PROCESSES OF FORMATION AND DEGRADATION OF MARSHES ALONG THE LOUISIANA GULF COAST

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PROCESSES OF FORMATION AND DEGRADATION OF MARSHES ALONG THE LOUISIANA GULF COAST

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ABSTRACT

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Processes governing the stability of Louisiana's rapidly deteriorating Gulf coast marsh were investigated. Vertical marsh accretion determined from ^{137}Cs dating were compared to water level increase obtained from tide gauge data. In subsiding coastal environments the continued existence of marsh habitat is dependent on the ability of marsh to maintain elevation through vertical marsh accretion (mineral sediment and organic matter accumulation). Coast-wide average vertical accretion was 0.60 to 0.80 as compared to water level increase of over 1 cm year. Rapid water level increase, attributed primarily to subsidence, was 3 to 5 times greater than eustatic sea level changes reported to be 0.23 cm yr^1.

The measured accretionary deficits (difference between water level increase and vertical marsh accretion) parallels reported marsh disappearance of over 100 $km^2\ yr^1$. Organic matter accumulation was identified as an important component of marsh aggradation in response to changes in water level. A appreciable amount of organic production of marsh macrophytes remains on the marsh as peat or is decomposed to carbon dioxide or methane. Organic matter on a dry weight basis constituted an increasing fraction of soil solids as its marine influence diminishes inland from the coast. Organic matter is of greatest structural significance in low density, fresh, and brackish marsh environments. However, on a unit volume basis, the organic matter occupies the same volumes in fresh, brackish, and salt marshes.

Louisiana Gulf coast marsh will likely continue disappearing at a rapid rate unless means are implemented for distributing Mississippi River sediment to the marshes. The combined effect of rapid subsidence, eustatic sea level rise and accompanying salt water intrusion will likely destroy much of these marshes. Results presented may represent future conditions for many coastal regions of the world, which may experience a rapid rise in water-level as a result of the predicted "greenhouse" warming and resultant accelerated worldwide sea-level rise.

Statements

1. Soil organic matter on a volume basis is the same in fresh, brackish and salt marshes of the Mississippi River Deltaic plain. Soil bulk densities differ as a result of the decreasing mineral sediment contributions with distance from the coast.

2. Nitrous oxide emission from coastal wetlands are low in marshes not receiving extraneous nitrogen input from municipal or agricultural sources.

3. Sulfide diffusing from anaerobic marsh soil or sediment can be chemically oxidized to elemental sulfur. This process is quantitatively important in the sulfur and energy budget of coastal marshes and has been overlooked by other researchers in the field.

4. Nitrification-denitrification processes at the sediment water interface of bottom sediment is an important process in removing nitrogen from lakes and streams.

5. Excess flooding and increases in salinity can reduce carbon assimilation rates of wetland plant species.

6. The oxidized rhizophere surrounding the roots of wetland plants is important in neutralizing potential toxins found in flooded soil and sediment.

7. Sediment is the primary source of nitrogen in Louisiana's salt marsh. Nitrogen fixation is the main source in fresh and brackish marshes.

8. Sediment pH-redox conditions influence the degradation of petroleum hydrocarbon and other toxic organics entering wetland environment.

9. In recent years, the sediment load of the Mississippi River has been reduced.

10. An influx of Dutch Scientists and Engineers can perhaps reverse Louisiana coastal land loss problems.

R.D. DeLaune
Processes of Formation and
Degradation of Marshes Along
the Louisiana Gulf Coast
Wageningen, 3 June 1988

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Acknowledgement

1. INTRODUCTION

Louisiana contains vast (3.2 million ha) coastal marshes representing 41 percent of those in the continental United States (Turner and Gosselink, 1975). The marshes extend inland from the Gulf of Mexico for distances ranging from 24 to 80 km and reach their greatest width in southeastern Louisiana (Chabreck, 1972). Features of the Louisiana Coast are closely related to the geological history of the Mississippi River.

The marshes are related to the geology of the area. Over the past several thousand years a series of Mississippi River distributaries have along the central and eastern Louisiana coast formed a deltaic plain (Kolb and Van Lopik, 1966) (Figure 1). Historically, in the deltaic plain the Mississippi River has undergone a major natural diversion every 1,000-2,000 year. Annual flooding of the distributaries of the Mississippi over their natural levees resulted in the formation of broad expanses of marshlands. Active distributaries built new land, but when the flow of the river shifted to a new route the abandoned delta and adjacent marsh underwent subsidence and erosion. As the marsh deteriorated small water bodies and streams formed, and the interface length between the land and water increased. Land building has exceeded erosion over historical time and resulted in formation of a large deltaic plain with extensive marsh area (Frazier, 1967).

In this century sedimentation has decreased. This resulted partly from efforts to force the Mississippi River down its present channel, depriving wetlands of sediment. Maintaining the Mississippi River flow down the current channel halted this process, causing sediment to be deposited off the continental shelf, and preventing the natural meander

down the Atchafalaya River. This loss of sediments and compaction of existing sediment is a primary factor in the loss of Louisiana wetlands. Deterioration of the coastal wetlands began in the early nineteenth century in approximately the same period that the Mississippi River was leveed. Currently marshes are deteriorating at the rate of over 130 km^2 yr^{-1} (Gagliano, 1981).

Within the Mississippi River Deltaic plain, marshes associated with the emerging Atchafalaya River delta is now actively building marshes, thus representing one of the few areas along the Louisiana coast where land loss is not a problem. Control structures, however, allow the Atchafalaya to capture only a third of the present Mississippi River flow, thus limiting delta formation. Near the rapidly prograding distributary network, large areas of Atchafalaya marsh have changed from brackish to freshwater. An opposite process has taken place in the older deltas of the Mississippi River deltaic plain, where abandonment and subsidence results in invasion of marine water. Now wetlands are rapidly disappearing in older delta lobes of the Mississippi River deltaic plain. Wetlands developing in the Atchafalaya delta are evolving under conditions similar to those in earlier delta lobes of the Mississippi River. Emergence of the Atchafalaya delta has caused dramatic changes in the wetlands, inland waters, an in the nearshore of central Louisiana. Such spatial sedimentation or accretion patterns must be clearly understood if changes in such a dynamic coastal system are to be accurately predicted.

The 200-km section of coastal wetlands in southwest Louisiana known as the Chenier Plain is distinct and different from the rest of the Louisiana coast (Figure 1). The term chenier refers to old beach ridges characteristic of the area. The smooth and relatively straight form of the

Figure 1. THE LOUISIANA COASTAL ZONE

western half of the coast reflects a depositional history different from that of the Mississippi River deltaic plain. As sea level rose from -5 m to its present level, a transgressive sequence of marine sediments was deposited over the Pleistocene Prairie Formation, first filling estuaries, then later spreading across shallow bay and marsh environments, thus forming what is known as the Chenier Plain.

The marshes of the coastal wetlands both deltaic and chenier plains exhibit a striking zonation of emergent plants (Figure 2). Vegetation types range from saline near the Gulf of Mexico to brackish and then fresh and bottomland hardwood with increasing distance from the Gulf. Water levels in the marshes are affected by rainfall, tides, and local drainage patterns. Vegetation types are influenced by hydrology, salinity, and the type of sediment involved.

Water levels are typically within 30 cm of the marsh surface with exceptions occurring with storm tides or during periods of excessive rainfall or prolonged drought. The effects of tides are greater in areas nearer the Gulf of Mexico, however, tide levels in the gulf also affect water drainage from interior marshes. Tides along the Louisiana Coast are generally diurnal and small. Mean tidal range for the coast is on the order of 30 cm (Marmer, 1954). Water level on the marsh is governed to a degree by wind direction. Water level in the marsh is lower in winter months following northerly cold front passage. In addition to its effect on marsh water levels, tidal action and southerly winds also provides a source of highly saline water to the marshes. The daily fluctuating action causes highly saline waters to move inland and mix with advancing fresh water to form a vast estuarine basin. The mixing of salt water from the gulf and fresh water from inland   sources provides a spatial zonation in water

Gulf of
Mexico

Spartina alterniflora
Juncus roemerianus

Salt Marsh

Spartina patens

Brackish
Marsh

Cladium jamaicense
Scirpus californicus
Typha latifolia
Sagittaria falcata
Panicum hemitomon
Phragmites communis

Fresh Marsh

Salix nigra
Taxodium distichum
Nyssa aquatica

Swamp Forest

Liquidambar styraciflua
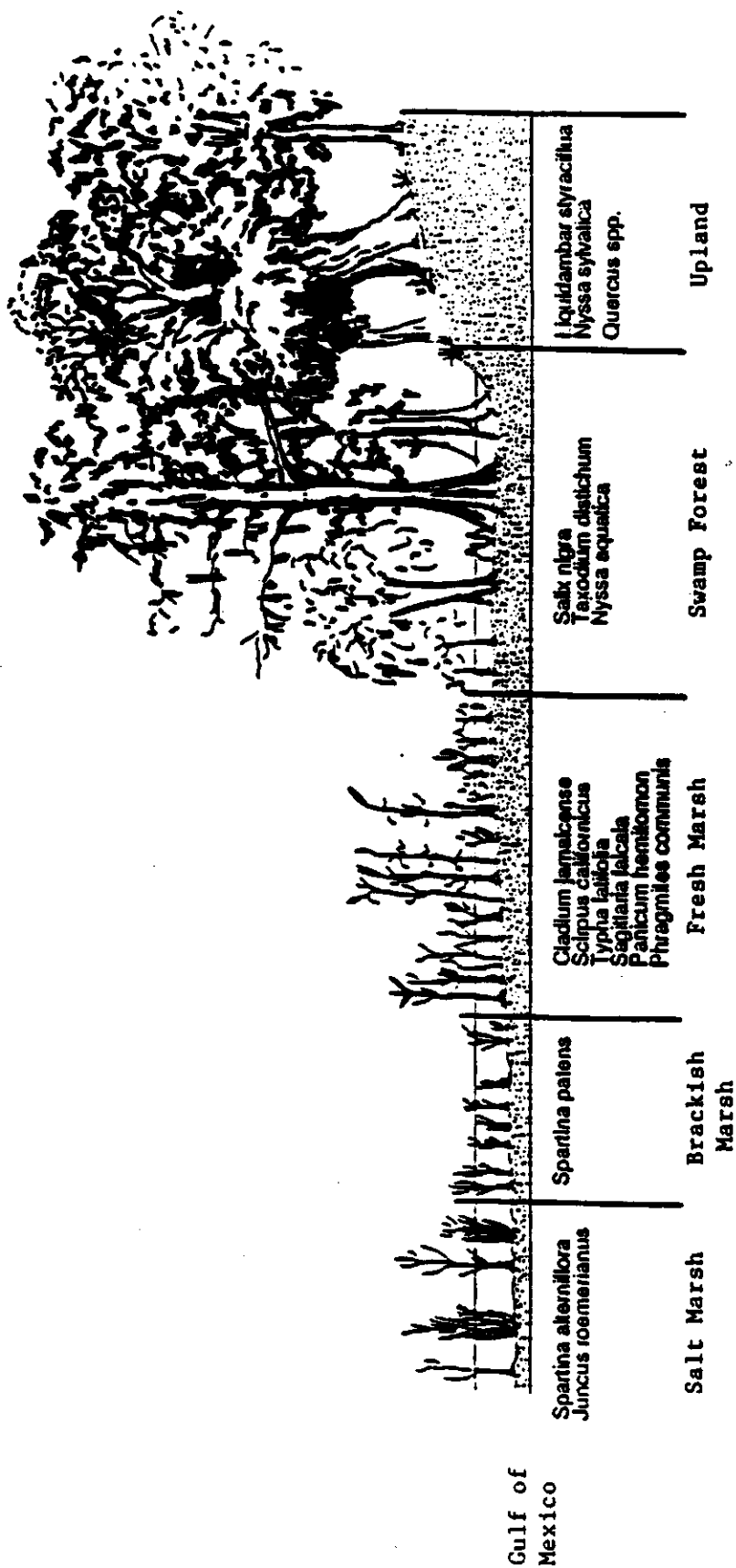Nyssa sylvatica
Quercus spp.

