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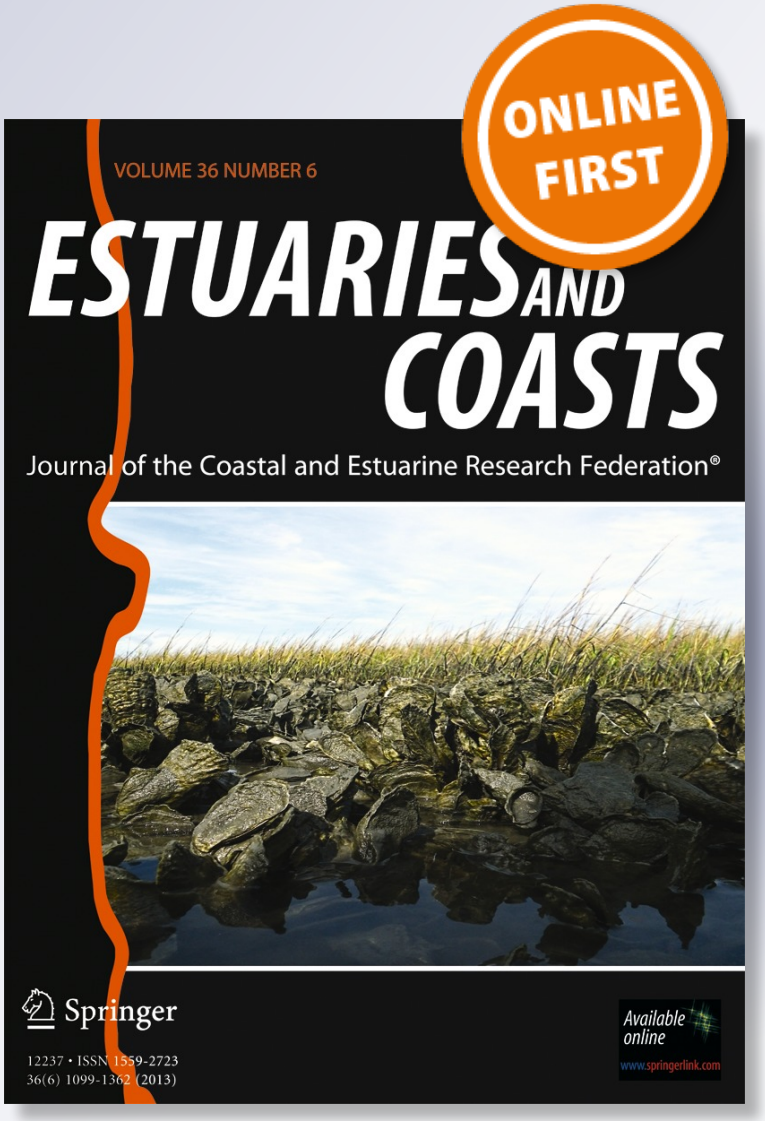

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Abstract We evaluated the biogeomorphic processes of a large (309 ha) tidal salt marsh and examined factors that influence its ability to keep pace with relative sea-level rise (SLR). Detailed elevation data from 1995 and 2008 were compared with digital elevation models (DEMs) to assess marsh surface elevation change during this time. Overall, 37 % (113 ha) of the marsh increased in elevation at a rate that exceeded SLR, whereas 63 % (196 ha) of the area did not keep pace with SLR. Of the total area, 55 % (169 ha) subsided during the study period, but subsidence varied spatially across the marsh surface. To determine which biogeomorphic and spatial factors contributed to measured elevation change, we collected soil cores and determined percent and origin of organic matter (OM), particle size, bulk density (BD), and distance to nearest bay edge, levee, and channel. We then used Akaike Information Criterion (AICc) model selection to assess those variables most important to determine measured elevation change. Soil stable isotope compositions were evaluated to assess the source of the OM. The samples had limited percent OM by weight (<5.5 %), with mean bulk densities of 0.58 g cm^{-3}, indicating that the soils had high mineral content with a relatively low proportion of pore space. The most parsimonious model with the highest AICc weight (0.53) included distance from bay's edge (i.e., lower intertidal) and distance from levee (i.e., upper intertidal). Close proximity to sediment source was the greatest factor in determining whether an area increased in elevation, whereas areas near landward levees experienced subsidence. Our study indicated that the ability of a marsh to keep pace with SLR varied across the surface, and assessing changes in elevation over time provides an alternative method to long-term accretion monitoring. SLR models that do not consider spatial variability of biogeomorphic and accretion processes may not correctly forecast marsh drowning rates, which may be especially true in modified and urbanized estuaries. In light of SLR, improving our understanding of elevation change in these dynamic marsh systems will play a crucial role in forecasting potential impacts to their sustainability and the survival of these ecosystems.

Keywords Accretion · Akaike Information Criterion · Climate change · Marsh · Sea-level rise · San Francisco Bay

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Introduction

Tidal salt marshes are complex dynamic systems that can maintain their surface elevation relative to local sea levels given enough time and accretion potential (Goodman et al. 2007; Reed 2002; Temmerman et al. 2004). The biogeomorphic interplay of vegetation structure and hydric soil sedimentation processes are important in marsh development across geographic space and time (Reed 2000). Accretion occurs as mineral sediment and organic matter (OM) accumulate on the marsh surface, maintaining the marsh

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elevation in relation to tidal inundation and erosional processes. Biogeomorphic processes and marsh surface elevation change are sensitive to small changes in suspended sediment load and compaction, eustatic and isostatic sea-level change mechanisms, tectonics, tidal energy, storm surges, salinity, anoxia, and biotic interactions (Bricker-Urso et al. 1989; Cahoon et al. 1995; Zedler 2010).

