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Response of Tidal Salt Marshes of the U.S. Atlantic and Gulf Coasts to Rising Sea Levels[1]

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ABSTRACT

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A salt marsh responds in many diverse ways to a rising sea level. A major factor is its ability to maintain surface elevations with respect to the mean high water level. Other influences include local submergence rates, sedimentation rates, density and composition of the indigenous flora, and type and intensity of cultural modifications. If sea level rise accelerates, it would be reasonable to assume that further stresses will be placed on these systems, most likely resulting in increased losses. If the relative rate of sea level rise reaches catastrophic proportions (exceeding 10 mm yr^{-1}), substantial reductions in wetland area and a corresponding increase in open water habitats is projected. Due to the complex interrelationship of natural processes and cultural alterations that have previously influenced marshes, it is difficult at the present time to separate and identify responses. Thus, each marsh must be assessed individually until we have a more thorough understanding of these systems in general.

ADDITIONAL INDEX WORDS: *Marsh grasses, mud flat, sea level, salt marsh, wetlands.*

INTRODUCTION

During the last 100 years, there has been a net loss of wetland areas along the seaboard of the continental United States. This has been attributed to a variety of causes, both natural and culturally-induced. At the present time the rate of sea level rise is accelerating, and it is possible that this trend will continue into the future (HOFFMAN *et al.*, 1983). What effect such a rise (combined with subsidence) would have on future development of salt-marshes is not clear. We now present a state-of-the-art analysis of the pertinent literature based principally on research conducted along the Atlantic and Gulf coasts of North America. Included in this paper is an analysis of the various factors in salt marsh development and possible ways a marsh can respond to a rise in sea level.

Tidal salt marshes are intertidal grass-dominated wetlands inundated daily with partial or full strength seawater. Due to major physiographic differences along the Atlantic and Gulf coasts of the US, salt marshes range in spatial extent and distribution from the small, steeply sloping bays of New England to the broad gently-sloping plain of the Gulf coast. CHAPMAN (1960) classified salt marshes of the eastern US into two major types based on soil characteristics: (1) New England type (Maine to New Jersey) with fewer silts due to bedrock, and (2) coastal plain type (New Jersey to Texas) with highly eroded uplands and large amounts of silt. All are located in elevation between mean low water (MLW) and mean spring high water (MSHW).

Due to the stressful environments in which they have developed, salt marshes include a variety of habitats (*i.e.*, marine to terrestrial). As summarized

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by FREY and BASAN (1979), natural factors affecting habitat diversity include: (1) character and diversity of indigenous flora, (2) effects of climate, hydrographic and edaphic factors, (3) availability, composition, transport and compaction of sediments (both organic and inorganic), (4) organism-substrate interrelationships, including microbial and faunal influences as well as vegetation characteristics, (5) topographic and areal extent of depositional surface, (6) range of tides, (7) wave and current energy, and (8) eustatic behavior and tectonic stability of coastal areas.

TIDAL MARSH DEVELOPMENT

Principal Models

Tidal salt marshes develop due to the interaction between rise of sea level, tides, accumulation of organic and inorganic sediments, and growth of halophytic grass species which characterize these areas (CHAPMAN, 1960; REDFIELD, 1972). Based on the interaction of these variables, tidal wetlands have developed in a number of ways. The three major processes of marsh development are as follows: (1) accumulation of marine sediments within protected bays and lagoons, (2) submergence of upland areas in direct response to a long-term rise of sea level (REDFIELD, 1972), and (3) accumulation of fluvial sediments associated with the formation of a river delta system (GOSSELINK, 1980).

REDFIELD and RUBIN (1962) proposed a model of marsh development based on a bidirectional expansion of marsh in response to a rising sea level (accumulation of marine sediments and submergence of upland areas). This development scheme was based, in part, on the works of earlier investigations, particularly those of MUDGE (1856) and SHALER (1886). According to this model, there is often an accumulation of sediments at the land-sea boundary in low energy environments which moves inward as sea level rises. Where tidal flat elevations are adequate (above MLW), marsh grasses can become established. Accumulating sediments continually build mud flats at the bayfront border allowing low marsh grasses to colonize in a seaward direction as surface elevations build toward mean high water (MHW). Since the rising sea is encroaching on upland borders, high marsh vegetation tends to replace submerged terrestrial species and expand the marsh landward. The growth of the marsh will continue as long as the rates of accretion (sediment accumulation) are equal to or higher than that of relative sea level rise. This development process commonly occurs within protected bays and lagoons or leeward of barriers and rock outcrops along the Atlantic seaboard.

