Wetland Sediment Accumulation at Corte Madera Marsh and Muzzi Marsh

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INTRODUCTION

Tidal wetlands are found in the upper portion of the tidal range in protected bays and estuaries (Grewell et al. 2007). Over time, elevation relative to the tides within these wetlands is decreased by increases in sea level, local subsidence, decomposition, and surface sediment compaction (Callaway et al. 1996b, Friedrichs and Perry 2001, Turner et al. 2006). Relative elevation is increased by accumulation of sediment on the surface of the wetland, as well as input of organic matter from local plant production. In most tidal wetlands these processes are in relative balance, leading to stable elevations and vegetation over time; however, in coastal Louisiana, Chesapeake Bay and other locations with high rates of local or regional subsidence, wetlands may be losing elevation (Stevenson et al. 1986, Kearney and Stevenson 1991, Boesch et al. 1994).

Within a particular wetland, rates of vertical sediment accretion tend to be higher in areas of the wetland that are more frequently inundated, i.e., areas closer to creeks and at lower elevations. Craft et al. (1993) found higher accretion rates adjacent to tidal creeks; however, accretion rates were greater in irregularly flooded areas of the wetland than in regularly flooded areas due to high rates of organic matter accumulation in irregularly flooded portions of the wetland. Similarly, French and Spencer (1993) found very slow rates of tidal accretion in infrequently flooded parts of the wetland. Hatton et al. (1983) showed a significant decrease in accretion rates from the low to high marsh, and others have found similar trends (French and Stoddart 1992, Callaway et al. 1997, Weis et al. 2001). These patterns from natural tidal wetlands are also likely to be reflected in restored wetlands (Callaway et al. 2012). In particular, many restored wetlands are slightly lower in elevation and may receive more input from tidal inundation (e.g., recently salt ponds in south San Francisco Bay, Callaway personal observations).

In addition to spatial variation in sediment dynamics, there are temporal patterns in measured rates of sediment accumulation because of belowground processes that affect sediment characteristics over time. Decomposition and shallow compaction can lead to consolidation of sediment and reduce the volume/depth of accumulated sediment over time, i.e., 1 cm of sediment on the surface of a wetland may be substantially reduced over time as it is buried and subjected to belowground processes (Turner et al. 2006). On the other hand, input of roots and rhizomes belowground can increase sediment volume/depth and counteract the above processes over time (McKee 2011). Given these counteracting processes, a range of methods have been used to evaluate sedimentation rates over different time periods and to focus on particular processes of interest (Cahoon et al. 1995).

On the shortest time scale, sediment plates or pads have been used to measure sediment accumulation over periods of days to weeks (Reed 1989, Neubauer et al. 2002). Because of the short interval and small amount of sediment that accumulates, these methods typically focus on measuring mass-based rates of sediment accumulation rather than vertical rates. Marker horizons (e.g., feldspar, brick dust, etc.) have been used widely to measure vertical rates of accumulation over the period of months to years (Cahoon and Turner 1989, Stoddart et al. 1989, French et al. 1995). This method works well in depositional areas, as are typically found in coastal wetlands in San Francisco Bay. Bioturbation typically is not a problem in vegetated wetlands and should not affect the markers. However, markers measure surface accumulation and do not incorporate the belowground processes identified above. Surface Elevation Tables (SETs) are used in conjunction with marker horizons to measure changes in wetland surface elevation with very high precision (within a few millimeters) and incorporate both surface sediment accumulation as well as belowground processes (Boumans and Day 1993). The difference between surface accumulation (measured with marker horizons) and changes in relative elevation (measured with SETs) gives an estimate of local compaction and other belowground processes (Cahoon et al. 1995).

Dated sediment cores have been used to measure longer term sediment dynamics and incorporate both surface and belowground processes throughout the depth of the core (Armentano and Woodwell 1975, DeLaune et al. 1978, Ritchie and McHenry 1990, Craft and Richardson 1998, Ellison 2008). Wetland sediment cores typically have been dated using ^{137}Cs and ^{210}Pb, which provide data on integrated rates of accretion and belowground processes over approximately 50 and 100 year time spans, respectively. Collecting sedimentation data using a variety of methods allows for comparisons of different processes and time scales.

The tidal wetlands at Corte Madera Ecological Reserve offer an opportunity to evaluate wetland sediment dynamics across a range of conditions, as this site encompasses both a remnant natural tidal salt marsh on the northern portion of the Reserve (hereafter referred to as Corte Madera Marsh) and a fairly old restored wetland in the southern portion (Muzzi Marsh). In addition, Muzzi Marsh includes a range of tidal elevation related to the history of the site. The site was diked off and had experienced some local subsidence prior to restoration in 1976. The landward edge of Muzzi Marsh was filled with dredged material to increase elevations and promote rapid plant establishment prior to breaching and initial restoration. No filling was done in the bayward portion of Muzzi Marsh, and elevations here remain lower than in the filled portion of the site.

We evaluated sediment dynamics at both Corte Madera Marsh and Muzzi Marsh using sediment pads (very short-term, mass-based rates of sediment accumulation), marker horizons (surface sediment accumulation) SETs (changes in relative elevation), and sediment cores (longer-term sedimentation rates). This work was completed in conjunction with studies of mudflat and subtidal sediment dynamics by the US Geological Survey and others.

METHODS

Transects and Sampling Stations

All sampling was done along transects that were established along a gradient from the bay edge to the landward edge of each wetland with low, mid, and high stations. Two transects were established at both Corte Madera Marsh and Muzzi Marsh (see Figures 1 & 2 and Table 1 for sampling locations). This design provided information on variation in processes across the wetland (low to high stations) and allowed for comparison with data from other sites where similar have been collected (Callaway et al. 2012). Each sampling station was marked using a high-precision, RTK GPS receiver that has an overall accuracy of a few cm, both vertically and horizontally. This provided precise estimates of elevation for each sampling station and allowed for easy relocation of sampling stations.

