

Landsat Imagery Shows Decline of Coastal Marshes in Chesapeake and Delaware Bays

Dramatic losses of tidal wetlands in the Mississippi Delta and a few areas along the U.S. Atlantic coast have raised concerns about whether these marshes will survive if global sea level continues to rise due to greenhouse warming [Stevenson *et al.*, 1986]. Original greenhouse warming sea-level scenarios projected global sea levels several meters or more higher than present by 2100 [Barth and Titus, 1984], which would result in the disappearance of all coastal marshes, as the scarcity of marsh deposits from the rapid transgression during the middle Holocene testifies [Rampino and Sanders, 1981]. However, more recent estimates of global sea-level change suggest that some coastal marshes could survive [Douglas *et al.*, 2000].

Attempts to predict future marsh losses have involved submergence models incorporating information on coastal setting and a variety of marsh criteria [Armentano *et al.*, 1988]. The utility of these models is nevertheless limited, since information on vertical accretion rates—the principal factor controlling marsh adjustments to sea level—is either lacking for many marshes, or too site-specific to be representative in larger marsh systems. More important, evidence suggests that the severity of marsh losses from any future increase in the rate of sea-level rise depends on the existing stage of degradation of the marsh [Kearney *et al.*, 1988]. In particular, the formation of open water bodies (interior ponds), which can rapidly enlarge from wave erosion during storms, may set the stage for the wholesale disappearance of the marsh within decades [Stevenson *et al.*, 1985; Stevenson and Kearney, 1996]. In the case of quaking and other oligohaline marshes, where older sediments are often loose and vulnerable to erosion, marsh reconstruction could prove extremely difficult, if not impossible.

Traditional coast-wide assessments of changes in coastal marshes have relied on aerial photography. However, as an assessment tool for identifying rapid, short-term changes in coastal marshes, aerial photography is often hampered by the paucity of recent large-scale photographs for many areas and the need to fly new missions to obtain updated information. Relying on aerial photography even just a decade old could easily lead to erroneous conclusions for marshes where the rate of substrate degradation is high and subject to further acceleration under the

influence of coastal storms. To overcome these problems, we have developed a spectral mixing model based on Landsat Thematic Mapper imagery, which results in a marsh surface condition index (MSCI) that emulates the progressive degradation of marsh substrates that accompanies the marsh loss cycle.

Background

Increases in the period of tidal inundation, highly organic sediments, and declining plant vigor, as measured by culm height and biomass, are some of the early signals that marshes are not keeping pace with sea-level rise. However, delineating the role of sea-level forcing of such phenomena can be difficult to distinguish from inter-annual variations over the short term and in any event, can predate by years and even decades the appearance of characteristic morphological features such as

the widening of tidal creeks and small interior ponds that are the unmistakable precursors of eventual marsh loss [Kearney *et al.*, 1988]. Determination of vertical accretion rates, using marker horizons, sediment elevation tables (SET), or radionuclide dating of recent marsh sediments have commonly been relied on to determine a marsh's vulnerability to sea-level rise. There have been questions concerning the length of the period of measurement versus regional sea-level trends, particularly if a trend of only a few years spans a period of the short-term acceleration or deceleration in the sea-level record, which can vary considerably over decadal scales (Figure 1).

Donald Cahoon of the U.S. Geological Survey is currently coordinating a program that monitors vertical accretion rates using sediment elevation tables (SET), and it promises to provide the first international assessment of marsh vertical accretion rates across a variety of coastal settings. However, SET measurements are sometimes ambiguous, at least in the short run, and these data may not become widely available for several years. Moreover, for marshes that have yet to exhibit distinct signs of substrate deterioration, low vertical accretion rates are at best an indicator of the potential for loss at some indeterminate future time.

