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Submergence, Salt-Water Intrusion, and Managed Gulf Coast Marshes

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Abstract

Many coastal marshes are managed to improve wildlife habitat. Simultaneous salt-water intrusion and rapid submergence in Louisiana place additional demands on marsh managers and may become common worldwide because of the greenhouse effect. Current management practices often counter salt-water intrusion but not submergence, which is offset by soil formation. The purpose of this paper is to help Gulf Coast marsh managers understand how marsh management may influence soil formation by providing an overview of the relevant physical, chemical, and biological processes.

Organic matter accumulation controls soil formation in Louisiana marshes, thus vigorous plant growth should promote soil formation. Soil aeration controls many factors that limit plant growth. An indication of soil aeration is Eh, which is greater in drained soils than in waterlogged soils. Eh also depends partly on soil organic matter qualities. Eh is greater in *Spartina patens* soil than in *Panicum hemitomon* or *Spartina alterniflora* soil even when hydrological conditions are the same.

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Plant growth also depends partly on mineral sediments for nutrients and to buffer sulfides, thus increasing sedimentation may increase plant growth on mineral poor soils. This would require that water control structures are sometimes operated to promote sedimentation, which depends on river discharge and winter storms. Rapid drainage following sediment deposition is required to consolidate new sediments.

Soil organic matter decomposes and must be replaced by new production. The decomposition rate depends primarily on soil aeration, but also on organic matter qualities. *S. patens* soil decomposes slower than either *S. alterniflora* or *P. hemitomon* soil even when hydrological conditions are the same.

Salinity is not the only stress to increase during salt-water intrusion; sulfate (SO_4^{2-}) also increases. Sulfate is not a plant toxin, but soil bacteria convert it to toxic sulfides (H_2S, HS^-, and S^{2-}). Soil iron partially buffers against sulfides by precipitating them, and plant growth is related to soil iron content in saline marsh. This is probably why fresh marsh requires less mineral matter for soil formation than saline marsh. Sedimentation must therefore increase during salt-water intrusion.

In conclusion, brackish conditions may enhance soil formation in managed marshes because of the relatively slow decomposition, high soil Eh, and low mineral matter requirements. However, management must do more than prevent soil waterlogging and maintain brackish conditions. It must also allow marsh flooding with sediment rich waters, and rapid drainage after each flood event. Modifying current management practices may allow this. However, a risk of maintaining fresher conditions than in surrounding marsh is that levee failure could cause plant mortality and peat collapse. Re-establishing vegetation could be extremely difficult.

Introduction

The area of coastal wetlands is small compared to other habitat types but is extremely important to a large number of migrant and resident wildlife species. Many private landowners and government wildlife agencies manage coastal wetlands to

improve wildlife habitat by producing favorable plant communities (Chabreck 1976). However, salt-water intrusion and rapid submergence are common in some areas of Louisiana (Chabreck and Linscombe 1982, Ramsey and Penland 1989), and are related to wetland loss there and in Texas (DeLaune et al. 1983a, Sasser et al. 1986, Morton and Paine 1990). Some Louisiana marshes are managed to counter salt-water intrusion (Berry and Voisin 1989), but none appear to be managed to counter rapid submergence as well.

Global sea level rise and subsidence continually reduce the elevation of the marsh surface relative to water levels. This submergence is countered by soil formation, or vertical accretion, that creates a new, more elevated marsh surface, which prevents excessive flooding, plant dieback, and marsh loss. Soil formation during gradual submergence can be self regulating because tidal delivery of mineral sediments increases and soil organic matter decomposition slows as flooding increases (Mitsch and Gosselink 1986:178). As elevation is regained, mineral sedimentation slows and soil organic matter decomposition increases.

Global sea-level rise has been relatively slow since the end of the last ice age, but the rate may increase because of the greenhouse effect. Current global sea-level-rise is estimated at 0.24 cm/yr (Peltier and Tushingham 1989). Predictions of the rate of global sea-level rise range from 10 to 21 cm by 2025; which would cause widespread rapid submergence of coastal marshes (Titus 1986). In addition to increased flooding, marine influences will also increase in tidal fresh and brackish marshes (Titus 1986). Thus if sea level rise increases as predicted, then simultaneous salt-water intrusion and rapid submergence will become major problems even outside Louisiana. The purpose of this paper is to help Gulf Coast marsh managers understand how soil formation may be influenced by marsh management practices by providing an overview of the relevant physical, chemical, and biological processes. It is not our intent to encourage the impoundment of additional marsh area. That decision involves many concerns. For instance, coastal marshes are important nursery areas to some marine fisheries, and marsh impoundments will reduce dependent fish populations where they are limited by the availability of nursery area.