Along the Gulf coast, many marshes have developed on deltaic deposits. At the mouths of some major rivers, a reduction of water flow can initiate the deposition of large amounts of sediments, commonly forming fan-shaped deltas. Periodically, mudflats become exposed and are gradually colonized by freshwater marsh vegetation. The river intermittently abandons its old channel and extends its new course into the Gulf, cutting its own natural bed, building new levees and establishing a more direct route to the sea. These abandoned fresh water marshes are progressively inundated with salt water as sea level rises or subsidence takes place. Salt marsh grasses gradually replace the fresh water vegetation as the influence of salts increase (GOSSELINK, 1980). This process is prevalent in Louisiana where a major portion of the wetlands have developed along the Mississippi River delta (TURNER and GOSSELINK, 1975).

Factors Effecting Tidal Marsh Evolution

Coastal Submergence. By the end of the last great glacial age (Wisconsinan, approximately 10,000 B.P.), the melting ice sheets had already raised worldwide sea levels to about −40 m, and that trend continued intermittently until about 6000 B.P. At the same time, coastal land elevations were continuously adjusting to isostatic factors (*i.e.*, rebound, compaction, and neotectonic activity). These two major conditions, a rising eustatic sea level and local land adjustments along the US Atlantic and Gulf coasts, have resulted in relative sea level rise or coastal submergence. This relative (or local) net rate is important in salt marsh development and varies along the coast.

Radiocarbon dating indicates that the large expanse of present-day tidal coastal marshes generally formed no earlier than 4000 B.P. These dates coincide with reports of a substantial reduction in rates of relative sea level rise (from 2.5 mm yr^{-1} to 1.0 mm yr^{-1}, MILLIMAN and EMERY, 1962; COLEMAN and SMITH, 1964; REDFIELD, 1967). While salt marshes did develop at times before 4000 B.P., the rapid marine transgressions made these episodes brief and intermittent; salt marsh peat has been found on the continental shelf, some samples being radiocarbon dated at about 7000 B.P.; FIELD *et al.*, (1979). Due to a decrease in rates of relative sea level rise ca 4000 years ago, tidal marsh accretion rates were then able to equal or exceed coastal submergence, allowing for considerable salt marsh development and expansion.

Recent studies along the US northeast coast have suggested that rates of relative sea level rise have accelerated during the last 100 years and may be comparable to those reported for the pre-4000 year datum (HICKS and CROSBY, 1974; McCAFFREY, 1977). This behavior has also been reported for some localities along the south Atlantic and Gulf coasts (COLQUHOUN *et al.*, 1981; BAUMANN and DE LAUNE, 1982).

Sedimentation Processes. The accumulation of sediments plays an important role in marsh development by maintaining surface elevations and supplying a source of nutrients to the wetland plants (GLEASON *et al.*, 1979). Coastal lagoons, estuaries, and deltas are optimal environments for marsh devleopment due to the abundant sediment supply. Major sources of sediment include: (1) sands, silts and clays carried either landward by wave action during the marine transgression, or seaward during upland erosion, (2) deposition of organic detrital material from outside the system (*e.g.*, twigs and leaves from trees), and (3) *in situ* deposition of organic material from the grasses growing on the substrate.

Mechanisms of sediment transport include movement of bedload material along the bottom and suspension of particles within the water column depending on particle size and current competence. The movement of lighter organic material is accomplished by flotation processes. Deposition usually occurs at slack tide when current velocities are lowest (POSTMA, 1967).

The accumulation of sediments varies according to local biologic and geographic parameters (Table 1). Often these accumulated sediments will result in the building of mudflats within the intertidal zone at the mouths of rivers as well as in protected bays and lagoons. It has also been suggested that microalgae may play a role in the building of mudflats (COLES, 1977). Many varieties of diatoms produce mucoidal mats as they move through the substrate. This film could act as a cement, binding loose sediments and stabilizing mud surfaces (COLES, 1977).