Sediment pads were established on Transect A at Corte Madera Marsh (Figure 1) and Transect A at Muzzi Marsh (Figure 2). In addition to the low, mid, and high stations, sediment pads were placed at stations on the wetland/mudflat interface just below the low stations (referred to as low low stations in the Results section) in order to evaluate sediment inputs at this interface. Feldspar marker horizons were established at low, mid and high stations on both transects at each wetland, and the SET station was established at the mid station on transect A at

Corte Madera Marsh (Figures 1 &2). Sediment cores were collected at low, mid and high stations on both transects at each wetland (Figures 1 & 2).

Short-term Sedimentation Rates

Sediment Pads

In order to estimate short-term, mass-based rates of sediment accumulation, we used a modification of the "filter paper" method (Reed 1989). Rather than placing a filter paper on the existing substrate, we used a pre-weighed, thin rubber disk of approximately 12.5 cm diameter. This method had been used successfully on mudflats on the east coast (Jill Rooth, personal communication) where tidal currents and wind waves could remove or damage filter paper, and we have used the method in the Island Ponds in South San Francisco Bay. We placed two disks on top of one another and only the top disk is used to measure accumulation. We secured the disks to the wetland surface using nails or screws pushed into the sediment surface. Disks were left in place for a two-week period approximately every three months from August 2011 to July 2012 (see Table 2 for sampling periods). A two-week period was chosen as this represents a full spring-neap sequence of tidal conditions. After two weeks, the pre-weighed disk and all sediment that have accumulated on it were collected and placed into a ziploc bag. In the lab, the pre-weighed disks and all sediment were dried and weighed.

Marker Horizons and SETs

In order to evaluate seasonal and annual sediment accretion, we measured vertical sediment accretion using feldspar marker horizons and changes in wetland surface elevation using a Sedimentation-Erosion Table (SET). We established marker horizons at the mid, low and high stations on all transects at both Corte Madera Marsh and Muzzi Marsh. At each station, four marker plots (0.5x0.5 m) were established, and data from all four plots were averaged for each station. A single SET station was established at the mid station on transect A at Corte Madera Marsh.

To measure accretion, we laid down a feldspar marker over the existing wetland surface in a 0.5x0.5-m area (see Table 2 for installation and sampling dates). This area was marked with PVC posts for easy relocation, and the area was sampled at subsequent dates by collecting a small plug of sediment with a sharp knife. The depth of newly deposited sediment on top of the marker horizon was measured, indicating the vertical accretion of sediment over the time period. Two sediment plugs were collected per plot, and data from all four plots were averaged for each station.

We pounded an aluminum pipe into the wetland sediment to establish a permanent benchmark, and attached the SET to this benchmark to measure changes in the elevation of the wetland surface over time. The SET station was set up adjacent to the marker horizon plots at the mid station on transect A at Corte Madera so that accretion could be measured simultaneously with changes in sediment elevation at this station, allowing for the determination of shallow subsidence (Cahoon et al. 1995). Following establishment, stations were monitored quarterly (see Table 2 for installation and sampling dates).

Long-term Sedimentation Rates

Core Collection and Preliminary Sample Preparation

Cores from the tidal wetlands were collected with a sharp-edged soil coring tube (15-cm diameter). Large coring tubes are very useful for collecting uncompacted samples for profiles of soil characteristics (Hargis and Twilley 1994). Sediment cores were collected to a depth of approximately 50 cm (see Table 2 for sampling dates). At the time of core collection, the cover of dominant vegetation at each sampling station was recorded, and salinity of soil porewater was measured using a temperature-compensated refractometer. All cores were sectioned at 2-cm intervals to provide detail on sediment characteristics with depth. Cores were sectioned in the field, bagged in airtight ziploc bags, returned to USF, dried, weighed, and ground with a mortar and pestle (see Nyman et al. 1990, Callaway et al. 1996a for additional detail on these methods).

Sediment bulk density (g/cm^3) was measured using the dry weight of the sediment from each 2-cm sampling increment. Organic and mineral content of each section was determined using the loss-on-ignition method by burning a sediment sample in a muffle furnace at 450˚C for 8 hours (Ball 1964, Craft et al. 1991). Sediment organic matter content and carbon content are highly correlated (Craft et al. 1991, Callaway et al. 2012); we used a quadratic regression based on samples from San Francisco Bay tidal wetlands and similar to that developed by Craft et al. (1991) to convert the sediment organic matter content of each 2-cm soil section to carbon content (both expressed as % of dry weight), and to calculate carbon sequestration: sediment carbon content = (0.001217)*OM content^2 + (0.3839)*OM content (r^2=0.99, n=97; Callaway et al. 2012).

Sediment Dating with ^{137}Cs and ^{210}Pb

Once processed, the cores were dated using sediment profiles of ^{137}Cs and ^{210}Pb. Isotopic analyses were completed by Dr. Gene Turner and Charles Milan at Louisiana State University. Dr. Turner's lab has completed numerous studies using these methods and has published extensively in this field (Milan et al. 1995, Turner et al. 2000, 2004, 2006, Parsons et al. 2006). ^{137}Cs is a product of nuclear weapons testing and power plant accidents; it does not occur naturally. Significant levels of this isotope first appeared in the atmosphere in the early 1950s, with peak quantities detected in 1963, just prior to the banning of atmospheric nuclear testing. The sediment surface from 1963 can be identified based on the maximum activity of ^{137}Cs, and subsequent dates are assigned assuming a constant rate of sediment accretion since 1963. The ^{210}Pb method gives estimates of sedimentation rates on a time scale of approximately 100 years (Armentano and Woodwell 1975, Bricker-Urso et al. 1989). ^{210}Pb is a natural occurring isotope with a half-life of 22.3 years; it is part of the ^{238}U decay series. Assuming constant input of ^{210}Pb, you can calculate sedimentation rates based on the rate at which ^{210}Pb disappears from deeper sediments, as it decays to ^{210}Po.