Soil Formation

Marsh soil is composed of mineral and organic matter. Mineral and organic matter accumulation are related because sedimentation supplies plant nutrients (DeLaune et al. 1981) and because vegetation promotes sedimentation by reducing water velocity and by biologically trapping sediments too fine to settle from the water column (Gleason et al. 1979, Stumpf 1983). Thus plant biomass and soil mineral content are positively related in Louisiana brackish marsh (Nyman et al., unpub. ms. #1 in review) and saline marsh (DeLaune and Pezeshki 1988). Vertical accretion is determined by mineral matter accumulation in the southeast Atlantic coast and San Francisco Bay (see Stevenson et al. 1988), but by root growth in New England type marsh (Stevenson et al. 1988) and Louisiana (Hatton et al. 1983). Reasons for these differences are unknown.

Mineral Matter Accumulation. Mineral sediments originate either from oceanic sediments carried landward by bottom currents such as in some southeastern Atlantic coast marshes (Meade 1969), from river sediments deposited directly by rivers such as in the active Mississippi River delta (Frazier 1967), or from discharged river sediments that settle away from the river of origin such as in the Cheniere Plain of Louisiana (Gould and McFarlan 1959). Different flooding events, whether river, tides or storms, differ in sediment delivery because sediment availability varies seasonally and annually. The timing of maximum sediment availability in coastal waters depends on discharge of nearby rivers. During low discharge years, sediment maxima occur shortly before or coincide with maximum river discharge, thus highest sediment availability occurs in late spring (Mossa and Roberts 1990). During high discharge years however, sediment maxima occur in winter or early spring when the river bed is scoured to accommodate increased flow (Mossa and Roberts 1990).

Tides deliver mineral sediments to southeastern Atlantic coast marsh, and thunderstorms can cause sediment losses (Stevenson et al. 1988). However, storms deliver more sediments than tides in Louisiana and New England type marsh (Stumpf 1983, Reed 1989). The process is well documented on

the Louisiana coast (Reed 1989). Southeasterly winds preceding fronts increase water levels and wave action in bays and lakes. Wave action suspends bottom sediments from large water bodies, and high water allows their transport to the marsh. Following frontal passage, prevailing northerly winds lower water levels and the marsh surface rapidly drains. This dries and consolidates the newly deposited sediments, thus preventing their washing away during the next flooding event. This drying phase is especially important; Meeder (1987 cited in Reed 1989) noted that although Hurricane Juan deposited >6 cm of sediment, heavy rains following that hurricane washed away virtually all new sediment. It may be possible to design and operate water control structures to compliment sedimentation processes, and still allow water level and salinity management. However, these goals require such different practices that it may be most effective to manage for sediment capture every few years, and for wildlife habitat in other years (Cahoon 1991).

Organic Matter Accumulation. It is hard to understate the importance of organic matter to marsh soil formation on the Gulf Coast. Organic matter occupies more soil volume than mineral matter in fresh, intermediate, and brackish Louisiana marsh (Nyman et al. 1990). Organic matter accumulation, primarily via root growth, determines vertical accretion in Louisiana (Hatton et al. 1983) and New England marshes (McCaffrey and Thomson 1980), and also reduces erosion (McCaffrey and Thomson 1980, and personal observation). Much is probably produced by perennials that produce more root biomass than annuals (Mitsch and Gosselink 1984:277). Organic matter accumulation depends on plant production, soil organic matter decomposition, and litter accumulation.

Plant Growth.--Marsh managers may be able to contribute greatly to soil formation by promoting vigorous plant growth. Wildlife habitat is usually improved by producing desirable plant communities (Chabreck 1976) but impoundment drawdowns increase growth as well (e.g. Carney and Chabreck 1977, Kadlec 1962). Mineral sediments also promote plant growth because they contain phosphorus (DeLaune et al. 1981). Phosphorus is a limiting plant nutrient in sediment poor marshes such as Louisiana fresh marshes (Mitsch and Gosselink

1984:266-267), but not in sediment rich marshes such as Louisiana salt marshes (Patrick and DeLaune 1976). Two additional, major factors limiting plant growth are related to the microbial decomposition of soil organic matter in waterlogged soils: soil sulfides and low soil Eh. Sulfides occur only when Eh is low but the reverse is not true, and low Eh alone is not as stressful as sulfides and low Eh (Pearson and Havill 1988, Pezeshki et al. 1988). Because of their importance to plant growth, these factors are reviewed in detail.