As the mudflats continue to aggradate, rooted aquatic vegetation can become established further stabilizing the mud surface through root growth. The culms can also facilitate sedimentation by acting as a baffle to current energy so that sediments become trapped and settle out of the water column. For fine-grained material, principally in the clay size range, plant stems and leaves provide an increased opportunity of collision. Therefore, deposition of sticky clays is greatly facilitated by the presence in the water column of vegetation such as salt marsh plants at high tide, inasmuch as their settling times for deposition greatly exceed the tidal period.

Once sediments accumulate above MLW, low marsh grasses (principally *Spartina alterniflora*) can colonize and further stabilize the intertidal surface as well as become a very important organic sediment source (SHALER, 1886). Individual storm events will also add significantly to local sedimentation rates. Large storms are responsible for supplying large amounts of sediment, particularly to marsh areas removed from direct open water influences (NIERING *et al.*, 1977; STUMPF, 1981).

Vegetation. Vegetation plays an important role in the development and evolution of the salt marsh; therefore, knowledge of the ecology of these halophytes is important in understanding tidal wetland processes. One of the most striking features in a tidal salt marsh is the specific zonation and distribution patterns exhibited by the vegetation growing in these areas. Factors affecting plant zonation characteristics include: (1) salinity concentrations, (2) tidal amplitude, (3) duration of flooding, and (4) elevation of nearby land areas (MILLER and EGLER, 1950; CHAPMAN, 1960; ADAMS, 1963). Plant distribution characteristics are dependent upon a number of factors such as: (1) substrate composition, (2) soil oxygen potentials. (3) nitrogen limitations, and (4) interspecific competition (CHAPMAN, 1960; WOODFIN, 1976; VALIELA and TEAL. 1974; LEON, 1978). The understanding of these characterisitics has been a useful tool in constructing models of marsh development (REDFIELD, 1972).

Based upon the specific responses of these grasses to a particular set of physical parameters, it is possible to subdivide a salt marsh according to floral composition. Generally these divisions include: (1) low marsh/bayfront borders dominated by saltwater cordgrass (*S. alterniflora*) along the Atlantic coast and codominant with blackrush (*Juncus roemarianus*) along the Gulf coast; (2) high marsh dominated by saltmeadow cordgrass (*S. patens*) blackrush along the Atlantic and Gulf coasts, respectively; and (3) the upper border/upland fringe where important community members include reedgrass (*Phragmites australis*), switchgrass (*Panicum* sp.), blackgrass (*J. gerardi*),

Table 1. *Vertical growth rates of salt marshes along the Atlantic and Gulf coasts.*

State	Rate (mm yr^{-1})	Time Period	Reference
NH	1.1	4000 B.P. to present	Keene, 1971
MA	1.5	4000 B.P. to present	Redfield, 1967
CT	1.0	4000 B.P. to present	Bloom, 1964
CT	2.5	150 years	McCaffrey, 1977
NY	6.4	100 years	Armentano & Woodwell, 1975
DE	3.8	Holocene	Richter, 1974
DE	6.0	1935-1957	Stearns & MacCreary, 1957
MD-VA	1.5	5000 B.P. to present	Bartberger, 1976
GA	4.5	2 years	Letzsch & Frey, 1980
LA	8.0	24 years	DeLaune *et al.*, 1978

marsh elder (*Iva frutescans*), and groundsel tree (*Baccharis halimifolia*) amongst others.

Tidal Range. Tidal range affects the geographic distribution and local ecology of salt marshes. Along the United States coasts the tidal range can vary considerably, commonly ranging from 45 to 60 centimeters on the Gulf coast to 100 to 300 centimeters along the Atlantic seaboard. There is often a direct relationship between tidal range and spatial extent of salt marshes; the largest expanses of marsh are found in South Carolina and Georgia, areas with the greatest tidal range (CHAPMAN, 1977; POMEROY and WIEGERT, 1981). This does not apply, however, in northern Maine and the Bay of Fundy.

