic matter (organic accumulation in grams per square meter per year) is more important in determining vertical accretion (centimeter per year) of peat and, thus, elevation relative to the tidal frame (Stevenson et al. 1986; Warren and Niering 1993; Morris et al. 2002). Several researchers have shown that when factors that ultimately limit the accretion potential of a salt marsh are considered, the long-term sustainability of marshes has generally been found to depend on inorganic sedimentation (Hatton et al. 1983; Nyman et al. 1990; Temmerman et al. 2004). In contrast, others have shown that there are salt marshes in which organic accumulation is clearly the driver of vertical accretion (Bricker-Urso et al. 1989; Callaway et al. 1997; Nyman et al. 2006).

Recent work in brackish and freshwater tidal marshes in the Sacramento–San Joaquin Delta of California (hereafter, the Delta) has shown that the relative contributions of organic and inorganic matter to peat volume vary through the millennia, suggesting that either organic or inorganic deposition on a mass basis may be the more important constituent of peat at a particular time (Drexler et al. 2009a). Furthermore, the relative contribution of inorganic matter to soil volume is much greater in high energy sites than sheltered sites, but so is the variability of the inorganic contribution to the peat (Drexler et al. 2009a). This stems from the fact that the suspended sediment concentration of tidal rivers varies as a function of freshwater discharge, tidal range, and/or wind–wave activity (Leonard et al. 1995; Fettweis et al. 1998). In freshwater tidal marshes such as the Delta where tidal fluctuations are microtidal, suspended sediment concentration is controlled largely by the rate of freshwater discharge, which is closely tied to precipitation patterns (Wright and

J. Z. Drexler (✉)
US Geological Survey, California Water Science Center,
6000 J Street, Placer Hall,
Sacramento, CA 95819-6129, USA
e-mail: jdrexler@usgs.gov

Published online: 24 March 2011

Schoellhamer 2005). Through time, varying rates of freshwater discharge result in varying concentrations of suspended sediment, and this, in turn, is reflected in the inorganic content of the peat. This is similar to the role that hurricanes play in forming marsh peats in Louisiana, where the amount of sediment deposition is highly variable and depends strongly on the severity and duration of the storm season (Nyman et al. 1995; Turner et al. 2006).

The purpose of this study was to determine how peat formation processes have changed over the past ~6,000 years. Specifically, I focused on addressing temporal changes in (1) bulk density and organic matter content and (2) peat formation on a mass basis (i.e., organic accumulation, carbon sequestration, and inorganic sedimentation). This study differs from most related work in that the focus is over the entire lifetime of marshes and not the past 50–100 years (e.g., Bricker-Urso et al. 1989, Neubauer 2008).

The research was carried out in the Delta, which lies at the head of the San Francisco Bay Estuary. The Delta was once a 1,400 km^2 tidal marsh region ranging from brackish to fresh, but within the past 150 years over 90% of the region has been drained for agriculture (Atwater 1982). Currently, very little is known about peat formation in the Delta, let alone organic accumulation, inorganic sedimentation, and carbon sequestration. Goman and Wells (2000) studied two peat cores from Browns Island as part of a paper on paleohistorical river flows into the San Francisco Estuary. Their work characterized the organic matter content, grain size, and plant species composition of the peat. There is just one recent study by Reed (2002) on sedimentation and organic accumulation and no published studies on carbon sequestration. In a 2-year study on both restored and references marshes, Reed (2002) found that inorganic sediment, though variable, was more important than organic matter as a recent contributor to marsh soils, and sites nearest to the Sacramento River had the highest rates of inorganic sedimentation. Clearly, a more complete picture is needed of peat formation processes in the Delta in order to determine whether marshes will continue to be sustainable despite land use changes, dam building, water diversion, and the increasing impacts from climate change.

Materials and Methods

Study Sites

The Delta is the most inland part of the San Francisco Bay Estuary of California (Fig. 1). Tides over the 1,400 km^2 region are semidiurnal with normal tidal range of approximately 1 m; however, during floods, the river stage can exceed 2 m (Shlemon and Begg 1975; Atwater 1980). The climate in the Delta is characterized as Mediterranean with cool winters and hot, dry summers (Thompson 1957). Mean annual precipitation is approximately 36 cm, but actual yearly precipitation varies from half to almost four times this amount. Over 80% of precipitation occurs from November through March (Thompson 1957). Beginning in the mid-1800s, the Delta was largely drained for agriculture (Thompson 1957), resulting in its current configuration of over 100 islands and tracts surrounded by 2,250 km of man-made levees and 1,130 km of waterways (Prokopovich 1985). Within the channels, small relatively undisturbed, remnant marshes remain, which can be used as archives of environmental change in the region.

Marsh study sites were chosen to incorporate the various geomorphic settings and salinity regimes of the Delta. Sites were chosen along the historic floodplain of the Sacramento River as well as the glacial outwash area along the San Joaquin River. In addition, sites were selected from high-energy environments such as the confluence of the Sacramento and San Joaquin Rivers to more quiescent environments such as distributaries of the San Joaquin River. The four sites, Browns Island (BRI, 268 ha), Franks Wetland (FW, 28 ha), the Tip of Mandeville Tip (TT, 12 ha), and Bacon Channel Island (BACHI, 10 ha), are all relatively undisturbed marshes, which, unlike those in the vast majority of the region, were not converted for agriculture. Study site characteristics including elevation, peat thickness, hydrogeomorphic setting (i.e., the position of a marsh in the greater watershed and its basic hydrodynamics; Brinson 1993), and relative energy regime are reported in Table 1.

Peat coring was carried out as close as possible to the center of each site. This was done in order to obtain a core that was a record of processes at the entire site level and not at a smaller, more dynamic scale such as at the periphery of a site. The coring location on Browns Island was near the marsh center as well as approximately 100 m from the main channel that flows through the island. This coring location was chosen because it is removed from the island periphery, where deposition and scour are thought to be greatest, but not from major watershed processes that strongly affect peat formation.

Vegetation on the marsh islands is dominated by emergent macrophytes and shrub–scrub wetland species. On Browns Island, which is situated at the western border of the Delta, vegetation is dominated by *Schoenoplectus americanus* (American bulrush) and *Distichlis spicata* (saltgrass). On Bacon Channel Island, the overstory is dominated by *Salix lasiolepis* (arroyo willow) and the understory is dominated by *Cornus sericea* (red-osier dogwood) with smaller amounts of *Phragmites australis* (common reed) and *Rosa californica* (California wild rose). On Franks Wetland, the vegetation is dominated by *C. sericea* and *S. lasiolepis* with the coring site having a large population of *Athyrium filix-femina* (western lady fern). The Tip of Mandeville Tip is dominated by *C. sericea* and *S.*

