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Effects of historic tidal restrictions on salt marsh sediment chemistry

J.W. PORTNOY[1] & A.E. GIBLIN[2]
[1]*National Biological Service, Cape Cod National Seashore, 99 Marconi Rd., Wellfleet, Massachusetts 02667;* [2]*Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts, 02543*

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Abstract. The effects of tidal restrictions by diking on salt marsh biogeochemistry were interpreted by comparing the hydrology, porewater chemistry and solid phase composition of both seasonally flooded and drained diked marshes with adjacent natural salt marshes on Cape Cod, Massachusetts. Flooding periods were greatest in natural and least in drained marshes.

Differences between the chemistry of the natural and diked marshes depended upon the depth of the water table and the supply of sulfate for anaerobic metabolism. Drained marsh sediments were highly acidic (pH <4) with porewaters rich in dissolved Fe; the natural and diked flooded marshes had pH 6–7.5 and Fe orders of magnitude lower. Porewater nutrients, sulfides and alkalinity were much lower in both flooded and drained diked marshes than in the natural marsh.

Sediments of the drained marsh had subsided 90 cm relative to the natural site due to organic matter decomposition and compaction. However, despite the loss of organic matter, much of the P and N was retained, with NH_4 likely protected from nitrification by low pH and PO_4 adsorbed on Fe and Al oxides. Iron, and to a lesser degree sulfur, had also been well retained by the sediment. Despite eight decades of diking, substantial amounts of reduced S, representing potential acidity, persisted near the top of the water table.

In contrast, the surface of the seasonally flooded marsh was only 15 cm below the natural marsh. Accretion since diking amounted to 25 cm and involved proportionally less mineral matter.

The restoration of seawater flow to both seasonally flooded and drained diked marshes will likely extend flooding depth and duration, lower redox, increase cation exchange, and thereby increase NH_4, Fe(II), and PO_4 mobilization. Increased porewater nutrients could benefit recolonizing halophytes but may also degrade surface water quality.

Introduction

The diking or empoldering of coastal wetlands has been extensively practiced along the coasts of the western North Atlantic and western Europe for hundreds of years. In New England, at least half of the salt marshes present at the time of European settlement had been diked and/or filled for the construction of road- and railways, for insect control or for agricultural purposes by the mid-1970's (Nickerson 1978; Niering & Bowers 1966). Salt marsh diking has been practiced widely on Cape Cod. By the late 1930's, hundreds of acres had been altered in this way and by subsequent ditch drainage (DeSista & Newling 1979). Although the consequent loss of economically important estuarine habitats is now well appreciated, more subtle effects on wetland biogeochemical cycles are poorly understood.

Most of the organic matter production in salt marshes occurs below ground (Valiela et al. 1976; Schubauer & Hopkinson 1984) where sulfate reduction is a major pathway of organic decomposition (Howarth & Teal 1979, Howes et al. 1984) As a result, salt marsh peats are characterized by high concentrations of C, N, P, S and Fe. The potential release of these elements by alterations of marsh hydrology has important consequences for the ecosystem. Nitrogen release can stimulate primary production in both the emergent marsh (Valiela & Teal 1974) and in downstream receiving waters (Howarth 1988; Valiela et al. 1990). Phosphorus release can also stimulate production under conditions of high N or low salinity (Caraco et al. 1987). The oxidation of the reduced sulfur and iron minerals in salt marsh peat can drastically reduce the pH of salt marsh creeks (Soukup & Portnoy 1986) and greatly depress oxygen concentrations in the water column (Portnoy 1991).

The mobility and fate of all of these elements depend on their interactions with hydrology, salinity, sediment redox and pH, and the influences of rooted vegetation (Howes et al. 1981; Scudlark & Church 1989), all of which are altered by diking. Diking reduces or eliminates seawater flow allowing surface water and marsh porewater to freshen. Brackish and freshwater wetland plants commonly invade diked marshes over a time span of decades (Roman et al. 1984), as salt marsh halophytes lose their competitive advantage. Diking also blocks the 1–2 m semidiurnal tidal excursion typical of the New England coast (Steever et al. 1976). As a result, the average marsh water table drops from about mean high water to mean sea level, i.e. the elevation of discharging ground water.

Diked marshes are generally either seasonally flooded or perennially drained, depending on the freshwater drainage capacity of culverts and creek systems. Where dikes fitted with small culverts physically impede freshwater discharge, the water table remains high and freshwater wetland communities develop over the flooded salt marsh peat. However, ditching and creek channelization in many diked marshes has increased freshwater discharge. Resulting water table depression can be intensified by the encroachment of freshwater wetland and upland plants that transpire more water than salt marsh grasses (Hussey & Odum 1992). Consequent increases in peat aeration can cause radical changes to sediment biogeochemistry including pyrite oxidation and the acidification of marsh soils and drainage water (Lynn & Wittig 1966; Calvert & Ford 1973; Edelman & Van Staveren 1958; Gosling & Baker 1980; Soukup & Portnoy 1986; Breemen 1982). Increased redox and decreased pH can alter the mobility of phosphorus, iron and other metals (Lord 1980; Zottoli 1973).

Despite the clearly demonstrated interdependencies of salt marsh hydrology, plant cover and nutrient dynamics (Tyler 1971; Valiela & Teal 1974; Howes et al. 1981; Lord & Church 1983), and despite detailed knowledge of major changes in marsh hydrology and vegetation following tidal restrictions (Roman et al. 1984; Rozsa 1987; Zedler 1988; Sinicrope et al. 1990), the effects of diking on the reserves and mobility of sedimentary nutrients are largely unstudied. This gap is especially important in view of the potential effects of nutrient mobilization on the quality of coastal waters.

In this paper, the hydrologic, sedimentary and vegetational conditions of both seasonally flooded and drained diked marshes are compared to an adjacent natural salt marsh to evaluate the biogeochemical effects of altered salinity and water level over decadal time scales. Effects on hydrology and porewater chemistry were examined by monthly monitoring over a 19-mo period; effects on sediment solids are described for cores collected in the three marsh types.

Study sites

The principal study sites are located along the eastern shore of Cape Cod Bay (Figure 1), where portions of most coastal marshes are altered by dikes restricting seawater flow. Most diking in this region was accomplished between 1800 and 1930 for salt marsh mosquito control and as a consequence of road and railway construction. These tidally restricted salt marshes have become vegetated with freshwater wetland species or, if effectively drained during the growing season, with terrestrial herbs and even trees.

Study sites were selected to represent diked, seasonally flooded (DF), diked-drained (DD) and natural (NA) treatments using historical documentation and field inspections. Both diked sites were 1) originally intertidal *Spartina alterniflora* (Loisel) marsh, ascertainable from rhizome identification (Niering et al. 1977); 2) predominantly vegetated with herbaceous plants; and 3) consistently either seasonally flooded or drained since first diking.

Natural marsh (NA)

A natural salt marsh (NA), exhibiting the salinities, tidal range and vegetation typical of tidal marshes in the Cape Cod region, was selected within the North Sunken Meadow system of Eastham (MA) to serve as a control. Selection was also based on its proximity to a diked, seasonally flooded marsh (see below) with which it was compared. The study site (Figure 1, NA) was vegetated

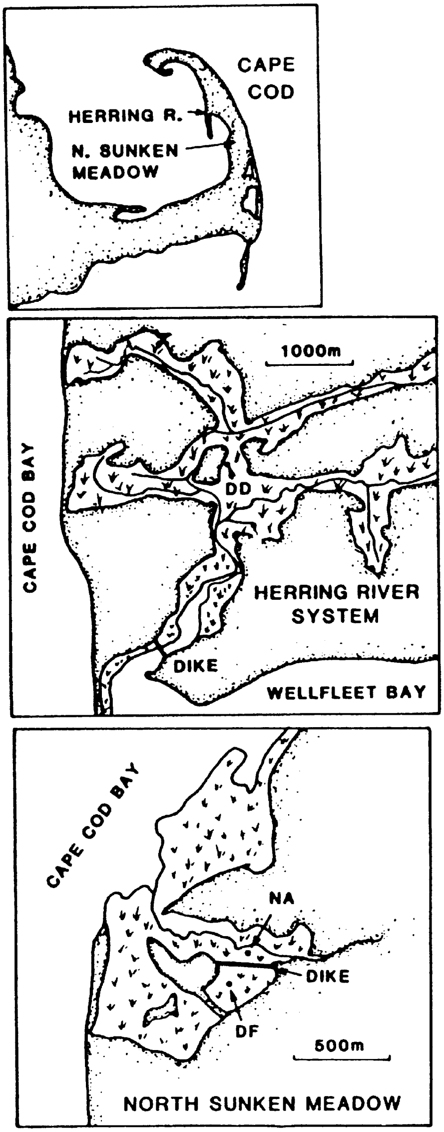
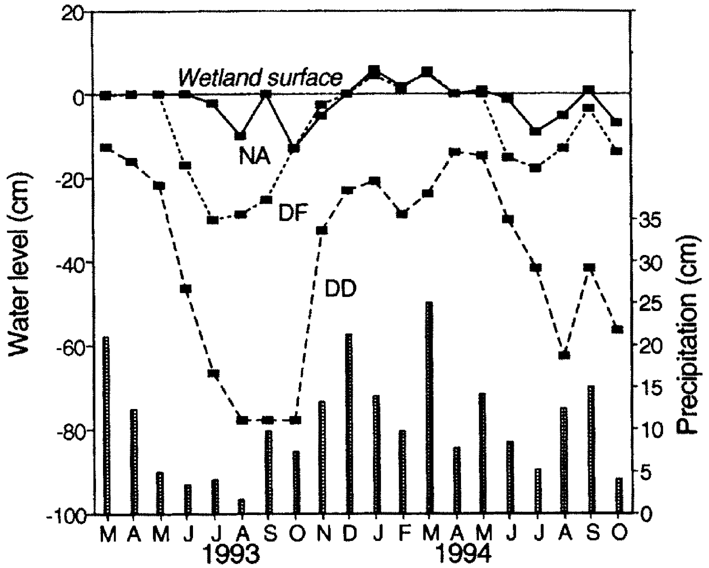