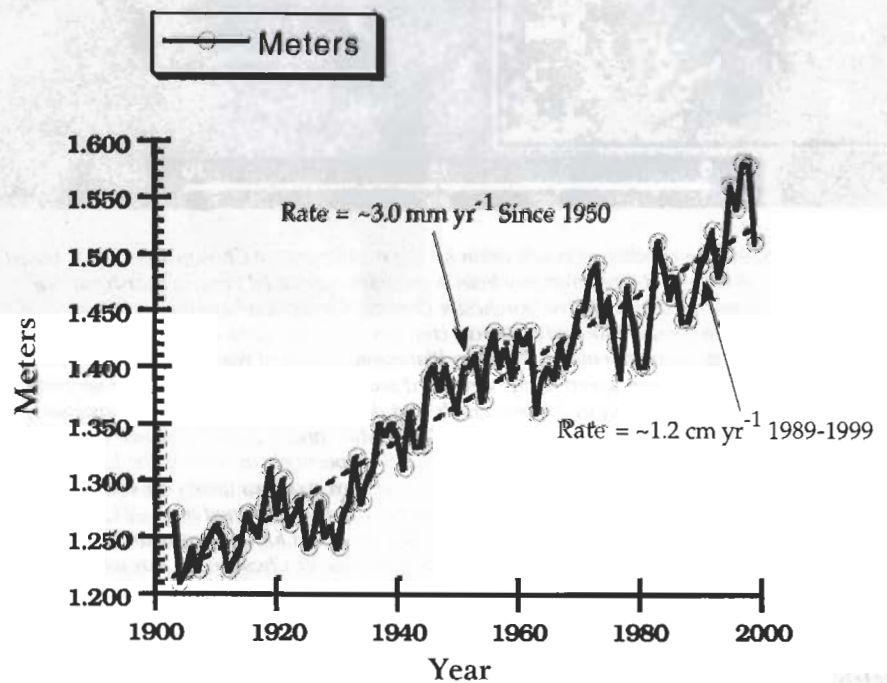


Fig. 1. Graphed here is the tide gauge record for Baltimore, Maryland, since 1900.