A biogeomorphic perspective, where the vegetated landscape is included when assessing geomorphic characteristics and processes, is valuable for understanding and modeling marsh responses to future sea-level rise (SLR; Stallins 2006; Reed 2002). Marsh vegetation can trap sediment, reduce erosion, increase OM contributions to below- and above-ground biomass, and add nitrogen and carbon to the system (Goman et al. 2008; Morris et al. 2002; Pethick 2001; Temmerman et al. 2004). Species composition, structure, and density of vegetation will influence sediment deposition and rooting pore spaces (Nyman et al. 1990, 2006). OM accumulation and biomass has been shown to be important components in maintaining marsh elevation (Goodman et al. 2007; Reed 2002; Culberson et al. 2004; Callaway et al. 1997). Marsh vegetation can stabilize the substrate and trap sediment (preventing erosion) which can increase marsh surface elevation. However, once vegetation is removed or dies, erosion and subsidence can occur (Culberson et al. 2004; Ford and Grace 1998).

Projections of global SLR range from 19 to 58 cm (IPCC 2007), with more recent projections up to 190 cm for 2100 (Vermeer and Rahmstorf 2009). For areas south of Cape Mendocino along the California coast, sea level is projected to rise up to 167 cm by 2100 ("Sea-level rise" 2012). In San Francisco Bay, CA, sea level has averaged 2.01 mm year^{-1} ± 0.21 mm based on monthly mean sea level data from 1897 to 2006 (Cayan et al. 2006).

Vertical marsh accretion is necessary in order to keep pace with relative SLR to avoid submergence if marsh transgression is not possible (Morris et al. 2002). In estuaries such as San Francisco Bay, hundreds of millions of dollars are being spent on wetland protection and restoration projects to improve the spatial extent and ecological functions of marsh habitats. However, the value and longevity of such projects is more difficult to assess in light of SLR projections if these wetlands are not able to maintain their marsh surface elevation. Our study evaluated if marshes in the northern reaches of San Francisco Bay kept pace with SLR over a recent 13-year period by assessing surface elevation change. In addition, we evaluated biogeomorphic and spatial properties that may contribute to changes in elevation.

Study Site

San Francisco Bay is the largest estuary on the Pacific Coast of North America and an important ecological region for migratory birds, marine mammals, and marsh wildlife. The tidal regime is mixed semi-diurnal, with an average diurnal range of 1.78 m (Golden Gate tide gauge; http://tidesonline.nos.noaa.gov). San Pablo Bay lies in the northern reach and supports some of the largest sections of intact tidal marsh. However, nearly 85 % of the marshes in San Pablo Bay have been altered by human activities such as diking, mining, salt pond development, road construction, and farming (USFWS 2007). This has created a landscape mosaic of highly fragmented marshes, urban areas, and agriculture lands (Fig. 1). The marshes are dominated by halophytic plants such as common pickleweed (*Sarcocornia pacifica*), Pacific cordgrass (*Spartina foliosa*), and gum plant (*Grindelia stricta*).

The 309 ha tidal marsh area examined in this study is within the U.S. Fish and Wildlife Service, San Pablo Bay National Wildlife Refuge, hereafter SPBNWR (38°08′N, 122°24′W). The SPBNWR marsh is situated along the northern edge of San Pablo Bay, a relatively shallow bay with an average depth of 3.7 m with a major deep water shipping channel to the east and river drainages to the north including the Napa River in the northeast and the Petaluma River in the northwest (Jaffe et al. 2007). The SPBNWR is influenced by tidal action and local freshwater input from both Sonoma Creek and the Petaluma River, and it is bordered to the north by a highway and levees that protect private agriculture land (Fig. 1). There are no large bare areas or pans within the study site. The SPBNWR is home to California or federally listed species including the federally endangered endemic salt marsh harvest mouse (*Reithrodontomys raviventris*) and California clapper rail (*Rallus longirostris obsoletus*), and the state-threatened California black rail (*Laterallus jamaicensis coturniculus*).

Methods

Elevation Evaluation

Two elevation surveys were conducted 13 years apart. The first survey-grade elevation study (x,y accuracy ±1 cm, orthometric heights ±2.0 cm) was in 1995, when six benchmarks were used to provide North American Vertical Datum of 1988 (NAVD88) vertical control. Using standard leveling techniques, transects were conducted with 15 horizontal and vertical control stations which were 50–100 m apart.