The ^{210}Pb and ^{137}Cs activity was determined using an integrated gamma-spectroscopy system consisting of a Princeton Gamma-Tech 60 mm-diameter intrinsic germanium "N" type coaxial detector (40% efficiency) interfaced to an EG&G Ortec 92X Spectrum Master® mutichannel spectrum analyzer. A profile of each isotope's activity with depth was developed for each core. As noted above, accretion rates using ^{137}Cs are based on the depth of its peak activity in the core (Ritchie and McHenry 1990), and rates using ^{210}Pb are based on its rate of decay with depth (Armentano and Woodwell 1975, Thomas and Ridd 2004). More details on methods can be found in Milan et al. (1995) and Callaway et al. (2012). In order to calculate long-term, mass-based sediment accretion rates for each core, we used vertical accretion rates from the isotope dating, as well as profiles of sediment bulk density and sediment mineral and organic matter content. Profiles of sediment characteristics are used to convert the vertical-based sediment accretion data into mass-based mineral and organic matter accumulation and carbon sequestration rates (DeLaune et al. 1983, Callaway et al. 1997, Roman et al. 1997, Craft and

Richardson 1998). These mass-based sequestration rates are relevant to the same time period as the vertical accretion measurements from each method: ^{137}Cs (approximately 45 years) and ^{210}Pb (approximately 100 years).

RESULTS AND DISCUSSION

Short-term Sedimentation Rates

Sediment Pads

Short-term sediment accumulation measured with the sediment pads ranged from 0 to 15 g/m^2/day over two-week tidal-cycle intervals (Figures 3 & 4). Consistently the lowest rates were found at the low low station at both Corte Madera Marsh and Muzzi Marsh, with no sediment accumulation occurring at these stations on almost all sampling dates (Figures 3 & 4). This was surprising, as the low low stations typically had the highest sediment accumulation rates at other salt and brackish marsh locations in San Pablo Bay and Suisun Bay (unpublished data from recent CALFED project). High rates are to be expected at lower elevations within the wetland as these areas are flooded more frequently (Hatton et al. 1983, French and Stoddart 1992, Callaway et al. 1997, Weis et al. 2001). We hypothesize that the low rates at lower elevations within Corte Madera Marsh and Muzzi Marsh are due to more significant wave exposure at this site than at other sampling locations in the Bay, although additional data are needed to confirm this hypothesis.

Exclusive of the low low station, there were not strong trends across the wetland at Corte Madera Marsh (Figure 3). At Muzzi, accumulation rates were greater in low and mid Stations (Figure 4; as was found for other measures of sediment accumulation below). As above, higher rates of sediment input are expected at these stations as they are at slightly lower elevations than other stations (Table 1) and thus are more frequently inundated by the tides. The low stations at Corte Madera Marsh were slightly higher in elevation than the mid and high stations. In addition to spatial patterns, we were surprised to find the highest rates of sediment input in summer (June 2012; Figures 3 & 4). Research in other systems has identified that storm events typically lead to the highest periods of sediment input (Reed 1989), often in the winter. However, we had very low inputs of sediment in March following a series of small rainstorms. This was likely due to rain washing sediment off our collecting pads (an artifact of this collection method). In any case, even the highest rates collected during June 2012 are not exceptionally high compared to rates from other salt marshes and restored sites in San Francisco Bay (measurements at the Island Ponds averaged ~100 g/m^2/day with many individual measurements substantially higher than the mean, while most measurements at these sites were <10 g/m^2/day).

Marker Horizons and SETs

Rates of vertical accretion measured with the feldspar markers were low at Corte Madera Marsh, with 2-4 mm of sediment accreting over the 15-month sampling period (Figure 5). The change in relative elevation based on the SET at the mid-station on transect A at Corte Madera was very similar to the measured accretion rates, indicating that there was little surface consolidation occurring at the site (Figure 5). However, a single year of data is not sufficient to evaluate this, as these processes are relatively slow. Typically rates are compared over a three to five year period to evaluate shallow compaction.

Vertical accretion was highest at the low and mid stations at Muzzi Marsh (Figure 6; 12-13 mm of accumulation over 15 months). Accretion at the high station at Muzzi Marsh was slightly higher but comparable to rates from Corte Madera Marsh (5.6 mm of accretion over 14.5 months), and this station is comparable in elevation to the stations at Corte Madera Marsh (Figures 5 & 6). As with the data from the sediment pads, there was little indication of higher sedimentation rates in winter, as most sites showed a constant gradual increase in cumulative sediment accretion rather than a strongly seasonal pattern (Figures 5 & 6).

Converting cumulative rates over the entire sampling period, annual rates of accretion at Corte Madera Marsh were 0.30, 0.21, and 0.17 cm/yr for low, mid, and high stations, respectively. Rates at Muzzi Marsh were 0.80, 0.80, and 0.39 cm/yr for low, mid, and high stations, respectively.

Long-term Sedimentation Rates

Sediment Dating with ^{137}Cs and ^{210}Pb

All six sediment cores from Corte Madera Marsh were successfully dated using ^{137}Cs. Three cores had indications of sediment mixing in the lower cores (B low, A mid, and B high), and one core accumulated sediment so rapidly that the 50-cm core covered <100 years (A low). Because of these issues, it was not possible to date these cores to 100 years using ^{210}Pb, as is common with undisturbed cores; however, we dated these cores to the depth of the undisturbed layer for the three cores with mixing issues and to 50 cm/83.3 years for A low (see footnotes to Table 3 for depths).

There was a very slight decrease in the average rate of vertical accretion based on the ^{137}Cs peaks from low to high stations (Table 3; average rates for both transects 0.435, 0.405, and 0.36 cm/yr from low, mid and high stations, respectively). This gradient in accretion rates is not as strong as that found at many other tidal wetlands and could be due to the mature nature of this wetland, including slightly higher elevations at the low stations at Corte Madera Marsh. This also parallels the lack of any strong spatial gradient in current accretion rates measured with the feldspar markers at Corte Madera Marsh.