Figure 1. Herring River (Wellfleet), and North Sunken Meadow (Eastham) diked salt marshes along the eastern shore of Cape Cod Bay showing coring sites.

primarily with short form (10–20 cm tall) *S. alterniflora,* but included some *S. patens* (Muhl) and *Distichlis spicata* (Greene). Total peat depth was 2.6 m. Surface water salinity was typically 25–30 ppt. Tidal range was about 1 m (Figure 2) and the marsh surface was about 1.86 m NGVD (National Geodetic Vertical Datum).



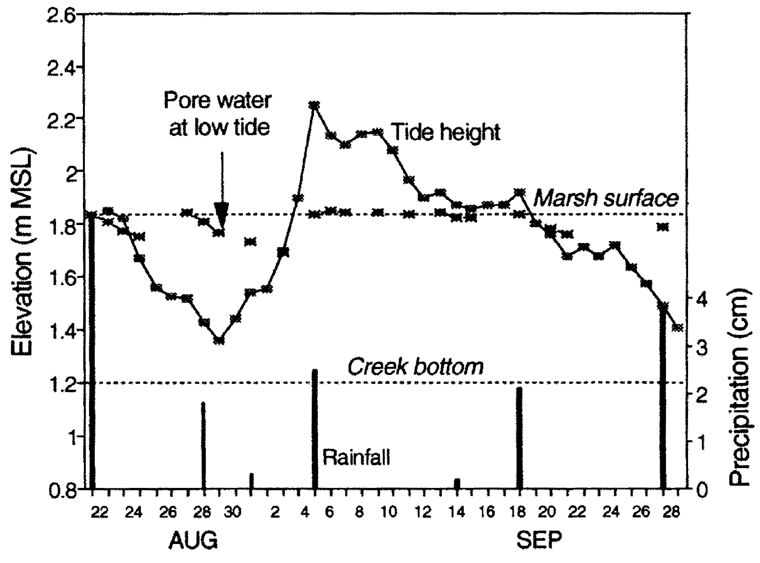


Figure 2. Top: Monthly water table elevations and precipitation at natural (NA), diked-freshened (DF), and diked-drained (DD) sites. *Bottom:* Daily water table elevations, tide heights and precipitation over a spring-neap cycle at NA.

Diked, seasonally flooded site (DF)

A 12-ha diked portion of the North Sunken Meadow system of Eastham was selected for study (Figure 1). This wetland (hereafter “DF”) consisted of a diverse herb-shrub community of saline, brackish and freshwater wetland plants dominated by the grasses *S. patens* and *Scirpus americanus* (Persoon), but including substantial patches of *Baccharis halimifolia* (L.), *Myrica gale* (L.), *Phragmites*, *Typha angustifolia* (L.) and *Erechtites hieracifolia* (L.) and scattered *Distichlis spicata*.

The marsh was probably diked about 1840 (D. Sparrow, Eastham Historical Society, pers. comm.). A weir installed just upstream of the dike's 0.91-m diameter discharge culvert helped to maintain a high water level and waterlogging in the wetland upstream. Seawater occasionally leaked through the culvert's flap valve during storm tides but during two years of monitoring (October 1992–October 1994) was restricted to the bottom of the main drainage ditch and did not reach the study site. Salinity of porewater, and episodic standing surface water, at the coring site never exceeded 1 ppt. The wetland surface elevation was about 1.71 m NGVD (National Geodetic Vertical Datum), i.e. 15 cm below that of the unaltered wetland seaward of the dike. Total peat depth is 1.6 m. The presence of the weir and a sandy sediment horizon at 7–17 cm suggests cranberry farming in the 1800's.

Diked, drained site (DD)

The 400-ha Herring River estuarine complex in Wellfleet (MA) (Figure 1) is the largest diked wetland system on outer Cape Cod (Soukup & Portnoy 1986; Portnoy 1991) and occupies a glacial outwash valley on the eastern shore of Cape Cod Bay. Tidal flow to most of the original *Spartina* marsh was eliminated by inlet closures in the eighteenth and nineteenth centuries, and by a dike built across the mouth of the main stream in 1908 (Whitman & Howard 1906). Stream channelization and ditch drainage was begun before dike construction and has continued to the present. The modern dike structure included three 4-m^2 rectangular sluiceways providing a large opening for freshwater discharge at low tide. During high tide, hydraulic pressure closed the top-hinged doors on two of the sluiceways, preventing seawater flow upstream. The third sluiceway was partially open (cross-sectional area about 1 m^2) allowing some seawater entry; however, seawater flooding of the diked marsh surface was limited to 500 m upstream. This regimen of tidal restriction and artificial drainage was responsible for the drained condition of wetland peats upstream.

Historic photographs taken just before the 1908 diking show an apparently continuous stand of salt marsh grasses along the shore of the Herring River. Core analyses by R. A. Orson (Roman 1987) documented the presence of *S. alterniflora* on the flood plain presently vegetated with *Holcus lanatus* (L.), *Spiraea latifolia* (Ahles) and *tomentosa* (L.), and *Solidago rugosa* (Miller) and *tenuifolia* (Pursh). Much of this herbaceous cover succeeded to *Prunus serotina* (Ehrhart) forest over the past few decades. The marsh surface elevation was 0.95–1.01 m NGVD, or about 90 cm below modern unaltered *Spartina* marsh seaward of the Herring River dike.

Other sites

Additional diked salt marshes were examined to verify treatment effects on sediment characteristics. Diked and drained marshes were cored in the Herring River (Wellfleet, MA) system about 750 m from DD (DD2), and at Pine Creek, Fairfield (CT) (DD3). Management histories and current water table depth and vegetation were similar to DD.

Additional cores from diked-flooded marshes were obtained in the North Sunken Meadow system (DF2), about 300 m northeast of previously described DF, and in the upper Pamet River (DF3; Truro, MA). The wetland elevation, hydroperiod and vegetation at DF2 were similar to DF. In the DF3 marsh, seawater flow was blocked by a railway in 1870 (Giese & Mello 1985); wetland drainage programs followed. In 1952, a highway was constructed which impeded drainage, raised the water table and waterlogged the diked wetland upstream. Modern vegetation includes mostly *Typha angustifolia*, *Rhus vernix* (L.) and *Rubus* sp. The wetland surface is about 60 cm below that of unaltered salt marsh seaward of the dike and waterlogged throughout the winter.

Field and laboratory methods

Water table and precipitation monitoring

At Herring River and North Sunken Meadow coring sites, the wetland water table was monitored on a monthly basis from October 1992 to October 1994. To obtain a more detailed picture of porewater levels over a spring-neap tidal cycle, more frequent monitoring was conducted in August–September 1994 at the North Sunken Meadow Marsh, seaward of the dike. Monitoring wells were 3 cm diameter PVC tubes screened throughout their lengths and pushed about 1 m into, but not completely penetrating the wetland peat.

Precipitation data were obtained from a continuously recording rain gauge located 2 and 8 km, respectively, from the Herring River and North Sunken Meadow coring sites.

Porewater chemistry

Salinity, pH, alkalinity, total sulfides, total and reduced Fe, NH_4, PO_4 and NO_3 were monitored nearly monthly from May 1993 to October 1994 in porewater from the Herring River (DD) and North Sunken Meadow Marsh (NA and DF) coring sites. All constituents were sampled at 45 cm depth.

