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Subsidence, accretion, and sea level rise in south San Francisco Bay marshes

Abstract—Accelerated sea level rise that is predicted to occur as a result of the greenhouse effect is likely to have a significant effect on the world's salt marshes. For salt-marsh vegetation to remain productive and even to survive in a period of rising sea level, the marsh must accrete sufficient sediment to maintain the marsh surface within an appropriate tidal range. Accretion and subsidence were studied in three south San Francisco Bay salt marshes that differed greatly in subsidence over the past few decades. Marsh accretion as a result of sedimentation and peat formation has been able to compensate for high rates of subsidence and the low rate of sea level rise and to maintain the elevation of the marsh surface above mean high water (MHW). South San Francisco Bay appears to be a sediment-rich system that transports enough sediment by tidal action and during storm events to compensate for sea level rise and subsidence in the fringing salt marshes.

There is considerable interest in the capacity of salt marshes to maintain their elevation relative to sea level. Accelerated sea level rise that is predicted to occur as a result of the greenhouse effect (Titus 1986) is likely to have a significant effect on salt marshes. In order for salt-marsh vegetation to remain productive and even to survive in a period of rising sea level, it is necessary that the marsh accrete enough material at its surface to remain intertidal. In a study of the relationship of growth range of salt-marsh plants to tidal range in 24 salt marshes, McKee and Patrick (1988) found few cases where marsh plants extended very far into the lower half of the tidal range. Salt marshes that fall in relative elevation too far down the tidal range, from whatever cause, will be subject to excessive inundation and the adverse effects that accompany waterlogging.

A marsh surface can decrease in elevation relative to sea level from several causes. True sea level rise contributes to relative marsh surface depression. Worldwide, sea level is rising at a rate estimated to be ~0.12 cm yr^{-1} by Gornitz et al. (1982), 0.23 by Barnett (1984) and 0.24 by Peltier and Tushingham (1989). Marshes can lose elevation as a result of subsurface water extraction and from consolidation or compaction of the organic sediments composing the marsh. Tectonic

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subsidence has also been shown to lower west coast marsh surfaces (Atwater 1987).

If conditions are favorable, salt marshes subjected to an increase in water elevation respond by increasing their surface elevation relative to water elevation (Krone 1987). The increase in surface elevation is dependent on the influx of mineral sediment and the production and incorporation of organic matter in the root zone. Both the mineral and organic components are considered essential for salt-marsh surface growth. The mineral component is required both as a source of plant nutrients for marsh vegetation and for redox buffering that helps to neutralize toxic materials such as reduced sulfur compounds (DeLaune et al. 1983*a*). Plant roots and partially decomposed organic material stabilize the organic and inorganic components of the marsh surface layer into a matrix that is resistant to erosion. This stable surface layer serves as a base for additional marsh growth.

Salt marshes in various coastal regions of the U.S. are subjected to considerably different changes in relative water level. In general, along the east coast, change in water level is due to sea level rise, with some areas experiencing higher rise due to local conditions of subsurface water extraction or changes in surface water hydrology (Kearny and Ward 1986; Orson et al. 1985). Along the Gulf Coast in the Mississippi River deltaic plain, consolidation of alluvial sediments from the river is causing the marsh surface to decrease more than in other coastal areas of North America. These marshes are deteriorating, in some cases rapidly (Gagliano et al. 1981). Marsh surfaces are becoming lower in the tidal range. For the salt-marsh areas in Barataria and Atchafalaya basins, subsidence of slightly >1 cm yr^{-1} is occurring via sediment consolidation. Other areas are keeping pace with relative water level rise, and still other marshes are accreting faster than the relative rise in water level (DeLaune et al. 1983*b*; Hatton et al. 1983). The differential responses of these marshes to an increase in water level are due largely to differences in sediment supply. Where ample sediment is available, marshes can keep pace with rising water level and in some cases even gain elevation relative to water level, while in areas without enough input of sediment they cannot. Such marshes break up and are converted to open water.