The second survey-grade elevation study was in 2008 with a Leica RX1200 real time kinematic (RTK) global positioning system (GPS) rover (x,y accuracy ±1 cm, orthometric height ±2.0 cm; Leica Geosystems, Norcross, GA). The rover positions were received from the Leica Smartnet system (www.leica-geosystems.com), which we referenced to a National Geodetic Survey benchmark (X552, 1956, Mare Island). Our measured vertical accuracy at

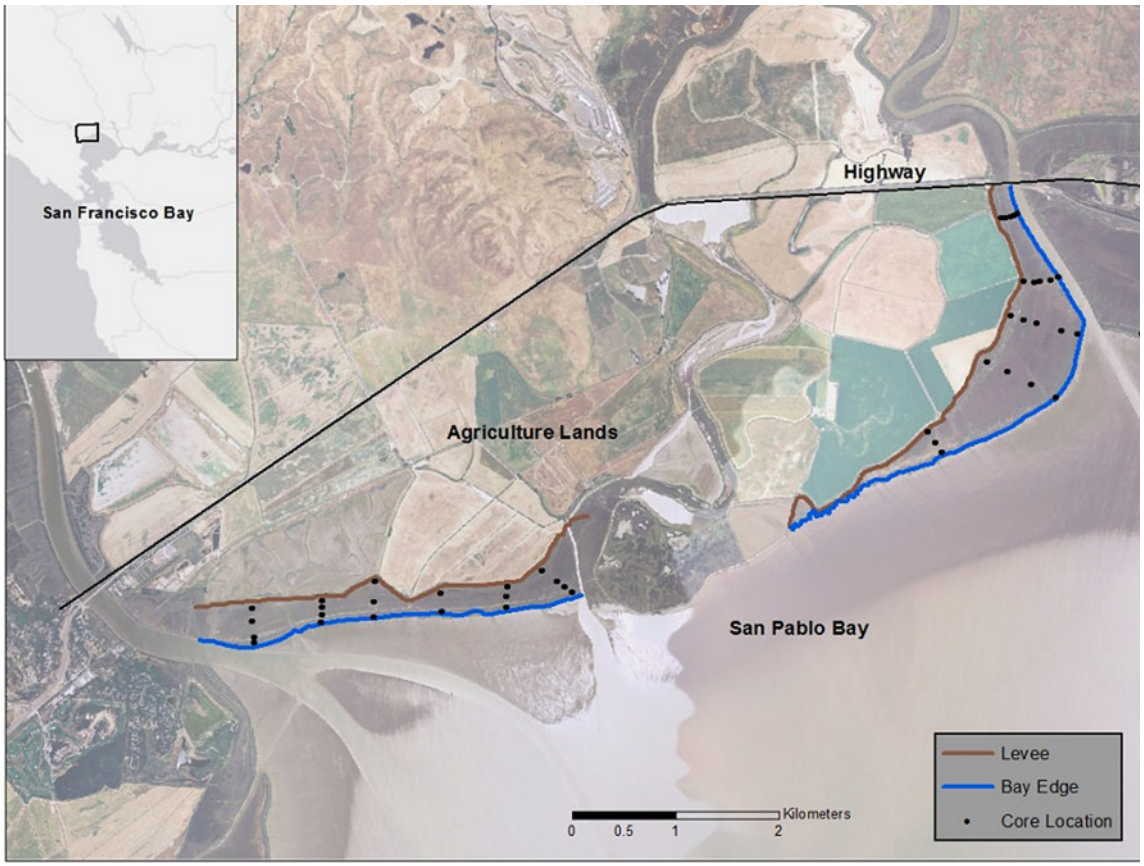

Fig. 1 San Pablo Bay National Wildlife Refuge (SPBNWR) located in the northern embayment of the San Francisco Bay estuary in northern California. SPBNWR contains large expanses of tidal salt marsh which provide habitat for salt marsh wildlife. Comparable elevation surveys were done in 1995 and in 2008 to evaluate elevation change over time. NAIP 2010 imagery was used

the benchmark was ±2.0 cm which was similar to the estimated vertical error of the Leica rover. Elevation data were surveyed perpendicular to the bay edge with a point taken every 25 m along transects separated by 50 m. The Geoid03 model was used in calculating elevations (NAVD88) under horizontal datum NAD83, UTM Zone 10. Elevations (NAVD88) were transformed into mean high water (MHW) values using the San Francisco Golden Gate tide gauge (#9414290). We did not use light detection and ranging (LiDAR)-derived elevation data to calculate elevation change, because when compared with ground orthometric elevation surveys, differences ranged between 10 and 35 cm (Foxgrover et al. 2011; Morris et al. 2005) depending on vegetation density.

We created separate 5×5 m^2 gridcell elevation models for 1995 and 2008 using ArcGIS 9.3 (ERSI 2009, Redlands, CA). Elevation models were created with spatial analyst applying inverse-distance weighting (IDW) methods (power 2, variable search radius, 12 number points, 5 m cell size), and model parameters were adjusted to minimize the root-mean-square (RMS) error, an internal measure of model performance for both data sets. We used the ArcGIS raster math tool to subtract the 1995 from the 2008 surface to determine marsh surface elevation changes over 13 years.

SLR was assumed to be 2.01 mm year^{-1}, with a 95 % confidence interval (95 % CI) of +0.21 mm year^{-1} based on monthly mean sea level data from 1897 to 2006 from the San Francisco Bay tide gauge (http://tidesandcurrents.noaa.gov/sltrends; Cayan et al. 2006) for a maximum increase of 2.86 cm possible over the 13-year study period. Any areas with increasing marsh surface elevations at or above 2.86 cm were considered to be "keeping pace" with SLR.