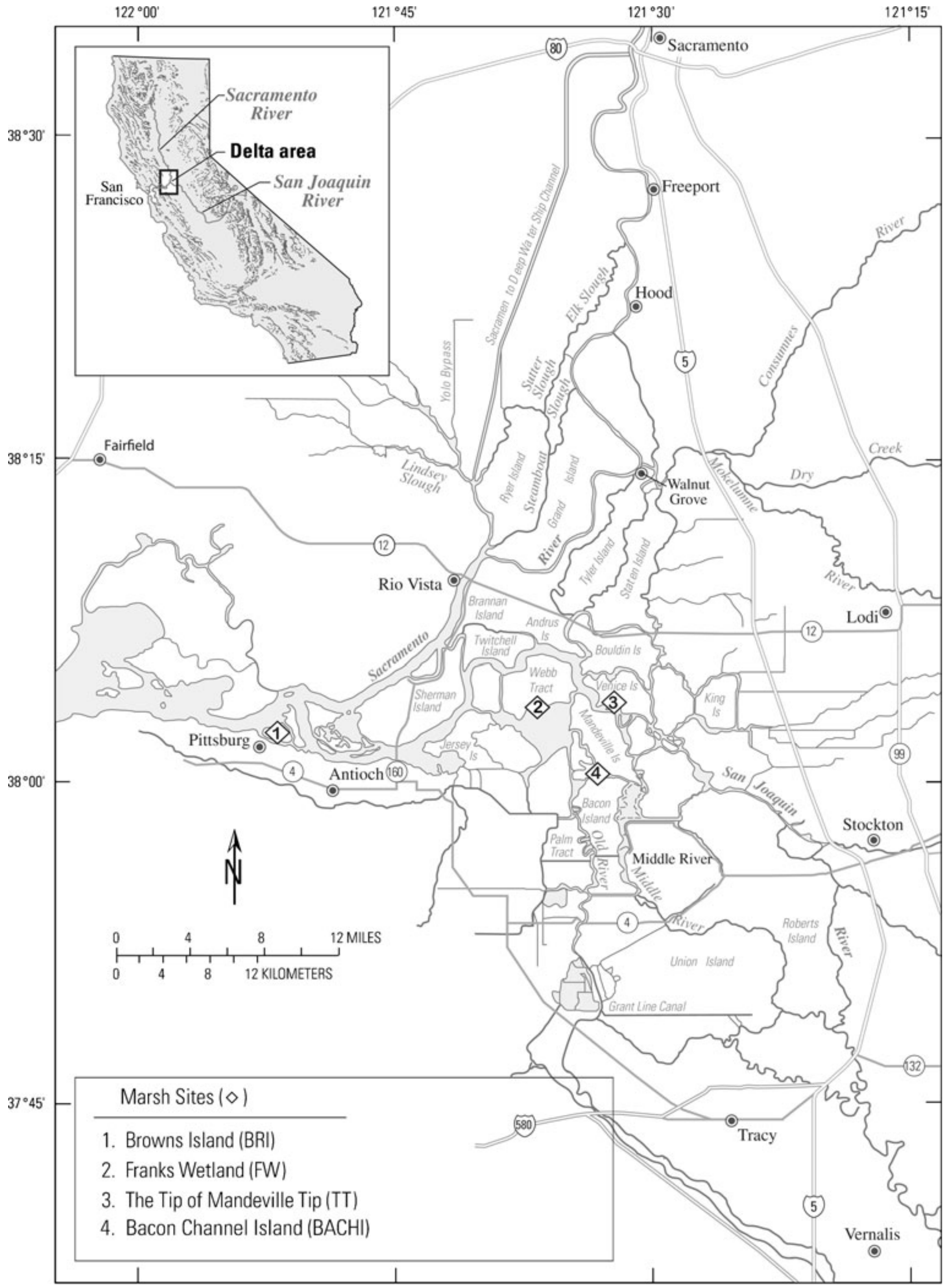

Fig. 1 Site map showing the marsh study sites and key features of the Sacramento–San Joaquin Delta as well as the location of the Delta in California, USA

lasiolepis. Several species such as *Schoenoplectus acutus* (hardstem bulrush), *P. australis*, and *Typha* spp. (cattails) are found at all sites. All nomenclature follows Hickman (1993).

Field Work

In the summer of 2005, one peat core from each of the marsh islands was collected using a modified 5-cm diameter Livingstone corer (Wright 1991). Cores were collected in multiple drives all the way to refusal in the underlying clay layer, which was found at all sites, to ensure that the entire peat column was collected. The peat column at each site formed a continuous layer. Total peat thicknesses are shown in Table 1. Core drives were extruded onto cellophane-lined polyvinyl chloride (PVC) tubes cut longitudinally in half, photographed, and then visually described in the field. The cores were quickly wrapped in cellophane, covered with the other longitudinal half of the PVC tube, and taped shut. All cores were immediately placed in a large cooler until being transported to the laboratory where they were stored at

Table 1 Basic characteristics of the study sites in the Sacramento–San Joaquin Delta

Coring site name	Peat thickness (cm)	Elevation (MSL in m)	Salinity regime in channel	Hydrogeomorphic setting	Relative energy regime
Browns Island (BRI)	922	0.51	Mixohaline	Confluence of SR and SJR	High
Franks Wetland (FW)	608	0.27	Fresh	Distributary of SJR, sheltered by natural marsh breakwaters, adjacent to permanently flooded farmed island	Very low
The Tip of Mandeville Tip (TT)	424	0.20	Fresh	Glacial outwash region in main channel of SJR	Medium
Bacon Channel Island (BACHI)	726	0.21	Fresh	Glacial outwash region along distributary of SJR	Low

Salinity data represent typical, non-drought conditions in adjacent sloughs and are based on Atwater (1980). Mixohaline (brackish) refers to a range of approximately 0–10 ppt, with higher salinities found during the dry season. Terminology follows Mitsch and Gosselink (2000). Descriptions of hydrogeomorphic settings follow those described in Atwater (1980) *SR* Sacramento River, *SJR* San Joaquin River

approximately 3°C. At Browns Island, the first core, BRIC4, unlike all the other cores in the study, did not have good recovery near the surface due to a particularly dense root mat. In addition, BRIC4, though 775 cm long, did not reach the underlying mineral substrate, even though much clay was already present below 700 cm. Therefore, in order to remedy this situation, an additional core of peat thickness 922 cm was collected in March of 2007 within 2 m of the BRIC4 site, and a soil monolith of 49 cm was excavated from the surface in order to improve recovery over that with the Livingstone corer.

Real-time kinematic geographic positioning was used to establish the elevations and coordinates of the coring locations. Full details of the survey can be found in Drexler et al. (2009b). Ellipsoid heights from the survey were converted to orthometric elevations (NAVD88) using a GEOID03 model. Tidal benchmark LSS 13 (National Oceanic and Atmospheric Administration tidal station 9415064 located near Antioch, CA, USA) with a static surveyed ellipsoid height of −28.75 m was used to adjust the elevations of the coring sites to local mean sea level.

Laboratory Work

In the laboratory, cores were individually unwrapped, split lengthwise, and immediately photographed. Core stratigraphy was documented, and one longitudinal half of the core was wrapped in cellophane and archived for future use. Bulk density was obtained by sectioning cores into 2-cm thick blocks, measuring each dimension, obtaining wet weight of the sample, drying for 24 h at 105°C, and then weighing again to obtain dry weight (Givelet et al. 2004). Bulk density was obtained for every 2-cm core section, except for <5 sections per core that contained an abnormality in volume due to a root ball, missing material, or indentation from the piston. Core data were examined for compression and/or expansion, but no mathematical corrections were needed. The only correction made was to remove a small amount of peat (generally ~2 cm or less) from the top and bottom of some drives only when it was visually apparent that the drives contained non-contiguous peat from elsewhere in the core. The presence of noncontiguous peat was confirmed in the laboratory by anomalous bulk density values that differed from the rest of the drive. The soil monolith removed from the surface of Browns Island was corrected for expansion.