Most west coast marshes only need to keep pace with the small increase in global sea level rise to maintain their elevation and viability, since there does not seem to be any general subsidence of the magnitude seen on the Gulf Coast. In some west coast marshes, however, local conditions of higher subsidence that occur largely as a result of subsurface water extraction in recent decades subject the marsh to higher than average increases in water level.

In this note we report the results of a study of subsidence and accretion during the past few decades in three marshes in south San Francisco Bay and the capacity of the marshes to keep up with subsidence and sea level rise. These marshes were selected because they represent areas of the bay subjected to different amounts of subsidence, but all three maintained their surface at, approximately, 0.1 m or more above mean high water (MHW).

Site 1 (Fig. 1) is a pristine marsh relatively unaffected by subsidence on Bird Island on the west side of the bay (122°14′18″W, 37°33′5″N). The vegetation at the site is a mixture of *Salicornia virginica, Distichlis spicata,* and *Spartina foliosa.* Dead plant roots and peat are present in the marsh profile to a depth of slightly more than a meter. Mean high water at this location is 1.04 m [elevations are NGVD (Natl. Geodetic Vertical Datum)] and the elevation of the marsh surface is 1.19 m (Towill Inc. unpubl. rep).

A second marsh that had undergone considerable subsidence was selected in the southern part of the bay on Coyote Creek near Alviso (121°58′35″W, 37°27′28″N). A thick stand of *S. virginica* is the major vegetation. This site has subsided considerably over the past few decades as a result of groundwater extraction, with a decrease in elevation of over a meter reported during the period 1934–1967 (Poland 1969). The sediment on which the vegetation is growing is soft clay with remains of plant roots and stems throughout the profile. The marsh elevation at this site is 1.14 m. Mean high water is not precisely known, but it is 1.04

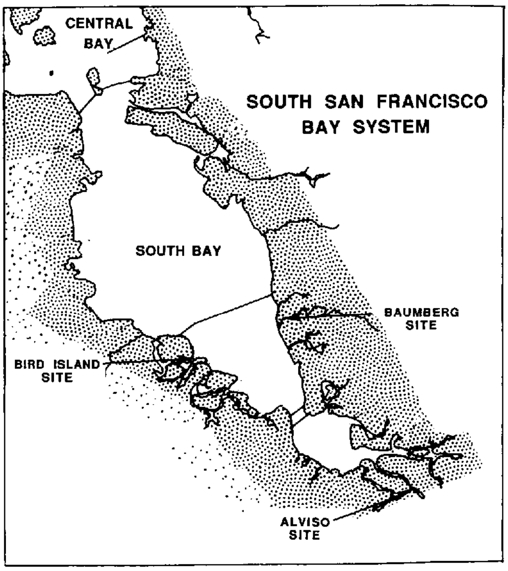

Fig. 1. Location map of study sites.

m at the Mud Slough Drawbridge 1 km north of the sample site (R. Thinggaard pers. comm.).

A third marsh was selected on the east side of the bay near Baumberg at 122°8′34″W, 37°36′2″N. The sample location is ~250 m from the bay. The vegetation is a healthy, almost pure stand of *S. virginica*. The site had been in a salt crystallization pond for several years and could be identified as such on a 1928 aerial photograph. Salt operations ended in 1929 (Ver Planck 1957) and the abandoned levees apparently broke soon afterward, exposing the former diked area both to tidal action and sedimentation. Old timbers associated with salt operations still existed in the area at the time of sampling. The upper part of the profile has a considerable quantity of plant roots, alive and dead, as well as partially decomposed peat. A layer of rock salt several centimeters thick was found at a depth of 50 cm throughout the area. The rock salt was formed at the original surface of the crystallizer pond before abandonment. Directly below the salt layer is another peat layer from the original marsh surface that existed before the area was converted to salt production. The surface layer of the buried marsh has a higher organic matter content than does the present marsh surface. Partially decomposed plant parts, some of which appeared to be *Spartina,* were noted in the buried marsh. The elevation of the marsh is 1.20 m. Mean high water at this site is 1.05 m (MHW based on elevations of Tidal Benchmarks B&E for Alameda Creek Tide Gauge).