Site Characteristics

Soil samples were collected in August 2009 at 44 locations. Equal numbers of samples were collected along a transect from high to low elevation in areas of positive, negative, or no elevation change. Sample locations were selected randomly along those transects using ArcGIS images and found in the field using a GPS to limit site selection bias. Three soil sample replicates were collected at each site and averaged ($n = 132$). The upper 25 cm of the marsh soil was collected with a Russian Peat Borer (http://www.aquaticresearch.com/russian_peat_borer.htm). Samples were stored in sealed plastic bags and all visible roots were removed. Samples were dried and ground with a mortar and pestle until homogenized. They were

analyzed at the University of California, Davis, CA, Analytical Laboratory to assess percent OM, particle size (sand/silt/clay), and bulk density (BD). BD, the ratio of the mass of dry solids to the bulk volume of the soil, was determined by drying (105 °C) and weighing the soil sample with the known volume determined by the core size (9×25 cm^2; Blake and Hartge 1986). Soils with a high proportion of pore space to solids have lower bulk densities than those that are more compact and have less pore space. Percentage OM was determined by the Walkley–Black method, with a detection limit of approximately 0.10 % (see method detail in Nelson and Sommers 1982).

Sand particles were considered smaller than 2 mm but larger than 0.05 mm in diameter (Sheldrick and Wang 1993). Silty soils can retain more water (i.e., have lower permeability) with silts classified as particles smaller than 0.05 mm but larger than 0.002 mm. Particles smaller than 0.002 mm were classified as clay, with greater capacity to absorb water and settle out slowly when suspended in water. Particle size was determined by settling rates in an aqueous solution with a hydrometer and detection limit of 1 % (Sheldrick and Wang 1993). Soil classifications were identified with the U.S. Department of Agriculture Soil Survey, Sonoma County, CA (http://websoilsurvey.sc.egov.usda.gov).

Plant species were recorded and percent cover was determined within 0.25 m^2 quadrats at all 44 core locations (see Table 1 for the summary of plant species recorded for each sample site). Dominant species were determined by the highest percent cover within a quadrat (>50 % vegetated cover). The nearest distance to bay's edge, channel, and levee were measured in the field by walking a straight line to the edge of the feature. Any distances>35 m were measured in ArcGIS and applying the measuring tool and Google Earth imagery (Google, Cupertino, CA).

The soil stable isotope compositions were investigated to evaluate application of C and N isotopes as a source-specific marker for the OM (derived and washed from terrestrial organisms, phytoplankton, macro-algae, seagrasses, or rooted salt marsh plants). Soil subsamples were taken from the 44 core samples and were analyzed for C–N isotopic signatures. Soil was dried and homogenized and processed at the University of California, Davis, CA, Stable Isotope Facility with a PDZ Europa 20–20 continuous flow isotope ratio mass spectrometer (Sercon, Cheshire, UK). During analysis, samples were interspersed with four lab reference standards. Results were presented as $\delta^{13}C$ and $\delta^{15}N$ (‰) deviations from standards. The long-term standard deviation was 0.2 ml^{-1} for ^{13}C and 0.3 ml^{-1} for ^{15}N.

Model Assessment

We used Akaike's Information Criterion (AIC) to select the most parsimonious model that best explained elevation change (Burnham et al. 2011; Burnham and Anderson 2002). AIC ranks models from best to worst with an estimator of precision or parsimony. This provides a means of quantitatively ranking models and covariates to determine their relative value and importance to our question of what biogeomorphic and spatial properties contributed to marsh elevation change.

We used second-order AIC (AICc) for small sample sizes (Burnham and Anderson 2002) where $n/K\leq40$, n = sample size and K = number of estimated parameters included in the model. AICc was defined by [AICc=-2(log-likelihood)+$2K$+$\{2K(K+1)\}/(n-K-1)$] and was used to determine the most parsimonious model. We identified a set of candidate models that represented good approximations of the relationships of the covariates to the response variable defined as elevation change over 13 years. Covariates included percent OM, BD, distance to bay's edge (DistBay), distance to levee (DistLevee), distance to nearest channel (DistChannel), and percent silt (silt). Suspended sediment in San Pablo Bay is mainly composed of silt and was included in models. Sand was not used in candidate models because of its consistently low values (≤10 %), and clay was omitted because it was considered not a component of local suspended sediment. Nine candidate models were developed (Table 2), and selection of the best model was used to make inferences from the dataset. We calculated $\Delta AICc_i$ ($\Delta AICc_i = AICc_i$-min AICc) as a measure of each model relative to the best model, whereas models with a $\Delta AICc_i \leq 7$ were considered to have ecological importance to the dataset (see Burnham et al. 2011). Akaike weights (w_i) were computed as [$w_i = \exp(-\Delta AICc_i/2)/\sum\exp(-\Delta AICc_i/2)$]. To provide model-based inference across covariates, model averages were estimated (*see* Burnham and Anderson 2002; Table 3). Data were tested for autocorrelation, and statistical analyses were completed with nlme and AICcmodavg libraries in R (www.cran.r-project.org).