Upland

Figure 2. Schematic of plant distribution found along salinity gradient extending inland from the Louisiana Gulf coast.

salinities. Water salinities range from highly saline (20 to 25 ppt) near the coastline and gradually decline inland until a zone of fresh water is reached along the northern perimeter of the marsh region (Charbreck, 1981).

The vegetation is confronted with progressively rising water levels (submergence) in many wetland habitats of the Louisiana's Gulf Coast primarily because of rapid subsidence. Water level increase along the coast which is due primarily to subsidence is several times faster than eustatic sea level change for the Gulf of Mexico, which has been estimated to be 0.23 cm yr^{-1} (Barnett, 1984). Salinity increases simultaneously occur in the coastal marshes. These processes may be relevant to coastal marshes worldwide if the sea level rise resulting from climatic change occurs as rapidly as predicted.

Studies show that brackish and salt marshes are deteriorating faster than any of the other wetland habitats (Gagliano and Van Beek, 1970; Adams et al., 1976; Chabreck et al., 1968). The rate of land loss reported for brackish marshes is 1,355 ha/yr, whereas it is 701 ha/yr for the saline marshes, 499 ha/yr for freshwater marshes, and 223 ha/yr for the swamp forest (Craig et al., 1979). Craig et al. (1979) found that the wetlands in Barataria Basin (an interdistributary basin in the deltaic plain) are receding more rapidly than those in any other area of the Louisiana coastal zone. By contrast, in other coastal regions of the United States, marsh aggradation has kept pace with increases in water level and with coastal water (Letzsch and Frey, 1980).

Marsh surfaces developing in rapidly subsiding sediment deficient environments such as those in coastal Louisiana are maintained in the intertidal zone through plant growth, organic detritus accumulation, and limited mineral sediment deposition. The depth of organic layer is

determined by the amount of real and local subsidence, eustatic sea level change, organic matter oxidation, and vegetative growth. As plant growth tends to keep pace with the relative rise of sea level, both organic detritus and mineral sediments are entrapped, resulting in the gradual aggradation of the surface. The two processes can be viewed as working in a synergistic manner.

In subsiding environments, such as coastal Louisiana, the continued existence of marsh is partially dependent on its ability to maintain its elevation in respect to changing water level through vertical accretion. This must be accomplished through some combination of peat formation and mineral sediment accumulation. The two are interrelated, as the influx of sediments also supplies nutrients for plant growth (DeLaune et al., 1980). Increased plant growth results in more material available for peat formation and increases in stem density result in an enhanced ability to further entrap and stabilize sediment (Gleason et al, 1979).

Marsh deterioration along the Louisiana Gulf Coast is a complex problem and is seemingly the result of numerous factors that cumulatively have a spiralling effect. In addition to geological factors, man-induced activities, such as canal construction and leveeing, are also cited as having an indirect effect on land loss (Craig et al., 1979) by accelerating rate of water level increase and reducing sediment availability and storage. The site specific factors influencing the rate of formation and depth of Louisiana Coastal marsh soils include: 1) changes in hydrology, 2) plant primary production, 3) local subsidence, 4) eustatic sea level rise, and 5) oxidation and compaction of surface peats.

Figure 3 summarizes the processes influencing the rate of formation of coastal marsh along the Louisiana coast in relation to changing water
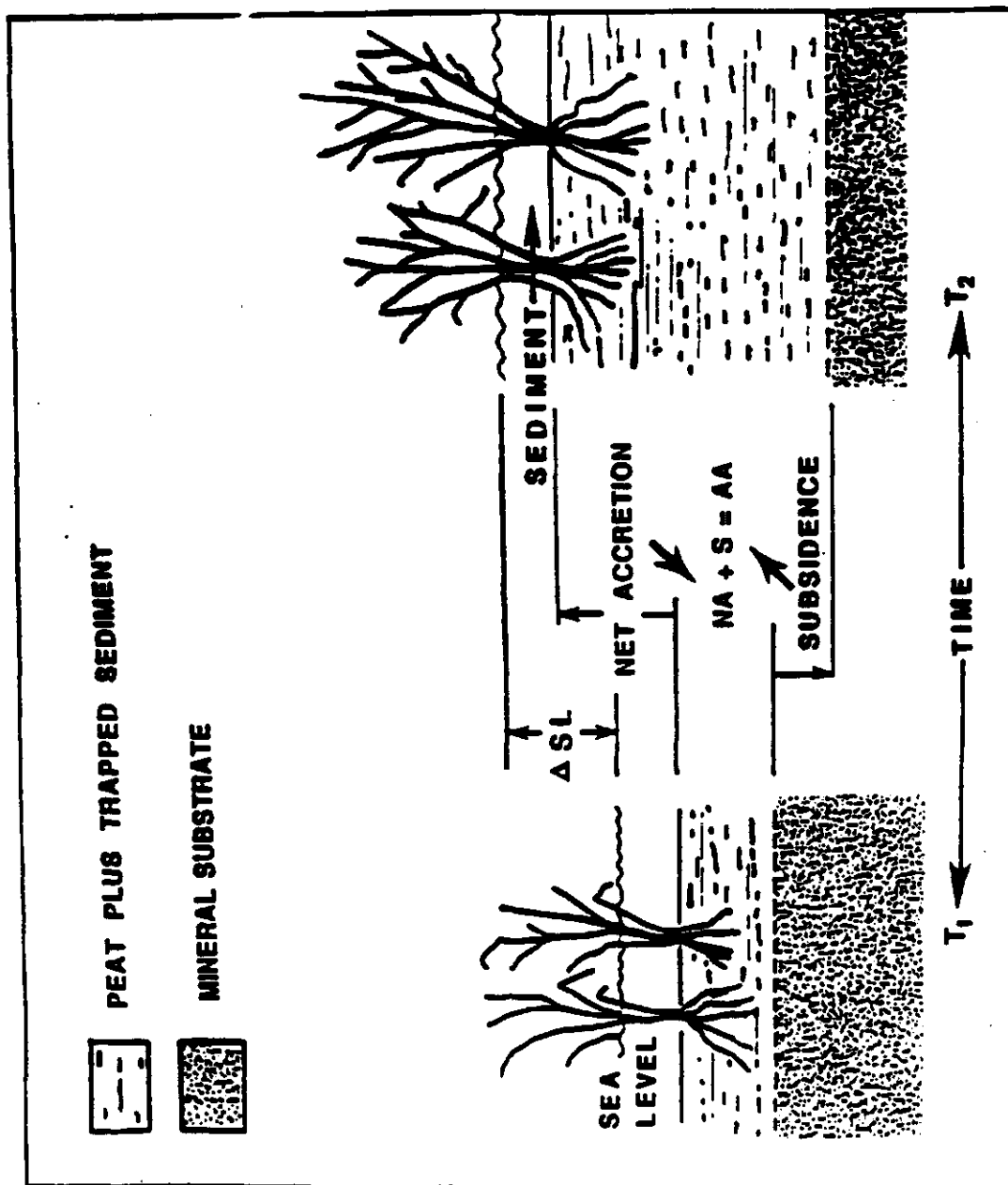
Figure 3. Schematic model of processes governing marsh accretion (ΔSL = Eustatic Sea Level Change, NA = Net Accretion, S = Subsidence, AA = Absolute Accretion).

level. The two main driving functions influencing marsh accretion are subsidence and eustatic sea level change. In this figure, net accretion depicts that which is attributed to eustatic sea level changes. Absolute accretion represents that attributed to both subsidence and eustatic sea level changes. In a marsh maintaining its evaluation with respect to mean sea level, net accretion equals eustatic sea level change, and absolute accretion equals subsidence plus eustatic sea level change. Note that vertical accretion rates reported in this study represent only the amount of marsh formed over the 1963 spike representing the peak ^{137}Cs fallout.

Water level change or apparent sea level rise reported in this study represent water level change resulting from subsidence and eustatic (true) sea level change.

The above processes are quantified in the following series of research papers. The papers are a result of work conducted by the author over the past decade in which extensive coastal studies of vertical accretion in relation to change in water level were conducted. Special emphasis is given to the role of organic carbon which is important in marsh soil formation in Louisiana sediment deficient coastal areas.

Tide gauge data providing evidence for increases in water level is summarized in Chapter 2. Also in Chapter 2, coastwide data on rates of vertical marsh accretion determined from ^{137}Cs dating is presented. Chapters 3 through 10 detail information on aspects of vertical marsh accretion in relation to changes in waterlevel at key sites along the Louisiana Gulf coast. The role of carbon cycling in marsh formation is presented in Chapters 11, 12, and 13. Chapter 14 summarizes changes in coastal land forms occurring along the Louisiana coast in relation to processes of marsh formation and deterioration. In the final chapter (15) a detailed budget of marsh soil formation processes in fresh, brackish and salt marshes of Louisiana's Barataria Basin is presented.