Sediment cores were taken in 1983 with a thin-walled, 7.6-cm-diameter corer designed to minimize compaction of the sample. Organic C and bulk density profiles were determined for each of the marshes. Vertical marsh growth or accretion since the mid-1950s was determined with the ^{137}Cs technique (DeLaune et al. 1978). ^{137}Cs activity was determined on the oven-dried sediment with a detector that responded only to gamma emission of Cs. This method for determining sedimentation rate is based on the known date of atmospheric fallout of hydrogen bomb-derived ^{137}Cs. Fallout began in 1955, reached a maximal rate in 1963, and has decreased since then. The depth in the sediment at which Cs first appeared corresponds to the 1955 surface, and the depth of maximal Cs accumulation usually corresponds to the 1963 surface. Cs moves to only a slight degree because it is tightly bound by expanding lattice clays, which are the dominant type in the bay area. At Alviso, Cs dating was done on the 1983 cores; at the Bird Island and Baumberg sites additional 15-cm-diameter cores were taken in 1988.

At Bird Island bulk density and organic C profiles are typical for a natural salt marsh (Fig. 2) and show a decrease in organic C and an increase in bulk density with depth. The bulk density values of 0.4–0.6 g cm^{-3} throughout the profile are within the range usually encountered in salt marshes and are less than half that of a drained mineral soil. Organic C is high, especially in the root zone, and the large accumulation of organic matter suggests that the marsh has been relatively undisturbed for long time. For the Alviso marsh, organic C is uniformly low throughout the profile, and bulk density changes only slightly with depth, reflecting the rapid accumulation of mineral sediment with little opportunity for organic matter buildup. For the Baumberg marsh, the C and bulk density profiles show the presence

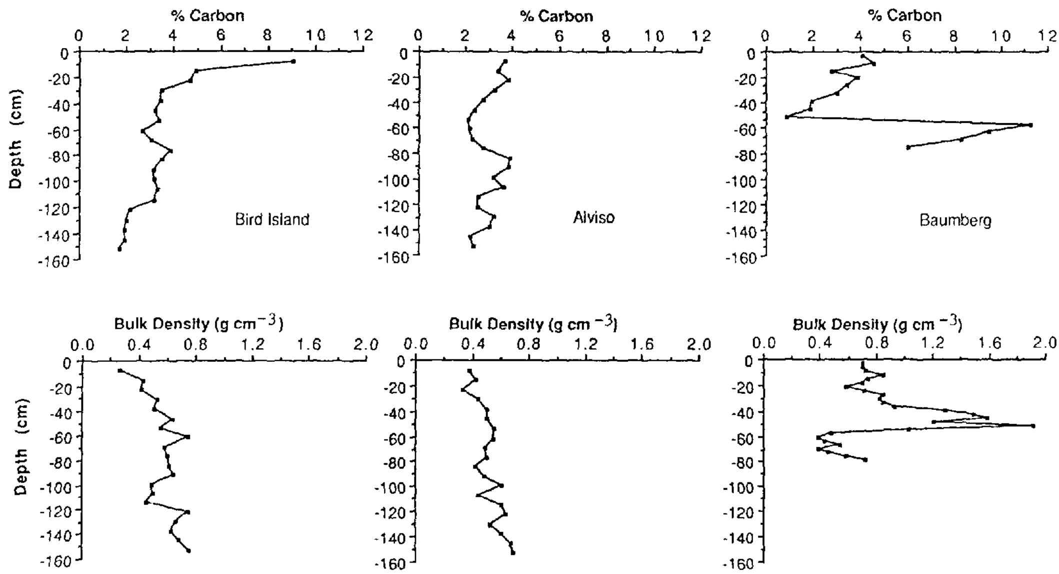

Fig. 2. C content and bulk density of the marsh soil profiles. The cores were sliced horizontally into sections (3–8 cm thick), dried for bulk density determination, and ground for organic C and ^{137}Cs determinations. Organic C was determined by dry combustion.