Water was withdrawn from the sediment through a 3-mm ID stainless steel tube with slotted point into a syringe. Air was purged from the probe prior to collecting a sample. Aliquots for sulfide analysis were immediately discharged from the syringe into 2% zinc acetate and stored at 4 °C (Portnoy 1996); sulfide was determined colorimetrically (Cline 1969). Salinity was measured using a hand-held refractometer. pH and alkalinity were determined within 6 h of collection using a KCl-filled combination electrode with calomel junction; alkalinity was determined by Gran titration (Edmond 1970). The remaining sample was filtered (0.45 μm Millipore). A 10-ml aliquot was degassed with N_2 and refrigerated for sulfate and chloride analysis by ion chromatography. The remainder was acidified to pH 2 with trace metal grade HCl and stored at 4 °C for determination of nutrients and iron. Ammonium, phosphate and nitrate were measured by flow injection analysis using automated phenolate, ascorbic acid and cadmium reduction colorimetric methods, respectively (APHA 1992). Reduced iron was determined by the ferrozine method, as was total Fe after reduction with hydroxylamine (Stookey 1970).

Solid phase analysis

Duplicate sediment cores (7.5-cm diameter × 50 cm deep) were obtained during fall and winter to characterize the solid phase chemistry of marsh peat from all study sites. Compaction of the sediment in the core was <5 cm for drained soils and <3 cm for waterlogged sediment. Cores were stored at 4 °C under an N_2 atmosphere and extracted within 12 h of collection.

General sediment characteristics, including color, texture, the degree of organic decomposition, and the identification of plant rhizomes (Niering et al. 1977) were recorded for each 5-cm core section as it was extracted. pH and Eh were measured within 5 min of extraction by forcing electrodes about 5 mm into each sediment section at three locations. Eh was measured using a platinum electrode calibrated with ZoBell's solution (ZoBell 1946).

Percent water was estimated from the weight loss of oven-dried (105 °C) sediment. Bulk density was computed by dividing dry weight by the original volume (200 ml) of each 5 cm core section. Percent organic matter was determined from the weight loss on ignition at 550 °C for 2 h. Sediment volumes occupied by mineral matter, organic matter and pore space were computed from measured bulk and published particle density values (Brady 1990).

Total Fe was determined by digesting about 0.1 g of dry sediment in 5 ml of concentrated HNO_3 in a water bath at 70 °C for 2 h, followed by the addition of 5 ml of concentrated HCl and further heating for another

1 h. Resulting extracts were filtered, diluted and Fe content was determined by atomic absorption. Total and inorganic P were extracted according to Krom and Berner (1981); P in extracts was determined by flow injection analysis using the ascorbic acid reduction method (APHA 1992). Total S was determined by combustion in a Leco sulfur analyzer equipped with a halogen trap (Portnoy 1996). Carbon and N were determined by combustion in a Perkin-Elmer elemental analyzer. Exchangeable NH_4-N was extracted with 2M KCl (Page et al. 1982) and measured colorimetrically using the phenolate method. The same extracts were used for exchangeable Fe(II) and Fe(III), determined by the ferrozine method (Stookey 1970).

Inorganic reduced sulfur was determined by chromium reduction for a representative set of DD sediments according to methods described in Giblin (1988). Chromium-reducible sulfur (CRS) includes pyrite, elemental sulfur, and acid volatile monosulfides, all of which release acidity with oxidation.

Selected sediment samples were analysed for stable carbon isotopes to identify the horizons where wetland vegetation shifted from halophytic to fresh water communities after diking. Previous workers (DeLaune 1986; Chmura & Aharon 1995) have demonstrated distinct δ^{13}C signatures for fresh and saline wetland peat based on the greater isotopic fractionation, and light ^{12}C uptake, by predominantly C-3 freshwater plants. Analyses were performed by the Department of Chemistry, University of Wisconsin. Results are for carbonate-free (HCl-leached) sediments.

Results and discussion

Flooding regimes

Seasonal fluctuations in wetland water tables were observed in monthly sampling at all three study sites (Figure 2, top panel); however, seasonal changes were least pronounced in NA where the water table was maintained by regular tidal flooding. Results from daily sampling show typical growing season hydroperiods (Figure 2, bottom) for NA. This marsh was waterlogged to the surface for about half of the spring-neap cycle, corresponding with tide heights $>$1.8 m. Water levels dropped below the wetland surface during neap tide periods to a depth expected from water loss by evapotranspiration (Dacey & Howes 1984), except when rainfall replaced some of this water. Rainfall, normally 9.7 cm mo^{-1} (1983–1992 National Atmospheric Deposition Program data, North Truro (MA) collection site), amounted to only 2.3 cm mo^{-1} in June, July and August 1993, but was closer to average in summer 1994 (8.7 cm mo^{-1}).

Monthly monitoring of water level at the coring site in the DF marsh showed seasonal fluctuations (Figure 2) responding to seasonal changes in groundwater inflow and wetland water use. Because the dike dampened short-term tidal fluctuations and the small culvert and weir impeded freshwater drainage, sediment was waterlogged to the surface from December through March.

The effectiveness of the long history of diking and drainage at DD was evident in the constantly drained condition of the soils at the coring site (Figure 2), despite apparent subsidence (see above). Ground water was never $<$15 cm from the surface during the monitoring period and regularly dropped below 40 cm during the summer.

In summary, the combined effects of differing tidal forcing and drainage at the three sites resulted in distinctly different water periods. NA was waterlogged to the surface more than 50% of the time during the growing season, i.e. during all but neap tides, and evidently continuously during the winter; DF was constantly flooded from December through May; DD was never waterlogged to the surface.

Porewater chemistry

There was little seasonal variation in pH and alkalinity in all three marsh types at the 45-cm depth. [Gaps in the DD record occurred when the water table dropped below the 45-cm-deep sampling point.] Soil reactions were clearly dominated either by the net reduction of sulfate at waterlogged NA and DF sites, or by the oxidation of reduced sulfur at the drained marsh (Figures 3, 4, 5). Sulfate reduction and its production of bicarbonate consistently buffered pH to about 6.5 at both saline and fresh waterlogged sites (NA and DF); however, alkalinities were generally at least three times higher in NA regularly flooded with sulfate-rich seawater. pH never exceeded 4.0 at DD; alkalinity was detectable ($>$0.1 mEq/l) only during extended flooding in mid-winter and spring.

Sulfide concentrations were about 10 times higher in NA than DF (Figure 4). In contrast Fe varied much less between NA and DF sites probably because of the common origins of the two marshes and the relative immobility of this element in sulfide-rich environments. Millimolar Fe concentrations at drained DD reflect the extensive oxidation of pyrite; more than half of the porewater Fe was ferrous, consistent with pH and Eh conditions. High summertime sulfide concentrations were present only at NA, where SO_4 was abundant enough to dominate Fe and S cycling; coincident peaks in Fe were expected as salt marsh grasses oxidized the sediment and increased Fe dissolution (Giblin & Howarth 1984).

SO_4:Cl ratios (Figure 5) reflected the modern supply of marine salts plus the redox state of sulfur in the three marshes. In the natural marsh, constant anaerobiosis (at the 45 cm sampling depth) and high seawater supply

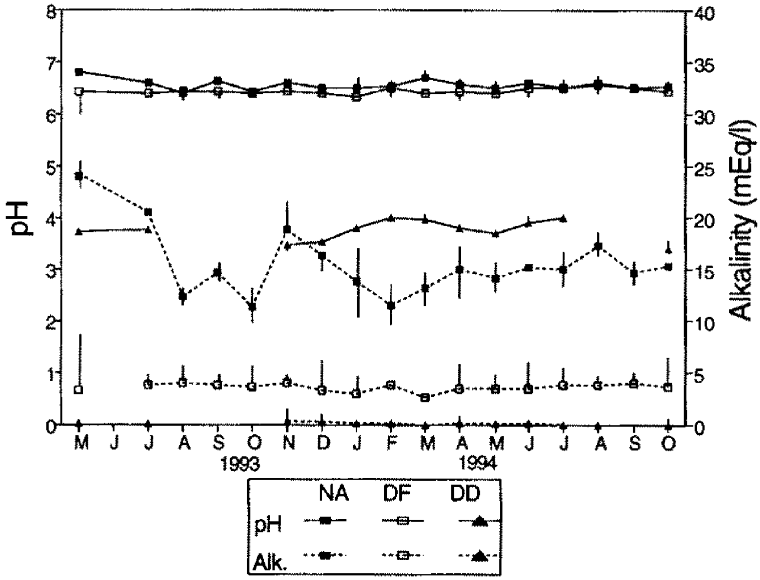


Figure 3. Monthly pH and alkalinity of the porewater at 45 cm depth in natural (NA), diked-freshened (DF), and diked-drained (DD) salt marshes. Means ± SE, $N = 3$.

promoted sulfate reduction, indicated by consistently low ratios. In DF, SO_4:Cl fluctuated seasonally, probably due to limited SO_4 supply. Low values occurred in summer when temperature-dependent heterotrophic activity depleted the available SO_4, limited in supply because of the blockage of seawater flow. Low SO_4:Cl in February followed a two-month period of frozen peat which must have restricted infiltration of more oxidized and sulfate-rich seawater. At DD, drainage since diking has caused pyrite oxidation and Cl^- leaching, resulting in high ratios. The apparent increase in SO_4:Cl, and dissolved Fe (Figure 4, bottom), in 1994 was probably the result of unusually deep soil aeration, and pyrite oxidation, caused by the drought in the previous year (see Figure 2). Periods of low soil water followed by resaturation at DD likely caused episodic sulfate dissolution, pH declines and consequent fish mortality in the Herring River (Soukup & Portnoy 1986).