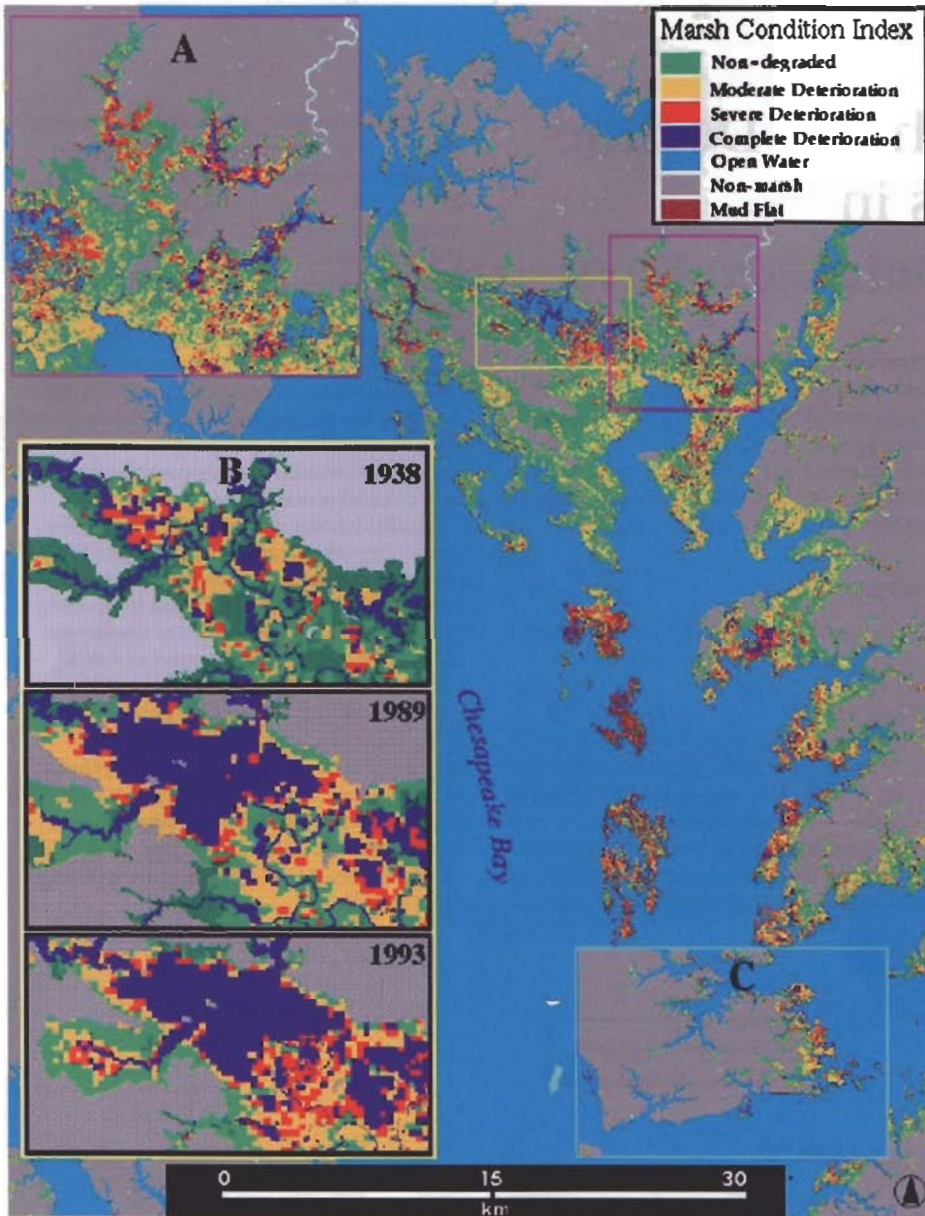


Fig. 2. This marsh surface condition classification for the middle part of Chesapeake Bay is based on 1993 Landsat Thematic Mapper imagery. Inset A provides a detailed view of marsh surface condition in the large marsh systems of Dorchester County, Maryland, where marsh loss is pronounced. Inset B shows summarized historical changes in marsh surface condition aggregated at 2.5 ha scale for marshes within and adjacent to Blackwater National Wildlife Refuge (Figure 4) between 1938 and 1993, where green is non-degraded marsh, yellow is moderately to severely degraded marsh, red is completely degraded marsh, and dark blue is open water. The changes are based on corrected and digitized 1:12,000 black and white and 1:20,000, color-infrared aerial photography acquired on 8 May 1938, and 28 April 1989, respectively, as well as the Landsat imagery. Between 1938 and 1989, almost 1700 ha of degraded marshes were converted to open water in the area shown, while coverage of non-degraded marshes declined from ~2150 ha to ~950 ha during this period. Inset C shows marsh surface condition for an area near Gloucester Point, Virginia, north of the York River, one of the areas in the lower Chesapeake Bay where marsh loss has been rapid (Figure 4).

Spectral Mixture Modeling of Marsh Surface Condition

Previous work in Chesapeake Bay [Kearney *et al.*, 1988] demonstrated that the degree of marsh substrate degradation—even in relatively early stages—could be delineated by examining recent large-scale color and color-

infrared aerial photography for the presence and extent of a number of physical indicators. More recently, a spectral mixing model was developed using Landsat Thematic Mapper (TM) imagery that emulates these principal changes in surface condition that occur as marsh substrates degrade when rates of sea-level rise outpace rates of vertical accretion.

Spectrally, marsh substrate degradation can be conceptualized as a change in reflectance from marsh vegetation through a transitional shift to increased soil (sediment) reflectance as the vegetation thins and, finally, growing dominance of water reflectance in the final stages. The spectral mixing model decomposes pixels from summer Landsat scenes into spectral end members of vegetation, soil, and water. Standard linear mixture models for these three end members and three spectral bands may be represented as:

$$\rho_w f_w + \rho_v f_v + \rho_s f_s = R_1$$

$$\rho_w f_w + \rho_v f_v + \rho_s f_s = R_2$$

$$\rho_w f_w + \rho_v f_v + \rho_s f_s = R_3$$

where ρ 's represent the reflectance of a particular substrate in a particular band; w, v, and s represent water, vegetation, and soil, respectively (hence, ρ_w would be the reflectance of water in band 1); the f 's representing the proportion of the pixel covered by a particular cover type; and the R 's representing the total reflectance in each band of all the individual substrate reflectances. Two additional assumptions are that $f_w, f_v,$ and $f_s \geq 0$ and $f_w + f_v + f_s = 1$. Central to this procedure is the identification of end members where a single surface type occupies 100% of a pixel. Examination of various plots of the spectral data revealed that bare sediments did not occupy a single location in the reflectance data, but instead encompassed a wide range of reflectance values [Borel and Gerstl, 1994] even when applied principal components analysis was applied, which is useful for defining the location of end members. Instead, three spectral indices calculated by normalized difference transformation were used to create a data space (NDX) where the differences in soil end member spectra are reduced: the Normalized Difference Water Index (NDWI), (Band 3 - Band 5)/(Band 3 + Band 5); the Normalized Vegetation Index (NDVI), (Band 4 - Band 3)/(Band 4 + Band 3); and the Normalized Difference Soil Index (NDSI), (Band 5 - Band 4)/(Band 5 + Band 4). End members were then selected using the NDWI and NDSI indices, which yielded clear groupings on scatter plots.