Basal contacts of the peat columns with the underlying mineral (epiclastic) sediment were generally sharp and could usually be determined by a spike in bulk density for sections immediately beneath the peat. At Browns Island, however, the transition from peat to epiclastic sediment was gradual. Therefore, we also used the definition of an organic soil (USDA Soil Conservation Service 2006) to differentiate peat from underlying mineral sediments.

To determine percentage organic matter, standard loss on ignition procedures were followed in which the dried bulk density samples were milled and heated to 550°C for 4 h (Heiri et al. 2001). Loss on ignition was analyzed at 4-cm intervals both at the top meter of the core and at the bottom meter before contact with the epiclastic sediment underlying the peat. At all other places in the cores, loss on ignition was conducted at 10-cm intervals. On average, a duplicate loss on ignition sample was run for every 9.5 samples. Average error for duplicates $(\text{error} = |(\text{duplicate A} - \text{duplicate B})/(\text{larger of A or B})*100|)$ was 0.74% (range=0.00–4.8%).

Total carbon was determined for samples from the four marsh islands as part of a larger study on peat accretion throughout the Delta (Drexler et al. 2009a). A total of 100 samples were submitted to the Department of Agriculture and Natural Resources laboratory at the University of California, Davis (AOAC International 1997, Method 972.43). The samples were randomly selected from each 1 m core segment in each of 12 peat cores collected in the study by Drexler et al. (2009a). To avoid possible contamination, samples were not selected from the upper and lower 10 cm of each drive. For quality assurance, 13 blind samples were also submitted to complement the 14 duplicates run by the lab as part of their quality control process. Duplicates averaged within 1.2% of their original total carbon sample. In addition, several samples with the highest bulk density from each site were selected (for a total of 29 samples) and analyzed for carbonate following the method of the US Salinity Laboratory Staff (1954). Peat samples had an average of less than 0.4% carbonate, indicating that total carbon percentage accurately approximates the organic carbon percentage of the peat. Loss on ignition values were converted to organic carbon values using a regression relationship in which organic carbon=0.55(organic matter)−2.69 ($F_{1,98}$=5,285, R^2=0.98, p<0.0003; Drexler et al. 2009b).

Organic fragments for radiocarbon analysis were sampled directly from the split core face where visible, or a 2- to 4-cm-thick sample of peat was sieved to concentrate seeds, charcoal, or other terrestrial macrofossils. *Schoenoplectus* achenes in particular were sought out as these were well distributed in the peat cores and have been shown to be a reliable material for radiocarbon dating (Wells 1995). Radiocarbon samples were analyzed by accelerator mass spectrometry at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory in Livermore, CA, USA. Ages were calibrated using CALIB (version 5.0.1; Stuiver and Reimer, 1993) with the INTCAL04 curve (Reimer et al. 2004). Spline fit age-depth models for the complete peat profiles were constructed following the procedure in Heegaard et al. (2005). The following number of radiocarbon samples was used for each of the spline fit age–depth models: FW (n=9), BRI (n=24), and BACHI (n=12). Additional details related to the radiocarbon data, construction of spline fit age–depth models, and estimated calibrated ages used in this study can be found in Drexler et al. (2009a).

Statistical Analyses

Simple regression was used to determine relationships between vertical accretion and both inorganic sedimentation and organic accumulation. All data were log-transformed prior to analysis in order to approximate normality. Residuals were checked for trends between predicted and actual values. The gap between measurements was far enough apart with respect to time (mean "gap" between measurements=50–90 years) that issues of temporal dependence were ruled to be minor and were disregarded (Gotelli and Ellison 2004).

Results

Bulk density and percent organic matter fluctuated throughout the millennia at each of the marsh sites (Fig. 2). There were particularly sharp increases and decreases in percent organic matter that occurred within only 30–50 years (e.g., from 80.4% to 61.6% between 2,950 and 2,920 calibrated years before present (cal yr BP) at Franks Wetland and from 60.8% to 88% between 3,430 and 3,390 cal yr BP at Bacon Channel Island; Fig. 2). For the most part, when bulk density increased, percent organic matter decreased and vice versa. At Franks Wetland and Bacon Channel Island, the more quiescent marsh sites compared to Browns Island and the Tip of Mandeville Tip, bulk density was high and percent organic matter was low near the surface but then bulk density decreased to around 0.1 g cm^{-3} for much of both cores. Percent organic matter still fluctuated considerably in both cores but generally stayed >50% between −1.0 and −6.0 m relative to mean sea level (MSL) and then decreased upon contact with the epiclastic sediment (Fig. 2a and c).

At Browns Island and the Tip of Mandeville Tip, the higher energy sites, there was also a layer of peat with higher bulk density and lower percentage of organic matter near the surface (Fig. 2b and d). There was a steady increase in bulk density (and decrease in percentage of organic matter) beginning at approximately −1 m MSL at Browns Island (~0.15 g cm^{-3}) and −0.5 m MSL at the Tip of Mandeville Tip (~0.10 g cm^{-3}) until approximately −5 m MSL at Browns Island (~0.70 g cm^{-3}) and −4 m MSL at the Tip of Mandeville Tip (~0.40 g cm^{-3}). Below −5 m MSL at Browns Island, bulk density ranged from ~0.20–0.45 g cm^{-3} and percent organic matter ranged from 20% to 30%, until reaching the peat-epiclastic transition zone (Fig. 2b). At the Tip of Mandeville Tip, deeper than −4.0 m MSL was already within the epiclastic sediment, and therefore, this part of the core had high bulk density and low organic matter content (Fig. 2d).

Patterns of deposition rates for both inorganic and organic matter varied through time (Fig. 3). For both Franks Wetland and Bacon Channel Island, which are low energy sites, organic accumulation rates (and, for periods, carbon sequestration rates) were greater than inorganic accumulation rates for most of the 4,000+ and 5,800+years, respectively, of their existence. Mean organic accumulation rates over the lifetime of each marsh were over twice as high as inorganic sedimentation rates (Table 2). Patterns of carbon sequestration, organic accumulation, and inorganic sedimentation appeared quite similar at Franks Wetland except at the very top where inorganic sedimentation was much greater than organic accumulation/carbon sequestration and at the bottom of the peat profile where all three rates essentially came together. Bacon Channel Island had the most unusual relationship between the curves as sometimes they mimicked each other (e.g., between −2.5 and −5 m), sometimes inorganic sedimentation and organic accumulation/carbon sequestration were the mirror image of each other (e.g., approximately −5.5 to −6.25 m), and at