Oxygen is preferred for respiration because it is the most energy efficient terminal electron acceptor. This results in the reduction of O_2 to CO_2, and the oxidation of soil organic matter. Microbial respiration in wetland soils is altered by flooding that restricts diffusion of O_2 into soil, and much respiration in flooded soils is carried out by facultative and strict anaerobes using electron acceptors less efficient than O_2. Respiration therefore proceeds via fermentation, and via the reduction of NO_3^- to NH_4^+, of Mn^{+4} to Mn^{+2}, of Fe^{+3} to Fe^{+2}, of SO_4^{2-} to S^{2-}, or even of CO_2 to CH_4 (Mitsch and Gosselink 1986:88-104). As the pool of an electron acceptor is reduced, electron pressure increases, and decomposition using the next most efficient electron acceptor begins. This causes different classes of decomposers to predominate at different degrees of soil waterlogging, thus SO_4^{2-} reducing bacteria do not become active until all NO_3^-, Mn^{+4}, and Fe^{+3} is reduced. The demand for electron acceptors in soil stresses vegetation by decreasing the amount of oxygen that reaches plant roots. Some species develop air passages in roots and switch to less efficient anaerobic respiration; even so, waterlogging can be so severe that root development and growth may be poor (Pezeshki and DeLaune 1990).

Redox potential (Eh) is a measure of electron pressure on a Pt electrode, which indicates the intensity of reduction. In reduced conditions, Eh ranges from -300 to +400 millivolts (mV); in oxidized conditions Eh may be as high as +700 mV. Although Eh measurements may be used to determine the status of specific ions in simple or controlled situations, Pt electrodes in flooded soils respond to many redox couples, and chemical equilibrium is rare (Stumm and Morgan 1981). This complicates

using Eh measurements to determine the status of specific electron acceptors, but Eh measurements may be used to distinguish degrees of waterlogging (Whitfield 1969), and expected changes in marsh soil water chemistry coincide with changes in soil Eh (Feijtel et al. 1988). Thus soil Eh is used as an indicator of waterlogging stress on marsh vegetation (e.g. DeLaune et al. 1983b).

Soil Eh can be higher in brackish soil than in fresh and saline marsh even when water-table depths are the same (Nyman et al. 1991). This suggests that with similar degrees of soil drainage, less stress would result from low Eh on brackish marsh vegetation than on fresh and saline marsh vegetation. The most likely reason for this is that microbial respiration rates differ among fresh, brackish and saline marsh (Nyman et al. 1991).

Sulfides, or reduced sulfur, also affect plant health. Although oxidized sulfur in the form of sulfate, SO_4^{2-}, is not toxic at natural concentrations, reduced sulfur, i.e., sulfides: H_2S, HS^-, or S^{2-}, are (Pearson and Havill 1988, Pezeshki et al. 1988). The degree of sulfide stress on vegetation is not likely the same among fresh, brackish, and saline marsh. Sulfate reduction depends partly on SO_4^{2-} availability (Nedwell 1982), and SO_4^{2-} increases from fresh to brackish to saline marsh because seawater is the primary SO_4^{2-} source (Brupbacher et al. 1973, Feijtel et al. 1988). Thus sulfide stress is likely greatest in saline marsh and least in fresh marsh, which is the most likely reason that plant stress and mortality occurs in excessively flooded saline marsh soils (DeLaune et al. 1983b, Mendelssohn and McKee 1988), whereas near permanent flooding can be survived by many fresh and intermediate marsh plants such as species of *Scirpus*, *Zizaniopis*, *Cladium*, and *Typha*.

Soil Fe also influences sulfide toxicity. Sulfate reducing bacteria become active only after Fe reducing bacteria exhaust the oxidized Fe pool. The resulting reduced iron pool is also important because reduced iron precipitates with reduced sulfur, thus removing sulfides from the soil solution. Saline marsh requires almost twice as much mineral matter as

Table 1. Estimated mineral and organic matter inputs required to counter submergence, where x = submergence in cm/yr (from Nyman et al. 1990).

Marsh Type	Organic input ($g\ m^{-2}\ yr^{-1}$)	Mineral input ($g\ m^{-2}\ yr^{-1}$)
fresh marsh	1,700 + 269x	424x
brackish marsh	553 + 583x	1,052x
saline marsh	923 + 601x	1,798x

brackish marsh for soil formation (Table 1), likely to provide Fe for SO_4^{2-} buffering and precipitation (Nyman et al. 1990), and soil iron is positively associated with saline marsh plant production in Georgia marsh (King et al. 1982). Thus salt-water intrusion increases salinity stress, sulfide stress, and sedimentation requirements.

Litter Accumulation.--Litter accumulation might be important in some marshes, although examination of scores of shallow cores suggests that root production is most important in Louisiana (personal observation) and New England marsh (McCaffrey and Thomson 1980). Where liter is an important source of soil organic matter, tidal flushing may affect organic matter accumulation. Generally, tidal flushing removes less litter from Texas and Louisiana marsh than from Atlantic coast marsh, reflecting differences in tidal range (Hopkinson et al. 1978). As expected, tidal flushing removes more litter from saline marsh than from brackish marsh (White et al. 1978). Also, detritivores such as fiddler crabs are apparently abundant enough to limit detrital buildup on the marsh floor in salt marshes.