Accretion rates based on ^{210}Pb profiles were slightly higher or similar to rates based on ^{137}Cs, even though the ^{210}Pb-based rates cover slightly longer time periods. Even more surprising, the rates based on isotopic profiles from the sediment cores (both ^{137}Cs and ^{210}Pb) were higher than the short-term rates based on marker horizons, and this was true across all three stations. Typically short-term rates are higher than longer-term rates (e.g., markers vs. rates from sediment cores, or ^{137}Cs-based rates vs. ^{210}Pb-based rates) because of compaction, decomposition, and other belowground processes which lead to reduced rates of accretion over longer timer periods. This unusual pattern at Corte Madera Marsh could be due to slightly higher rates of sediment accretion early in the 20th century or to erosion in recent decades. Either of these scenarios is possible, as reductions in suspended sediment concentrations have been documented over the last few decades (Wright and Schoellhamer 2004, Schoellhamer 2011), and wave action could affect sediment dynamics on the marsh plain.

Overall, the accretion rates based on the dated cores were similar to rates from other tidal wetlands from around the Bay (average rates based on ^{137}Cs for Whale's Tail in the South Bay, China Camp, Petaluma River Marsh and Coon Island in San Pablo Bay were 0.63, 0.42, 0.29 and 0.39 cm/yr, respectively; see Callaway et al. 2012 for additional details). All of the measured accretion rates (including feldspar markers and sediment cores) except for short-term rates based on marker horizons at mid and high stations at Corte Madera Marsh are slightly higher than recent rates of sea-level rise and indicate that even though rates are somewhat low, both wetlands are currently accumulating enough sediment to keep pace with sea-level rise.

Sediment organic matter content at Corte Madera Marsh ranged from approximately 10 to 20 percent in most cores and was lower at Muzzi Marsh, ranging from approximately 5 to 13 percent (Table 4). Values from Corte Madera Marsh are similar to values from other natural tidal wetlands in the Bay (Whale's Tail, China Camp, Petaluma River Marsh, and Coon Island averaged 12, 13, 16, and 17 percent organic matter, respectively; Callaway et al. 2012). Lower values at Muzzi Marsh are to be expected, as the accumulation of organic matter in restored tidal wetland soils can take many decades (Craft et al. 1999, Zedler and Callaway 1999). Sediment bulk density showed the opposite pattern, with higher values at the restored sites (Table 5), a result of the inverse relationship between sediment organic matter content and sediment bulk density (see Callaway et al. 2012, Appendix 6)

As with the vertical accretion rates based on ^{137}Cs and ^{210}Pb, mass-based rates of accumulation (Table 3) were similar to other San Francisco Bay tidal wetlands, with mineral accumulation rates averaging 1400 $g/m^2/yr$ at Corte Madera based on ^{137}Cs vs. 2865, 1780, 1300, and 1644 $g/m^2/yr$ at Whale's Tail, China Camp, Petaluma River Marsh, and Coon Island, respectively (Callaway et al. 2012). As with the vertical accretion rates, mineral accumulation rates based on ^{210}Pb were slightly higher than rates based on ^{137}Cs for most cores.

Organic matter accumulation and carbon sequestration rates were also similar to other tidal wetlands around the Bay (Table 3; Callaway et al. 2012). Carbon sequestration rates based on ^{137}Cs across the entire marsh at Corte Madera averaged 112 $g/m^2/yr$ compared to 122, 103, 71,and 110 $g/m^2/yr$ at Whale's Tail, China Camp, Petaluma River Marsh, and Coon Island, respectively (Callaway et al. 2012). Although we have not completed statistical analysis to compare sites, it is highly unlikely that there are any statistically significant differences across sites given the relatively small differences in rates and the small samples sizes for these comparisons. Also note that we have compared rates across San Francisco Bay tidal wetlands using values based on ^{137}Cs rather than those based on ^{210}Pb because of the varying time scales for ^{210}Pb dating on multiple cores at Corte Madera Marsh.

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Table 1. Locations and elevations for feldspar marker sampling stations at Corte Madera Marsh and Muzzi Marsh. Locations are UTM coordinates (UTM Zone 10), and elevations are relative to NAVD 88. Additional sampling locations (sediment pads, SET, and sediment cores) were located adjacent to these stations. Elevations for Corte Madera Marsh are from feldspar stations, and elevations for Muzzi Marsh are from adjacent sediment core locations.

		UTM Easting	UTM Northing	Elevation (m)
Corte Madera Marsh				
Low Low	A	543457.5	4199162.1	NA
Low	A	543437.3	4199147.6	1.83
Low	B	543438.3	4199346.7	1.88
Mid	A	543271.9	4199159.7	1.77
Mid	B	543245.7	4199351.8	1.76
High	A	543098.8	4199025.2	1.75
High	B	543061.8	4199330.7	1.75
Muzzi Marsh				
Low Low	A	543203.8	4198111.1	NA
Low	A	543624.2	4198106.2	1.66
Low	B	543622.2	4197860.1	1.57
Mid	A	543417.1	4198043.1	1.68
Mid	B	543392.3	4197816.6	1.74
High	A	543209.8	4197947.0	1.86
High	B	543158.8	4197760.3	1.84

Table 2. Dates for field sampling and lab work completed at Corte Madera Marsh and Muzzi Marsh.