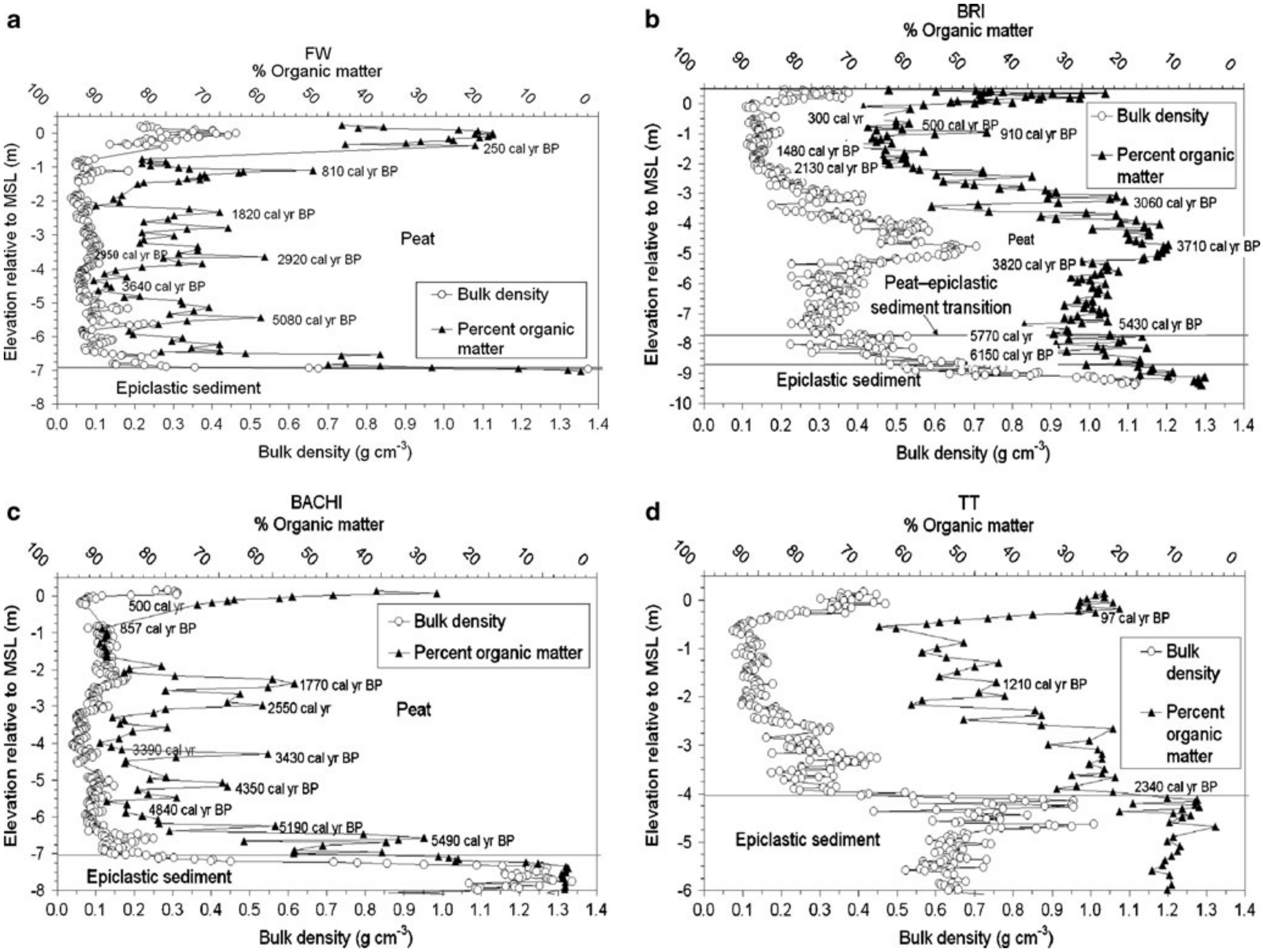

Fig. 2 Percent organic matter (with inverted axis) and bulk density vs. elevation relative to mean sea level (meters) for **a** Franks Wetland (FW), **b** Browns Island (BRI), **c** Bacon Channel Island (BACHI), and **d** the Tip of Mandeville Tip (TT). Ages shown for FW, BRI, and BACHI for different layers of the peat are estimated ages from spline fit age–depth models (Drexler et al. 2009a). Ages shown for peat layers at TT are the median probability of the 1-sigma range for each of three samples

one depth range there was a great increase in organic accumulation/carbon sequestration (approximately −1 to −2 m) that had only a minor corresponding change in inorganic sedimentation (Fig. 3). For Browns Island, a high-energy site at the confluence of two rivers, inorganic sedimentation rates through time were greater than organic accumulation rates (Fig. 3). Mean inorganic sedimentation rates at Browns Island were over three times higher than organic accumulation rates (Table 2). Browns Island had a massive increase in inorganic sedimentation that peaked at approximately 3,800 cal yr BP. In addition, organic accumulation rates had the same general shape as the sedimentation rates, but they were considerably dampened.

Organic accumulation was strongly related to vertical accretion at Browns Island, Franks Wetland, and Bacon Channel Island (Fig. 4, Table 3). There were too few radiocarbon dates available to produce a spline-fit age–depth model for the Tip of Mandeville Tip, so no estimates of organic accumulation or inorganic sedimentation were calculated for this site. Inorganic sedimentation was only strongly related to accretion at Browns Island, although there was a weak but significant relationship between accretion and inorganic sedimentation at Franks Wetland (Table 3). At Franks Wetland, organic production contributed over 4.5 g for every gram of inorganic sedimentation (Table 3).

For Franks Wetland, Bacon Channel Island, and Browns Island, mean rates of carbon sequestration ranged between 38 and 79 g organic C m^{-2} $year^{-1}$ (Table 2). The rate of 38.2 g organic C m^{-2} $year^{-1}$ at Franks Wetland was only valid for the first 608 cm of peat because below this the radiocarbon dates were not interpretable due to age inversions in the radiocarbon dating. At Browns Island and Bacon Channel Island, radiocarbon dates were interpretable for the entire peat column because there were no age inversions.