Equally important, the soil end member maintained a constant position in NDX space, while it can shift in PCA space depending on whether the marsh soils are wet, sandy, or muddy. Given the linear model in the equations above, ratios of the spectral bands would not necessarily be expected to scale linearly. In practice, calculating and subsequently averaging the indices on contiguous blocks of 100 pixels yielded very similar relationships to the reverse procedure of first averaging the reflectances and then calculating the indices, with r^2 values for regressions between the two data sets of NDWI, NDVI, and NDSI indices being 0.990, 0.993, and 0.945 respectively.

Multi-spectral remote sensing of coastal systems has sometimes been hampered by

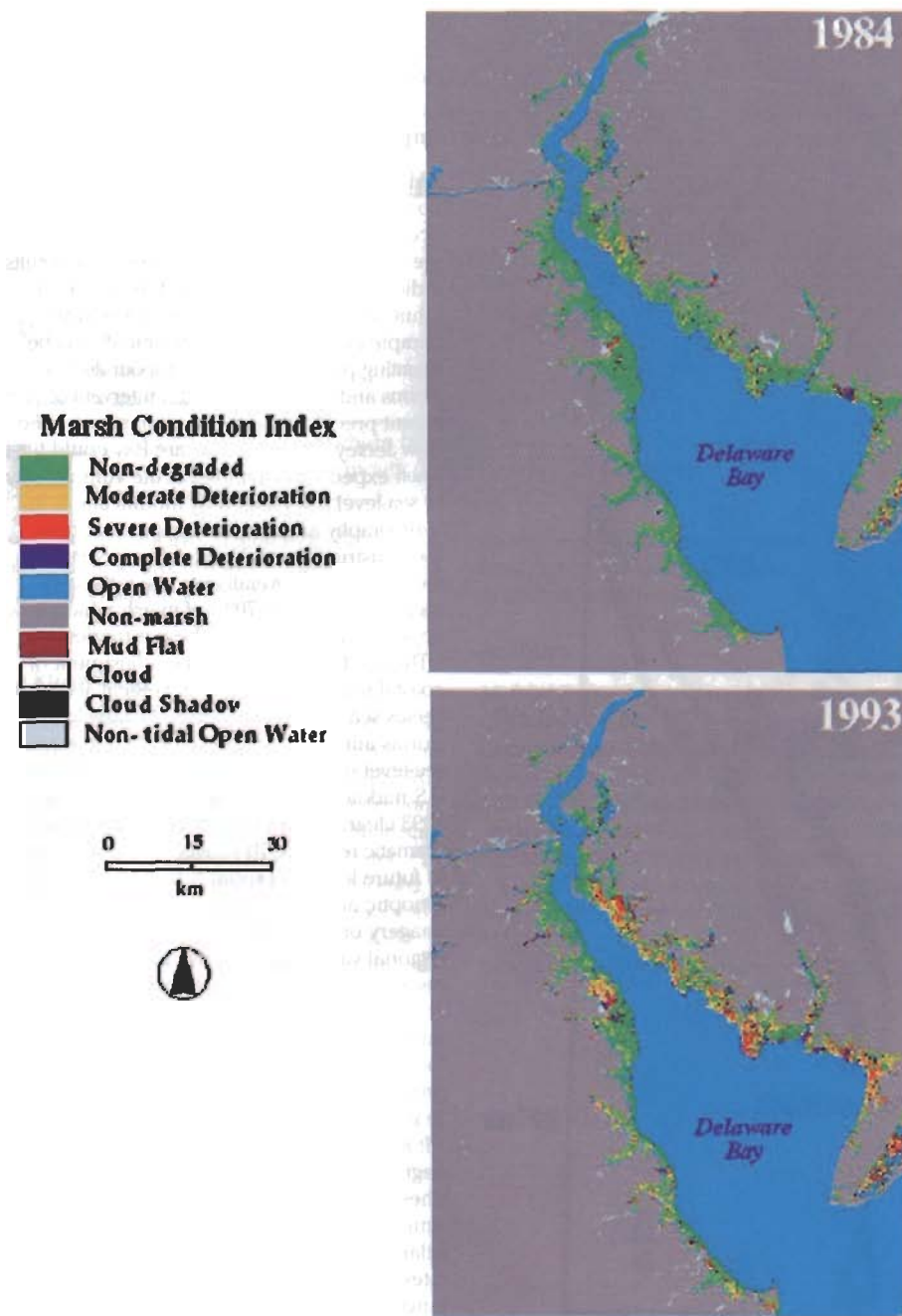


Fig. 3. Marsh surface condition in Delaware Bay is classified here for 1984 and 1993. The most rapid degradation of marsh surface condition in this estuary between 1984 and 1993 occurred on the New Jersey (northern) shore, an area where extensive marsh reconstruction began in 1994.

the changes in the absorption of near-infrared radiation (NIR) by water from tidal variations. In the model we used, differences in the level of inundation of the marsh surface during the tidal cycle could have significant effects on the water/wetness index and the ultimate classification of the degree of substrate degradation. In aerial photography, timing the flight overpass to specific tidal conditions can accommodate this potential error. However, in satellite imagery, this is obviously not practicable, and the incidence of cloud cover and other atmospheric factors can limit the choice of scenes to a few widely differing in tidal stage. Moreover, in large complex estuaries

like the Chesapeake Bay, time lags in the progression of the tidal wave up the estuary produce spatial variations in tidal stage, which can be corrected for the main stem of the system and its major tributaries but not for the myriad of tidal creeks.

The potential effects of changes in tidal stage on the classification of marsh substrate degradation by the spectral mixing model were examined by constructing spectrally opaque, water-tight mesocosms in marsh substrates at Blackwater Wildlife Refuge, Maryland, which is dominated by typical species like *Spartina patens*, *Spartina alterniflora*, *Distichlis spicata*, and *Scirpus americanus* [Kearney et al., in prep.,