Porewater inorganic nutrients measured at 45 cm depths showed no clear seasonal trends and contrasted sharply among the 3 sites with NA $>>$ DD $>>$ DF for dissolved inorganic nitrogen (DIN), and NA $>$ DD = DF for phosphorus (DIP) (Figure 6). Sustained anaerobiosis and microbial sulfate reduction at NA should yield higher DIN and DIP, compared to the more aerobic sites, because more organic turnover is required by heterotrophs for an equal metabolic energy yield (Fenchel & Blackburn 1979). N:P ratios (Figure 6, bottom) were consistently higher at NA than DF.

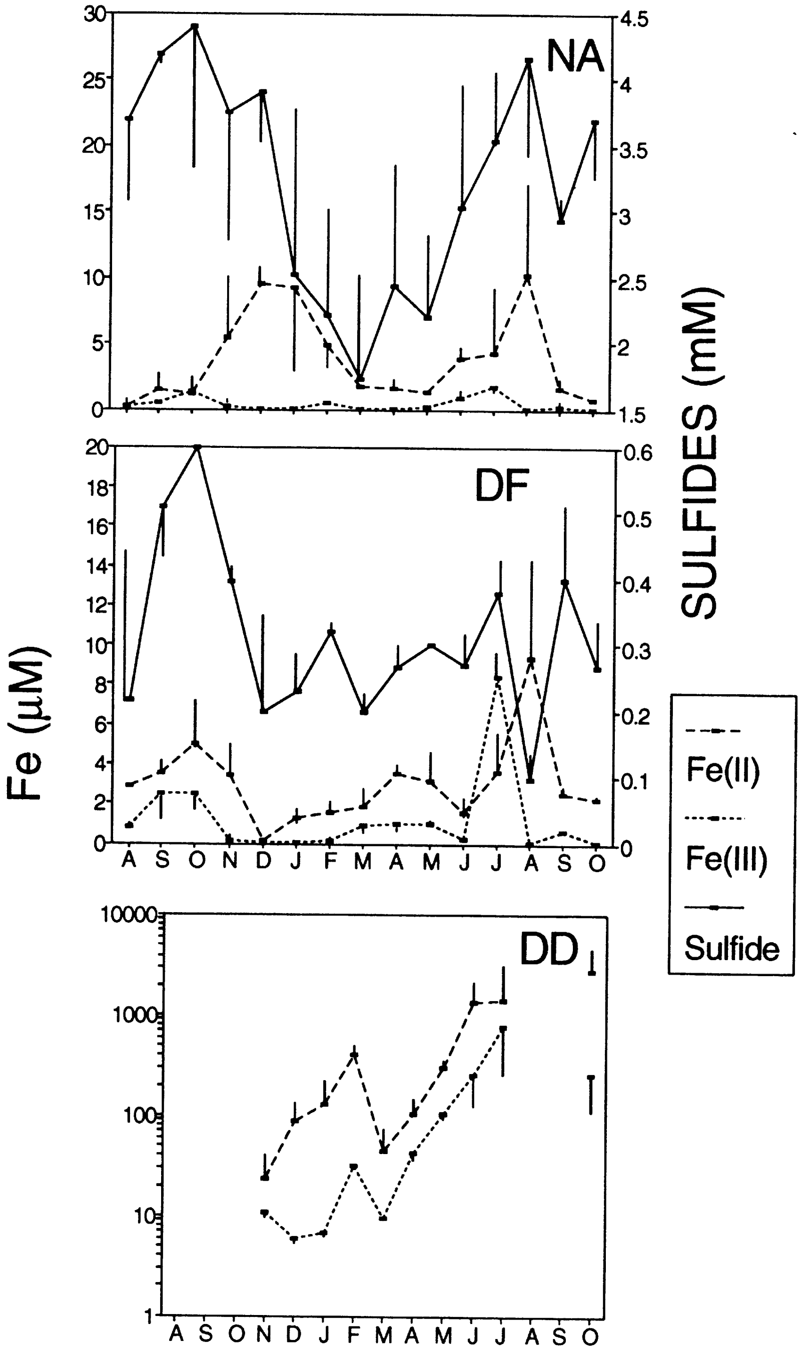


Figure 4. Monthly (1993–94) Fe(II), Fe(III) and sulfide concentrations of the porewater at 45 cm depth in natural (NA), diked-freshened (DF), and diked-drained (DD) salt marshes. Means ± SE, $N = 3$. No sulfide was detected at DD.

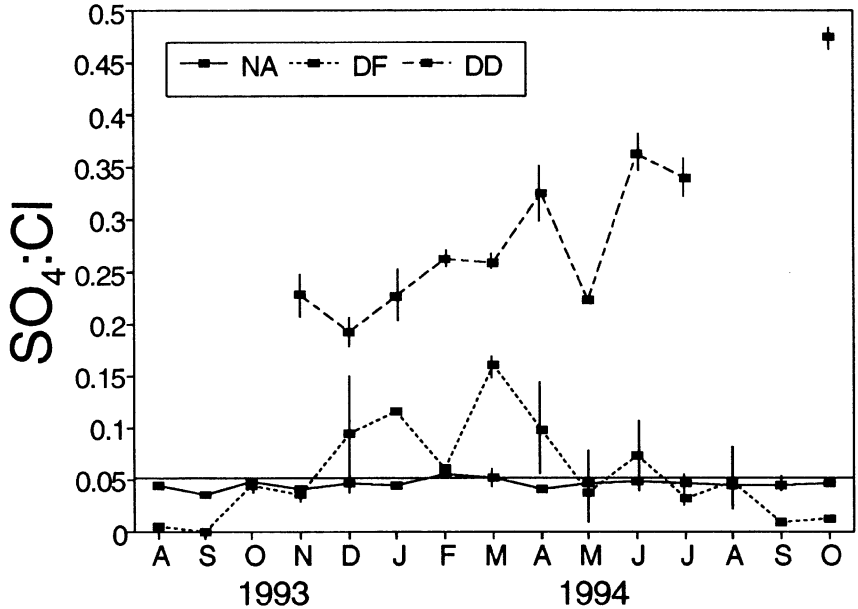


Figure 5. Monthly SO_4:Cl molar ratios in 45-cm deep porewater from NA, DF and DD marshes; mean ± SE. The horizontal line at SO_4:Cl = 0.0 5 marks the ratio characteristic of seawater. Means ± SE, $N = 3$.

Porewaters of the drained marsh were replete with inorganic N, but nearly devoid of P. Ammonium concentrations were regularly about 100 μm. Though nitrate was undetectable in sulfidic NA and DF sediments, it episodically reached $>$100 μm at DD when the soil reflooded after dry periods. Thus some nitrification of adsorbed ammonium is possible even under acidic conditions with prolonged aeration.

Solid phase characteristics

Deep sediments (>45 cm) from NA, DF and DD contained halophyte rhizomes reflecting their common pre-diking histories. More shallow sediments showed clear differences in the species of persistent rhizomes, stable carbon isotopic ratios, and the apparent degree of organic decomposition, indicating the effects of different water management (Figure 7). In NA marsh cores, undecomposed *Spartina* and *Distichlis* rhizomes and sulfide odors occurred throughout; live roots and rhizomes were evident above 20 cm. δ^{13}C values were heavy, characteristic of C-4 halophytic grasses (DeLaune 1986; Chmura & Aharon 1995), both in the modern root zone near the surface and in 35–40 cm deep sediments. A layer of sandier peat at 25–30 cm, proba-