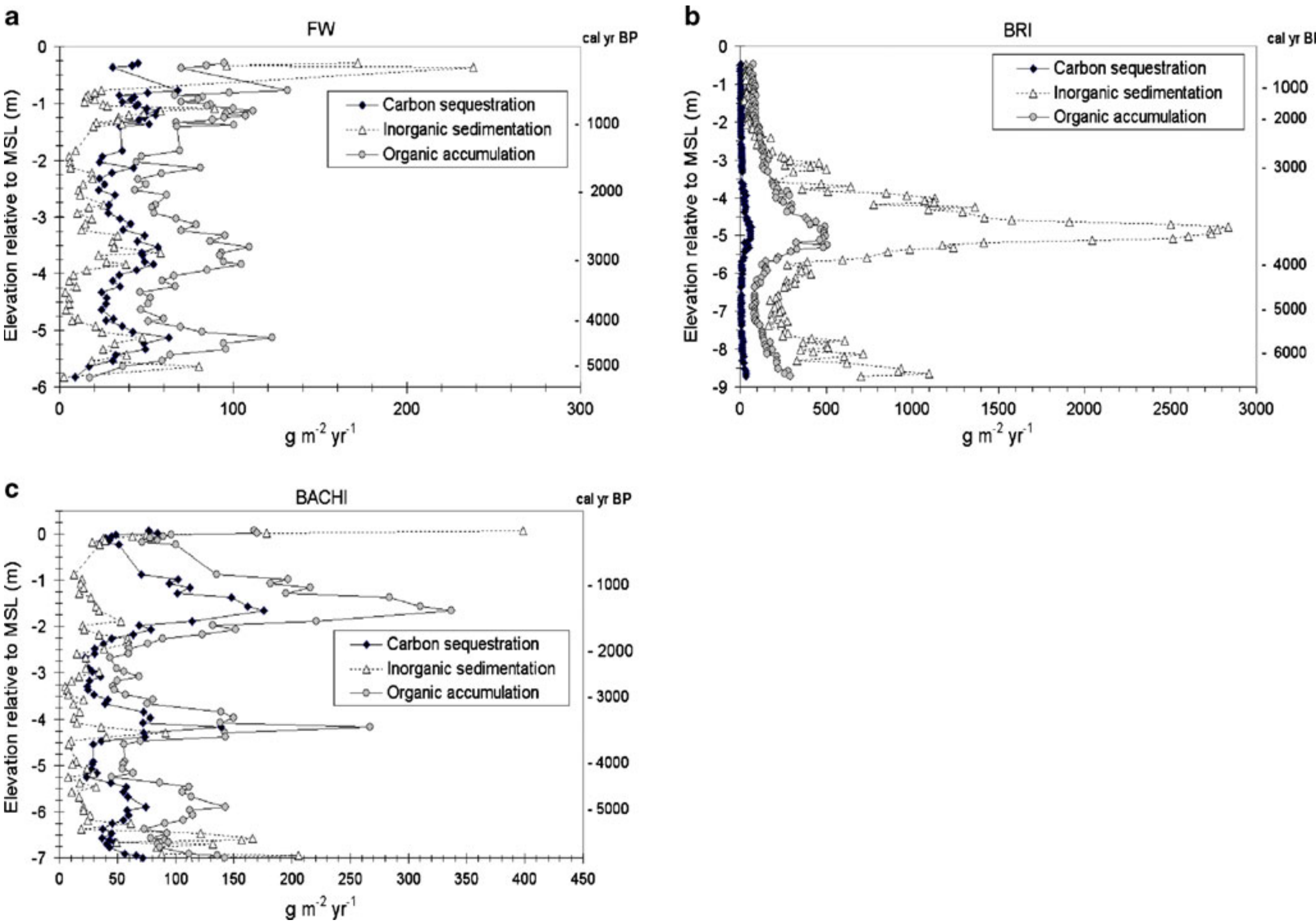

Fig. 3 Estimates for carbon sequestration (g organic carbon m^{-2} year^{-1}), organic accumulation (g organic matter m^{-2} year^{-1}) and inorganic sedimentation (g sediment m^{-2} year^{-1}) through time at **a** FW, **b** BRI, and **c** BACHI. Radiocarbon dates for all the calculations were estimated using spline fit age–depth models (see Drexler et al. 2009a). Too few radiocarbon dates were available to produce a spline fit age–depth model for TT, so no estimates are given

Bulk density and percent organic carbon measurements throughout each core were used to estimate total organic carbon storage (kg m^{-3}) and total organic carbon storage per area at each marsh site (Table 4). Organic carbon storage was greatest at Browns Island (41 kg m^{-3}) and least at Franks Wetland (34 kg m^{-3}). The greatest amount of organic carbon storage per area was at Browns Island with 378 kg m^{-2} and the least amount was at the Tip of Mandeville Tip with 155 kg m^{-2} (Table 4). These estimated storage values rely heavily on accretion rates and the thickness of the peat column of each marsh (Table 1).

Discussion

Organic vs. Inorganic Components of Peat

The relative contributions of inorganic and organic matter and the bulk density of peat have varied both gradually and rapidly over the past 6,000 years in the Delta (Fig. 2). Bulk density and percent organic matter have been, for the most part, mirror images of each other even though percent organic matter has varied to a greater extent (Fig. 2). Previous research in tidal marshes has shown that variability in bulk density is strongly related to the relative contribution of inorganic sediment to the peat (Turner et al. 2001). In the Delta, the contribution of inorganic sediment has been shown to vary as a function of the sediment supply from the watershed and river discharge rate, which is largely controlled by climate (Wright and Schoellhammer 2005).

Overall, trends in bulk density and percent organic matter content at the different study sites suggest that Franks Wetland and Bacon Channel Island have been highly organic sites containing little mineral sediment for much of their existence (Fig. 2). The highly organic nature and low bulk density of their peats can be explained by their sheltered hydrogeomorphic setting and low-energy status in the landscape, which prevent much mineral sediment from depositing at these sites (Table 1). In

Table 2 Mean rates of carbon sequestration (g organic C m^{-2} $year^{-1}$), organic accumulation (g organic matter m^2 $year^{-1}$), and inorganic sedimentation (g sediment m^{-2} $year^{-1}$) over the lifetimes of each marsh

Site	Mean carbon sequestration rate (SD)	Mean organic accumulation rate (SD)	Mean inorganic sedimentation rate (SD)
BACHI	58.7 (33.7)	114.5 (64.6)	48.3 (62.2)
BRI	79.0 (46.1)	179 (119)	552 (678)
FW	38.2 (11.9)	74.3 (23.1)	27.0 (33.1)

No such estimates could be determined for TT, because there were too few radiocarbon dates to construct a spline fit age–depth model (Drexler et al. 2009b)

contrast, Browns Island and the Tip of Mandeville Tip have peats of higher bulk density, lower organic content, and greater variability in these parameters suggesting that these high energy sites are dominated by larger watershed processes (Table 1, Fig. 2). The same conclusion was also reached in an analysis of vertical accretion rates and the relative contribution of inorganic and organic matter to soil volume at these sites (Drexler et al. 2009a). It is important to note, however, that there may be other within-site processes acting to control bulk density and percent organic matter content. Such processes could include shifting of natural levees, migration of marsh channels over time, changes in the connectivity between river channels and marsh, and/or shifts in the discharge rate between channels. The only way these processes could be evaluated would be to analyze multiple cores per site, which was beyond the scope of this study.

Organic Accumulation vs. Inorganic Sedimentation

Patterns in organic accumulation and inorganic sedimentation also appear to be a result of the hydrogeomorphic setting of the sites. Through time, Franks Wetland and Bacon Channel Island have had greater organic accumulation than inorganic sedimentation whereas Browns Island has had much higher inorganic sedimentation than organic accumulation. Such differences are not surprising as previous work in salt marshes has shown that sites with high tidal range (i.e., high energy sites with strong connectivity to the greater watershed) receive more inorganic sediment than sites with low tidal range (French 2006; Allen 2000). Therefore, in the case of this study, and perhaps for other microtidal freshwater marshes as well, this statement would more generally be true if "tidal range" were substituted with "connectivity to the greater watershed".