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2. Vertical Accretion and Waterlevel Increase Along the Louisiana Gulf Coast: A Data Base

by

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Vertical Accretion and Waterlevel Increase Along the Louisiana Gulf Coast: A Data Base

The following set of Figures and Tables are data summarizing vertical accretion and waterlevel increase along the Louisiana coast. The data collected by the author was used in developing a series of publications on the relationship of marsh formation and deterioration along the Louisiana Coast.

Rates of vertical marsh accretion throughout coastal Louisiana were determined using ^{137}Cs dating of sediment obtained from intact sediment profiles of the marsh (Table 1, Figure 1). Water level changes was determined by measuring increase in water level by analyses of tide gauge data. Forty-seven tide gauge stations maintained by the Army Corps of Engineers were analyzed for determining water level increase in coastal Louisiana (Table 2). Location of each station along the coastal zone is shown in Figure 2.

Tide gauge measurements at each station were plotted relative to mean sea level. Linear regression analysis was used to determine rate of rise in water at each locality. Level adjustments or missing observations were corrected or accounted for in the analysis. Comparing accretion rates to water level changes identified marsh environments that were accreting at rates sufficient or insufficient to maintain their intertidal elevation and consequently their stability.

While in certain locations marsh elevation was being maintained, deficits between water level increases and vertical accretion were apparent along selected areas of the Louisiana coast. Coastwide, marshes were vertically accreting at rates of approximately 0.7-0.8 cm yr^{-1} as compared to a water level increase greater than 1.2 cm yr^{-1} in many locations.

Extrapolated linear data presented suggests many areas along the coast will likely, in the future, experience rapid marsh deterioration unless means are developed for mitigating their losses. Specific details will be given in following papers.

Table 1. Rate of vertical marsh accretion at selected sites throughout coastal Louisiana as determined by ^{137}Cs dating.

Site Number	Area Location	Number of Cores	Vertical Accretion cm yr^{-1}
1.	South Pass, Mouth of Mississippi	5	>2.0 ± 0.14
2.	Shell Beach, St. Bernard Parish	5	0.54± 0.13
3.	Empire	4	1.4 ± 0.51
4	Rigolets	4	0.77± 0.09
5.	Grand Terre	3	0.55± 0.05
6.	Grand Isle	3	0.79± 0.05
7.	Bayou Feblanc, Leeville	10	0.74± 0.20
8.	North Bayou Feblanc, North L.	11	0.78± 0.15
9.	Clovelly Farm-Little lake	11	0.78± 0.20
10.	Des Allemands	8	0.68± 0.16
11.	Grand Bayou Blue	6	0.86± 0.15
12.	Golden Meadow Oil Field	5	0.70± 0.24
13.	East Timbalier	2	0.98± 0.13
14.	Timbalier	2	1.0 ± 0.17
15.	Cocodrie	5	0.70± 0.24
16.	Terrebone Marsh Complex (Bayou Penchant)	5	0.81± 0.28
17.	Four League Bay Marshes	5	0.65± 0.14
18.	Four League Bay Bottom Sediment	5	>1.5
19.	Palmetto Bayou-Bayou Creole-Plumb Bayou Marsh Area	3	0.93± 0.15
20.	Belle Isle-Wax Lake Outlet	4	1.4 ± 0.40
21.	Marsh Island	7	0.70± 0.14
22.	White Lake	5	0.86± 0.13
23.	Rockefeller Wildlife Refuge	3	0.90± 0.41
24.	Mermentau River-Grand Lake	3	0.69± 0.23
25.	Lower Calcasieu Marshes	5	0.70± 0.14
26.	Atchafalaya Bay Bottom	5	>2.0
27.	West Cote Blanche Bay	3	0.9 ± 0.30
28.	Each Cote Blanche Bay	5	2.0 ± 0.41
29.	Grand Cheniere	3	0.69± 0.23
30.	Lake Verret Swamp Forest	5	0.63± 0.35
31.	Paul Rainey	4	0.82± 0.16
32.	West Bay Subdelta	5	1.8 ± 0.14
33.	Pointe La Hache	5	0.73± 0.13
34.	Caernarvon	5	0.75± 0.12
35.	Cataoutche Area	5	1.0 ± 0.18
36.	Manchac	4	1.07± 0.20
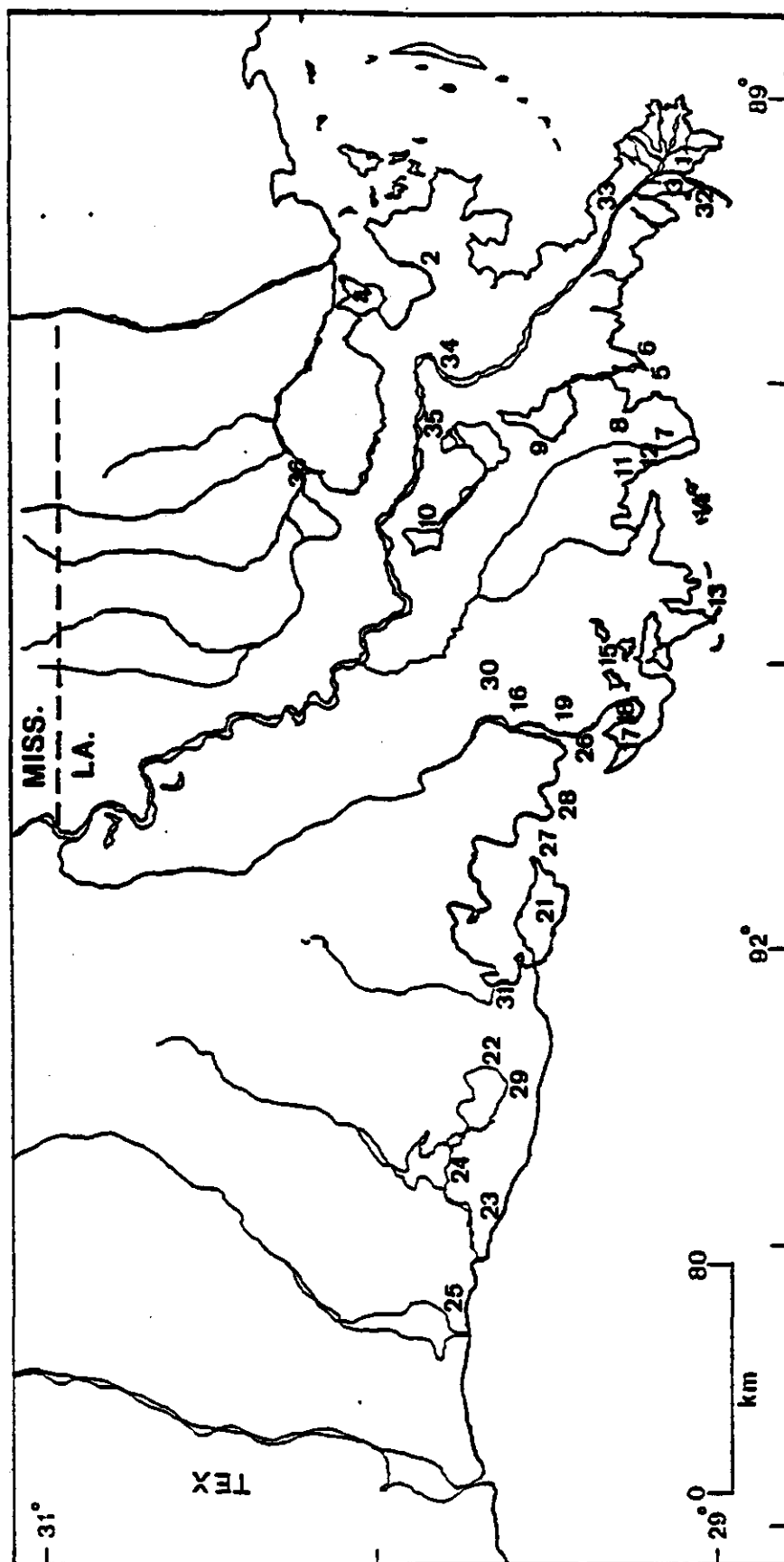
Figure 1. Locations along the Louisiana coast at which sedimentation or vertical marsh accretion rates were measured.

Table 2. Rate of water increase in coastal Louisiana (corrected for level adjustment and missing observations).

Army Corps of Engineers Gauging Stations	Period Analyzed	Water Level Increase (Slope of Change) (cm/yr)	r^- Correlation
1. Gulf of Mexico at Biloxi	1940-1983 1963-1983	0.12 0.15	0.23 0.17
2. South Pass Port Eads	1943-1983 1963-1983	1.15 0.82	0.85** 0.52**
3. Mississippi River- Head of Passes	1950-1983 1963-1983	0.37 0.19	0.22 0.06
4. Breton Sound at Gardner Island	1963-1983	-0.44	-0.20
5. Mississippi River (Southwest Pass) at East Jetty	1963-1983	1.08	0.40
6. Mississippi River- Gulf Outlet at Shell Beach	1963-1983	-0.27	-0.17
7. Lake Borgne- Rigolets	1963-1983	1.05	0.79**
8. Rigolets Near Lake Pontchartrain	1938-1983 1963-1983	0.45 0.78	0.78** 0.70**
9. Chief-Menteur Pass Near Lake Borgne	1963-1983	-0.50	-0.30
10. Mississippi River- West Point A La Hache	1950-1983 1963-1983	1.09 3.80	0.31 0.63**
11. Lake Pontchartrain (Irish Bayou) Near South Shore	1963-1983	1.37	0.87**

Table 2.
Cont'd

Army Corps of Engineers Gauging Stations	Period Analyzed	Water Level Increase (Slope of Change) (cm/yr)	r^- Correlation
12. Intracoastal Water-way (IWW) New Orleans Paris Road Bridge	1963-1983	2.92	0.93**
13. Bayou Rigaud-Grand Isle	1963-1979	1.83	0.93**
14. Bayou Barataria-Lifitte	1963-1983	0.31	0.29
15. Bayou Barataria-Barataria	1963-1983	0.35	0.28
16. Bayou Lafourche-Leeville	1963-1983	1.45	0.89**
17. Pass Manchac Near	1963-1983	0.90	0.64**
18. Bayou Des Allemands Des Allemands	1963-1983	1.16	0.81**
19. Bayou Petit Caillou-Cocodrie	1969-1983	0.72	0.55**
20. Bayou Chevreuil-Chegby (NR)	1963-1983	1.04	0.65**
21. IWW at Houma	1963-1983	1.85	0.79**
22. Bayou Black-Greenwood	1963-1983	2.71	0.86**
23. Bayou Boeuf-Amelia	1963-1983	1.61	0.61**