Decomposition.--Soil decomposition is continuous on the Gulf Coast and southeastern Atlantic coast even though rates are slower in winter than in summer (Morris et al. 1986, Smith et al. 1983). This oxidizes significant amounts of soil organic matter that must be replaced to maintain marsh elevation (Nyman et al. 1990). Soil drainage increases decomposition (Nyman et al. 1991), thus excessive drainage could oxidize a great deal of soil organic matter. Organic matter requirements for marsh soil

formation differ among marsh types (Table 1) because brackish marsh soil decomposes slower than fresh and saline marsh soils (Nyman et al. 1991). Thus plants resistant to decomposition may promote soil formation. All brackish marsh species may not decompose at the slow rate observed for *Spartina patens* soil, and it is possible that species such as *Scirpus olneyi* may provide a better diet for soil microbes. This might increase organic matter required for soil formation by increasing decomposition, and might stress vegetation by decreasing soil Eh.

Management Implications

If the rate of global sea level rise increases as expected, it will be accompanied by salt-water intrusion (Titus 1986). Options designed to counter these processes are currently needed in managed marshes in some areas of Texas and Louisiana, and may be needed elsewhere in the near future. It would be a mistake to focus management solely on prevention of salt-water intrusion, which would likely result in practices that limit soil formation, or solely on sedimentation processes, which would likely result in practices that do little to maintain or improve wildlife habitat. Thus an integrated approach to simultaneously counter these processes is needed. It should be noted that some degrees of submergence and salt-water intrusion may be so great that it would be impractical to prevent marsh loss.

Promoting vigorous plant growth appears to be the best counter-measure to rapid submergence and salt-water intrusion. In addition to optimum salinity and water levels, plant growth also appears to require a certain amount of mineral sediments. Thus, increasing sedimentation may improve plant growth on mineral poor soils. Inadequate sedimentation can lead to inadequate plant growth and subsequent inadequate organic matter accumulation, vertical accretion deficits and wetland loss (Nyman et al., unpub. ms. #2 in review). Rapidly submerging, sediment poor marshes should therefore be flooded frequently with sediment rich water, as well as rapidly drained so that newly deposited sediments consolidate before the next flooding event. Thus management practices should incorporate knowledge of river discharge and the relative importance of tides or storms in the sediment delivery processes. For instance, low natural levees that are topped by storm tides, and large-capacity water control structures that allow rapid drainage during the low water levels that follow cold fronts might be successful management tools in some areas of Louisiana where litter accumulation in unimportant.

Preventing brackish marsh from converting to saline marsh during salt-water intrusion might reduce wetland loss, especially in sediment poor areas. Brackish conditions reduce SO_4^{2-} influx, and thus should reduce sulfide stress on vegetation, while *Spartina patens* soil organic matter decomposes slowly, reducing soil organic matter losses as well as waterlogging stresses on vegetation. This should also prevent mineral matter requirements from increasing as brackish marsh converts to saline marsh. Such measures may not be necessary to prevent marsh loss when salt water intrusion is accompanied by increased sediment availability sufficient to counter submergence of saline marsh, although allowing conversion of brackish to saline marsh would likely reduce the wildlife value of the managed area.

Maintenance of fresher marsh in more saline areas via impoundments is not without risk. At some point, the benefits of drawdown to plant growth will be outweighed by increases in soil organic matter decomposition. While there is not enough information with which to determine how long of a drawdown is too long, fresh marsh impoundments likely cannot tolerate as lengthy of a drawdown as brackish marsh impoundments because soil organic matter decomposes so much faster in fresh than in brackish marsh. Furthermore, if impoundment levees fail, extensive salt burns likely follow. Even more important than actual plant mortality, is the collapse of surface peats (over 10 cm) following plant mortality (DeLaune et al., unpub. data). It may be near impossible to reestablish plant growth in resulting depressions before soil erosion begins unless forced drainage is available. This may be especially important if management had previously negatively affected soil formation processes, which might not be apparent in functional impoundments because of water level control.

Hopefully, more will be learned about wetland soil processes and the effects of various management strategies. Marsh managers may use the following types of data to help evaluate the magnitude of submergence in their region, and the effects of marsh management on soil formation. Submergence rates can be estimated from long term, i.e. 20-50 years, tide gauge analyses. The U.S. Army Corps of Engineers and the National Ocean Survey are two data sources, and those data from the Gulf of Mexico are already analyzed and published (Ramsey and Penland 1989). Soil formation can be estimated by marking the marsh surface with a layer of feldspar (Cahoon and Turner 1990). Filter papers techniques can indicate the relative contributions of tide and storm events (Reed 1989). A record of weather conditions, operation of water control structures, continuous water level data, and soil formation will likely also be necessary to evaluate the factors controlling soil formation in managed marsh.

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