The balance between inorganic sedimentation and organic accumulation has varied through time at the sites (Fig. 3). At Browns Island, this alternation between processes occurred over periods ranging from a few hundred years to over 1,000 years (from ~2,300 cal yr BP to recent times). In addition, at Bacon Channel Island, near the bottom of the peat column and at Franks Wetland, at the very top and bottom of the peat column, inorganic sedimentation was greater than organic accumulation (Fig. 3). Therefore, it appears that at a particular time, a "unit parcel" of marsh can rely more strongly on either inorganic or organic matter for peat formation. Although data are not available to demonstrate this effect at a marsh scale, this result in itself suggests that generalizations regarding marsh vertical accretion relying on either inor-

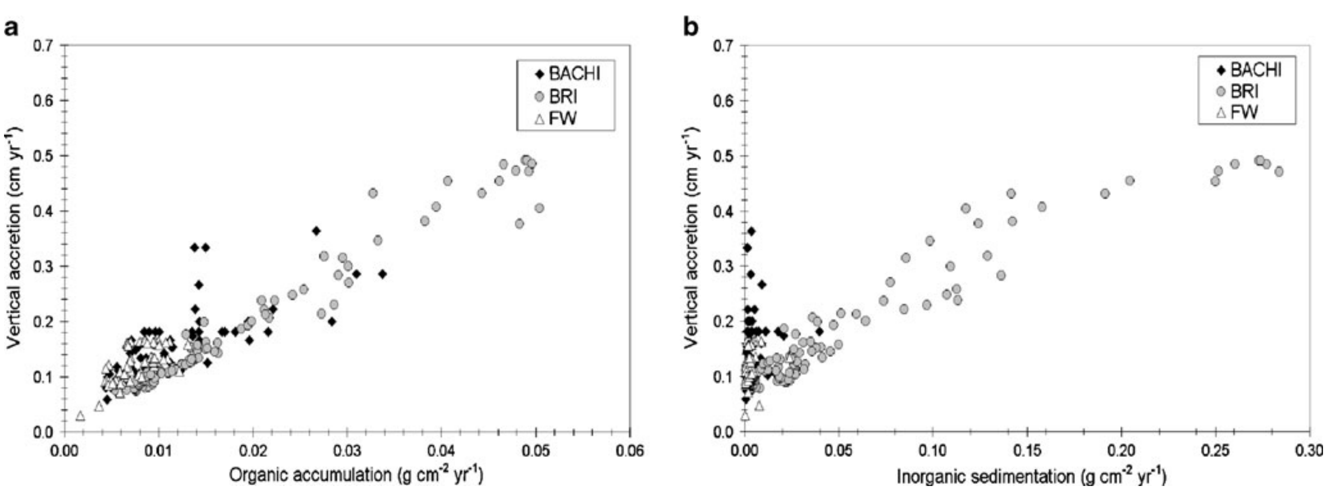

Fig. 4 Plots of vertical accretion (cm $year^{-1}$) against **a** organic accumulation (g cm^{-2} $year^{-1}$) and **b** inorganic sedimentation (g cm^{-2} $year^{-1}$) during the lifetimes of BRI, BACHI, and FW

Table 3 Simple regression relationships between vertical accretion (cm year^{-1}) vs. both organic accumulation (g organic matter m^{-2} year^{-1}) and inorganic sedimentation (g sediment cm^{-2} year^{-1})

Site	n^a	Accretion vs. inorganic sedimentation		Accretion vs. organic accumulation	
		Equation	R^2; p value	Equation	R^2; p value
BACHI	66	NA	NS; >0.05	$y=1.14+0.68x$	67.4; <0.001
BRI	120	$y=-0.51+0.38x$	82.1; <0.001	$y=1.96+0.91x$	96.2;< 0.001
FW	59	$y=-1.15+0.16x$	18.2; 0.001	$y=1.44+0.73x$	64.3; <0.001

All data were log-transformed prior to analysis

NA not applicable, *NS* not significant

[a] The number of data points (n) corresponds to the number of estimates per core of inorganic sedimentation and organic accumulation

ganic or organic matter may be inappropriate, especially in estuarine settings.

Changes in the relative constituents of peat can affect the rate at which peat is accreted because there are differing relationships between both inorganic and organic matter and vertical accretion rates (Turner et al. 2001). In a comparison of tidal freshwater marshes in the northeastern, southeastern, and Gulf coast of USA, Neubauer (2008) found that overall both mineral and organic inputs were important with respect to vertical accretion, but on a weight basis, organic matter contributed about four times more toward vertical accretion than inorganic matter. In this study, both inorganic sedimentation and organic accumulation were associated with vertical accretion throughout the lifetimes of Browns Island and Franks Wetland, but only organic accumulation had a significant relationship with accretion at Bacon Channel Island (Table 3). At Browns Island and Franks Wetland, the patterns for inorganic sedimentation and organic accumulation were quite similar to each other through time, suggesting that some of the organic material deposited in the marsh may have been allochthonous and/or the result of a fertilization effect from sediment deposition (Neubauer 2008). At Franks Wetland, organic accumulation was much more important in relation to vertical accretion than inorganic sedimentation. The equations in Table 3 for Franks Wetland show that for every unit gain in accretion, organic accumulation contributed over four times as much as inorganic sedimentation.

A closer look at existing patterns between organic accumulation and inorganic sedimentation reveals some important marsh processes. At Franks Wetland, increases in inorganic sedimentation generally occurred with a corresponding increase in organic accumulation and this also occurred, though to a lesser extent, at Bacon Channel Island. This relationship was also found at Browns Island, however, there was essentially one main pattern in that core (which may be related to a very wet period in California history at approximately 3,800 cal yr BP, LaMarche 1973; Stine 1990; Goman and Wells 2000, Drexler et al. 2009a). Such results suggest that, in the Delta, the rate of peat formation is strongly related to periodic deliveries of sediments and accompanying nutrients, which have resulted in increases in *both* inorganic sedimentation and organic accumulation. Currently, sediment delivery to the watershed is largely related to storm activity (Wright and Schoellhamer 2005). This relationship appears to be longstanding as research on Lake Tahoe, California sediments suggests that storms have been a major agent for the mobilization of sediments in the region for the past 7,000 years (Osleger et al. 2009).

In the most recently accreted peats, there was a pattern of low percentage of organic matter and high bulk density, low organic accumulation, and high inorganic sedimentation (Figs. 2 and 3). This high mineral content at the marsh surface has been observed by other researchers studying peat cores in the Delta and Suisun Bay (e.g., May 1999; Goman and Wells 2000). It has also been observed by Reed (2002) in a study of recent peat accretion in reference and restored marshes in the Delta. This increased sediment contribution to peat appears to originate from as far back as ~300 cal yr BP and may be related to the advent of European settlement and heightened land clearing for agriculture. Such land use changes culminated in the hydraulic mining era between the late 1880s and early 1900s. During this period, a huge plug of sediment was liberated into the watershed, thus increasing vertical accretion in the marshes (Gilbert 1917; Orr et al. 2003).

Table 4 Estimated mean organic carbon density and organic carbon storage per area in Delta marshes

Site	Organic carbon density (kg m^{-3}) (SD)	Organic carbon storage per area (kg m^{-2})
BACHI	39.2 (11.6)	285
BRI	41.0 (15.1)	378
FW	34.2 (7.2)	246
TT	36.6 (5.2)	155

Carbon Sequestration Rates

Few other studies have estimated carbon sequestration rates in tidal freshwater marshes, let alone throughout the millennia, making it difficult to compare the results in this study to other geographical regions. Nevertheless, some comparisons can be made. The mean total accumulation rates for the Delta marshes in this study (i.e., inorganic sedimentation rates+organic accumulation rates) were approximately 0.01 g cm^{-2} year^{-1}. This is similar to the deepest sediments (0.03 g cm^{-2} year^{-1}; dated 1,379–1,039 cal yr BP) in a Maryland tidal freshwater marsh (Khan and Brush 1994). However, both of these estimates are less than the current carbon sequestration rate estimated for a tidal freshwater marsh in Virginia (0.05±0.035 g organic C cm^{-2} year^{-1}; Neubauer et al. 2002).