2001]. The mesocosms, allowing precise control of the inundation of substrates, were used to simulate changing water levels in the marsh. Spectroradiometric measurements made approximately 2 m above the marsh canopy showed that near-infrared reflectance predictably decreased with increasing water levels, thereby indicating that the importance of the water/wetness index in the model was indeed potentially subject to variations in water level. Nevertheless, significant errors—such as intact substrates being assessed as severely degraded—in the classification of apparent marsh degradation versus actual degradation occurred only with a 30% reduction in the NIR channel, equivalent to complete inundation of the marsh surface with total submergence of the culms of low species like *Spartina patens*. In the micro-tidal middle Atlantic Coast, such conditions in estuarine marshes generally occur only during meteorologically driven tides from coastal storms or from upstream flooding events associated with heavy precipitation, neither of which characterized any of the scenes used.

Patterns and Changes in Marsh Surface Condition

Results from the mixture model (Table 1; Figures 2 and 3) suggest that considerable deterioration in surface condition had already occurred by 1993 (just prior to extensive marsh restoration and the creation of several impoundments in Delaware Bay) in the estuarine marshes of the middle Atlantic coast. The results for both estuaries were validated between 1994 and 1998 at a wide variety of sites using a combination of field surveys and aerial photography, as well as existing information on vertical accretion rates (Figure 4).

In Chesapeake Bay, the greatest proportion of degraded marshes occurs in the middle portion of its eastern shore at Blackwater Wildlife Refuge. Marshes in the upper reaches of Chesapeake Bay and Delaware Bay are generally less degraded than in middle and lower reaches, which is also reflected in the major tributaries of Chesapeake Bay. The greater degradation of marshes in lower and middle reaches is due to the effect of diminishing riverine sediment influx toward the mouths of estuaries. A disparity in mineral sediment influx exacerbated by impoundments also may account for the greater number of degraded marshes on the northeast (New Jersey) shore of Delaware Bay compared to the southwest (Delaware) shore. Unlike the eastern shore of Chesapeake Bay, overwash from northeasters imports substantial amounts of nearshore sediment to the fringing marshes on the leeward shore of Delaware Bay [Stumpf, 1983]. Nevertheless, at the scale of individual marshes, similar patterns of marsh degradation emerge in both estuaries and confirm previous findings that interior areas of large marshes, where sediment inputs are low, are the most susceptible to loss [Stevenson et al., 1985]. This phenomenon is most evident in Delaware Bay, where the predominance of