Results

Elevation Evaluation

The 1995 survey comprised 1,369 points with a range of 2.97 m ($\bar{x}$ =0.22 m, SD=0.32; MHW, NAVD88), a minimum elevation of -1.37 m (MHW), and a maximum of 1.59 m (MHW) with 89 % of the points above MHW (m, NAVD88). The elevation survey in 2008 contained 669 elevation points with an overall range of 2.54 m ($\bar{x}$ =0.23 m, SD=0.28; MHW, NAVD88), a minimum of -1.05 m (MHW), and a maximum of 1.48 m (MHW) with 92 % of the points above MHW (m, NAVD88). The interpolated elevation models for 1995 and 2008 had RMS error of 0.070 and 0.068. The average elevation was similar between both years; however, marsh platform elevation decreased within the interior of the marsh (e.g., upper marsh platform) while most accretion occurred near San Pablo Bay or the lower marsh edge (Fig 2). Changes in

Table 1 Summary of plant species recorded for each sample site and $\delta^{13}C$ (‰) and $\delta^{15}N$ (‰) summary statistics for 44 soil samples

	$\delta^{13}C$(‰)			$\delta^{15}N$(‰)			
	Min	Mean	Max	Min	Mean	Max	*n*
Sarcocornia pacifica	-27.36	-25.72	-22.41	6.02	6.81	7.95	38
Spartina spp.	-24	-23.54	-23.04	5.77	6.07	6.56	4
Frankenia salina	NA	-24.05	NA	NA	6.78	NA	1
Grindelia stricta	NA	-26.01	NA	NA	5.9	NA	1
Mean	-27.36	-25.49	-22.41	5.77	6.72	7.95	44

n number of sample points

marsh surface elevation ranged from -1.16 m to +1.41 m ($\bar{x}$ = -0.01, SD=0.15). When comparing all 5-m pixels across the marsh surface, the categories with the largest amount of change were - 0.1 to 0 m (39 %), 0 to +0.10 m (26 %), and -0.2 to -0.1 m (13 %) (Fig. 3). Whereas 55 % (169 ha) of the marsh area subsided over the study period, 37 % (113 ha) of the marsh increased in elevation at a rate that would keep pace with SLR, while 63 % (196 ha) did not keep pace with SLR (Fig. 4).

Site Characterization

The nearest distance to the edge of San Pablo Bay for the soil cores was $\bar{x}$ =189.6 m, with a range from 1.4 to 639.5 m. Mean distance to the nearest levee was 217.8 m ranging from 20.6 to 782.5 m. Mean distance to the nearest channel ranged from 1 to 331 m and averaged 77.5 m. Vegetation was similar between quadrats with 38 of 44 (86 %) containing *S. pacifica* (perennial pickleweed) with a mean percent cover of 97 %. *S. foliosa* (Pacific cordgrass) was the next most common species across quadrats, with 75 % mean cover at four quadrats. *Frankenia salina* (alkali heath) or *G. stricta* (Oregon gumplant) were each dominant at one quadrat. *Cuscuta salina* (salt marsh dodder), a parasitic plant on common pickleweed, was present at 19 (43 %) of the quadrats. *Lepidium latifolium* (perennial pepperweed), a local invasive species was present at two quadrats. In general, the vegetation community was uniform across most of the marsh surface and these species composed >50 % of the cover.

Soil Characteristics

Bulk densities ranged from 0.41 to 0.77 g cm^{-3} ($\bar{x}$ =0.58 g cm^{-3}), indicating that soils had a relatively low proportion of pore space for marshes. Highest values of BD were along the bay's edge with lower values observed in the interior of the marsh. Percent OM was relatively low for marshes with a mean of 3.76 % and ranged from 2.15 % to 5.44 %. OM content was highest in the interior of the salt marsh and lowest along the bay's edge. Soil texture or particle size composition included silt which ranged from 29.3 % to 52.7 % ($\bar{x}$ =39.3 %), sand

Table 2 The models with the highest AICc weights included the distance from the bay edge and levee, highlighting that spatial attributes in this study to be the most important. Surprisingly, our models did not show that organic matter (OM), bulk density (BD), or silt were good indictors for elevation change for this system. Four models were the most parsimonious in explaining elevation change with a cumulative AICc weight of 0.98. Models that have substantial support (ΔAICc≤7; Burnham et al. 2011) are in italics

Candidate model	K[a]	Log-likelihood	AICc[b]	ΔAICc[c]	AICc wt. (w_i)[d]	Cumulative wt. (w_i)
DistBay + DistLevee	*6*	*18.06*	*-21.85*	*0*	*0.53*	*0.53*
DistBay + DistLevee + DistChannel	*7*	*18.46*	*-19.8*	*2.05*	*0.19*	*0.72*
DistBay + DistLevee + OM	*7*	*18.17*	*-19.22*	*2.63*	*0.14*	*0.87*
DistBay + DistLevee + DistChannel + OM +BD + Silt	*10*	*22.72*	*-18.78*	*3.08*	*0.11*	*0.98*
DistBay + DistLevee + DistChannel + OM + BD	9	18.7	-14.11	7.74	0.01	0.99
OM + BD + Silt	7	15.21	-13.31	8.55	0.01	1
OM	5	7.15	-2.72	19.13	0	1
OM + BD	6	8.44	-2.61	19.24	0	1
BD	5	5.97	-0.37	21.48	0	1

[a] The number of estimated parameters in the model including the variance

[b] Second-order Akaike's information criterion (AICc)

[c] The difference in the value between AICc of the current model and the value for the most parsimonious model

[d] The likelihood of the model given the data, relative to the other models in the candidate set

Table 3 Multimodel inference can be made by averaging covariates to assess the importance for each variable. Note that bulk density, organic matter, and distance to channel had confidence intervals that passed through zero indicating uncertainty in their influence in elevation change

Covariates	Model-averaged estimates	Standard error	95 % Confidence intervals	
			Lower	Upper
Bulk density	0.028	0.272	-0.51	0.56
Organic matter	-0.002	0.044	-0.09	0.084
Silt	0.017	0.006	0.006	0.03
Distance to levee	0.0006	0.0002	0.0002	0.001
Distance to channel	0.0004	0.0003	-0.0003	0.001
Distance to bay	-0.0006	0.0003	-0.001	-0.0001

from 5.0 % to 13.7 % ($\bar{x}$ = 10.0 %), and clay from 34.3 % to 57.0 % ($\bar{x}$ =50.7 %).