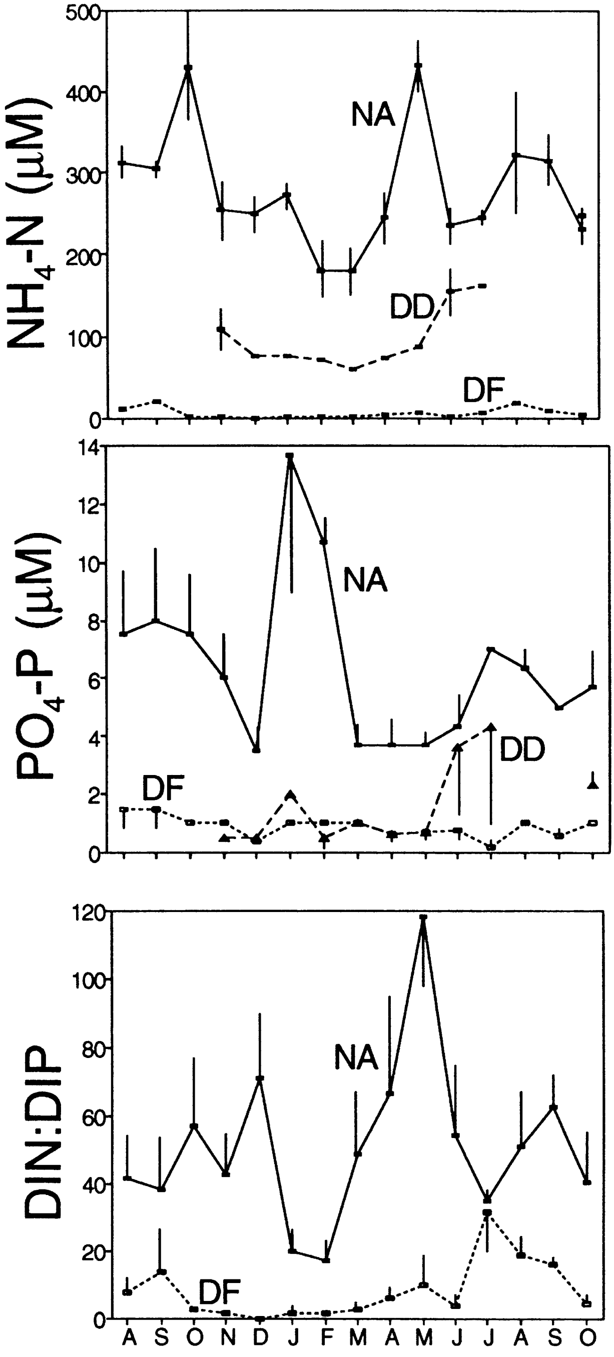


Figure 6. Monthly NH_4-N (top), PO_4-P (center) and N:P ratios (bottom panel) in 45 cm deep porewater from NA, DF and DD marshes. DD is omitted from the N:P plot because PO_4-P was often below the 1 μM detection limit.

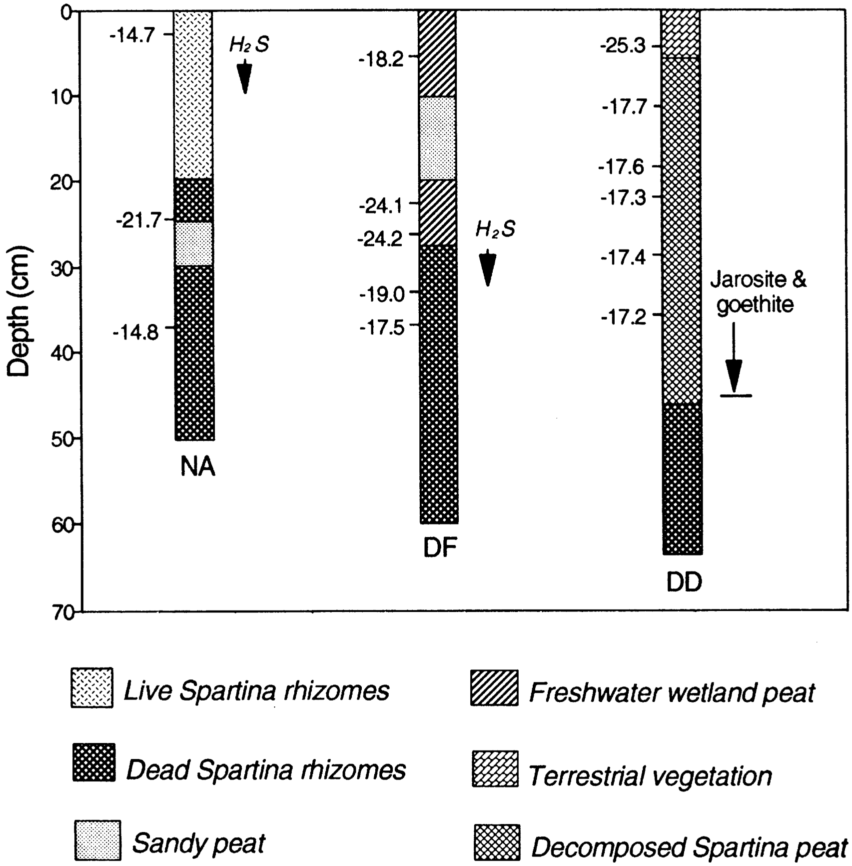


Figure 7. Sediment stratigraphy and $\delta^{13}C$ for natural (NA), diked-freshened (DF), and diked-drained (DD) coring sites. Numbers to the left of the profiles are $\delta^{13}C$ values. Also shown are the occurrence of volatile sulfide (H_2S) and jarosite. See text for management histories.

bly deposited by a storm surge, was accompanied by lighter $\delta^{13}C$ values than expected for salt marsh peat and may indicate terrigenous input.

The DF marsh core had freshwater wetland peat and generally light $\delta^{13}C$ above about 27 cm, representing the salt/fresh boundary. Volatile sulfide was evident below this depth. Higher $\delta^{13}C$ near the surface may indicate more frequent seawater entry, and halophytic growth, due to recent deterioration and leakage of the culvert-weir system. Values lower than NA in deep *Spartina* peat at DF probably resulted from root penetration by C-3 plants after diking. As mentioned, the shallow sand lens found only on this impounded side of the dike is typical of suspected cranberry cultivation. Its occurrence above freshwater peat proves that it was deposited after a period of diking and is probably not associated with storm overwash.

Sediment from DD consisted of highly decomposed salt marsh peat from 5 to at least 45 cm; $\delta^{13}C$ values were consistently high except in the root zone of modern terrestrial plants. Values consistently less than modern *Spartina* peat within the DD horizons are attributed either to root penetration of original salt marsh peat by C-3 terrestrial plants or to the preferential loss of labile, and isotopically heavy, plant compounds as decomposition proceeds (Chmura & Aharon 1995). Both yellow and brown granular precipitates, probably jarosite ($KFe_3(SO_4)_2(OH)_6$) and goethite ($FeO{\cdot}OH$) (Dent 1986), occur in root channels above the continually waterlogged peat containing intact salt marsh rhizomes.

Sediment water and organic content differed greatly among sites (Figure 8, bottom left, right). Waterlogged sediments at NA and DF retained high organic content, about 5 and 7 times higher by mass, respectively, than DD sediments. The natural site's organic content of about 50–70% is typical of shallow peat in New England salt marshes (Howes et al. 1981; Bricker-Urso et al. 1989; Giblin & Howarth 1984) wherever aeolian sand transport is not an important factor, but consistently lower than the DF core. Salt marsh peat usually has a higher mineral content than that of freshwater wetlands (Kosters et al. 1987) and impounded salt marshes (Thom 1992). This relationship was also clear in bulk density profiles (Figure 9). Organic matter changed little below 30 cm, where DF's unconsolidated, mucky peat exceeded NA by at least 20%. Total carbon trends are similar (Figure 10, bottom left).

It was noted above that the DF marsh surface was only 15 cm below unaltered NA on the opposite side of the dike; therefore, any subsidence that occurred after diking, plus concurrent rises in sea- and ground water levels, must have been largely offset by marsh accretion. With the dike's blockage of tidally-transported inorganic sediment, the accumulation of organic matter and associated pore space became more important to sediment accretion (Table 1). Organic matter accumulated because the restricted drainage at DF promoted waterlogging (Figure 2) and slowed decomposition. The dike's interruption of the normal tidal regime therefore encouraged the development of peats which resemble those of freshwater wetlands in bulk density and organic content (DeLaune et al. 1990), a phenomenon also reported for tidally restricted marshes in the Pacific Northwest (Thom 1992). This process may allow diked marshes, if not intensively ditched and drained, to persist as emergent wetlands despite the blockage of tidal flow.

In contrast, soils of the drained site below the root zone of modern terrestrial vegetation contain about 75% less organic matter by mass than NA (Figure 8, bottom right). We assume that the organic content of the two sites was originally similar given comparable topographic settings, rhizome characteristics below the annual minimum water table (Figure 7), and histor-

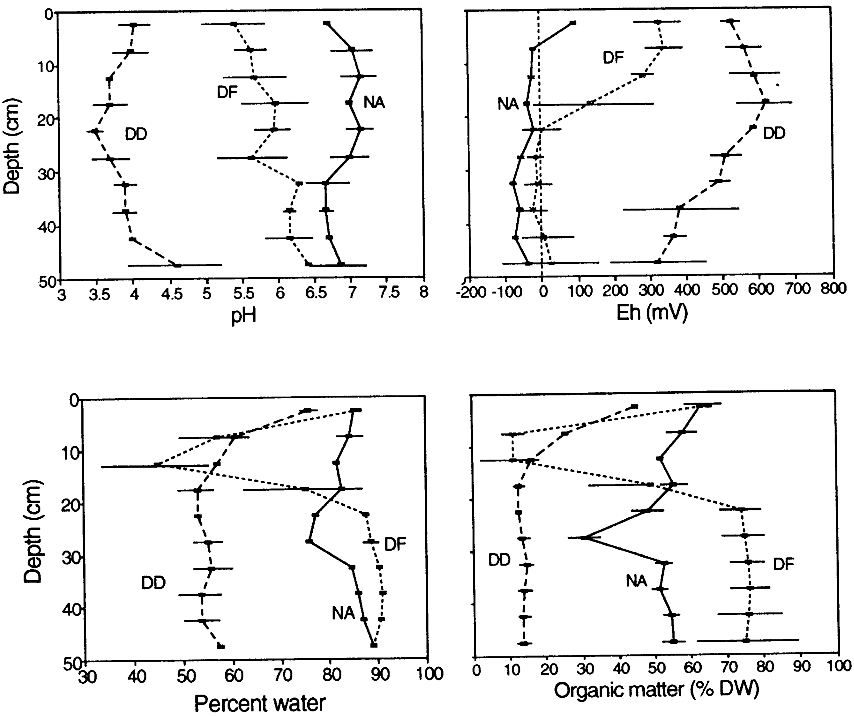


Figure 8. pH, Eh, percent water and organic matter in natural (NA), diked-freshened (DF), and diked-drained (DD) salt marshes; mean ± SE, $N = 2$.