Tidal range has been shown to affect plant productivity (STEEVER *et al.*, 1976) and sedimentation processes (RANWELL, 1964; HARRISON and BLOOM, 1977). The tidal range will influence low marshes to a greater extent due to the frequency and intensity with which these are inundated by daily tidal cycles. REDFIELD (1972) suggested that tides might be the "most significant environmental factor responsible for the segregation of salt marsh vegetation."

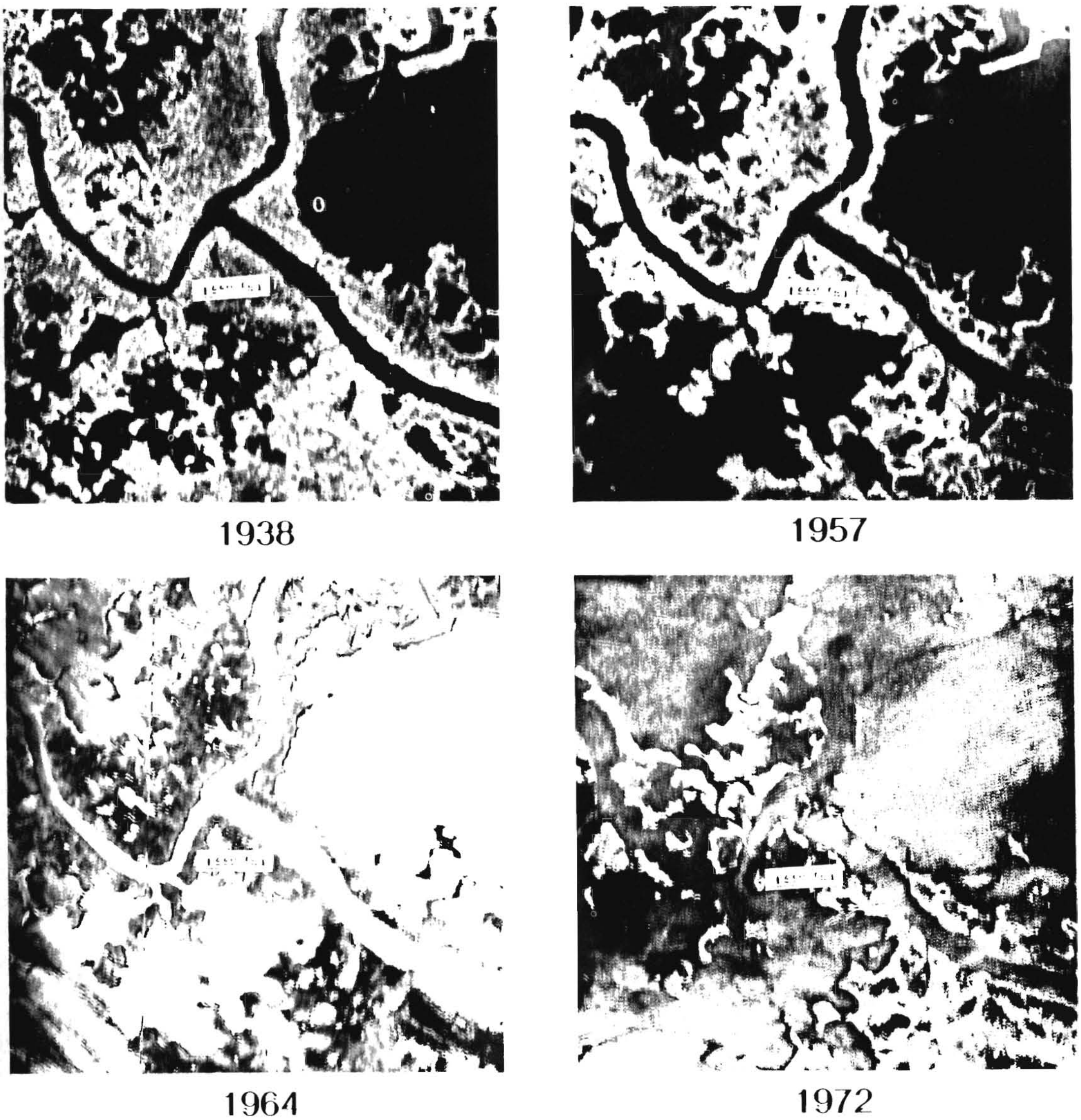
DISCUSSION

There are three major responses a salt marsh could have to a rising sea level: (1) the marsh system could drown if rates of coastal submergence exceed the marshes ability to accrete vertically, (2) the marsh may remain stable if the input of sediments equals the rates of coastal submergence so that surface elevations are maintained, and (3) the marsh can actively expand both vertically and laterally if accretion rates are higher than rates of coastal submergence.