Sediment Pads	**Feldspar**	**SET**	**Sediment Cores**
	Installation: March 17 & April 28, 2011	Installation: Dec 2010 Initial measurements: Apr 28, 2011	Collected: Nov & Dec 2010, Jan & May 2011
Sampling periods: Aug 17 to 31, 2011 Nov 16 to 30, 2011 Mar 16 to 30, 2012 Jun 21 to Jul 6, 2012	Measurements: Aug 17 & 31, 2011 Nov 30 & Dec 14, 2011 Mar 2 & 30, 2012 Jun 21 & 22, 2012	Measurements: Aug 17, 2011 Dec 14, 2011 Mar 30, 2012 Jun 22, 2012	Processing at USF completed: Jun 2011 Dating at LSU: completed: Apr 2012

Table 3. Rates of sediment accretion and mass-based sediment accumulation derived from sediment cores collected at Corte Madera Marsh. Rates based on ^{137}Cs are relative to 47 years (1963 to the collection date); rates based on ^{210}Pb are relative to 100 years except were indicated below.

		rates based on ^{137}Cs				**rates based on ^{210}Pb**			
Station	Transect	Accretion (cm/yr)	Mineral Accum (g/m^2 yr)	Organic Accum (g/m^2 yr)	Carbon Accum (g/m^2 yr)	Accretion (cm/yr)	Mineral Accum (g/m^2 yr)	Organic Accum (g/m^2 yr)	Carbon Accum (g/m^2 yr)
Low	A	0.49	2056.5	303.9	121.5	0.60[1]	2708.4[1]	356.5[1]	142.1[1]
Low	B	0.38	1631.9	261.8	105.0	0.49[2]	2240.6[2]	333.2[2]	133.3[2]
Mid	A	0.49	2151.4	372.7	149.9	0.49[3]	2439.3[3]	429.3[3]	172.8[3]
Mid	B	0.32	659.8	212.3	87.9	0.30	719.6	197.9	81.4
High	A	0.36	1109.2	242.7	98.6	0.39	1194.3	245.0	99.2
High	B	0.36	1034.2	260.7	106.8	0.30[4]	860.6[4]	217.2[4]	89.0[4]

[1]rates based on ^{210}Pb relative to 83.3 years and 50 cm for this core, due to rapid accretion rate
[2]rates based on ^{210}Pb relative to 55.1 years and 27 cm for this core, due to mixing below
[3]rates based on ^{210}Pb relative to 22.4 years and 11 cm for this core, due to mixing below
[4]rates based on ^{210}Pb relative to 76.6 years and 23 cm for this core, due to mixing below

Table 4. Sediment organic matter content (percent) averaged for 10-cm intervals for sediment cores collected at Corte Madera Marsh and Muzzi Marsh.

		Sediment Organic Matter (percent)				
		0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm
Corte Madera Marsh						
Low	A	13.2	12.8	13.4	10.9	9.6
Low	B	15.3	12.0	11.6	9.6	13.6
Mid	A	15.3	14.7	16.1	15.1	17.0
Mid	B	23.8	25.5	17.2	12.8	13.9
High	A	19.2	16.8	16.9	15.2	16.1
High	B	22.0	19.9	17.3	11.8	11.7
Muzzi Marsh						
Low	A	15.4	9.5	7.6	6.0	4.7
Low	B	11.2	8.4	7.4	5.2	5.6
Mid	A	14.6	10.8	8.4	7.6	6.5
Mid	B	12.4	8.1	7.2	6.7	5.4
High	A	12.0	8.1	7.1	7.5	7.2
High	B	13.5	9.5	6.6	6.2	5.6

Table 5. Sediment bulk density (g/cm^3) averaged for 10-cm intervals for sediment cores collected at Corte Madera Marsh and Muzzi Marsh.

		Sediment Bulk Density (g/cm^3)				
		0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm
Corte Madera Marsh						
Low	A	0.455	0.501	0.451	0.544	0.603
Low	B	0.485	0.534	0.540	0.533	0.463
Mid	A	0.579	0.487	0.387	0.445	0.501
Mid	B	0.285	0.268	0.365	0.447	0.389
High	A	0.384	0.353	0.370	0.374	0.321
High	B	0.358	0.359	0.453	0.552	0.549
Muzzi Marsh						
Low	A	0.311	0.517	0.544	0.656	0.867
Low	B	0.468	0.461	0.542	0.797	0.733
Mid	A	0.344	0.425	0.464	0.643	0.923
Mid	B	0.439	0.561	0.532	0.589	0.674
High	A	0.754	0.930	0.898	0.826	1.039
High	B	0.441	0.592	0.753	0.781	0.880

Figure 1. Map of sampling stations at Corte Madera Marsh. Sediment pads were deployed on transect A (transect B did not have a low low station, as these were only used for sediment pads). Feldspar marker horizons were established at all stations. A SET benchmark was established at the mid station on transect A, and sediment cores were collected at all stations (except the low low station) for sediment dating and analysis of sediment characteristics.