Table 1. Relative volumes (mean ± SE, $N = 2$) of pore space, organic matter and mineral matter in the top 50 cm of the three marsh types. Anomalous sandy lenses at NA (25–30 cm) and at DF (7–17 cm) are excluded from calculations.

	Volume percent		
	Pores	Organic	Mineral
NA	90.8 ± 2.2	6.6 ± 1.5	3.0 ± 1.0
DF	92.8 ± 1.5	6.0 ± 1.2	1.1 ± 0.4
DD	76.8 ± 3.8	6.5 ± 1.3	16.6 ± 4.5

ical data (in Study Sites). Organic matter loss has probably occurred through aerobic decomposition, known to be faster than anaerobic catabolism (Tate 1979; DeLaune et al. 1981).

Treatment effects on sediment structure are evident in the relative volumes occupied by pore space, organic and mineral matter in the three marsh types (Table 1). DF's similarity to NA in surface elevation, pore space and organic

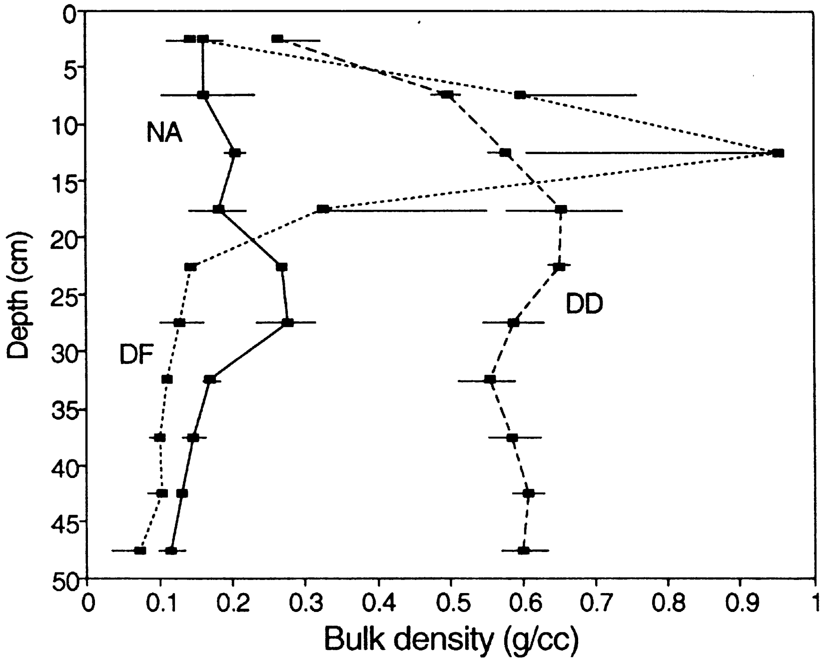


Figure 9. Bulk density in natural (NA), diked-freshened (DF), and diked-drained (DD) salt marshes; mean ± SE, $N = 2$.

Table 2. Element ratios (mean ± SE, $N = 2$) of sediment stocks from the three marsh types. Data are for the top 50 cm.

	C:Fe	C:P	C:S	C:N
NA	39 ± 4	401 ± 7	12 ± 0	19 ± 0
DF	62 ± 12	530 ± 78	16 ± 0	18 ± 1
DD	2 ± 0	96 ± 1	6 ± 2	11 ± 0

volume, and its even lower inorganic volume, indicate little compaction since diking. In contrast, sediment from the subsided DD site had much less pore volume, more mineral volume and higher bulk density (Figure 9) than either NA or DF. Though simple compaction could increase bulk density without associated organic decomposition, organic matter should have increased along with mineral matter, which it did not. Therefore, subsidence at DD must have followed a significant loss of organic matter. Much lower C:Fe, C:P, C:S and, to a lesser degree C:N, ratios at DD than NA or DF (Table 2) are further evidence for substantial organic decomposition since diking.

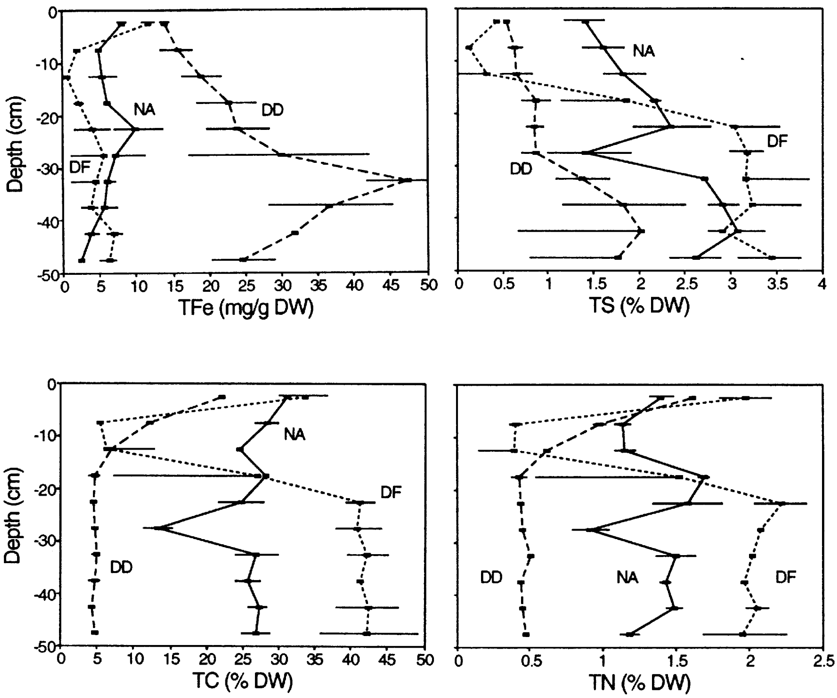


Figure 10. Total Fe, S, C and N in natural (NA), diked-freshened (DF), and diked-drained (DD) salt marshes; mean ± SE, $N = 2$.

Treatment effects on pH and redox potential were consistent (Figure 8, top) throughout the sediment profiles with NA > DF >> DD in pH, and NA < DF << DD in Eh. Contrasts among treatments reflected the consequences of desalination and aeration particularly on pyrite oxidation and SO_4 release. Redox declined considerably with sediment depth, especially in DF and DD which included both aerated and waterlogged strata. Negative Eh values accompanied sulfide odors in waterlogged sediment from both saline and diked, desalinated sites.

Though diked for 90 to perhaps 150 years, sediments of all study sites still contained the large reserves of Fe and, for waterlogged strata, S that characterize unaltered salt marsh peat (Figure 10). Total Fe (TFe) and total S (TS) profiles were similar at depths >30 cm in NA and DF cores. These deep sediments had a common origin as salt marsh deposits (Figure 7). Nearer the surface, Fe(II) diffused upward from anaerobic porewater to oxidize and accumulate as Fe(III) minerals at redox discontinuities, i.e. 0–5 cm at NA and DF and 30–35 cm at DD (Figure 10), also apparent in Fe:S ratios (Figure 11). In general, the above differences among treatments described

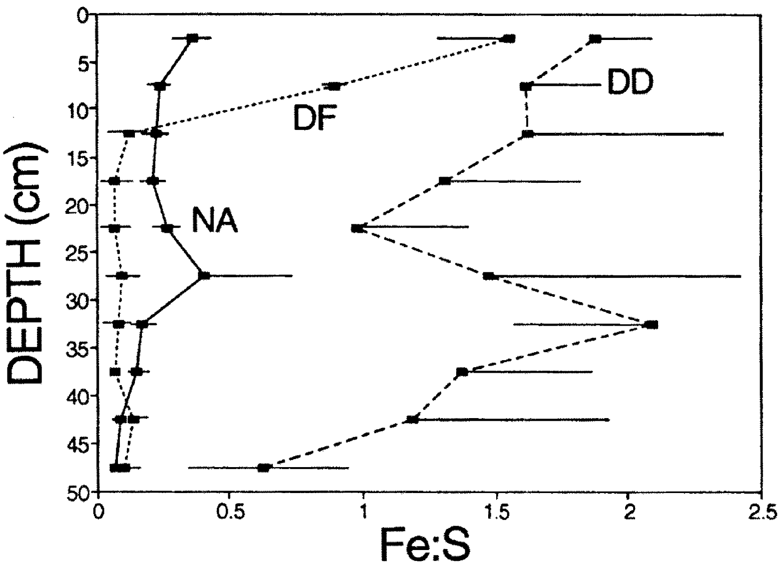


Figure 11. Fe:S ratios in natural (NA), diked-freshened (DF), and diked-drained (DD) salt marshes; mean ± SE, $N = 2$.

the contrasting mobilities of Fe and S under different flooding regimes, with aeration causing the oxidation of reduced iron-sulfur minerals to leachable sulfates but particulate iron minerals (Breemen 1982).