The range of mean carbon sequestration rates found in this study (0.38–0.79 Mg C ha^{-1} year^{-1}) brackets the mean carbon sequestration rate of 0.71 Mg C ha^{-1} year^{-1} for peatlands in the conterminous USA estimated by Bridgham et al. (2006). Unlike the carbon sequestration rates determined for Delta marshes in this study, which were calculated at small time intervals throughout the entire lifetime of each marsh, this estimate by Bridgham et al. (2006) was determined using the long-term apparent rate of carbon accumulation (LORCA) method. This method relies on basal peat dates alone, assumes a linear accumulation rate through time, and is thought to overestimate carbon accumulation (Bridgham et al. 2006). Other LORCA-derived estimates exist including rates for a salt marsh and a freshwater marsh in southern California (0.20 and 0.39 Mg C ha^{-1} year^{-1}, respectively, over a 5,000-year period; Brevik and Homburg 2004) and a 0.82 Mg C ha^{-1} year^{-1} estimate for Pacific coast undisturbed organic soil wetlands (Armentano and Menges 1986).

The long-term carbon sequestration rates in this study are less than short-term estimates for other coastal wetlands. In a review paper by Chmura et al. (2003), carbon densities for salt marshes from the Gulf of Mexico and the northeast and northwest Atlantic were within a similar range as the marshes in this paper (Table 4), but the salt marsh sites had much higher carbon sequestration rates (mean=174; 72–456 g organic carbon m^{-2} year^{-1}; all peats <100 years old; Chmura et al. 2003). The global average rate of carbon storage in salt marshes and mangroves was estimated to be approximately 210 g organic carbon m^{-2} year^{-1} (<100 years; Chmura et al. 2003), which is almost three times the millennial rate estimated for Browns Island.

These few comparisons raise several questions. Of particular importance is whether tidal saline or tidal freshwater wetlands have higher carbon sequestration rates, especially when methane emissions are accounted for, or simply whether older peats are subject to greater losses of sequestered carbon due to ongoing decomposition processes. Clearly, more research is needed, especially over long, well-calibrated time scales in order to address such questions. These issues are of greater than academic importance because, if carbon sequestration in marshes is to be utilized for mitigating carbon pollution, storage trajectories will surely be important beyond the 50–100 year time scale commonly reported in the literature.

Acknowledgments This study was funded by the CALFED Science Program of the California Resources Agency, Agreement #F-O3-RE-029. I am grateful to Jim Orlando, Jacob Fleck, Matt Kerlin, Curt Battenfeld, Stephanie Wong, Patricia Orlando, and Nicole Lunning for their help in the field and lab. I also want to thank Christian de Fontaine for his excellent leadership of the field and lab components of this research. Thomas Brown was instrumental in providing expertise and assistance regarding the radiocarbon analyses. Peat core analyses would not have been possible without the facilities provided by Greg Pasternack at the University of California, Davis. Skip Vecchia provided helpful statistical advice. Brian Atwater, Lisamarie Windham-Myers, and two anonymous reviewers provided comments that greatly improved the quality of the manuscript.

Conflict of Interest Notification Page The cooperator in this study was the CALFED Science Program of the California Resources Agency. The author has no special financial relationship with this agency except for conducting research through their Agreement #F-O3-RE-029. The author has full control of all primary data for this research and would allow the journal to review all data from this project if requested.

References

Allen, J.R.L. 2000. Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. *Quaternary Science Reviews* 19: 1155–1231.

AOAC International. 1997. *Official methods of analysis of AOAC International*, 16th ed. USA: AOAC International.

Armentano, T.B., and E.S. Menges. 1986. Patterns of change in the carbon balance of organic soil wetlands of the temperate zone. *Journal of Ecology* 74: 755–774.

Atwater, B. F. 1980. Attempts to correlate late Quaternary climatic records between San Francisco Bay, the Sacramento–San Joaquin Delta, and the Mokelumne River, California. Ph.D. Dissertation. University of Delaware, Newark, DE, USA

Atwater, B.F. 1982. Geologic maps of the Sacramento–San Joaquin Delta, California: US Geological Survey Miscellaneous Field Studies Map MF-1401, scale 1:24,000, pamphlet 15 pp.

Brevik, E.C., and J.A. Homberg. 2004. A 5,000 year record of carbon sequestration from a coastal lagoon and wetland complex, Southern California, USA. *Catena* 57: 221–232.

Bricker-Urso, S., S.W. Nixon, J.K. Cochran, D.J. Hirschberg, and C. Hunt. 1989. Accretion rates and sediment accumulation in Rhode Island marshes. *Estuaries* 12: 300–317.

Brinson, M. M. 1993. A hydrogeomorphic classification for wetlands. Technical Report WRP-DE-4, US Army Engineer Waterways Experiment Station, Vicksburg, MS, 103 pp.

Bridgham, S., J.P. Megonigal, J.K. Keller, N. Bliss, and C. Trettin. 2006. The carbon balance of North American wetlands. *Wetlands* 26: 889–916.

Callaway, J.C., R.D. DeLaune, and W.H. Patrick Jr. 1997. Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. *Journal of Coastal Research* 13: 181–191.

Chmura, G.L., S.C. Anisfeld, D.R. Cahoon, and J.C. Lynch. 2003. Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles* 17: 1–22.

Drexler, J.Z., C.S. de Fontaine, and T.A. Brown. 2009a. Peat accretion histories during the past 6,000 years in marshes in the Sacramento–San Joaquin Delta, California, USA. *Estuaries and Coasts* 32: 871–892.

Drexler, J.Z., C.S. de Fontaine, and S.J. Deverel. 2009b. The legacy of wetland drainage on the remaining peat in the Sacramento–San Joaquin Delta, California, USA. *Wetlands* 29: 372–386.

Fettweis, M., M. Sas, and J. Monbaliu. 1998. Seasonal, neap-spring and tidal variation of cohesive sediment concentration in the Scheldt Estuary, Belgium. *Estuarine, Coastal and Shelf Science* 47: 21–36.

French, J. 2006. Tidal marsh sedimentation and resilience to environmental change: exploratory modeling of tidal, sea-level, and sediment supply forcing in predominantly allochthonous systems. *Marine Geology* 235: 119–136.

Gilbert, G.K. 1917. *Hydraulic-mining debris in the Sierra Nevada. US Geological Survey, Professional Paper 105*. USA: US Government Printing Office.

Givelet, N., G. Le Roux, A. Cheburkin, B. Chen, J. Frank, H. Goodsite, M. Kempter, T. Krachler, N. Noernberg, S. Rausch, F. Rheinberger, A. Roos-Barraclough, C. Sapkota, C. Scholz, and W. Shotyk. 2004. Suggested protocol for collecting, handling and preparing peat cores and peat samples for physical, chemical, mineralogical and isotopic analyses. *Journal of Environmental Monitoring* 6: 481–492.