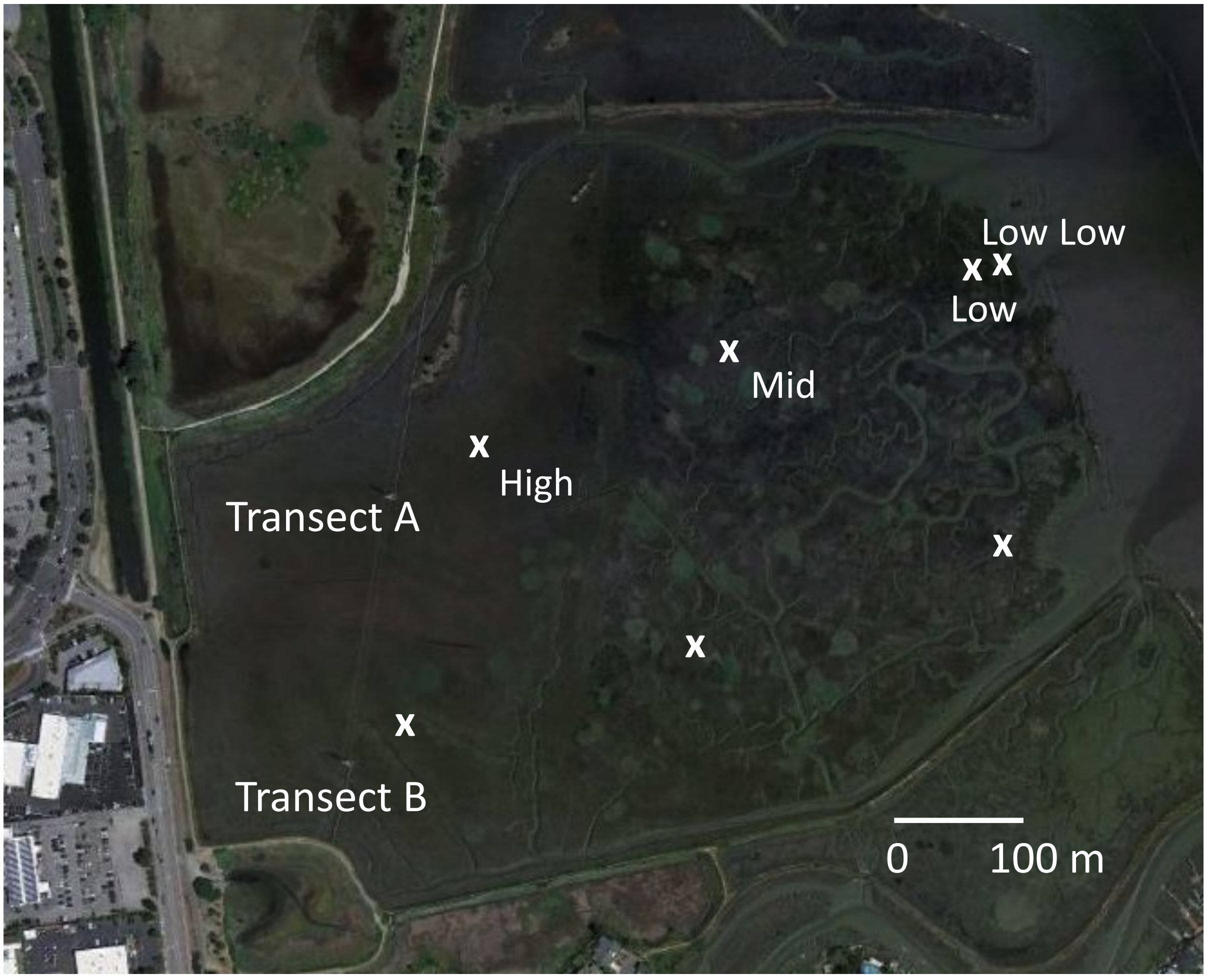

Figure 2. Map of sampling stations at Muzzi Marsh. Sediment pads were deployed on transect A (transect B did not have a low low station, as these were only used for sediment pads). Feldspar marker horizons were established at all stations. Sediment cores were collected at all stations for analysis of sediment characteristics (except the low low station); no sediment dating was completed at Muzzi Marsh.

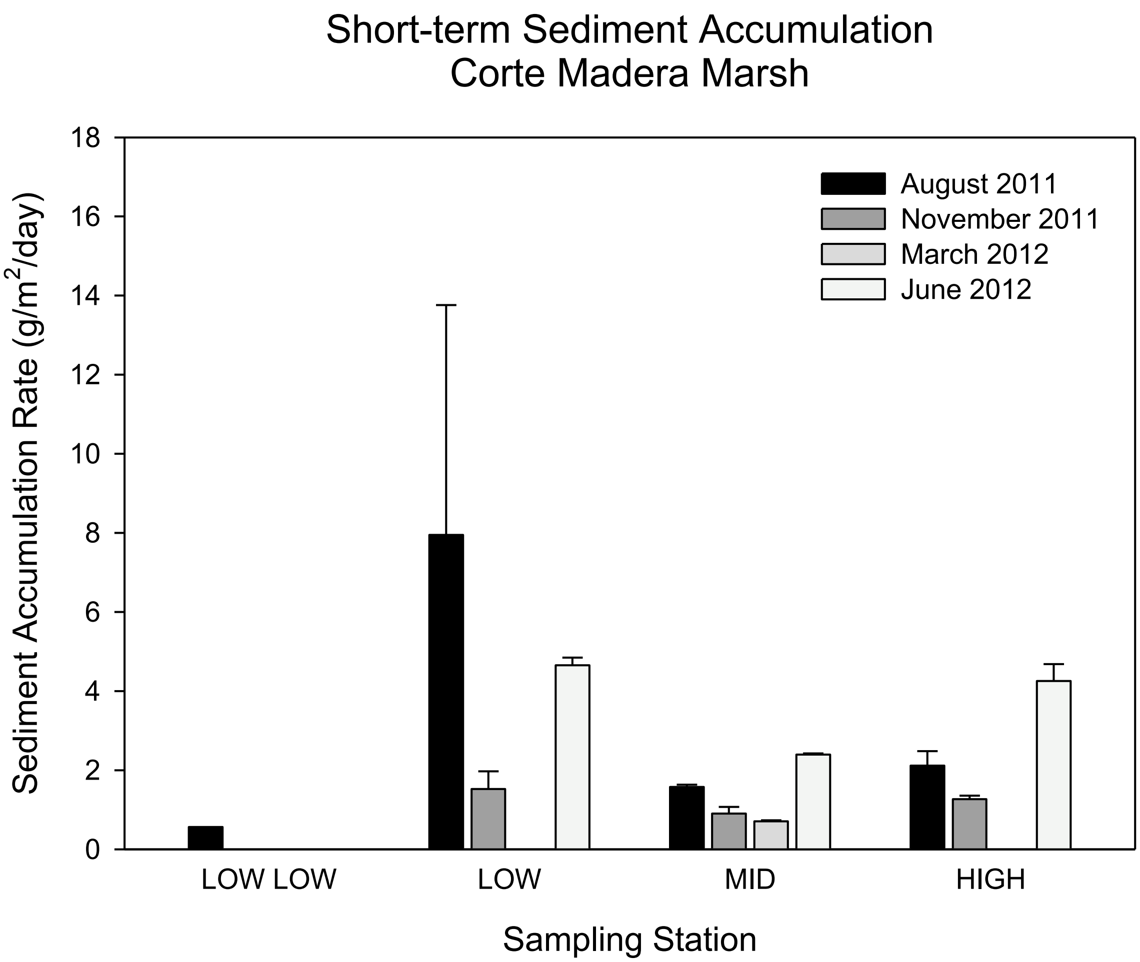

Figure 3. Short-term sediment accumulation rate ($g/m^2/day$) at Corte Madera Marsh, measured quarterly using sediment pads over two weeks at four stations from August 2011 to June 2012.