Site DD's extremely acidic (pH <4.0) conditions suggested that a substantial portion of the iron could comprise Fe(II) adsorbed to silts and clays (Brookins 1988; Moore & Parick 1989). Exchangeable Fe(II) was abundant in KCl extracts of the sediment (Figure 12). Both ferrous and ferric iron ranged 0.2 to 0.7 mg/g of sediment dry weight at DD, in sharp contrast with concentrations <5 μg/g for NA and DF marshes. The KCl-extractable Fe was about three times the water-soluble Fe throughout the DD cores. This demonstrated: 1. the importance of solution ionic strength on Fe mobility in DD's acid sulfate soils and 2. the likelihood for massive Fe mobilization if DD sediment were to be reflooded with seawater, thereby increasing cation exchange and lowering Eh.

The S mass fraction in DD sediment below 25 cm was about 30% less than the natural salt marsh. Chromium-reducible S at DD comprised 11–24% of TS in samples from 0–40 cm (22.8-40.2 μm/g DW), but reached 75% (603.8 μm/g) at 55–60 cm where waterlogging was nearly constant. This showed the retention of potential acidity after eight decades of seawater restriction especially in deeper, wetter horizons where most S persisted in reduced form. In contrast, low CRS and high Eh of the normally aerated

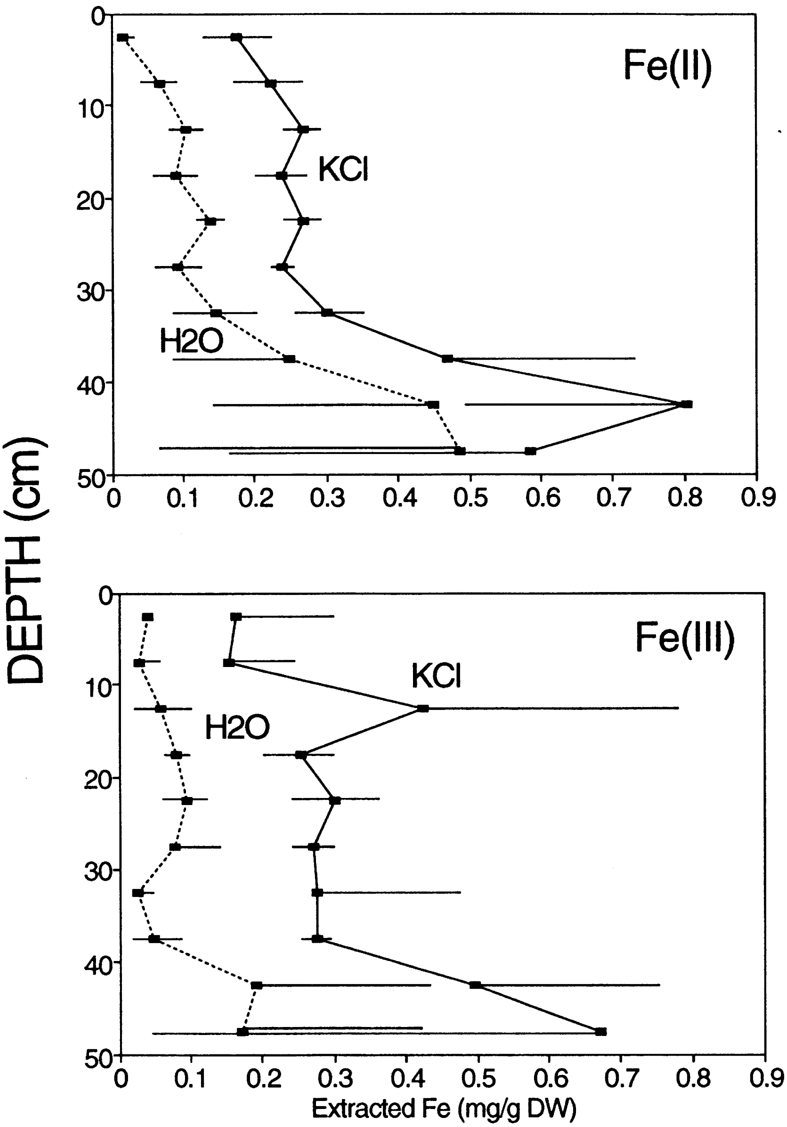


Figure 12. KCl-extractable and water soluble Fe(II) and Fe(III) at the diked-drained site; mean ± SE, $N = 2$.

surficial soils of DD indicated that most S existed as high-redox-state minerals (e.g., jarosite) rather than pyrite and did not represent potential acidity.

Total phosphorus concentrations were similar in the three marshes, though organic:inorganic proportions differed (Figure 13). Inorganic P accumulated at the surface and decreased with depth in the wetter NA and DF sites, expected with low-Eh mobilization in porewater and high-Eh adsorption near the surface (Carignan & Flett 1981). Macrophytes may have also contributed to relatively lower P at depth by translocating the nutrient to aboveground biomass (Pomeroy et al. 1969; Reimold 1972). Organic P nearly always exceeded inorganic P and was generally 3–4 fold the inorganic fraction at NA and DF. The ratio of organic to inorganic P was lower throughout the DD core due to the aerobic decay of organic matter and the retention of PO_4 as Fe and Al precipitates (Krairapanond et al. 1993) at high Eh. These precipitates reportedly resist P leaching even at pH 3.5–4.0 (Dent 1986), explaining why DIP was often undetectable (<1 μm) in porewater despite abundant P in sediment solids.

Carbon:nutrient ratios indicated the organic C losses through aerobic decay, and inorganic P and N retention, at DD compared to the wetter NA and DF marshes (Table 2). Exchangeable NH_4-N comprised 1–5% of the total N in DD cores, compared to <1% for both NA and DF (Figure 14). N leaching losses may have also been limited by low pH which inhibited ammonium nitrification (Focht & Verstraete 1977). The retention of abundant NH_4 sorbed to soil particles and of mineral PO_4 indicates the potential for DIN and DIP mobilization.

Other sites

Wetlands with similar management histories generally showed similar sediment characteristics (Figure 15); see Portnoy (1996) for sediment chemistries. Diked drained soils at DD2 and DD3 were low in organic content and acidic. The lack of an identifiable horizon of decomposed *Spartina* rhizomes in DD3 probably reflected better aeration and more complete decomposition in soils that were sandier than DD and DD2. Diked, seasonally waterlogged sediments at DF2 and DF3 had high organic and water content and near neutral pH. At DF3, the complicated history of diking and drainage, followed by impoundment and waterlogging, resulted in a mid-depth horizon of decomposed *Spartina* peat, topped by freshwater wetland peat. δ^{13}C signatures, obtained only for DD3 and DF3, were consistent with the history of hydrologic manipulations.

Conclusions and management implications

Differences among the sediments of the natural, seasonally flooded and drained wetlands pointed out the dependence of salt marsh elevation, stratigraphy and biogeochemistry on regular tidal flooding. The flood-tide-dominated salt marshes of this region (sensu Speer & Aubrey 1985) accreted

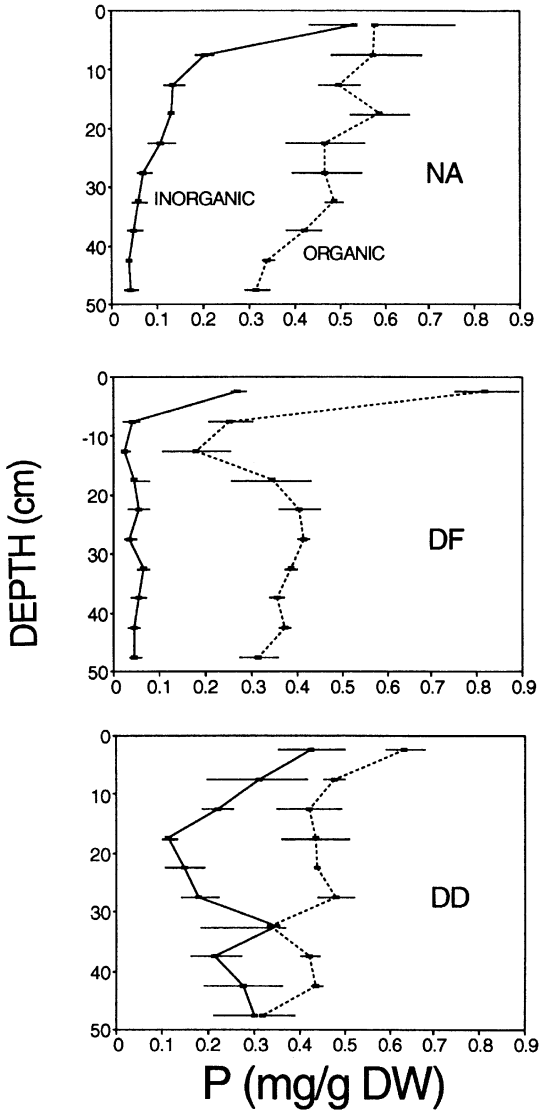


Figure 13. Inorganic and organic P in natural (NA), diked-freshened (DF), and diked-drained (DD) salt marshes; mean ± SE, $N = 2$.

