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FOUR POTENTIAL IMPACTS OF GLOBAL SEA LEVEL RISE ON COASTAL MARSH STABILITY

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Abstract: We developed four hypothetical scenarios describing how accelerated global sea-level rise might affect wetland area. These scenarios may not describe all possible responses but they guide our investigations and may represent a realistic classification system.

Stable wetland area is the first scenario, which requires sufficient marsh vertical accretion and pond-bottom vertical accretion to offset submergence (i.e., the combination of global sea-level rise and local subsidence). The presence of 1,000 year-old coastal wetlands indicates that this scenario is historically common. Marsh accretion mechanisms vary spatially and perhaps temporally. Most marsh accretion occurs via mineral sedimentation, but some occurs via a vegetative growth mechanism. We do not know what variables and driving forces determine if marsh accretion proceeds via mineral or vegetative mechanisms. Pond-bottoms accrete primarily via mineral sedimentation. Three non-stable scenarios are also possible.

One unstable scenario, flooding instability, occurs when marsh accretion is slower than submergence. Such inadequate marsh accretion leads to flooding that stresses plants and eventually causes open water to replace marsh as occurs in the rapidly subsiding Mississippi River Deltaic Plain where vegetative accretion averages 7.2 mm/yr. This may be the maximum rate of submergence that coastal marshes can tolerate. If true, then global sea-level rise may have little impact on wetland stability in slowly subsiding areas during the next 200 years. However, many areas subside, and the maximum sustainable rate of vegetative accretion at other latitudes and mineral accretion may be< 7.2 mm/yr.

Another unstable scenario, erosional instability, might occur when pond-bottom accretion is slower than submergence. Such inadequate pond accretion would deepen ponds, which would accelerate pond-edge erosion. This scenario might be more common where accretion proceeds via vegetative growth but there are no data to test this hypothesis.

The last scenario, Fe/S instability, might develop where marine conditions intrude into tidal, non-saline wetlands. Upland slope primarily determines how far wetlands can migrate inland. However, some non-saline wetland soils might develop insufficient soil Fe/S ratios to support saline wetlands. Iron may improve plant growth in the presence of SO_4^{2-} reduction, and the amount of S^{2-} that plants survive may depend partly on soil Fe. Marsh zone migration at the expense of tidal, non-saline marshes occurs in the rapidly subsiding Mississippi River Deltaic Plain. However, the role of soil Fe/S ratios in coincident wetland loss is undocumented.

Key Words: wetlands, global sea level rise, accretion, sedimentation, vegetative growth

INTRODUCTION

Marsh vertical accretion (here-in-after marsh accretion), which is an increase in surface elevation relative to a marker (e.g., feldspar or ^{137}Cs) resulting from the accumulation of mineral sediment and organic material (Mitsch and Gosselink 1984:178-181), has been widely studied (see Callaway *et al.*

1996 and articles cited there-in). Pond-bottom accretion (here-in-after pond accretion) is an increase in the elevation of a pond bed relative to a marker resulting from the accumulation of mineral sediment and organic matter; pond accretion has not been widely studied. Accretionary processes must be adequately understood to predict consequences of faster global sea–level rise on coastal and estuarine marshes. Otherwise, opportunities to preserve vulnerable marshes might be lost and resources might be wasted on marshes whose fate need not or cannot be managed should global sea–level rise accelerate. We used published data and tacit knowledge to predict how accelerated global sea–level rise might affect coastal marsh stability, which we define as a change in wetland area. That analyses resulted in four hypothetical scenarios involving marsh accretion, pond accretion, marine intrusion, and wetland stability. These scenarios may not accurately describe all possible responses of coastal wetlands to accelerated global sea–level rise but they guide our investigations and may represent a realistic classification system.

SCENARIO ONE: STABILITY

Stability requires sufficient marsh accretion and pond accretion to offset submergence; i.e., the combined effects of global sea–level rise and local subsidence. Wetland area is stable when marsh and pond accretion are sufficient to offset submergence because marsh surface elevation and pond depth relative to the tidal prism do not change over time. Conversely, marshes convert to shallow water via flooding stress and/or erosion if accretion is slower than submergence. However, marsh accretion has generally prevented marsh drowning during the relatively slow global sea–level rise prevailing since the end of the last ice age, which allowed marshes to survive and sometimes expand laterally (Redfield 1972, Allen and Rae 1988). We thus hypothesize that stability is currently common worldwide while noting that widespread wetland loss indicates that some wetlands are not stable (Phillips 1986, Hackney and Cleary 1987, Morton and Paine 1990, Kearney and Stevenson 1991, Britsch and Dunbar 1993).