The majority of the soils were silty-clay texture class, with a few samples with a greater percentage of clay texture. The soils were classified as Reyes Series silty clays in the subgroup Fluventic Haplaquepts and order Inceptisols. The A horizon as noted in our samples has 3.8 % to 5.4 % OM and was gray to dark gray in color. The B horizons were strongly mottled through redox processes with root channels and higher in clay according to field descriptions. The C horizons were strongly gleyed.

Mean soil δ^{15}N was $\bar{x}$ =6.72 with a range of 5.77 to 7.95 (Fig. 5). Mean soil δ^{13}C was $\bar{x}$ =-25.72 with a range of -27.36 to -22.41. Out of 44 data points, 35 (79.5 %) were within -25 and -27 for δ^{13}C. In comparison, Benner et al. (1991) reported -13.1 for δ^{13}C and 3.1 for δ^{15}N values for *Spartina* spp. in coastal Georgia; none of our values fell within this range. Our δ^{13}C results fell within the reported δ^{13}C range for *S. pacifica* for San Francisco Bay, with reported δ^{13}C values of -27.0 (Cloern et al. 2002), suggesting that this plant may have contributed to the soil organic carbon. However, our δ^{15}N mean was not within the published range for *S. pacifica* (12.8 for δ^{15}N; Cloern et al. 2002). Our mean δ^{15}N and δ^{13}C did fall within the average for C_3 emergent vascular plants (Howe and Simenstad 2007) suggesting that they contributed to marsh soil OM content.

Model Evaluation

Environmental variables were not auto-correlated and fit a Gaussian distribution. We found four models that were the most parsimonious in explaining elevation change within a ΔAICc ≤7 (Burnham et al. 2011) and a cumulative AICc weight of 0.98 (Table 2). The first model included the

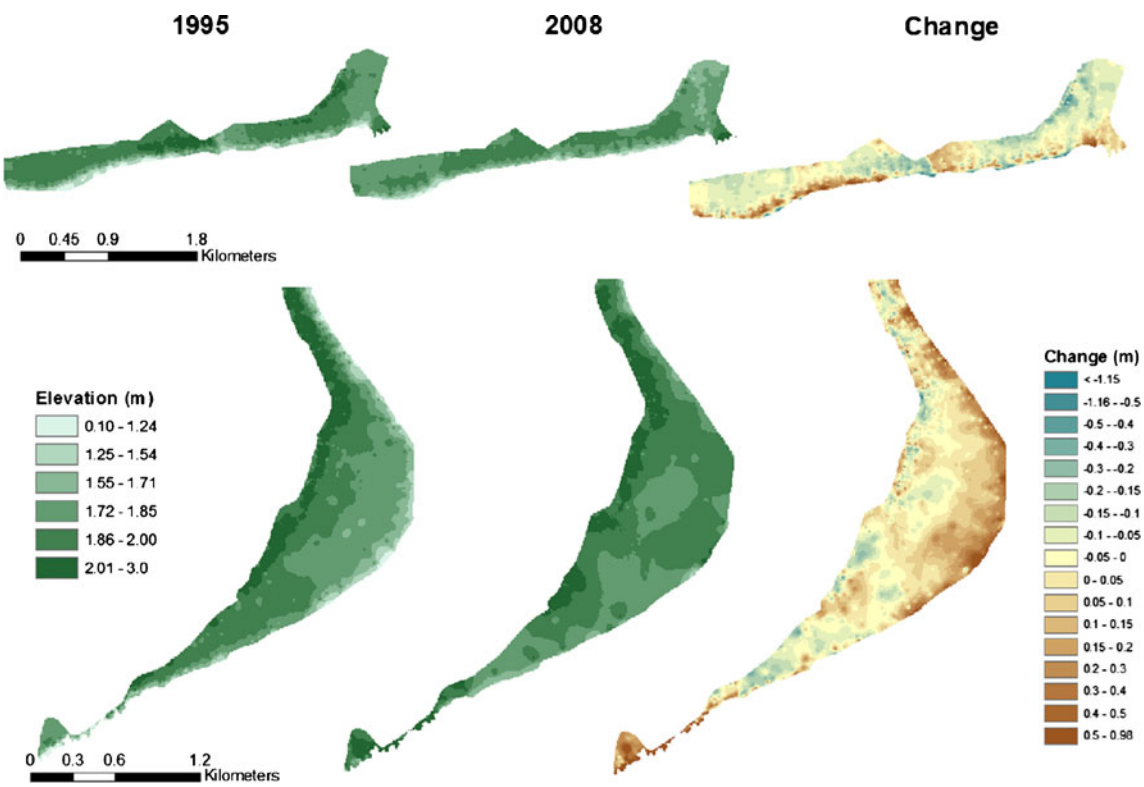

Fig. 2 Two elevation surveys were conducted on 309 ha of tidal salt marsh of the San Pablo Bay National Wildlife Refuge. Elevation datasets were used to create 5×5 m^2 grid cell elevation models for 1995 and 2008 (NAVD88), with ArcGIS 9.3 (ERSI 2009, Redlands, CA). A model of grid cell differences were created by subtracting elevation models to measure marsh surface elevation change during this time