Table 2.
Cont'd

Army Corps of Engineers Gauging Stations	Period Analyzed	Water Level Increase (Slope of Change) (cm/yr)	r^- Correlation
24. Lower Atachafalaya River-Below Berwick Lock (East)	1963-1983	3.17	0.57**
25. Lower Atachafalaya River-Below Sweet Bay Lake	1963-1983	2.51	0.76**
26. Lake Verret at Attakapas Landing	1963-1983	1.79	0.63**
27. Pierre Pass-Pierre Part	1963-1983	1.53	0.58**
28. Belle River Near Pierre Pass	1963-1983	1.16	0.47*
29. Atchafalaya Bay- Eugene Island	1963-1983 1940-1983	3.21 1.51	0.90** 0.85**
30. E. Cote Blanche Bay-Luke's Landing	1963-1983	1.96	0.91**
31. Vermillion Lock (East Auto)	1963-1983	0.91	0.71**
32. Schooner Bayou Control Structure (East Auto)	1963-1983	0.98	0.71**
33. Schooner Bayou Control Structure (East Staff)	1963-1983	1.00	0.72**

Table 2.
Cont'd

Army Corps of Engineers Gauging Stations	Period Analyzed	Water Level Increase (Slope of Change) (cm/yr)	r⁻ Correlation
34. Schooner Bayou Control Structure (West)	1963-1983	0.53	0.48*
35. Freshwater-Bayou Lock (North)	1963-1982	0.76	0.52*
36. Freshwater-Bayou Lock (South)	1963-1983	0.63	0.50*
37. Calcasier River Near Oberlin	1963-193	0.57	0.09
38. Mermentau River-Catfish Point Control Structure (South Auto)	1963-1983	1.35	0.76**
39. Mermentau River-Catfish Point Control Structure (South Staff)	1963-1983	1.31	0.78**
41. Mermentau River-Grand Cheniere	1963-1983	0.57	0.67**
41. Calcasier River and Pass-Lake Charles	1963-1983	0.99	0.74**
42. IWW Calcasieu Lock (East)	1963-1983	0.67	0.51**
43. IWW Calcasieu Lock (West)	1963-1983	1.21	0.82**
44. IWW Calcasieu Lock (West Auto)	1963-1983	1.24	0.82**

Table 2.
Cont'd

Army Corps of Engineers Gauging Stations	Period Analyzed	Water Level Increase (Slope of Change) (cm/yr)	r⁻ Correlation
45. Calcasieu River and Pass Near Cameron	1963-1983	0.94	0.68**
46. Calcasieu River and Pass Hackberry	1963-1983	0.20	0.14
47. Lower Calcasieu Estuary	1954-1980	1.17	0.87**

*5% level of significance correlation.
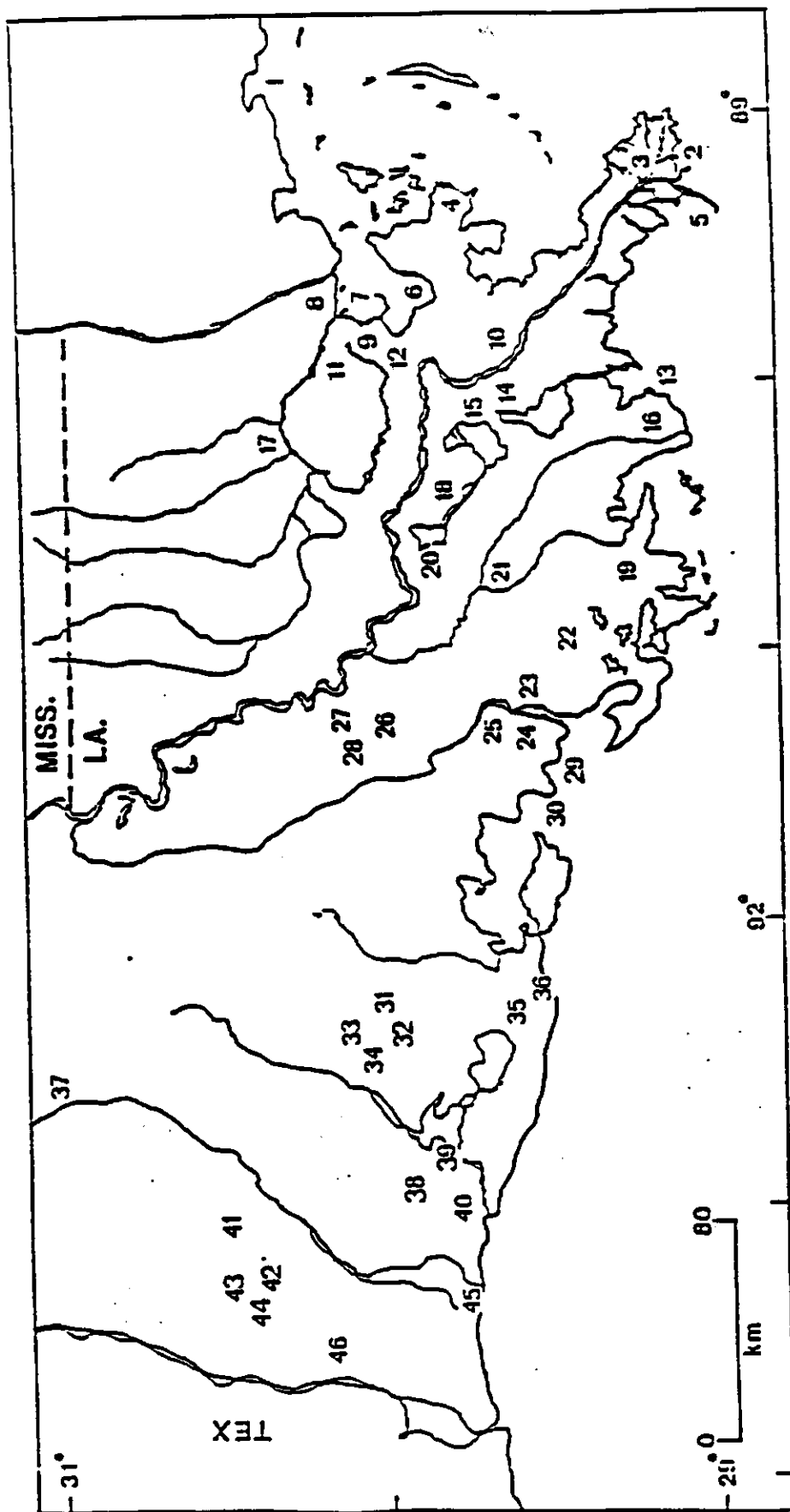**1% level of significance correlation.

Figure 2. Locations of gauging stations.

3.   Sedimentation Rates Determined by ^{137}C s Dating in a Rapidly Accreting Salt Marsh

by

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Sedimentation rates determined by ^{137}Cs dating in a rapidly accreting salt marsh

SEA-LEVEL records indicate that the coast of Louisiana and other parts of the Gulf Coast are rapidly subsiding[1]. Louisiana is now losing approximately 16 square miles of land per year, primarily to subsidence[2]; the rates of subsidence vary with location. Vertical marsh accretion is the process which counteracts subsidence and eustatic sea-level rise and prevents marsh deterioration, but, as in Louisiana's salt marshes, the pattern, rate and variability are sufficiently complicated to defy simple prediction. Conditions of marsh development vary throughout the coast, from the modern and Atchafalaya deltas through the abandoned deltas to the Chenier Plain[3]. In recent years, much of the coastal area such as Barataria Basin has been deprived of river-borne sediment through natural stream diversion and the construction of water-control embankments. In addition, dredging from petroleum operations has altered water flow and sedimentation patterns. The survival and productivity of Gulf Coast marshes depend on the influx and accumulation of sediment that offsets the effect of subsidence and maintains the marsh surface within the tidal range. To predict long-range trends in marsh stability, accurate measurements are needed of both subsidence and sedimentation rates. Information on subsidence is available from tide gauge measurements but no measurements have been made of sedimentation rates in marshland developed on Recent Mississippi alluvium. ^{137}Cs, a fallout product of nuclear testing, has become a useful tool for dating recent sedimentary sequency in lakes[4-8]. We report here its use in the measurement of sedimentation rates in a Louisiana coastal marsh, the first report of such use in coastal marshes.

Cores were taken from a streamside and inland *Spartina alterniflora* salt marsh and from an adjoining shallow water lake in Barataria Basin in Louisiana (29°13' N, 90°7' W). From the streamside location two sediment cores were taken 7 m inland and 5 m apart parallel to a natural stream. Another set of two cores was taken 45 m inland and 5 m apart parallel to the same stream. A third set of two cores was taken 350 m apart in adjacent Airplane Lake, a shallow 19-hectare lake. Cores were obtained by twisting a thin-walled aluminium cylinder of 15 cm diameter and 53 cm depth into the marsh soil or lake bottom. Compaction was minimal using these relatively large-diameter thin-walled cylinders. The sediment was sectioned into 3-cm increments, dried and ground, and each sample well mixed.

^{137}Cs activity in each section was determined by γ counting of the oven-dried sample using a lithium-drifted germanium detector and multichannel analyser[9]. Organic carbon was determined by dry combustion. Organic matter was estimated by multiplying carbon content by 1.724 (ref. 10). Density was determined from oven-dry sediment in the known volume of each section.

Sedimentation rates were calculated from the peak ^{137}Cs concentration found in the marsh and lake profile which corresponded to 1963, the year of peak ^{137}Cs fallout, and 1954, the first year of significant ^{137}Cs fallout[6,7]. There should be little mobility of ^{137}Cs in sediment, as it is rapidly adsorbed by clay components of sediment and soil[6,11]. Also, the sediment captured by the dense marsh grass is unlikely to be reworked.