Predicting the effects of accelerated global sea–level rise on coastal marshes requires knowing what factor limits accretion. Sea-level rise limits accretion during stability. This limitation is the reason that coastal wetlands do not accrete above the tidal prism. However, rapid wetland loss in the Mississippi River Deltaic Plain indicates that a factor other than submergence limits accretion during rapid submergence (e.g. see Hatton et al. 1983). We therefore examine accretion processes to explore what factor limits accretion when submergence no longer does.

We hypothesize that marsh accretion is controlled by mineral sedimentation in some wetlands at some times. Numerous studies support this hypothesis or are based on this hypothesis (e.g., Stevenon *et al.* 1986, Stoddart *et al.* 1989). Accretion via mineral sedimentation is hypothesized to result from negative feedbacks between elevation and sedimentation such that sedimentation is greater when elevation is lower (Mitsch and Gosselink 1984:178-181). The primary evidence for accretion via mineral sedimentation is the observation that accretion is often faster adjacent to streams where sediments are more available than in inland marsh areas (e.g. Stoddart *et al.* 1989). We hypothesize that mineral sediment availability limits accretion in these marshes when accretion is not limited by slow submergence.

We hypothesize that marsh accretion is limited by organic matter accumulation in some wetlands at some times. This hypothesis is supported by several studies (Table 1). McCaffrey and Thomson (1980) were the first to note that is some marshes, variation in mineral sedimentation did not result in variation in accretion. They also noted that accretion appeared to proceed via an undescribed “vegetative growth mechanism.” Other workers using similar qualitative grounds reached similar conclusions (Hatton *et al.* 1983, Bricker-Urso *et al*. 1989, Craft *et al.* 1993, Callaway *et al.* 1997). Nyman *et al.* (1993) demonstrated that accretion at their sites was statistically unrelated to mineral sedimentation but was related to organic matter accumulation. We hypothesize that organic matter production limits accretion in these marshes when accretion is not limited by slow submergence (see Nyman et al. 1993).

Accretionary mechanisms thus vary spatially with mineral sediments controlling accretion in some places and vegetative growth controlling accretion in other places. We hypothesize that accretion mechanisms can also vary temporally within a site but there are no data to test this hypothesis.

Excessive submergence, defined here as submergence too rapid for the marsh to tolerate, may affect marshes that accrete via mineral sedimentation differently than it affects marshes that accrete via vegetative growth. We hypothesize that the time required for excessive submergence to convert wetlands to open water may be shorter where accretion depends on vegetative growth. We base this hypothesis on a positive feedback loop that may develop among flooding induced plant stress, inadequate

Table 1. Studies that have considered what controls marsh vertical accretion.

Study	Sites	Mechanism
McCaffrey and Thomson (1980)	Connecticut, USA	Vegetative Growth
Hatton *et al*., 1983.	Louisiana, USA	Vegetative Growth
Bricker-Urso *et al.* 1989	Rhode Island, USA	Vegetative Growth
Craft *et al.* 1993.	North Carolina, USA	2 sites, 2 mechanisms
Nyman *et al.* 1993.	Louisiana, USA	Vegetative Growth
Callaway *et al.* 1997	Gulf of Mexico, USA	Vegetative Growth

organic matter production, and inadequate accretion (Nyman *et al.* 1993) and which would cause a very rapid change from marsh to open water. In marshes where accretion depends on mineral sedimentation, the change from marsh to open water is likely to be more gradual because accretion would not be affected by declining plant productivity and may actually accelerate as marsh elevation declines relative to the tidal prism.

It is not known what factors and driving forces determine which accretion mechanism occurs at a particular place or time. It is tempting to speculate that accretion occurs via vegetative growth where mineral sediments are lacking, but accretion via vegetative growth occurs across a wide range of conditions (Table 2).