of the two marsh profiles and the salt layer. For the present marsh, organic C decreases with depth to ~50 cm, and bulk density increases over the same depth. The salt layer is characterized by a low organic C content and a very high bulk density. Below the salt layer the surface layer of the buried marsh has a higher peat content than does the surface layer of the present marsh. Bulk density values of the surface layer of the buried marsh at Baumberg are ~0.4–0.8 g cm^{-3}, indicating that the soil in the crystallizer from which the core was taken had not been compacted.

At Bird Island and Baumberg, the 1963 peaks representing the period of maximal ^{137}Cs fallout are sharp (Fig. 3) and suggest little movement of ^{137}Cs after surface deposition. The Alviso profile has a ^{137}Cs maximum that is probably also due to the

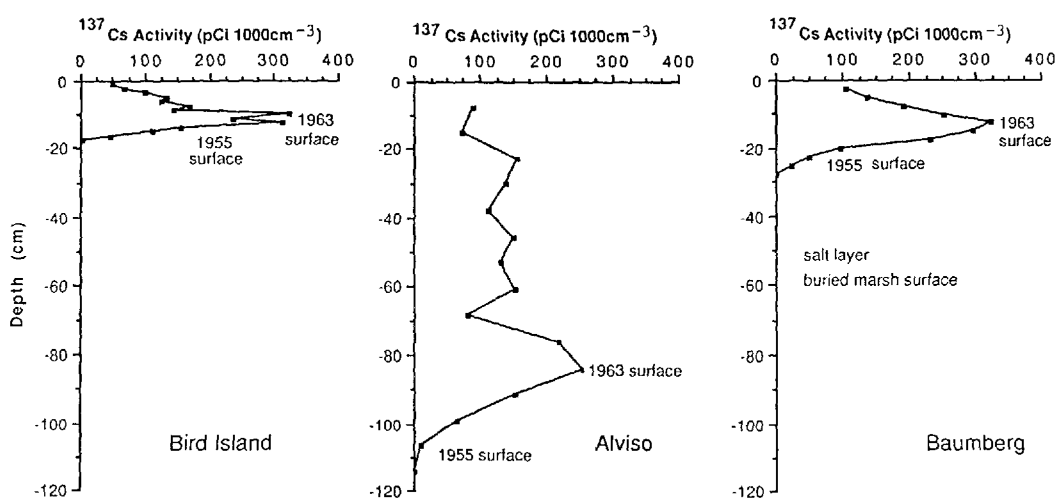

Fig. 3. Accretion rates determined from ^{137}Cs activity in air-dry sediment sections counted for 4 h with a shielded GeLi detector.

high 1963 atmospheric fallout. An estimate of subsidence and accretion rates in the three marshes over the last few decades can be made. These rates are based on the elevations of the 1955 and 1963 surfaces derived from Cs dating, the elevation of the present surface, and sea level rise since the mid-1950s when Cs first appeared in the sediment. For the Baumberg marsh the elevation of the buried salt layer and the approximate date of abandonment of the crystallizer are also used. At Bird Island the 1955 surface is 16 cm below the present marsh surface and the 1963 surface is 11 cm below the surface. The 5 cm of sediment that accumulated between 1955 and 1963 yield an accretion rate of 0.6 cm yr^{-1}. For the period 1963–1988, the accretion rate is 0.4 cm yr^{-1}. The average accretion rate for 1955–1988 is 0.5 cm yr^{-1}. Accretion apparently has been relatively constant throughout the whole period. At Alviso, where subsidence is known to be high, 24 cm accreted in the period 1955–1963 for a rate of 3 cm yr^{-1}. From 1963 to 1983, 84 cm accreted for a rate of 4.2 cm yr^{-1}; the average rate for the entire 1955–1983 period is 3.9 cm yr^{-1}.