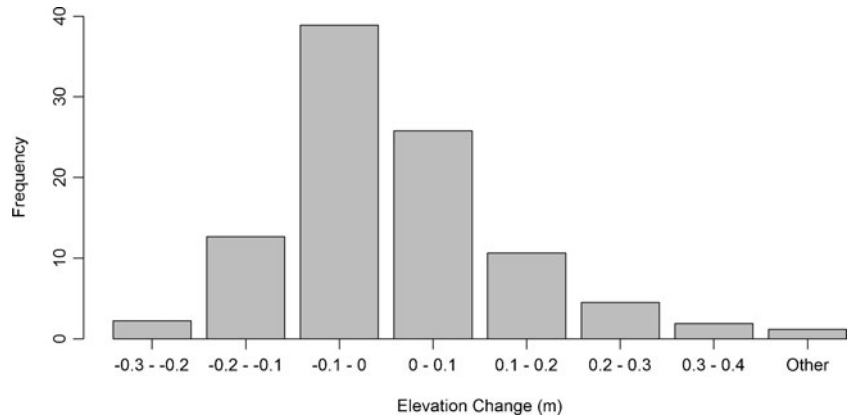

Fig. 3 An elevation change map was generated estimated by subtracting measured elevations in 1995 from 2008 in 5×5 m^2 grid cells. Any elevation change that was <1.0 % of the study area was included as Other

covariates DistBay and DistLevee which had the highest weight of w_i=0.53 (Table 2). The model with the second highest AICc weight (0.19) contained all distance covariates (DistBay, DistLevee, and DistChannel). The third highest model had an AICc weight of 0.14 and included DistBay, DistLevee, and OM. DistBay and DistLevee were found in all four top models, suggesting the importance of these attributes in explaining elevation change. DistChannel and OM covariates were found in two of the top four models.

Model averaging provided covariate model estimates with associated standard errors and 95 % CIs (Table 3). BD had the largest model estimator of 0.027 (SE 0.28), but a large 95 % CI (-0.51, 0.56). However, BD only appeared in one of the top four models. OM was -0.002 (SE 0.04), with a wide 95 % CI (-0.09, 0.08), and only occurred in two of the top four models. Although estimates for OM and BD were given, the confidence intervals for these covariates included zero. Silt had a model-averaged estimate of 0.017 (SE 0.006) and 95 %

Fig. 4 Areas depicted in *white* are those that were not maintaining their marsh surface elevation relative to sea-level rise during the study period. *Black* areas had an increase in elevation great enough to be keeping pace with relative sea level rise

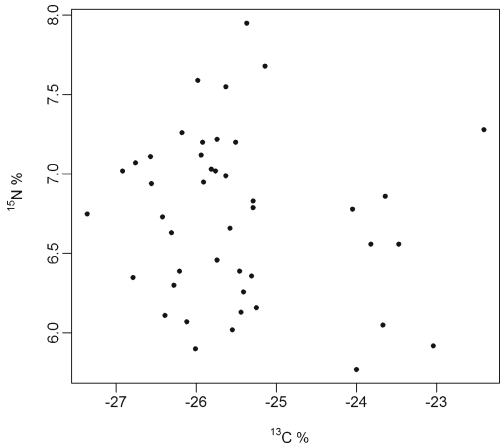

Fig. 5 Soil samples (n=44) evaluated for $\delta^{13}C$ (‰) and $\delta^{15}N$ (‰) composition to determine the origin of the organic matter in the soil. There was a relatively small range for $\delta^{13}C$ with only nine sample points falling outside of the -25 to -27 ranges. The $\delta^{15}N$ range was less variable with all data points falling within 5.5 and 8.0

CI of (0.006, 0.028). DistLevee, DistChannel, and DistBay had the smallest standard errors (all SE≤0.0003) and model-averaged estimates of 0.0006, 0.0004, and -0.0006, respectively.

Discussion

Elevation Change

We assessed marsh surface elevation change over 13 years to determine if the SPBNWR marshes were keeping pace with SLR. The best explanatory AIC models for elevation change included distance from bay edge and levees, illustrating the importance of proximity to sediment source for accretion processes. San Pablo Bay demonstrated annual and seasonal cycles of deposition and re-suspension of suspended sediment, especially during the winter and the spring from the Sacramento–San Joaquin River Delta and from local wind–wave action, although the percentage of suspended sediment varies between years (McKee et al. 2006; Schoellhamer et al. 2007). Increased elevation or accretion mostly occurred along the bay's edge at our study site, as would be expected with lower starting elevations and higher frequency of tidal inundation where sediment-laden flood tides first encounter marsh vegetation (Callaway et al. 1997).