We hypothesize that accretion via vegetative growth depends indirectly on mineral sediments. Sphagnum bogs in the far north, and floating wetlands associated with the Nile, Amazon, and Mississippi Rivers provide ample evidence that freshwater wetlands do not require significant sediment inputs to accrete. Sphagnum bogs have existed for centuries with only atmospheric deposition of sediment yet accrete continually. However, plant growth in mineral starved wetlands is often P limited (Davis 1994). Thus, sediments that weakly bind PO_4-, such as clays that contain free iron or aluminum oxide (Patrick and Khalid 1974), likely benefit plants in mineral starved wetlands. Sediment also promote plant growth in saline (Broome *et al.* 1975, DeLaune and Pezeshki 1988) and brackish marshes (Nyman *et al.* 1994). Thus, sediments may indirectly affect accretion via vegetative growth if sediments enhance plant production.

Stability also requires that pond-bottoms adjacent to the marsh accrete at a rate similar to submergence rates. Otherwise, ponds will gradually deepen over time relative to the tidal prism and eventually accelerate pond edge erosion. For instance, a 1 mm/yr deficit in pond accretion would cause ponds to deepen 1 m in only 100 years. The fact that marsh ponds have not deepened to 10 m in the last 1,000 years indicates that pond accretion is generally adequate for the recent global sea–level rise rates. We hypothesize that ponds accrete primarily via mineral sedimentation rather than organic matter accumulation. We accept this hypothesis even though it has not been tested.

SCENARIO TWO:
INSTABILITY VIA PLANT FLOODING STRESS

If marsh accretion is inadequate, then the duration of marsh flooding gradually increases. Eventually, flood duration will exceed the tolerance limits of vegetation and plants will die. Such flooding induced marsh loss occurs in the rapidly subsiding Mississippi River Deltaic Plain (DeLaune *et al.* 1983, Mendelssohn and McKee 1988). Following plant death, shallow ponds replace emergent wetlands (DeLaune *et al.* 1994). We hypothesize that the maximum sustainable marsh accretion rate is 7.2 mm/yr and that this scenario occurs where submergence rates exceed 7.2 mm/yr. We base this estimate of the maximum, sustainable accretionary rate on the average rate of accretion in brackish and saline marshes of the Mississippi River Deltaic Plain (Nyman *et al.* 1990). We have observed more rapid accretion (Nyman *et al.* 1993) but the resulting soil was extremely weak (personal observation) and it is not know if those rates are sustainable. Determining if 7.2 mm/yr is the maximum, sustainable accretion rate of vegetative accretion in other climates and of accretion via mineral sedimentation requires new data.

It is difficult to relate our hypothetical maximum sustainable accretion rate to predictions of global sea–level rise because those predictions are generally presented as a total elevation change rather than a rate. More importantly, our hypothetical maximum sustainable rate assumes there is no local subsidence, or oxidation and compaction of marsh soil. That

Table 2. Summaries of published (Nyman *et al.* 1993) and unpublished data indicating that vertical accretion via vegetative growth occurs across a wide range of conditions.

characteristic	range
mineral sedimentation (g m^{-2} yr^{-1}):	394 - 2,748
organic accumulation (g m^{-2} yr-1):	280 - 1,740
organic content (% by weight):	14 - 47
vertical accretion (mm/yr):	2.5 - 17.8
tidal flooding:	seldom drained to seldom flooded

caveat needs to be considered when noting that global sea-level rise may not reach 7.2 mm/yr within 100 years. For instance, there is a 20% chance that the effect of climate alone will exceed 7.2mm/yr of sea–level rise by 2100 (Titus and Narayanan 1995, but note that this likelihood based on polling experts in the field rather than statistical models). It also appears that, assuming eustatic sea–level rise of 1.8 mm/yr in 1990, then the likelihood of eustatic sea–level-rise exceeding 7.2mm/yr does not exceed 10% until 2150 and is less than a 50% at 2200 (from data in Titus and Narayanan 1995, but note that this likelihood based on polling experts in the field rather than statistical models). Little faith should be put into these predictions given the numerous assumptions regarding global sea–level rise and maximum sustainable marsh vertical accretion. It is also important to emphasize that submergence in rapidly subsiding areas such as the Mississippi River Deltaic Plain currently exceeds 0.72 mm/yr (Penland and Ramsey 1993); thus, any acceleration in global sea-level rise will accelerate wetland loss rates there and in similarly subsiding areas.