At the Baumberg site, the 1955 and 1963 surfaces at 25- and 12-cm depths give an accretion rate of 1.6 cm yr^{-1} for the period 1955–1963 and a rate of 0.5 cm yr^{-1} for the period 1963–1988. The average rate for the entire 1955–1963 period is 0.8 cm yr^{-1}. The accumulation of 50 cm of sediment over the salt layer at Baumberg suggests that sedimentation was rapid after the dike on the bay side of the crystallizer broke and tidal flow commenced. For the period between 1930, when the crystallizer was abandoned and exposed to tidal action, and 1955 there has been an accumulation of 25 cm of sediment. The average accretion rate for this period is ~1.0 cm yr^{-1} (Fig. 4).

The amount of accretion due to the response of the marsh to sea level rise alone can be estimated based on measured sea level rise in the bay area. With the average value of 0.13 cm yr^{-1} reported for San Francisco (Barnett 1984), ~1 cm of the accretion between 1955 and 1963 and 3 cm of that between 1963 and 1988 can be attributed to the marsh surface maintaining its elevation relative to sea level. The remainder of the accretion should have been in response to subsidence. On the assumption that the marsh surface has maintained its elevation relative to MHW for the period covered by this study, which seems to be the case because all of the marshes are presently several centimeters above MHW, the amount of accretion not associated with sea level rise should be about equal to subsidence at Bird Island and at Alviso. Subtracting the sea level rise from the amount of accretion at Bird Island gave values of ~4 cm between 1955 and 1963 and 8 cm between 1963 and 1988 that the marsh surfaces grew vertically in response to subsidence, amounts equivalent to accretion rates of 0.5 and 0.3 cm yr^{-1} for the two periods. At Alviso subsidence was so great due to subsurface water extraction that sea level rise had a smaller relative effect on the amount of accretion. Correcting for sea level rise gave values of 23 cm between 1955 and 1963 and 81 cm between 1963 and 1983 that the marsh surface had to rise to compensate for subsidence. These amounts equate to accretion rates of 2.9 and 4.0 cm yr^{-1} for the two periods.

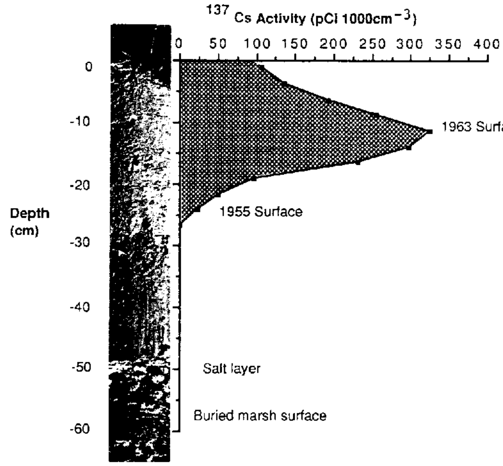

Fig. 4. Photograph of marsh soil profile at Baumberg site showing rock salt layer and ^{137}Cs profile.

At Baumberg, part of the accretion occurred as a result of the crystallizer surface being below MHW at the time the site was exposed to tidal activity. Accretion was obviously greater than subsidence plus sea level rise at this site from 1930 to 1988. Three

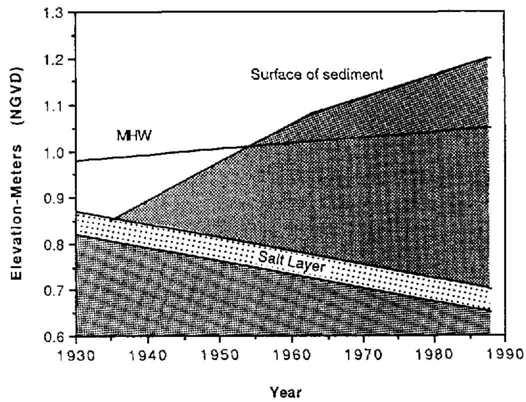

Fig. 5. Interaction of subsidence, accretion, and sea level rise at Baumberg, 1930–1988.

centimeters of the 25 cm accreted from 1930 to 1955, 1 cm of the 13 cm accreted from 1955 to 1963, and 3 cm of the 12 cm accreted from 1963 to 1988 were due to sea level rise; the rest was due to the initially depressed surface and to subsidence.