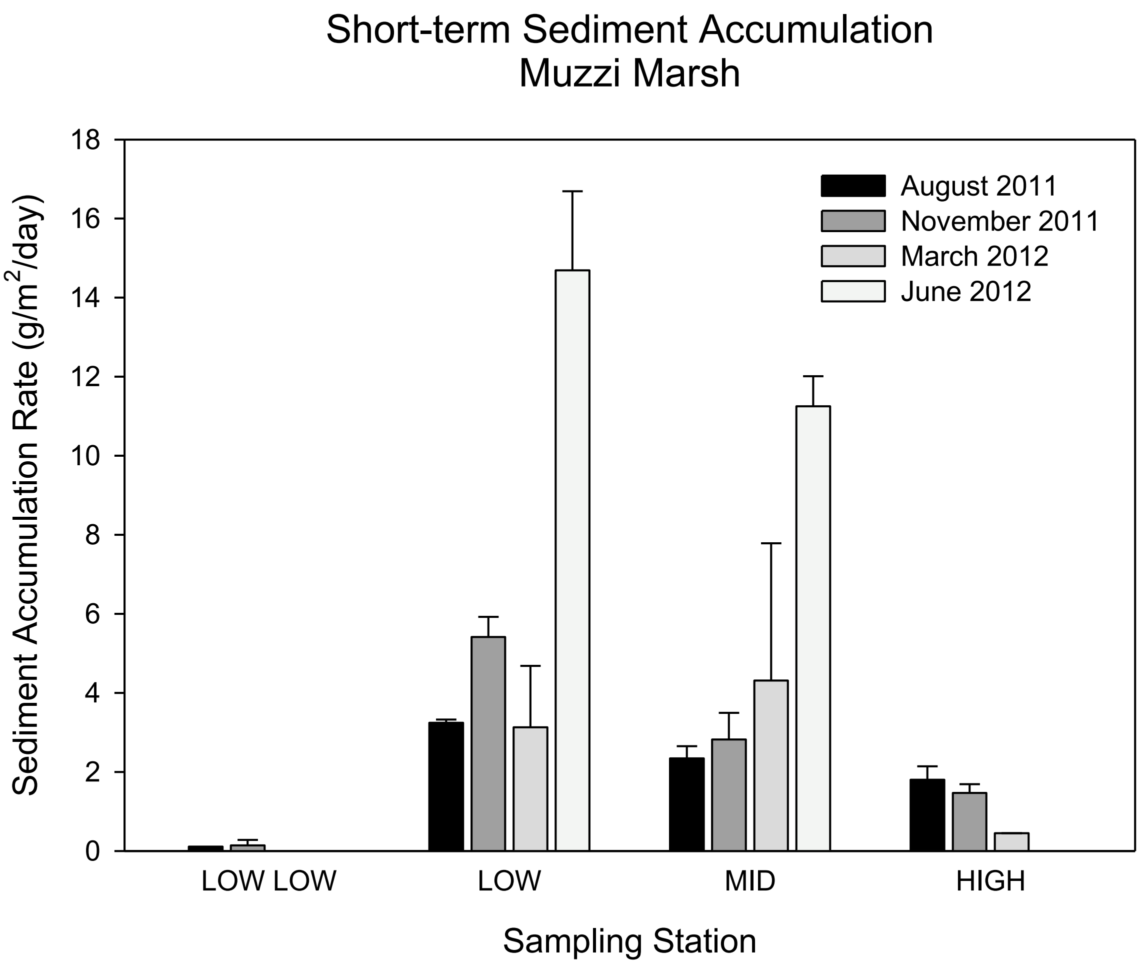

Figure 4. Short-term sediment accumulation rate (g/m^2/day) at Muzzi Marsh, measured quarterly using sediment pads over two weeks at four stations from August 2011 to June 2012.