SCENARIO THREE:
INSTABILITY VIA EROSION

Even if marsh accretion is adequate to offset submergence, marshes might convert to open water via lateral erosion at the edges of ponds if pond-bottom accretion is inadequate. The key step leading to erosion appears to be ponds becoming deeper than the depth of live roots in the adjacent marsh. Such a relationship among pond depth, root depth, and erosion results from the fact that soil strength depends on live roots. Pestrong (1969) and van Eerdt (1985a,b) noted that soil was stronger were they observed living roots, and McGinnis (1997) found that soil strength was statistically unrelated to soil mineral content and positively related to live root density. Thus, pond-edge erosion would increase as ponds became progressively deeper than the depth of live plant roots in the adjacent marsh. We hypothesize that this scenario is common where marsh accretion proceeds via vegetative growth but where the supply of mineral sediments is insufficient to allow adequate pond accretion. There have been no studies directed at investigating this scenario.

SCENARIO 4: INSTABILITY VIA
DECLINING FE/S RATIOS

Even if vertical accretion is adequate to counter submergence, upland slope determines if wetland area will change as global sea–level rises (Phillips 1986). Such inland migration of wetlands in response to global sea–level rise also causes marine intrusion into tidal, non-saline wetlands. Marine intrusion into tidal, non-saline wetlands may reduce coastal wetland area because some non-saline soils might not develop sufficient soil Fe/S ratios to support saline wetlands. Although fresh marshes apparently do not require sediments, the lack of floating brackish or saline marshes anywhere in the world suggests that non-fresh wetlands cannot exist without soil mineral matter. The requirement of non-fresh marshes for soil mineral matter may be related to sulfate (SO_4^{2-}) delivered by sea water, which is reduced to toxic sulfides (S^{2-}) by soil bacteria. Soil Fe precipitates with S^{2-}, removing it from soil solution, but S^{2-} supply can exceed Fe availability (Griffin and Rabenhorst 1989). Thus, Fe may improve plant growth in the presence of SO_4^{2-} reduction, and the amount of SO_4^{2-} that wetland plants can tolerate may depend partly on the amount of soil Fe. These relationships among soil Fe, soil SO_4^{2-}, soil S^{2-}, and plant growth were first proposed by researchers working within a Georgia salt marsh (King *et al.* 1982). If the amount of soil Fe required for plant growth varies with S^{2-} at a larger scale than previously proposed (King *et al.* 1982), then tidal, non-saline marshes experiencing marine intrusion may fail to convert to a more saline type unless mineral sedimentation increases because soil mineral matter content is generally much lower in tidal, non-saline marshes than in saline marshes (Mitsch and Gosselink 1984, Nyman *et al.* 1990). Thus, tidal non-saline marshes that accrete vegetatively may not survive marine intrusion even when the increase in salinity is very gradual unless sufficient soil Fe develops for salt marsh conditions. Marsh zone migration at the expense of tidal, non-saline marshes occurs in the rapidly subsiding Mississippi River Deltaic Plain. However, the role of soil Fe/S ratios in coincident wetland loss is undocumented.

CONCLUSIONS

Some of the hypotheses presented in this paper are likely to survive any tests of new data. For instance, the hypothesis that accretion can be controlled by mineral sedimentation in unlikely to be disproved by new data. Other hypotheses presented here are unlikely to persist as new data become available. For instance, the hypothesis that coastal marshes can survive 7.2 mm/yr of submergence is likely to be proven false under many conditions. However, until new data are available, our predictive ability is constrained by the, albeit limited, data. Thus, the value of developing hypotheses from limited data is not predictive capability. Instead, the primary value of these hypotheses is that they serve as targets for experimental testing and thereby make our efforts to develop predictive capability more efficient. A secondary value of these hypothesis is that the four scenarios may represent a realistic scheme for classifying wetland loss. A realistic system for classifying wetland loss is the first step in ensuring that protection and restoration efforts are appropriate for the situation specific to each site.

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