^{137}Cs profile distributions demonstrate rapid vertical marsh accretion (Fig. 1). The two marsh sites nearer the stream were found to be accreting at a rate of 1.35 cm yr^{-1}. The inland marsh was accreting at a slower rate (0.75 cm yr^{-1}). The inland marsh is beginning to deteriorate into small open water areas, presumably because its vertical accretion rate is not able to compensate for subsidence and eustatic sea-level rise. A tail of ^{137}Cs activity extended below the 1954 marker in the marsh profile but not in the lake profiles. This tail corresponds to the rooting depth of *S. alterniflora* and is probably the result of plant absorption of ^{137}Cs (ref. 10). ^{137}Cs activity was expressed on a volume (pCi per 3-cm section) basis.
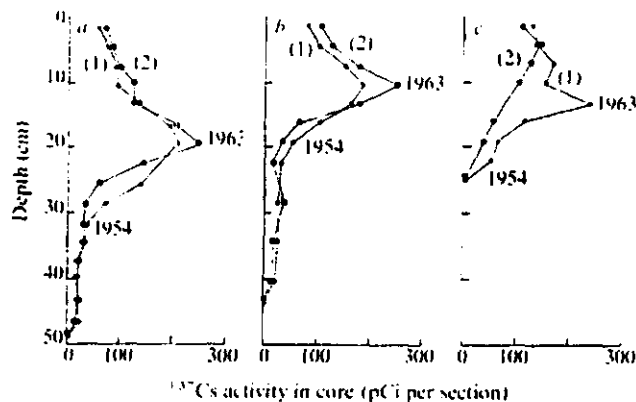

Fig. 1 Measured ^{137}Cs profiles at each location. a. Streamside 1 and 2; b. inland 1 and 2; c. Airplane Lake 1 and 2.

The distribution of ^{137}Cs in Airplane Lake cores implies accretion rates of 1.1 cm yr^{-1}. A greater amount of sediment mixing occurred in the lake than in the marsh. One of the lake sites did not have a distinct ^{137}Cs peak. However, the 1954 marker horizon for both cores extended to the same depth. A ^{137}Cs tail was no; found in the lake cores, apparently because of the absence of plant roots.

The accretion rates reported here are greater than those found in Atlantic coast salt marshes. Richard[13] recorded accretion rates of 0.34 cm yr^{-1} in a Long Island salt marsh using brick dust as a marker layer. Armentano and Woodwell[14], using ^{210}Pb, measured accretion rates of 0.47-0.63 cm yr also in a Long Island marsh. The rapid accretion rates obtained by ^{137}Cs

Fig. 2 Distribution of mineral and organic material at each location. a. Streamside 1; b. streamside 2; c. inland 1; d, inland 2; e. Airplane Lake ; f. Airplane lake 2. Light shading, mineral; dark shading, organic.
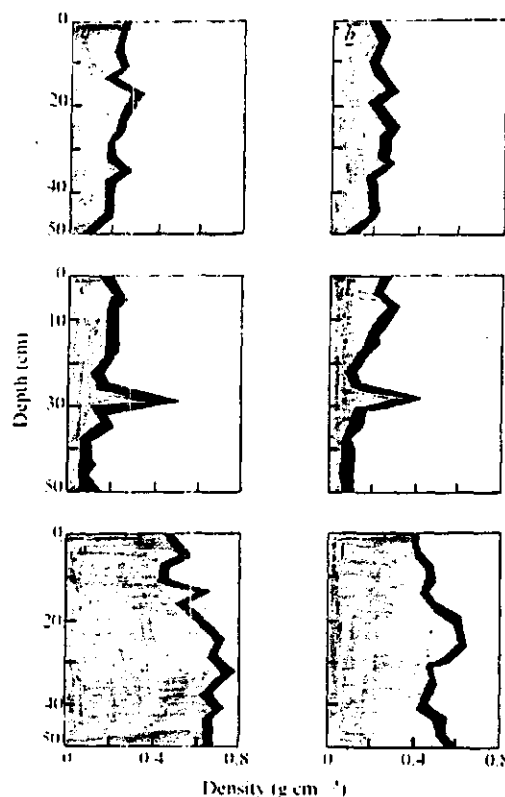
dating for this Louisiana salt marsh approximately equal reported subsidence rates of 1.29 and 1.12 cm yr^{-1} estimated by tide gauge measurements from 1959 to 1971 in this coastal area at Bayou Rigaud (29°16′N, 89°58′W) and Eugene Island (29°22′N, 91°23′W), respectively[1]. Even though there is a net land loss along the coast, vertical accretion is apparently compensating for a portion of the subsidence.

Density of the marsh soils ranged between 0.30 g cm^{-3} and 0.10 g cm^{-3}, depending on depth and location (Fig. 2). Density of the lake sediment ranged from 0.45 g cm^{-3} at the surface to approximately 0.65 g cm^{-3} at 50 cm. Both mineral and organic matter contribute to the density values. From density and carbon content of the cores, it is shown that the area vertically accretes through organic detritus accumulation and sediment input. The lake is receiving a larger amount of mineral sediment than the adjacent marsh.

The entrapment and stabilisation of suspended inorganic sediment on the marsh surface by vegetation is an important process in helping to maintain elevation with respect to sea level. The incoming sediment also supplies nutrients for plants which in turn enhance further sediment entrapment and stabilisation. The increased primary production contributes to the organic pool of these peaty marsh soils. Maintenance of a viable marsh is thus affected through aggradational processes of plant growth, organic detritus accumulation and inorganic deposition.

The ^{137}Cs dating technique thus seems to be useful in determining sedimentation rates over the past quarter-century in salt marshes that are rapidly accreting. Sediment deposited on the marsh surface is stabilised by the dense vegetation and, based on the slope of the ^{137}Cs profiles, there is little reworking and no pronounced biogenic disturbance of the deposited sediment.

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4. Relationships Among Vertical Accretion, Coastal Submergence, and Erosion in a Louisiana Gulf Coast Marsh

by

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RELATIONSHIPS AMONG VERTICAL ACCRETION, COASTAL SUBMERGENCE, AND EROSION IN A LOUISIANA GULF COAST MARSH[1]

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ABSTRACT: Vertical accretion in a southwest Louisiana *Spartina patens* brackish marsh has not kept pace with coastal submergence during the past three decades. The rate of accretion determined from ^{137}Cs dating and the use of artificial marker horizons averaged 0.8 cm yr^{-1}, whereas coastal submergence obtained from tide-gauge data averaged 1.2 cm yr^{-1}. Conversion from marsh to open-water bodies closely paralleled the increase in coastal submergence. If the resulting aggradation deficit continues, the marsh will likely complete its transformation to an open bay in less than 40 years. In view of recent projections of increasing sea-level rise the results presented may foreshadow a more widespread phenomenon.

INTRODUCTION

Coastal marshes are truly one of the most ephemeral of physiographical features, as they occupy the narrow intertidal zone and are therefore particularly susceptible to changes in the level of the oceans and in coastal displacement activity.

It has generally been assumed that marsh aggradation along submerging coasts has kept pace with local submergence rates (Rusnak, 1967). As a corollary, marsh aggradation rates are assumed to be enhanced by coastal submergence (Letzsch and Frey, 1980). These generalizations require the assumption that an adequate sediment supply is available. If the sediment supply decreases or coastal submergence accelerates beyond the capacity of the existing sediment supply to maintain the elevation, then marshes should undergo deterioration (erosion) as hypothesized by Chapman (1960, 1976). Our study provides evidence in support of Chapman's hypothesis.

An examination of tidal-marsh accretion studies summarized by Chapman (1960), Letzsch and Frey (1980), and Pethick (1981)

reveals that the marsh systems studied generally maintain their elevation relative to local water level. The Mississippi Deltaic Plain is an exception. DeLaune et al. (1978) examined a salt marsh in the Mississippi Deltaic Plain, where deterioration is an integral part of the system's developmental cycle, and noted that inland marshes (as opposed to streamside) were not keeping pace with subsidence through vertical accretion.

Major natural diversions of Mississippi River flow have occurred approximately every one to two thousand years, resulting in the formation of new delta systems and deterioration of older abandoned complexes (Kolb and Van Lopik, 1966; Frazier, 1967). The net balance during the Holocene was positive, increasing wetland area. After the late nineteenth century this trend was reversed, resulting in the present net reduction in wetlands (Gagliano et al., 1981). Net marsh deterioration in the Mississippi Deltaic Plain coincides with man-related sediment supply reductions (Tuttle and Combe, 1981) and dispersal modifications (Gagliano et al., 1981) although direct process-response links have yet to be documented.

We report in this paper the rates of vertical marsh accretion as determined by ^{137}Cs activity in the soil profile and by the use of artificial

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marker horizons, and relate them to coastal submergence and marsh deterioration in a *Spartina patens* marsh on the southern edge of Calcasieu Lake in southwest Louisiana (Fig. 1). The area is located in what is known as the marginal Mississippi Deltaic Plain or Chenier Plain (strandplain).

In order to avoid an implication of causal relationships we have employed the term *coastal submergence* (Settlemyre and Gardner, 1977) to refer to all factors which appear to elevate the sea in relation to the land as depicted by tide gauges. *Subsidence* is used here to refer to those factors which tend to lower the elevation of the land with respect to the sea, whereas *sea-level rise* refers to factors that elevate the sea with respect to the land.

Study Area Description

Development of the Chenier Plain began approximately 3,000 years B.P. via westward littoral transport of active and eroding Mississippi River delta sediments, combined with deposition of local fluvial sediments (Howe et al., 1935; Van Lopik and McIntire, 1957; Byrne et al., 1959). Development of recessional beach ridges (cheniers) coincides with eastward shifts in the course of the Mississippi River, whereas intervening mudflats are associated with westward shifts in the river's course (Byrne et al., 1959; Gould and McFarlan, 1959).

In theory, the Chenier Plain has a lower subsidence potential than the Mississippi Deltaic Plain due to substantially thinner Holocene sedimentary deposits, but marsh deterioration rates in the general area of our study site are as severe as in many areas of the Deltaic Plain proper (Gosselink et al., 1979).

The study site, known locally as part of the East Cove Marsh, lies within the Sabine National Wildlife Refuge, in a brackish to saline *Spartina patens*-dominated marsh on the south shore of Calcasieu Lake, Louisiana (Fig. 1). Radiocarbon dates and bore-hole logs of Byrne et al. (1959) and Gould and McFarlan (1959) indicate that the East Cove Marsh developed on the surface of mudflat deposits that prograded in this area between 2,800 and 1,100 B.P. coinciding with early Lafourche-Mississippi deltaic development (Frazier, 1967). At that time, Calcasieu Lake was still an open

estuary, but by 1,100 B.P., gradual westward constriction had separated Calcasieu Lake from the Gulf of Mexico, with Calcasieu Pass providing exchange between the two (Gould and McFarlan, 1959).

Our borings indicated that Holocene deposits were approximately 4 m in thickness at the lakeshore and gradually increased in a seaward direction to 6 m near Back Ridge. At the eastern extreme of the study area, however, a buried Pleistocene channel is evident, with maximum thickness of Holocene fill exceeding 14 m below the marsh surface. The north-south orientation of the channel suggests that it is an ancestral course of the modern Calcasieu River.