Goman, M., and L. Wells. 2000. Trends in river flow affecting the northeastern reach of the San Francisco Bay Estuary over the past 7,000 years. *Quaternary Research* 54: 206–217.

Gotelli, N.J., and A.M. Ellison. 2004. *A primer of ecological statistics*. Sutherland: Sinauer Associates, Inc.

Hatton, R.S., R.D. DeLaune, and W.H. Patrick Jr. 1983. Sedimentation, accretion, and subsidence in marshes of Barataria Basin, Louisiana. *Limnology and Oceanography* 28: 494–502.

Heegaard, E., H.J.B. Birks, and R.J. Telford. 2005. Relationships between calibrated ages and depth in stratigraphical sequences: an estimation procedure by mixed-effect regression. *Holocene* 15: 612–618.

Heiri, O., A.F. Lotter, and G. Lemcke. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments; reproducibility and comparability of results. *Journal of Paleolimnology* 25: 101–110.

Hickman, J.C. (ed.). 1993. *The Jepson manual*. Berkeley: University of California Press.

Khan, H., and G.S. Brush. 1994. Nutrient and metal accumulation in a freshwater tidal marsh. *Estuaries* 17: 345–360.

LaMarche Jr., V. 1973. Holocene climatic variations inferred from tree line fluctuations in the White Mountains California. *Quaternary Research* 3: 632–660.

Leonard, L.A., A.C. Hine, and M.E. Luther. 1995. Surficial sediment transport and deposition processes in a *Juncus roemerianus* marsh, west-central Florida. *Journal of Coastal Research* 11: 332–336.

May, M.D. 1999. *Vegetation and salinity changes over the last 2,000 years at two islands in the northern San Francisco Estuary, California. Master's thesis*. USA: University of California.

Mitsch, W.J., and J.G. Gosselink. 2000. *Wetlands*, 3rd ed. New York: Wiley.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetland to rising sea level. *Ecology* 83: 2869–2877.

Neubauer, S.C. 2008. Contributions of mineral and organic components to tidal freshwater marsh accretion. *Estuarine, Coastal and Shelf Science* 78: 78–88.

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

Nyman, J.A., R.D. DeLaune, and W.H. Patrick Jr. 1990. Wetland soil formation in the rapidly subsiding Mississippi River deltaic plain: mineral and organic matter relationships. *Estuarine, Coastal and Shelf Science* 31: 57–69.

Nyman, J.A., C.R. Crozier, and R.D. DeLaune. 1995. Roles and patterns of hurricane sedimentation in an estuarine marsh landscape. *Estuarine, Coastal and Shelf Science* 40: 665–679.

Nyman, J.A., R.J. Walters, R.D. DeLaune, and W.H. Patrick Jr. 2006. Marsh vertical accretion via vegetative growth. *Estuarine, Coastal and Shelf Science* 69: 370–380.

Osleger, D.A., A.C. Heyvaert, J.S. Stoner, and K.L. Verosub. 2009. Lacustrine turbidities as indicators of Holocene storminess and climate: Lake Tahoe, California and Nevada. *Journal of Paleolimnology* 42: 103–122.

Orr, M., S. Crooks, and P.B. Williams. 2003. Will restored tidal marshes be sustainable? *San Francisco Estuary and Watershed Science* 1 (1): Article 5. http://repositories.cdlib.org/jmie/sfews/vol1/iss1/art5.

Prokopovich, N.P. 1985. Subsidence of peat in California and Florida. *Bulletin. Association of Engineering Geologists* 22: 395–420.

Reed, D.J. 2002. Understanding tidal marsh sedimentation in the Sacramento–San Joaquin Delta, California. *Journal of Coastal Research SI* 36: 605–611.

Reimer, P.J., M.G.L. Baillie, E. Bard, A. Bayliss, J.W. Beck, C.J.H. Bertrand, P.G. Blackwell, C.E. Buck, G.S. Burr, K.B. Cutler, P.E. Damon, R.L. Edwards, R.G. Fairbanks, M. Friedrich, T.P. Guilderson, A.G. Hogg, K.A. Hughen, B. Kromer, G. McCormac, S. Manning, C.B. Ramsey, R.W. Reimer, S. Remmele, J.R. Southan, M. Stuiver, S. Talamo, F.W. Taylor, J. van der Plicht, and C.E. Weyhenmeyer. 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon* 46: 1029–1058.

Shlemon, R.J., and E.L. Begg. 1975. Late quaternary evolution of the Sacramento–San Joaquin Delta, California. In *Quaternary studies*, ed. R.P. Suggate and M.M. Creswell, 259–266. New Zealand: The Royal Society of New Zealand.

Stevenson, J.C., M.S. Kearney, and E.C. Pendleton. 1986. Vertical accretion rates in marshes with varying rates of sea-level rise. In *Estuarine variability*, ed. D. Wolf, 241–260. New York: Academic Press.

Stine, S. 1990. Late Holocene fluctuations of Mono Lake, eastern California. *Palaeogeography, Palaeoclimatology, Palaeoecology* 78: 333–381.

Stuiver, M., and R.J. Reimer. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* 35: 215–230.

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

Thompson, J. 1957. *The settlement geography of the Sacramento–San Joaquin Delta. California. Ph.D. Dissertation*. USA: Stanford University.

Turner, R.E., E.M. Swenson, and C.S. Milan. 2001. Organic and inorganic contributions to vertical accretion in salt marsh sediments. In *Concepts and controversies in tidal marsh ecology*, ed. M. Weinstein and D.A. Kreeger, 583–595. Dordrecht: Kluwer Academic Publishing.

Turner, R.E., J.J. Baustian, E.M. Swenson, and J.S. Spicer. 2006. Wetland sedimentation from hurricanes Katrina and Rita. *Science* 314: 449–452.

US Salinity Laboratory Staff. 1954. Alkaline-earth carbonates by gravimetric loss of carbon dioxide. In *Diagnosis and improvement of saline and alkali soils. USDA Agricultural Handbook 60*, ed. L. A. Richards, 105. USA: US Government Printing Office.

United States Department of Agriculture Soil Conservation Service, US Department of Agriculture. 2006. *Keys to soil taxonomy*, 8th ed. Blackburg: Pocahontas Press, Inc.

Warren, R.S., and W. Niering. 1993. Vegetation change on a northeast tidal marsh: interaction of sea-level rise and marsh accretion. *Ecology* 74: 96–103.

Wells, L.E. 1995. Radiocarbon dating of Holocene tidal marsh deposits: applications to reconstructing relative sea level changes in the San Francisco estuary. In *Quaternary geochronology and paleoseismology*, ed. J.S. Noller, W.R. Lettis, and J.M. Sowers, 3.95–3.102. Washington DC: Nuclear Regulatory Commission.

Wright Jr., H.E. 1991. Coring tips. *Journal of Paleolimnology* 6: 37–49.

Wright, S.A., and D.H. Schoellhamer. 2005. Estimating sediment budgets at the interface between rivers and estuaries with application to the Sacramento–San Joaquin River Delta. *Water Resources Research*. doi:10.1029/2004WR003753.