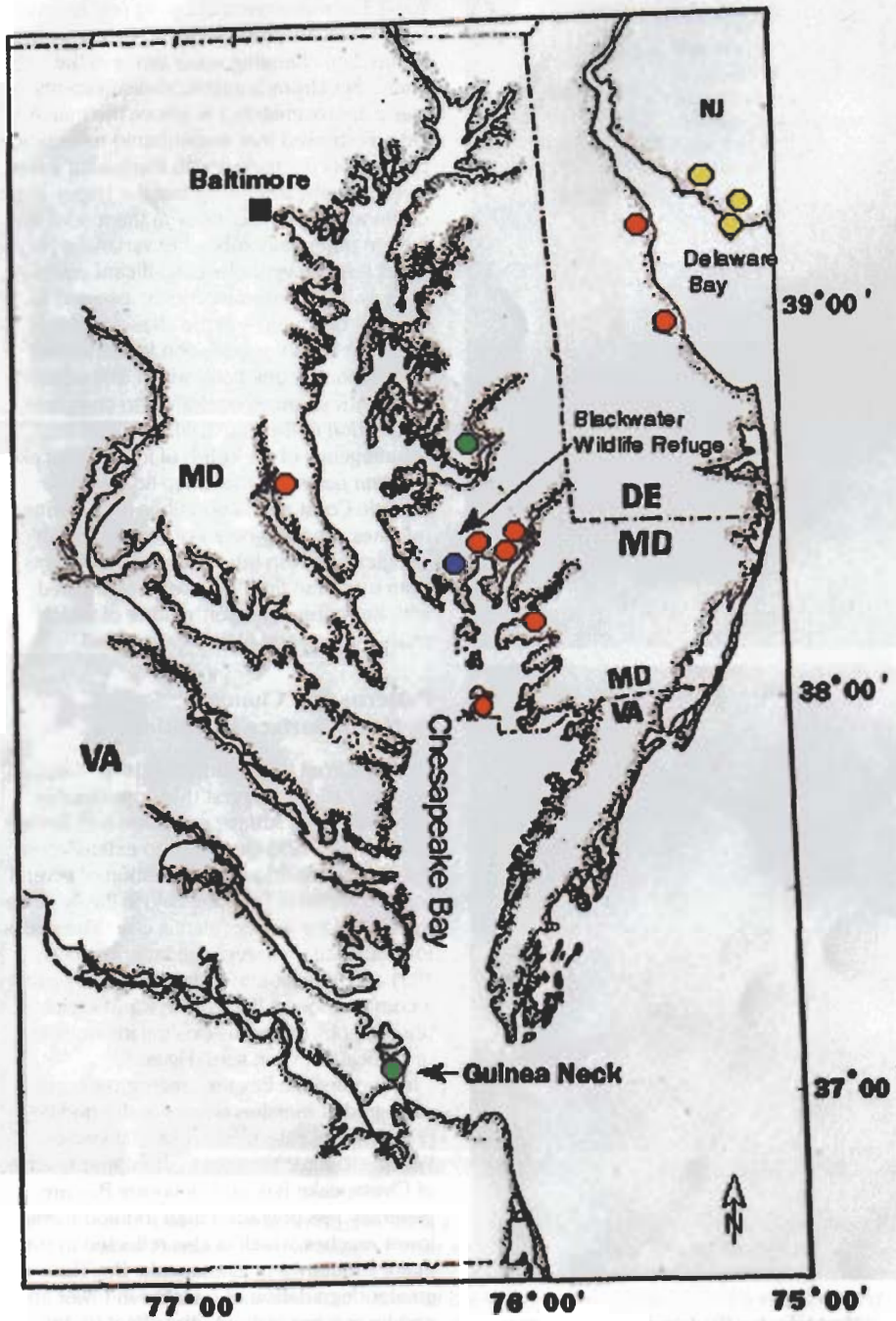


Fig. 4. Field sites for investigation of marsh degradation and loss in Chesapeake Bay and Delaware Bay are shown. Green indicates sites used for spectral mixing model validation, historical aerial photography, and spectral mixing model validation; red shows sites used in historical aerial photography and model validation; blue shows other sites used in analysis of historical aerial photography; and yellow shows other sites used for biomass analyses.

large, fringing marshes makes assessments of marsh condition less complicated because only one marsh type is generally present.