The Calcasieu River has a drainage area of 13,723 km^2 and provides a freshwater flow of 49.8 $\times$ 10^8 m^3/yr. Lesser freshwater inputs are derived through canals that connect Calcasieu Lake with neighboring estuaries and local precipitation, which averages 138 cm/yr, with a calculated surplus rainfall over evaporation of 49.3 cm/yr. This freshwater helps to maintain a high flushing rate (max. = 37 days) for the shallow ($\bar{x}$ = 1.5 m) and unstratified Calcasieu Lake (Gosselink et al., 1979).

According to Van Sickle (1977), the Calcasieu River has historically maintained a channel through the central portions of Calcasieu Lake, joining Calcasieu Pass along the western boundary of East Cove Marsh. Since 1871, the pass has been intermittently dredged and, commencing in 1937, a 10-m-deep ship channel was dredged along the western edge of the lake (Fig. 1). By 1946 the channel was deepened to 12 m, and in 1963 the depth was increased to 15 m. The ship channel has facilitated saltwater intrusion and decreased freshwater retention time during flood discharges, resulting in a significant increase in salinity at the upper end of the estuary (2.2‰ increase following the 1963 enlargement of the channel—Van Sickle, 1977). The effect the channel has had on salinity in the East Cove area is not well known, although modeling efforts (U.S. Army Corps of Engineers, 1950) predicted increases of less than 1‰. Salinity currently averages 15‰ in East Cove and generally ranges from 7 to 25‰ (Van Sickle, 1977). A comparison of vegetation maps of the area (O'Neil, 1949; Chabreck, 1972; Chabreck and Linscombe, 1978) indicates that

Marsh
Subaerial Pleistocene
Cheniers

CALCASIEU LAKE

PLEISTOCENE TERRACES

PLEISTOCENE TERRACES

CHENIER PLAIN

DELTAIC PLAIN

0   5   10
Kilometers

EAST COVE MARSH

REFUGE BOUNDARY

MENHADEN PLANT

CANAL

Kilometers

• MARKER HORIZON SITES
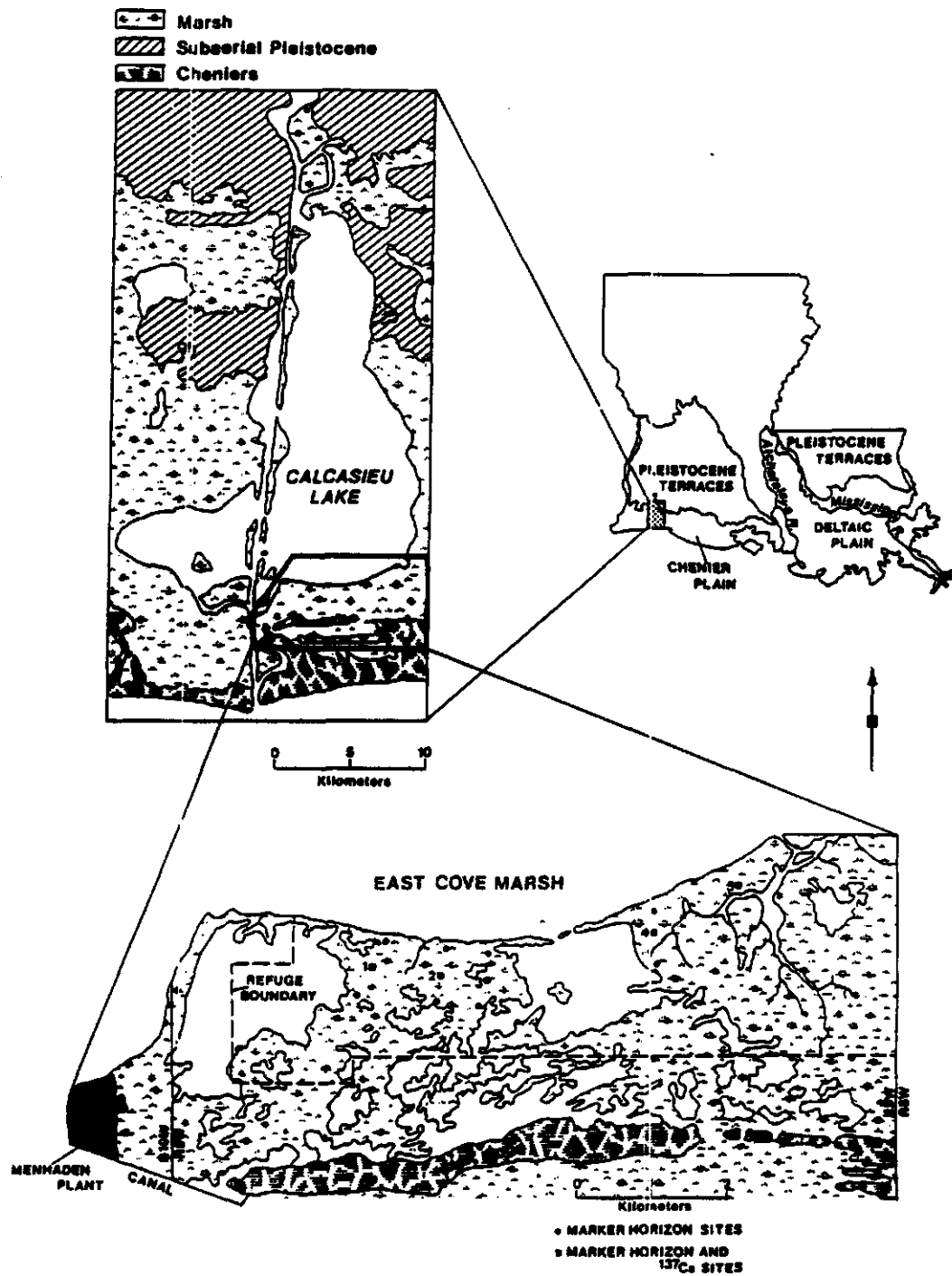▪ MARKER HORIZON AND
^{137}Cs SITES

FIG. 1.—Location and general physiography of study area.

there has been an increase in *Spartina patens* at the expense of *Scirpus olneyi*, but both species occupy the same salinity range and often coexist in the same area (Chabreck, 1972). Thus, it does not seem likely that salinities in East Cove have changed appreciably in the last 30 years.

MATERIALS AND METHODS

Five cores for ^{137}Cs dating were taken in the spring of 1978 at intervals of approximately 2 km along the southern edge of Calcasieu Lake in *Spartina patens*-dominated marshes (Fig. 1). The cores were obtained 200 m from the shoreline by twisting a thin aluminum cylinder 15 cm in diameter and 50 cm in length into the marsh soil. Compaction from sampling ranged from 2 to 3 percent. The soil cores were sectioned into 2-cm increments, dried, and ground.

[137]Cs activity in each section was determined by gamma counting of the oven-dried sample, using a lithium-drifted germanium detector and multichannel analyzer (DeLaune et al., 1978). Organic carbon was determined by dry combustion. Organic matter was estimated by multiplying carbon content by 1.724 (Wilson and Staker, 1932). Density was determined from oven-dried sediment and the known volume of each section.

Vertical accretion was determined from the ^{137}Cs distribution in the soil profile (DeLaune et al., 1978). [137]Cs is a product of nuclear-weapon testing and does not occur naturally. Significant fallout levels first appeared in 1954, with peak quantities occurring in 1963 and 1964 (Pennington et al. 1973). Tailing effects of the relatively low levels of the first few years of activity due to bioturbation by both plant roots (DeLaune et al., 1978) and meiofauna (Fisher et al., 1980) were taken into account in the manner described by Edgington and Robbins (1976) in order to prevent overestimation of aggradation rates.

The volume of soil occupied by mineral and by organic matter was determined from their weights in a known volume of soil and their densities determined by pycnometer measurements with appropriate calculations (Smith, 1943) on combusted and noncombusted soil. Particle density of the mineral fraction was 2.61 g/cc. Particle density of the organic fraction was 1.14 g/cc.

Marsh aggradation was also monitored with an artificial marker horizon. This technique augmented the ^{137}Cs analysis, as it provided short-term comparative data and enabled us to examine the effects of individual events, such as storms, on accretion. Approximately 7 kg of white feldspar clay (Feldspar 261-F, Feldspar Corp.) were distributed on each of 13 1-m[2] plots along 4 transects. On each transect, a plot was established approximately 50 m, 200 m, and 400 m inland from the shoreline. An additional plot was established on transect 3 in the bottom of a pond. Five of the plots were at the same stations as the five cores for ^{137}Cs analysis.

White feldspar clay was chosen as the artificial marker horizon in preference to four other clays, two types of brick dust, and two types of glitter after making comparison tests in the field for recognizability and in the laboratory for density. The white clay is easily differentiated from marsh sediments and, provided the organic content of the soil is less than 30 percent, maintains it position in the sedimentary column.

Artificial-marker-horizon plots were established in March 1978 and were sampled in March and September 1979, and in April, June, and October 1980. The June 1980 sampling was added to determine the effects of record rainfall and discharge. On each date a single core was taken from each marker horizon plot. Cores were obtained by pushing and twisting a metal cylinder with an inner diameter of 65 cm into the marsh surface. The resulting hole in the marsh was filled with a sample obtained a short distance away from the plot, to prevent sloughing of the remaining marker material. Samples that compacted more than 3 mm (practical limit of measurability) were discarded and the cores retaken. Cores were frozen, removed from the cylinder, and cut longitudinally. For each core, five equally spaced measurements of the distance from the top of the white clay to the new surface were made and averaged.

RESULTS AND DISCUSSIONS

[137]Cs-profile distributions in the five cores showed that the marsh has accreted vertically at an average rate of 0.78 cm yr^{-1} since 1954 (Fig. 2). All samples had higher average annual accretion rates for the 1954–1963 ($\bar{x}$ =

1.02 cm yr^{-1}) period than from 1963–1978 ($\bar{x}$ = 0.67 cm yr^{-1}), which may be a reflection of heavy deposition of fine-grained sediments in 1957 during Hurricane Audrey (Chamberlain, 1959) rather than a true change in accretion rates. Sites 2 and 3 had the lowest and highest aggradation rates respectively, a trend that was consistent during both time periods.