along with sea-level rise through the tidal import of largely inorganic sediment (Bricker-Urso et al. 1989; DeLaune et al. 1990). Diking blocked this sediment source (Warren & Niering 1989) and also lowered the depth of regular waterlogging by semidiurnal flood tides. Resulting drainage and aeration accelerated organic decomposition and reduced pore volume, leading

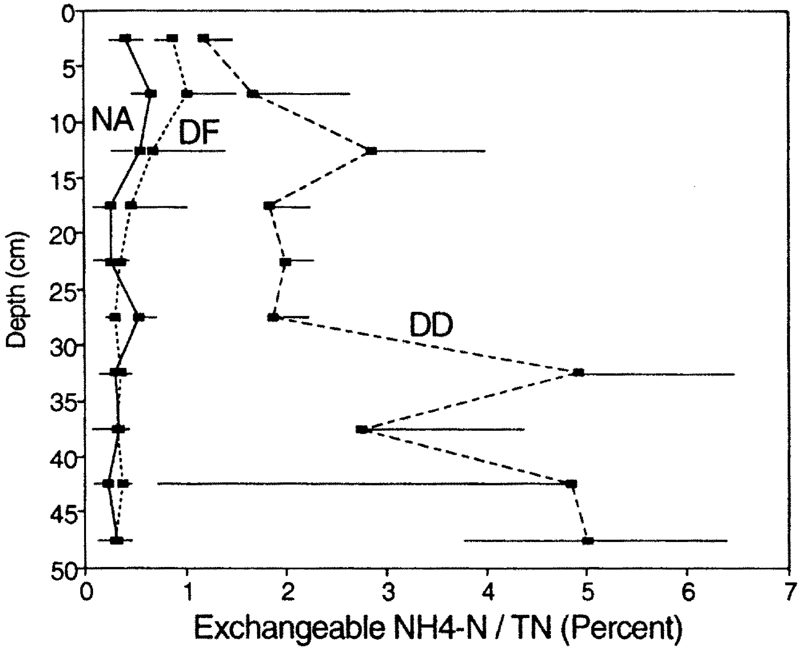


Figure 14. KCl-exchangeable NH_4-N as a percentage of total N in the three marsh types. Means ± SE; *N* = 2.

to compaction and subsidence. As the substrate subsided to an elevation near the freshwater table where soil waterlogging and anoxia were again frequent, the impounded salt marsh community was replaced by emergent freshwater wetlands.

For emergent plant survival, impounded marshes must (like salt marshes) accrete in response to rising water levels; however, with the dikes' blockage of the marine sediment supply, the impounded DF marshes relied more on organic production to maintain a constant position relative to the rising water table. Persistent freshwater wetland communities indicated that this mode of accretion was effective, but accumulating peat became more organic. In addition, with the exclusion of seawater, anaerobic decomposition likely became dominated by methanogens rather than sulfate reducers, reducing thermodynamic energy yields (Capone & Kiene 1988). This decreased the turnover of N and P, relative to the natural marsh, evident in the large proportion of these nutrients contained in sediment solids (Table 3).

The above sedimentary conditions in DF-type marshes suggest that management actions that either improve drainage or restore seawater supply will induce rapid sediment oxidation, subsidence, and nutrient mobilization (Bowden 1987) by providing higher energy-yielding electron acceptors,

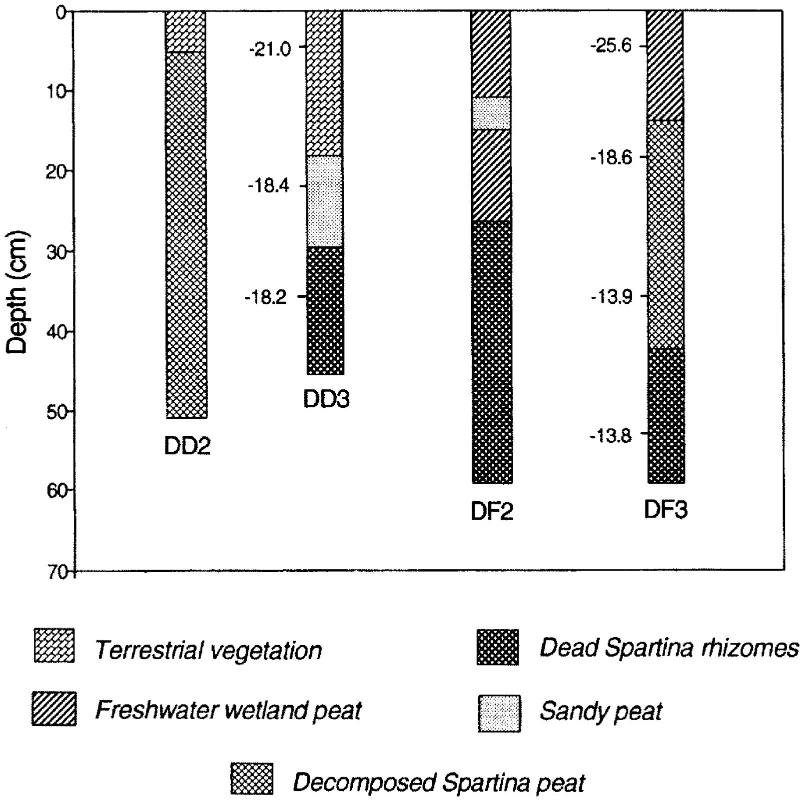


Figure 15. Sediment stratigraphy of additional diked-drained (DD2, DD3) and diked-freshened (DF2, DF3) marshes. Numbers to the left of profiles DD3 and DF3 are δ^{13}C values.

Table 3. Solid:aqueous ratios of N and P in the natural (NA), diked-freshened (DF), and diked-drained (DD) wetlands. Aqueous concentrations (μM) are mean values for July and August 1994. Solid phase units are micromoles/kg.

Site	N	P
NA	3,408	1,925
DF	692,250	11,880
DD	2,117	5,363

oxygen and sulfate, respectively. The loss of pore volume accompanying dewatering would also contribute to compaction. The depth of subsidence would be greatest in marshes impounded for many decades with consequently large accumulations of freshwater peat of low bulk density. Consequently, when seawater flow is restored to historically diked marshes, flooding depths and durations would exceed natural conditions. Open water rather than intertidal salt marsh may be the unintended result of programs which reintroduce copious seawater flow too quickly (Rosza 1987). Also, nutrient mobilization could affect the quality of surface waters.

Where drainage was intensified by ditching, creek channelization and the provision of large culverts for freshwater discharge, as in DD sites, wetland loss is apparently permanent. At Herring River, despite about 70 cm of subsidence and about 20 cm of sea-level rise since 1908 diking (Lyles et al. 1988), the water table rarely reached the surface and wetland plants were being replaced by terrestrial species (Portnoy et al. 1987).

In these drained sites, high sedimentary S reserves and the continued release of acidity after many decades of diking was unexpected, given the demonstrated rapid oxidation of pyrite from salt marsh sediments following dewatering (Giblin 1988). Long-term S storage occurs in marsh silts where high water-holding capacity leads to anaerobic micro-environments even above the water table (Dent 1986). A substantial fraction of the reduced S expected in salt marsh peat has persisted in seasonally aerobic horizons at Herring River, and nearly all is left in perennially waterlogged sediment, where potential acidity may persist for hundreds of years (Dent 1986).

Despite the oxidation of organic carbon, aerated diked drained soils retained high N and P concentrations, with ammonium adsorbed on silts and clays and phosphate likely associated with abundant Fe and Al oxides (Dent 1986). This has implications for restoration management, e.g. to mitigate the acid sulfate problem, for halophyte re-establishment, and for the preservation of coastal water quality. Seawater flooding after decades of diking could rapidly decrease redox, increase pH and cation exchange and thereby mobilize a large pulse of NH_4, PO_4 and Fe(II). The duration of nutrient enrichment may be short-term and may in fact enhance halophyte growth and recolonization (Portnoy, unpublished data); however, concerns for surface water quality urge a gradual and carefully monitored reintroduction of seawater to diked systems.

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