Primary production and OM accumulation can be large contributors to marsh development (Callaway et al. 1997). In San Francisco Bay, marsh stability has been reported to depend more on available suspended sediment for accretion processes (Stralberg et al. 2011). It has been assumed that SPBNWR has the needed local suspended sediment supply from San Pablo Bay for vertical marsh accretion processes and has been projected to be sustainable under moderate SLR (Orr et al. 2003; Stralberg et al. 2011). However, our results indicated that there was widespread subsidence and low rates of accretion in the interior of the marsh indicating variability in biogeomorphic processes that may undermine its long-term sustainability. No groundwater or oil extraction is ongoing in this region and were ruled out as contributing to subsidence rates. In addition, tectonic crustal subsidence for San Pablo Bay was not occurring (Atwater et al. 1977; BCDC 1987); therefore, subsidence in the interior of the marsh was likely indicative of altered biogeomorphic processes and possible influence from upland conditions, particularly levees. Levee barriers including those constructed for agricultural purposes, roads, and to alter surface water flow, may prohibit upland sediment inputs from creeks or overland flow. Any reduction of upland channel complexity that delivered water and sediment to these upper reaches could also contribute to subsidence (Reed et al. 1999; Ganju et al. 2005). For example, subsidence and natural compaction can occur by oxidation of root OM and collapse from drying (Day et al. 2011). Impoundment of water against the levees can cause increased erosion, and decomposition and compaction of the soil, also resulting in subsidence (Letzch and Frey 1980). By measuring the marsh surface elevation change, we captured both shallow and deep processes thus provided a more complete picture of elevation change (Cahoon et al. 1995). This measure could be important in areas where long-term accretion monitoring is not ongoing.

Biogeomorphic and Soil Properties

Important biogeomorphic and soil properties were assessed to identify key processes constructing the marsh surface. These soils were mineral-based with relatively low OM for marshes most likely reflecting their younger age (Jaffe et al. 2007). Surprisingly, our models did not show that OM, BD, or silt were good indicators of elevation change. BD was relatively high for marshes, indicating that soils had low proportion of pore space (higher compaction) compared to other marshes (Chmura and Hung 2004). For example, BD values for two marshes dominated by *Spartina patens* along the Atlantic coast fell between 0.14 and 0.29 g cm^{-3} (Twohig and Stolt 2011), and BD in tidal salt marshes of western Canada ranged from 0.15 to 0.38 g cm^{-3} (Chmura and Hung 2004). The BD value in SBPNWR marshes indicated that soils were formed by fine-grained mineral matter rather than by primary production or OM accumulation.

The recentness of the soils is shown in their soil profiles as Inceptisols (Fluventic Haplaquepts). They developed from fine sediments of primarily sedimentary and volcanic bedrock from streams and rivers which flow into San Pablo Bay and are re-suspended hydraulically and deposited by tidal processes. However, for the greater San Francisco Bay Estuary, historic hydraulic gold mining in the Sierra Nevada increased sediment delivery to the estuary (Hagwood 1981)

and resulted in the filling of San Pablo Bay (Jaffe et al. 2007). Mining debris entering San Francisco Bay was substantial between 1865 and 1951 (Jaffe et al. 1998) which could also account for the high mineral content and low channelization resulting from its rapid formation and altered biogeomorphic processes.

OM found in the sediment samples, regardless of location within the marsh or tidal frame, was consistent with high marsh C_3 vegetation (Lamb et al. 2006; Howe and Simenstad 2007). Our results indicated that local organic carbon may have been derived from the dominant C_3 species *S. pacifica* and that the soils had limited OM by weight (<5.45 %) for marshes. Other marshes have been shown to have OM percentages that ranged from ~30 % in Louisiana (Wilson and Allison 2008), 47–80 % on the East Coast of North America (Twohig and Stolt 2011) and an average of> 50 % in the Sacramento and San Joaquin River Delta (Drexler 2011). Drying of the upper marsh may lead to decomposition of OM and may have led to lowering of the marsh surface elevation at our study site.

Sea-Level Rise

Our study showed that only 37 % of the marsh kept pace with a SLR rate of 2.86 mm year^{-1}, primarily along the tidal edge of the bay (Fig. 4). Most of the marsh interior had a loss of elevation. Marsh subsidence has been observed in other modified systems where local suspended sediment is insufficient (Kirwan and Guntenspergen 2010; Ravens et al. 2009; Lane et al. 2006); however, our results are unique in that we were able to measure the spatial variability of the elevation change across the surface. Here, upland levees prohibit marsh transgression, and therefore, vertical marsh accretion is a key factor in long-term sustainability of this area.

Conclusion

Coastal marsh formation and persistence is a balance between accretion, subsidence, OM input, below and above ground biomass, mineral sediment input, erosion, and local SLR. However, in urbanized and developed estuaries, marshes are affected by changes in sediment availability and infrastructure such as levees and roads that can prohibit transgression. As a result, marsh long-term persistence relies mostly on vertical accretion rates relative to SLR (Kirwan and Guntenspergen 2010; Reed 2002; Morris et al. 2002). The methodology described herein provides an alternative means of estimating marsh accretion when long-term monitoring has not been done (Webb et al. 2013).

Many marshes are heavily modified and fragmented, and large-scale and costly restoration and enhancement projects are underway to improve the health of these ecosystems. However, long-term planning requires a comprehensive understanding of biogeomorphic feedbacks to better forecast the potential effects of SLR on these projects. The spatially explicit analysis presented herein allowed us to evaluate processes that may be disregarded or overlooked when taking few samples that are then extrapolated across the landscape. Analyses at the site level provide insights into restoration and enhancement efforts that can be conducted to reconnect or enhance natural tidal influence and delivery of sediment. In light of SLR, improving our understanding of elevation change in these dynamic marsh systems will play a crucial role in forecasting potential impacts to their sustainability and the survival of these ecosystems (Thorne et al. 2012).

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