The mean marsh accretion rate for 10 plots for the 2.5-year period 1978–1980, measured from above the artificial marker horizon, was 0.66 ± 0.22 cm yr^{-1}, which compared closely with the longer term ^{137}Cs analysis. The mean value represents an upper limit, as three plots were eroded below the horizon and had to be omitted from the final sample analysis. The loss of the three plots was because of lateral erosion from pond enlargement rather than from degradation of the marsh surface. Prior to the final sampling these three sites were all aggrading at a somewhat higher rate than the remaining sites, perhaps indicating a streamside effect (proximity to pond edge). Streamside marshes typically aggrade at a faster rate than marshes more distant from water bodies (DeLaune et al., 1978; Letzsch and Frey, 1980).

Seasonal trends were not readily apparent. Mean accretion during two winters was slightly greater than that during the two following summers. However, the difference was not statistically significant. Virtually all of the difference was accounted for by the plots closest to the lakeshore on each of the four transects. Those plots apparently received a greater amount of sediment washed over the lake berm during winter storm activity (cold fronts) than the more inland stations, as noted elsewhere along the Louisiana coast (Baumann, 1980; Van Heerden et al., 1981).

The aggradation rates reported in this study are generally equal to or greater than the rates reported for the Atlantic Coast marshes of the United States, a summary of which is provided by Letzsch and Frey (1980), but somewhat lower than rates reported for Mississippi Deltaic Plain marshes located 240 km to the east (DeLaune et al., 1978; Evola, pers. comm.). Submergence is regarded as the primary factor accounting for the relatively high accretion rate in comparison to the Atlantic Coast. Factors such as tidal range ($\bar{x}$ = 0.6 m), tidal type (mixed diurnal), and age (~1,100 years) all favor a substantially lower rate of marsh build-

up in the East Cove marsh versus coastal marshes of the United States or Europe.

Coastal submergence as measured at the nearby Cameron tide gauge, has averaged 1.20 cm yr^{-1} since 1954 (Fig. 3A) and 1.26 cm yr^{-1} since 1963. Other gauges to the north and east exhibit similar rates (Gosselink et al. 1979), corroborating the local data. Sea level has been rising on a global basis at an average annual rate of 1.2 mm for the past century (Gornitz et al., 1982) and probably since at least the beginning of the nineteenth century (Guttenberg, 1941). Along the relatively stable western Florida coast (Shepard and Wanless, 1971) sea level has been rising 1.4 mm yr^{-1} since the early part of this century (Hicks, 1981). Thus, eustatic and steric rises in sea level comprise approximately 10 percent of the total submergence trend at Cameron, leaving subsidence as the dominant factor.

Clearly, an accretion rate of 0.8 cm yr^{-1} is not sufficient to maintain the elevation of the marsh in an area that is submerging at 1.2 cm yr^{-1}. A continual decrease in the relative elevation of the marsh with respect to water level results in the eventual conversion of marsh to an open-water body. Open water comprised 4.5 percent of the East Cove marsh in 1954 increasing to 7.5 percent by 1963. Since 1963, the open-water area has been increasing approximately by a factor of 2 every 6 years (Fig. 3B). The wetland-loss response to the "aggradation deficit" (Fig. 3C) is rapid in the East Cove marsh because the elevational range of the marsh is narrow—a function of tidal range as demonstrated by Adams (1963).

Accretion Material Composition

Density and carbon analyses of the cores used in ^{137}Cs dating showed that the marsh accretes vertically through the accumulation of both mineral sediment and organic material. The density of the marsh soil ranged from approximately 0.1 g/cc to 0.8 g/cc, depending on its organic content, which was in the range of 20 to 30 percent of the dry weight.

The organic fraction occupied a volume equal to that of the mineral fraction (Fig. 4). The organic fraction consisted mainly of fibrous and peaty plant material. Apparently this fraction is important in adding structural support. As expected, a large portion of the volume of low-density marsh soils is occupied by
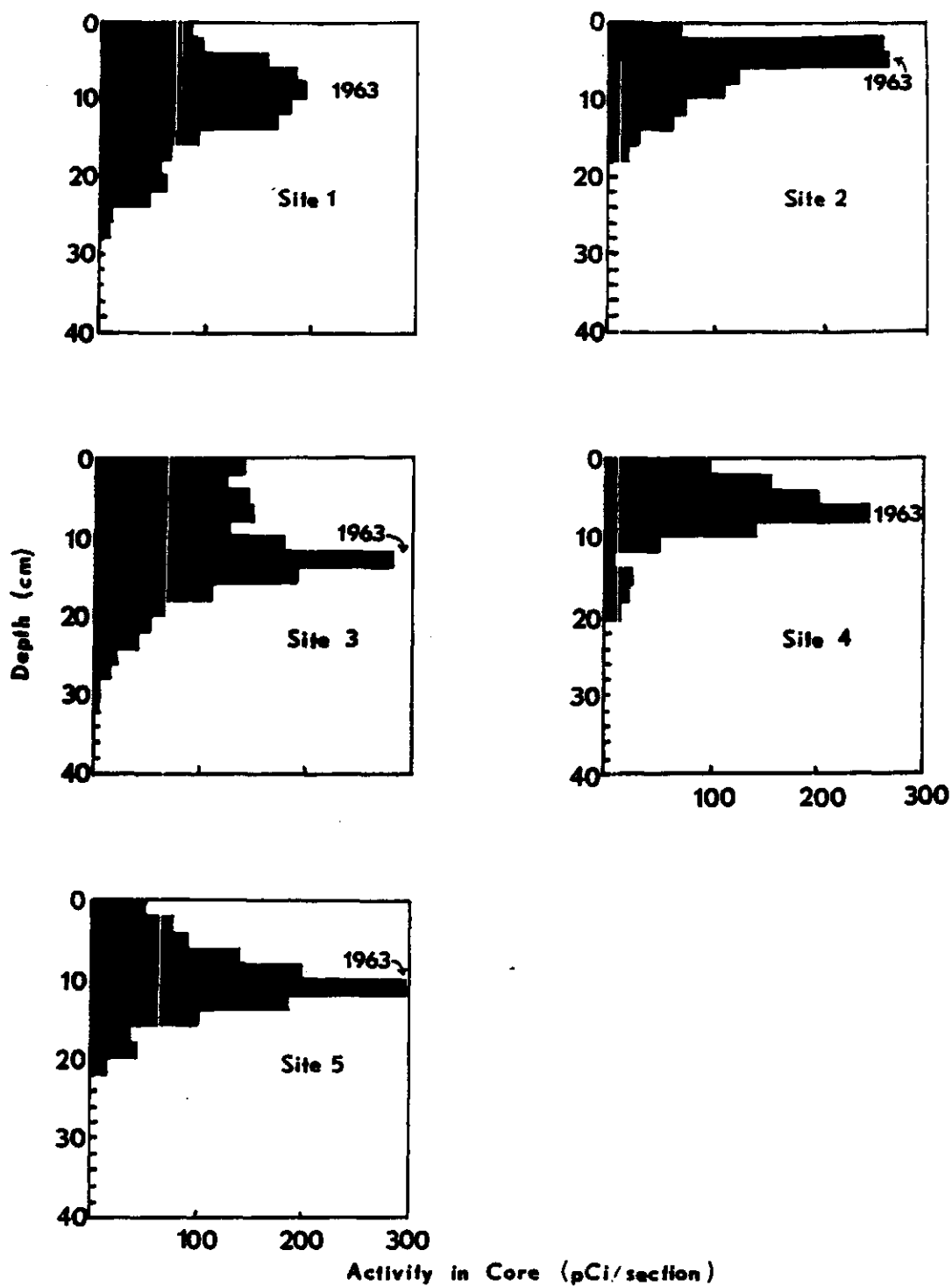
FIG. 2.—Profile distribution of ^{137}Cs for the five cores obtained. Site locations of the cores are depicted on Figure 1.
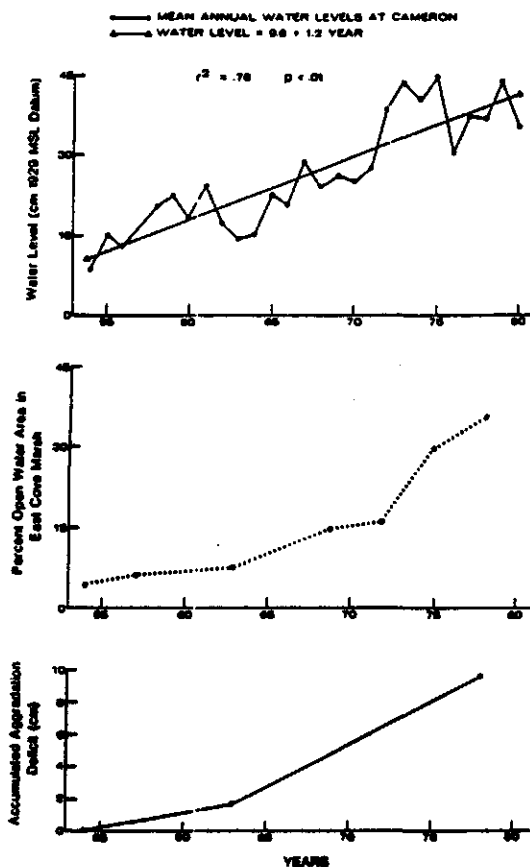
FIG. 3.—Relationships among apparent sea-level rise, wetland conversion to open water, and a calculated aggradation deficit in the East Cove marsh. Annual water levels were computed from 8 A.M. tide-gauge readings at Cameron. Open-water areas were planimetered from aerial photographs that varied in scale from approximately 1:6,000 to 1:24,000. The aggradation deficit was calculated by substracting the apparent rate of sea-level rise since 1954 at Cameron (A) from the average assumed rates of marsh accretion for the 1954–1963 and 1963–1978 periods as indicated by ^{137}Cs profile activity (see text).

water and entrapped gases.

Incoming mineral sediment has been shown to be important in marsh-building processes (DeLaune et al., 1979). In addition to its direct role in aggradation, sediment deposited on marsh surfaces by tidal inundation supplies nutrients for plant growth, which in turn enhances further sediment entrapment and stabilization. Thus, reduced sedimentation rates can indirectly affect plant growth, which is the source of organic material for the peaty marsh soil.

Sediment Source

The source of sediment for the present accretion could be entirely within the marsh system. The average bottom elevation of 40 ponds that have taken the place of marsh is 0.25 m below the marsh surface, and 30 percent of the study area has transformed from marsh to open water since 1954. If the volume of inorganic sediment lost in the transformation from marsh to open water were redistributed evenly over the remaining marsh, and the organic fraction remained constant, the present accretion rate would be twice the actual rate. This indicates a net inorganic sediment export from the marsh.