Marsh Drowning

When a non-aquatic plant is subjected to prolonged periods of submergence, the supply of oxygen to its roots becomes severely limited. Such exposure will gradually result in water-logging and death of the plant, hence the expression drowning. Due to this factor the marsh will experience reduction in plant biomass resulting in losses of *in situ* organic sediment sources and a concurrent loss in sediment trapping ability. These losses can initiate a relative lowering of the marsh surface and induce drowning of the system.

If vertical accretion rates of the marsh surface are lower than rates of sea level rise, a marsh site can be converted to an open water habitat due to drowning. This could be the result of reduced sedimentation rates and/or increased coastal submergence rates. DELAUNE *et al.*, (1983) showed that an accretion rate of 8 mm yr^{-1} was not sufficient to maintain the elevation of the marsh in an area that is submerging at 12 mm yr^{-1}. These wetlands have experienced a 30 percent reduction in area during the past three decades primarily attributed to this "aggradation deficit." PENDLETON and STEVENSON (1983) determined that the marsh at Blackwater National Wildlife Refuge, Maryland,



1938

1957

1964

1972

Figure 1. Aerial photographs of the confluence of Big and Little Blackwater Rivers (Dorchester County, Maryland) showing conversion of marsh to open water habitat at Blackwater National Wildlife Refuge (from Pendleton and Stevenson, 1983).

lost 2,300 ha between 1938 and 1979 (Figure 1). The major contributing factors for this loss were rates of sea level rise exceeding sediment accretion rates and, to a lesser extent, animal grazing and burrowing (Kearney *et al.*, 1983).

A marsh can experience drowning if local rates of subsidence are high. Marshes naturally subside under normal conditions due to compaction of peat under their own weight (KAYE and BARGHOORN, 1964). Sometimes, however, it is possible for artificial hastening of this process. Spoil piles dumped on marsh surfaces have been shown to increase compaction factors and inhibit lateral subsurface water movements (BRERETON, 1971). This activity is often associated with canal dredging and mosquito control ditching where the spoil piles are placed along the banks, creating artificial levees. Subsurface withdrawal of materials, including water, oil, gas, sulfur, and salt can also result in the lowering of surface elevations and cause wetland loss (CRAIG *et al.*, 1980; GAGLIANO *et al.*, 1981; BOESCH *et al.*, 1982). In Louisiana, for instance, subsurface withdrawals have resulted in subsidence rates as high as 45 mm yr^{-1} in coastal wetlands (EARLE, 1975).

Cultural modifications can greatly influence marsh development. The construction of a roadway along the upper border/upland fringe can impound runoff from upland areas and effectively reduce terrestrial sediment supply to the marsh surface. Canal dredging has been shown to reduce sediment sources by changing hydrologic and sediment transport processes (CRAIG *et al.*, 1980). It is also possible that impoundments along peripheral marsh areas can inhibit upland conversions (salt marsh invasion of terrestrial vegetation). Due to this obstruction of the natural marine transgressions, it is possible that the high marsh may no longer progress landward and may eventually be replaced by low marsh which in turn may be converted to open water habitat as the sea level rises.

Natural reductions in sediment sources can be caused by changes in river flow or upland erosional processes due to climatic fluctuations (FREY and BASAN, 1979). By starving the system of its sediment sources, the marsh surface will not be able to maintain accretion rates comparable to rising sea levels, resulting in marsh drowning.

Recent rates of wetland loss for the entire US have been estimated to be approximately 0.5 percent per year (GOSSELINK and BAUMANN, 1980). It is not known what part of this value can be attributed directly to marsh drowning. However, it does seem reasonable to assume that if sea levels continue to rise at present rates, losses in wetland area due to drowning will increase. Because of the numerous factors involved, it is not possible at this time to determine how much of an increase in wetland reduction could be anticipated.