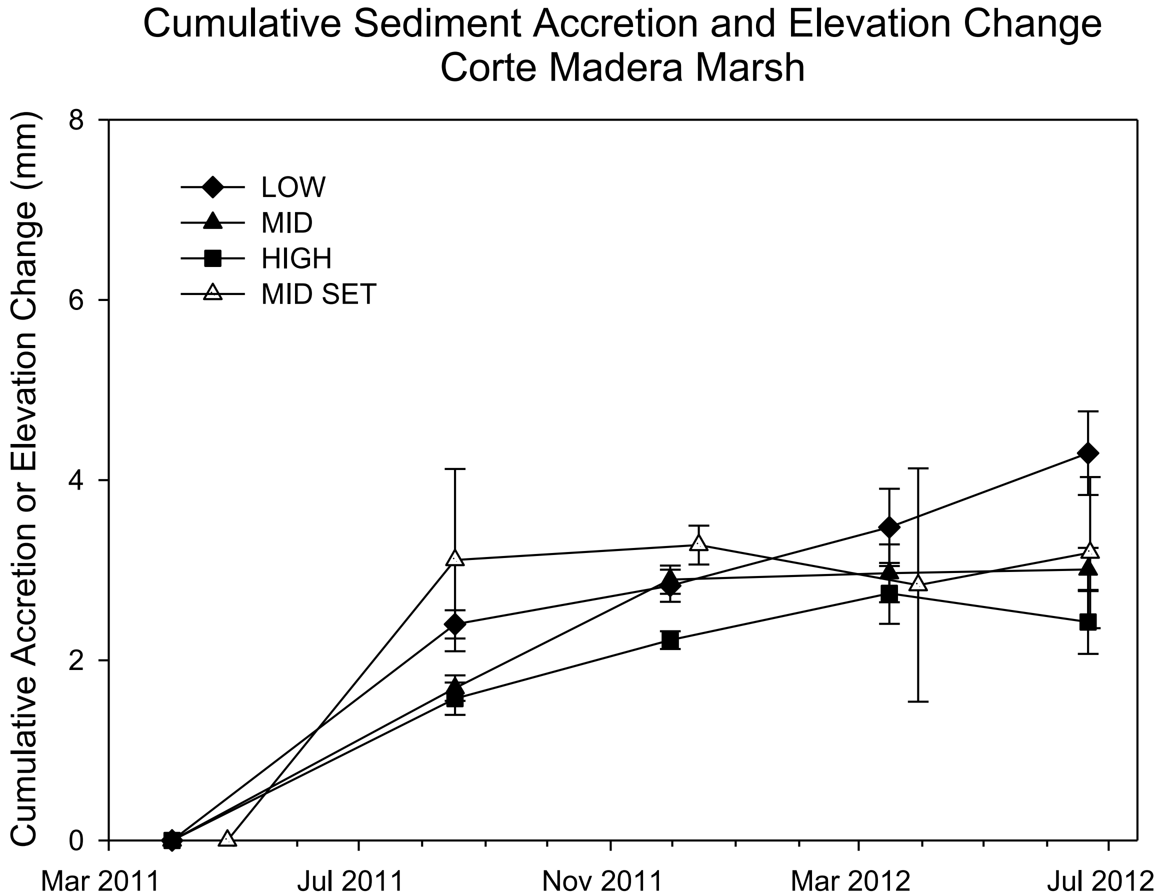

Figure 5. Sediment accretion and change in relative elevation from April to December 2011 at Corte Madera Marsh, as measured using feldspar markers (accretion) and SET (elevation change).

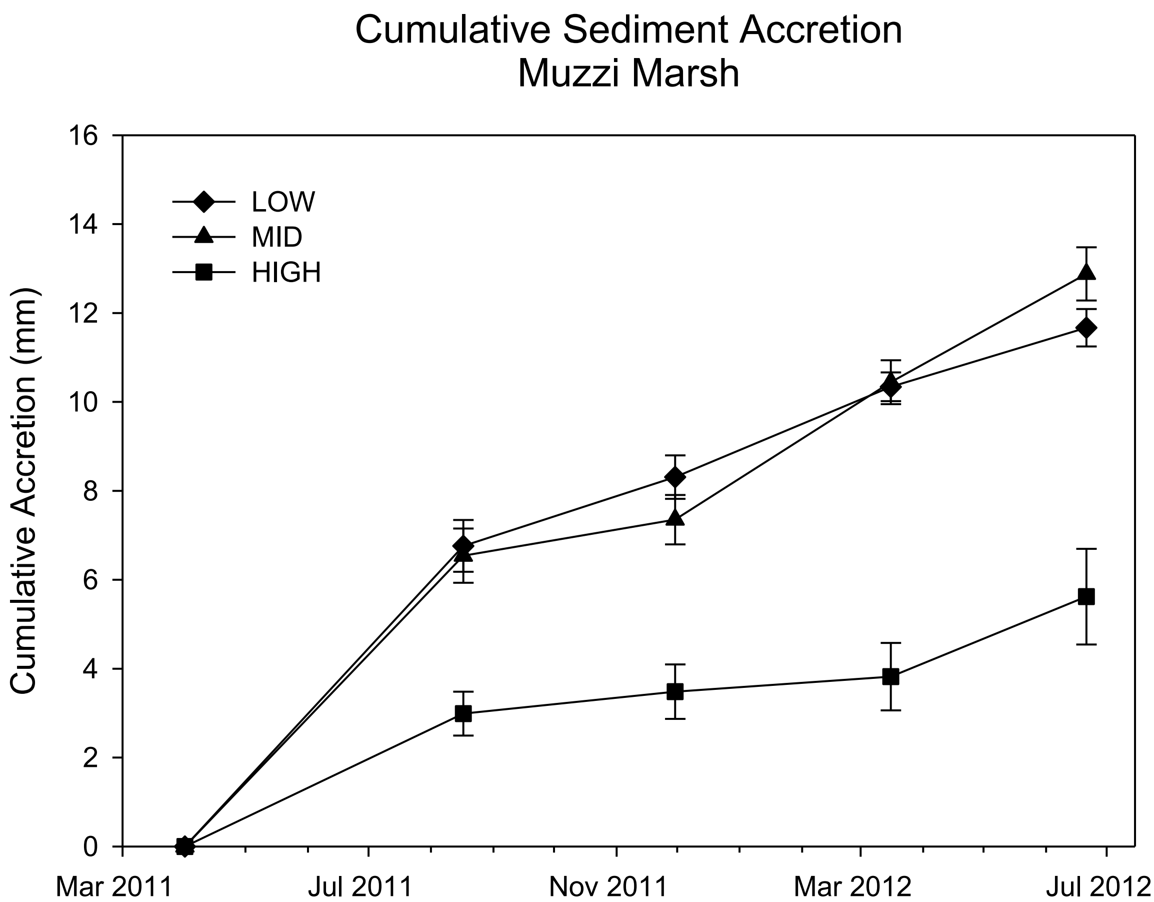

Figure 6. Sediment accretion from April to December 2011 at Muzzi Marsh, as measured using feldspar markers.