From the information gained in this study, a model can be constructed of the interaction of subsidence, sea level rise, and accretion for the period 1930–1988 at Baumberg (Fig. 5). If it is assumed that the subsidence rate for this period was the same as at Bird Island during 1963–1988 (0.3 cm yr^{-1}), then the initial surface in 1930 (the salt layer) subsided ~17 cm from 1930 to 1988. During this same period, sea level rose ~8 cm, and 50 cm of sediment accumulated over the salt layer. Although the rate of accretion and the elevation of the sediment over the salt layer cannot be accurately reconstructed for 1930–1955, the 1955, 1963, and 1988 surface elevations are known from Cs dating. The accretion rate seemed to decrease as the sediment surface rose above MHW. The present marsh surface is 15 cm above MHW and will probably accrete further only in response to sea level rise or subsidence.

This study shows that salt marshes in south San Francisco Bay have the capacity to maintain their surface above MHW over a wide range of subsidence rates. Subsidence as a result of subsurface water extraction of about a meter in three decades was compensated by enough sedimentation to maintain a healthy marsh. The accretion rate due to sedimentation and marsh growth was high enough to bring the surface of a former salt crystallizer above MHW and allow the reestablishment of healthy marsh vegetation. These results indicate that there is enough sediment transport into the bay marshes to compensate for projected sea level rise for some time to come.

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Flow around phoronids: Consequences of a neighbor to suspension feeders

Abstract—Dye visualization was used to assess the effects of closely spaced conspecifics to the flow microhabitat of the benthic suspension feeder *Phoronopsis viridis* Hilton (Phoronida), which lives in dense populations over a wide range of natural densities. Spacing between upstream-downstream neighbors affected water movement near the animals and the source of water processed by their filter-feeding tentacles. Visualization of flow around and between pairs consisting of living and model *P. viridis* revealed that water encountered tentacle crowns (lophophores) via upward transport from near the sandy substratum rather than from above the lophophore, close spacing of individuals (< 1 lophophore diam) inhibited this upward flow for the upstream neighbor, and turbulence generated by an upstream neighbor increased the useful area of feeding surface of the lophophore in the downstream individual. Upward movement of water is important because benthic food particles are an important component of the diet of *P. viridis*. Thus the presence of neighbors within populations of *P. viridis* could enhance the incorporation of benthic food particles into their diets. The consequences to feeding of having a neighbor should shift from positive at low densities (> 1 lophophore apart) to negative at high densities (≤ 1 lophophore apart).

The presence of neighbors drastically alters the flow-microhabitat experienced by individuals living in groups of suspension feeders. Although flow-microhabitat affects the feeding performance of suspension feeders (Okamura 1984, 1985; Patterson 1984; McFadden 1986; Hunter 1989) and although interspecific and intraspecific enhancement or depletion of food commonly occurs in dense groups of suspension feeders (Okamura 1986, 1988; Peterson et al. 1984), few studies (O'Neill 1978; Merz 1984; Chance and Craig 1986) have examined the consequences to flow of spacing between individual suspension feeders.

The present study examines how spacing between upstream-downstream neighbors affects water movement near *Phoronopsis viridis* and the source of water processed by its filter-feeding tentacles. *Phoronopsis viridis* is a wormlike, tubicolous, marine suspension feeder that lives in dense populations (up to 20,000 m^{-2}) on the intertidal sandflats of northern California. Its diet is rich in benthic food particles that are captured by a ciliated crown of tentacles (lophophore). When the tide is in, this lophophore projects about 1 cm above a sandy bottom into a velocity gradient.

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