Marsh Expansion

A continual rise of sea level does not necessarily result in a loss of wetland area; it is possible for a marsh to expand both laterally and vertically during relative sea level rise. If plant productivity and sedimentation rates can increase sufficiently, the marsh can expand even during periods of rapid rises in sea level. This may be due, in part, to a landward displacement of wave energy transporting suspended sediments and nutrients further across the marsh surface which may also contribute to increases in plant productivity (GLEASON *et al.*, 1979). FLESSA *et al.* (1977) showed that a New York salt marsh has been growing vertically at a maximum rate of 4.7 mm yr^{-1} and laterally at 16 mm yr^{-1} since the early 1800's. This study was conducted on an immature system where a majority of the surface was dominated by intertidal *Spartina alterniflora.* HARRISON and BLOOM (1977) found that the vertical accretion rates on mature systems in Connecticut ranged from 2.0 to 6.7 mm yr^{-1}. Both of these studies showed that accretion rates equaled or exceeded present rates of sea level rise.

Given a rapid rise in sea level, a marsh may be able to compensate and expand laterally if sediment input is sufficient. This is particularly applicable for marshes located at the mouth of rivers. A study of headwater wetlands along the tributaries of the Chesapeake Bay showed marshes to be rapidly expanding seaward (one marsh was shown to expand 37 ha since the mid 1800's; FROOMER, 1980). There is much evidence to suggest that land-clearing practices since Colonial times has greatly increased sedimentation rates along the coast and may be responsible for the high rate of marsh expansion (FROOMER, 1980; BRUSH and DAVIS, 1983). Along the Louisiana coastline, localized areas are also expanding at rapid rates due to the high input of fluvial sediments (WELLS and KEMP, 1982). These marshes are expanding even though local rates of coastal submergence appear to be accelerating.

Recent changes in land-use patterns (*e.g.*, a reduction in agriculture) along the US east and Gulf coastal plains may result in changes in sedimentation rates. It is possible that previous land-use patterns have masked the effects of a rising sea level on salt marshes by supplying increased sediments above natural fluviatile loads. If sedimentation rates are significantly reduced in the future, this may initiate increases in wetland loss.

Marsh Retreat

It is possible for a marsh to maintain its spatial extent in response to sea level rise if vertical growth can equal rates of coastal submergence. This commonly occurs with a landward displacement of the system at the leading edge of the marine transgression. At the upland fringe the marsh is encroaching over freshwater terrestrial vegetation while at the bayfront border the marsh is being submerged and eroded as the rising sea level floods these areas. Marshes that are fronted by a barrier beach can retreat as they are subjected to burial by beach rollover processes in response to sea level rise (LEATHERMAN, 1983). In this manner, new salt marshes are being continually formed in a geologic sense as the older ones are buried by the encroaching barrier sand so that all ecologic units of the barrier island system remain intact with landward migration.

CONCLUSIONS

The continued development of present day tidal salt marshes is dependent upon specific interactions among a number of factors including growth of salt tolerant grasses. Each system has its own set of controlling influences that must be assessed in order to determine its response to increases in coastal submergence. The understanding that our present knowledge is as yet incomplete requires that future management recommendations be specific for individual locations.

After the system has been assessed as to its influencing factors it may then be possible to determine future development of these areas. In general, if the system cannot maintain surface elevations necessary for continued plant growth with respect to rises in sea level, it will have a tendency towards more open water habitats. If, however, the marsh surface can maintain accretion rates either equalling or exceeding coastal submergence rates, then the marsh may remain stable or even actively expand. It is possible over time that changes in controlling factors can reverse previous trends and may even initiate losses where there were once gains.

Cultural activities have already had a great impact on our coastal wetlands. GOSSELINK and BAUMAN (1980) determined that as much as 50% of the tidal wetlands in the northeastern United States have been destroyed during the past century. The extent to which these activities have altered or masked natural processes may never be fully ascertained. Thus it becomes increasingly important to preserve remaining marsh areas. More research is necessary to help insure that tidal wetlands can continue to function as a productive natural interface between terrestrial and marine environments.

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