Comparisons of changes between 1984 and 1993 in marsh substrate condition in both estuaries show a substantial increase in the extent of severely-to-completely degraded marshes. This decline is particularly dramatic in Delaware Bay, where the areal coverage of degraded marshes of all classes more than doubled—from 25% in 1984 to 54% in 1993—

especially on the New Jersey shore (Figure 3). Field surveys reveal that the highest productivities in the most severely degraded marshes in this area only range between 175–430 gdw m², well below the peak productivities of 820–1030 gdw m² found in intact marshes elsewhere along the New Jersey shore. Similarly, in Chesapeake Bay, marsh substrate degradation in recent decades has been most pronounced on Maryland's lower Eastern Shore, but also in the archipelago of marshy islands that occur in

the Middle Bay—for example, Bloodworth and South Marsh Islands—where waves during storms erode highly degraded shorelines.

Implications

Marshes with low tidal ranges and irregular flooding appear to be particularly at risk from accelerated sea-level rise, although the reasons are complex [Stevenson *et al.*, 1986]. Our results indicate that predicting marsh response to future sea-level rise in large estuaries with complex depositional environments can be daunting, particularly when compounded by storms and a legacy of human intervention. The recent precipitous decline of marshes in the New Jersey shore of Delaware Bay could have been expected, given their acute vulnerability to sea-level rise created by modifications in hydrography and species composition from the construction of dikes and berms. Perhaps the most striking overall outcome is the very high percentages (~70%) of marsh, which now appear to be affected in these estuaries.

Though time frames for the adjustment of coastal marshes to deficits in vertical accretion versus sea-level rise may vary, the large coastal storms and short-term acceleration in relative sea-level rise (RSLR) that characterized the U.S. middle Atlantic coast between 1989 and 1993 clearly were the probable triggers of this dramatic response. This suggests that the tempo of future losses is probably best forecast from synoptic analyses of marsh loss using satellite imagery or similar data; this way, the range of regional variations in marsh response can be discerned. In Chesapeake Bay, actual losses in some marshes lagged by several decades the outstripping of vertical accretion rates by local submergence and clearly indicate the problems of relying on submergence models [e.g., Armentano *et al.*, 1988].

It is not clear if the advanced substrate degradation evident in the marshes of the Chesapeake and Delaware Bays points to similar conditions elsewhere along the U.S. Atlantic coast, as differences in subsidence rates, depositional environment, and tidal range complicate any extrapolation. However, in view of the great expanse of marshlands involved—over 300,000 hectares for Georgia and South Carolina alone (R. Tiner, pers. comm., 2001)—it is sobering to consider the possibility that trends for marsh loss in these two large estuaries could be occurring elsewhere. Widespread disappearance of Atlantic coast marshes during the 21st century could severely affect food webs and biogeochemical cycles of littoral ecosystems, but also the massive export of particulates into nearshore waters from eroding marshes will have serious implications for estuarine water quality. Flux measurements [Stevenson *et al.*, 1985] at Blackwater Wildlife Refuge showed that before 1980, marsh losses in this area alone probably released about 720,000 tonnes (~242 tonnes per hectare) of sediment into Chesapeake Bay through the Blackwater River and Fishing Bay, much of it long-sequestered carbon. Because coastal marshes may represent important carbon sinks,

Table 1. Marsh condition class percentages (hectares) for estuarine marshes in Chesapeake and Delaware Bays based on 1993 Thematic Mapper imagery

Area	Non-degraded	Slightly to moderately degraded	Severely to completely degraded
Chesapeake Bay			
Upper and middle Bay*	31 (25,201)	50 (40,647)	19 (15,446)
Lower Bay	28 (9,404)	52 (17,464)	20 (6,717)
Delaware Bay			
North Shore (New Jersey)	38 (27,095)	43 (30,660)	19 (13,547)
South Shore (Delaware)	55 (19,974)	35 (12,711)	10 (3,632)

*As used here, the southern boundary of the upper and middle Bay is the mouth of the Potomac River.

the potential collapse of hundreds of thousands of hectares of coastal marsh in coming decades could also have a significant impact on the overall North American carbon budget.

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