During May 1980, the Calcasieu River experienced record discharges and suspended loads (U.S. Geological Survey, 1980), resulting from the runoff of some 500 mm (375 mm in one day) of rainfall occurring May 13 through 18 (National Climatic Center, 1980). This event, however, did not affect the aggradation rate of the East Cove Marsh, as June samples did not significantly differ from the samples obtained in April. Therefore, the Calcasieu River does not seem to be a significant direct supplier of sediment to the East Cove marsh.

Long-term Versus Short-term Trend

During the past 25 years subsidence and sea-level rise have submerged the coast some 30 cm, whereas aggradation has only compensated some 19.5 cm. This trend could not have persisted too far into the past as the East Cove marsh would certainly already be part of Calcasieu Lake. The temptation to investigate possible impacts resulting from the construction and aperiodic enlargement of the Calcasieu Ship Channel is somewhat curbed when one examines longer term trends.

Based on radiocarbon dates and stratigraphic interpretations of the region (Byrne et al., 1959; Gould and McFarlan, 1959), the East Cove marsh probably had formed by 1,100 B.P., but base dates as young as 600 B.P. could be valid. Our borings indicate that the base of the marsh peat does not exceed 230 cm below the present surface and generally lies between 180 and 210 cm in depth. If one uses the youngest date and maximum peat accumulation depth, he can calculate a maximum long-term aggradation rate of 0.38 cm yr^{-1}, a

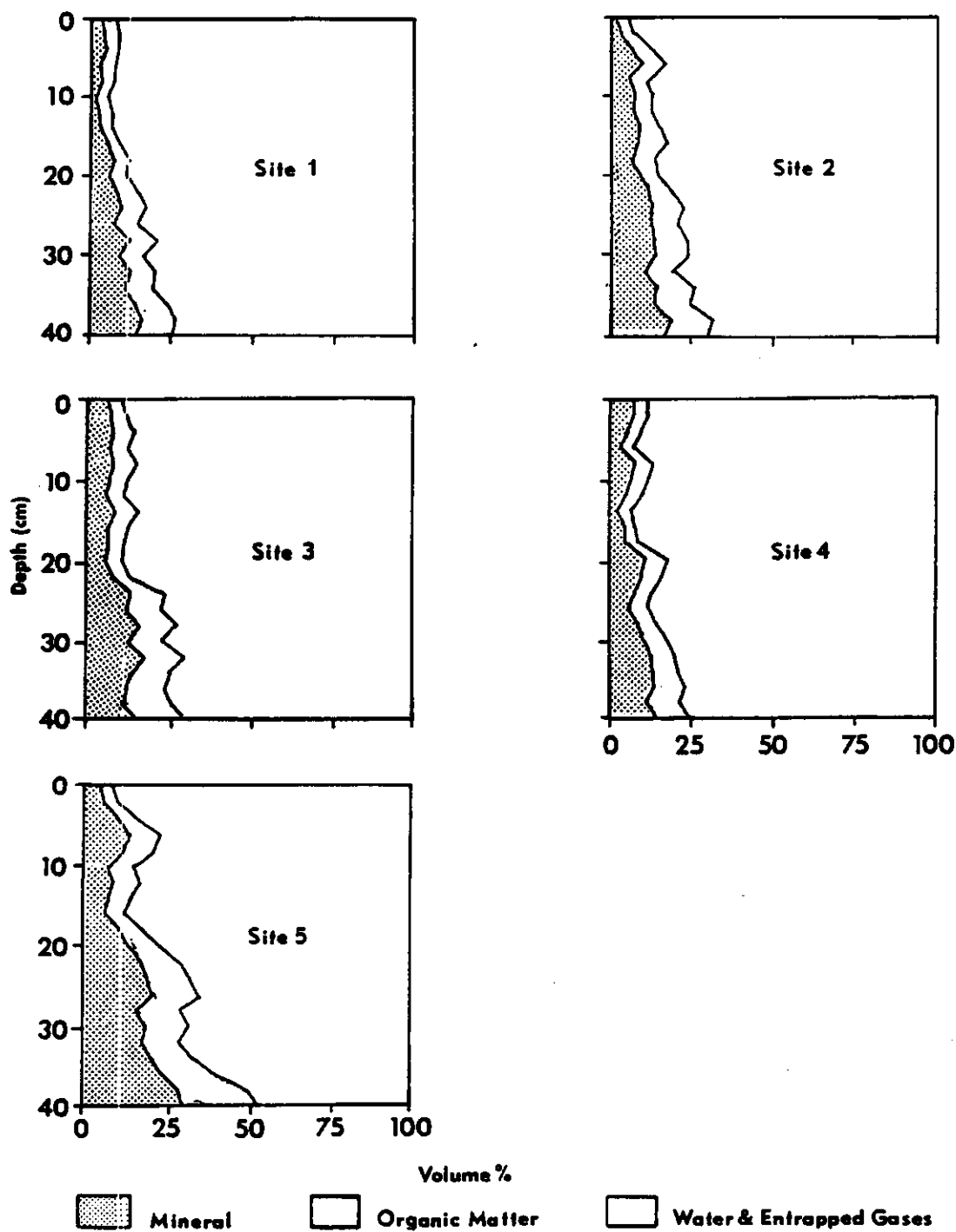R. D. DeLAUNE, R. H. BAUMANN, AND J. G. GOSSELINK

FIG. 4.—Volume components of the marsh soil profile on a dry-weight basis. Site locations are depicted on Figure 1.

value approximately half as large as the present accretion rate. Similarly, 0.16 cm yr^{-1} represents a minimum long-term aggradation rate.

Both the calculated maximum and minimum long-term aggradation rates exceed estimates of rates of late Holocene sea-level rise for the northern Gulf of Mexico (see Bloom, 1977). No long-term estimates of subsidence are known for the Chenier Plain, but in the more active neighboring Mississippi Deltaic Plain, Kolb and Van Lopik (1958) estimated an average regional subsidence rate of 14 cm/century.

Clearly, the present submergence rate of 1.2 cm yr^{-1} in the East Cove area of the Chenier Plain is substantially greater than average rates throughout the late Holocene. Whether this present trend is a short-term aberration is unknown, but it is clear that the vertical marsh accretion rate has not increased proportionately and the effects (loss of marsh) will remain, even if an aggradation-submergence balance were to return.

SUMMARY AND CONCLUSIONS

The inability of the East Cove marsh to keep pace with coastal submergence through vertical accretion is a recent phenomena. Apparent increases in the subsidence rate have not been fully compensated for by increases in the aggradation rate of the marsh. The resulting aggradation deficit is catalyzing the conversion of marsh to an open bay-lake environment. If the trends over the past 25 years continue, the East Cove marsh will complete its transformation to open water in less than 40 years. The general concept that subsidence and sea-level rise have an "enhancing" effect on aggradation rates (Letzsch and Frey, 1980) has finite limits.

The present submergence rate of 1.2 cm yr^{-1} is substantially greater than the average rates throughout the late Holocene. It is tempting to equate the recent changes in geomorphic processes with human activities in the region, particularly the construction of the Calcasieu Ship Channel, leading to salt intrusion and possible sediment diversion and to subsurface oil, gas, and groundwater withdrawals resulting in a possible acceleration of subsidence.

Two points need to be made about this pos-

sibility. First, although rates of geomorphic processes may have changed because of recent human activity, the basic mechanisms we have tried to elucidate remain the same—that is, marsh conversion to open water along this flat coastline is directly related to the balance between submergence and vertical marsh accretion.

Second, in the specific case of East Cove it is difficult to document the human component precisely because it is so pervasive and at least some of the expected effects are contrary to observed trends.

The Lake Calcasieu area has experienced large subsurface withdrawals of both fuels and water. The latter is the more probable cause of subsidence because the aquifer is relatively shallow, but the rapid submergence rates are typical for a large segment of the Louisiana coast, even though aquifer drawdown is a rather localized phenomenon (Gosselink et al., 1979).

Modifications of the natural freshwater flow through Lake Calcasieu could influence submergence by allowing salt intrusion which kills plants, decreasing their sediment stabilizing qualities, or by diverting inorganic sediments away from the marshes. We have seen no evidence of toxic-salinity effects on marsh vegetation. The East Cove Marsh is dominated by *Spartina patens*, and salinities are well within the range of its tolerance. Sediment diversion down the Ship Channel would decrease sediment supplies to East Cove. The lower rate of accretion for 1963 to the present than for 1954–1963 supports this hypothesis; however, the accretion rates since 1954 are higher than the average rate throughout the Holocene, and the relatively high 1954–1963 rate may be explained by Hurricane Audrey, as Baumann (1980) has found high marsh accretion rates associated with major storms elsewhere on the Louisiana coast. Clearly, human impacts are pervasive and additional studies are needed to isolate specific processes and clarify their magnitudes.

If sea-level rise is on the brink of accelerating due to the projected in-phase effects of atmospheric CO_2 increase (Hansen et al., 1981) and a return to a warming phase of natural climatic cycles (Broecker, 1975), the finite limits of marsh aggradation rates may be reached over a much greater geographic area.

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5. Sedimentation, Accretion, and Subsidence in Marshes of Barataria Basin, Louisiana

by

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Sedimentation, accretion, and subsidence in marshes of Barataria Basin, Louisiana[1]

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Abstract

Vertical accretion and sediment accumulation rates were determined from the distribution of ^{137}Cs in cores collected from freshwater, intermediate, brackish, and salt marshes in the Barataria Basin, Louisiana. Vertical accretion rates vary from about 1.3 cm·yr^{-1} in levee areas to 0.7 in backmarshes. Mineral sediment content of the marsh soil profile decreased with distance from the coast. However, vertical accretion rates were about equivalent in areas of the same type. Autochthonous organic matter appears to be an important factor defining the process and rate of vertical accretion, especially in the freshwater marshes. Except in natural levee areas, marsh accretion rates are less than subsidence measured by water level data, however this alone cannot account for observed land-loss patterns in the basin area.

In coastal marshes the substrate surface must remain adjusted relative to mean sea level in order for plants to survive. This stable equilibrium level is maintained as a balance between the rate of vertical accretion and changes in relative sea level. Land loss and marine transgression may generally be anticipated where aggradation is less than the relative rise in sea level.

Marshes in south Louisiana span some 3.2×10^6 ha, representing 41% of all wetlands in the United States (Turner and Gosselink 1975). With rapid subsidence and accelerating land loss in the area, a critical examination of natural land-building processes is of academic, managerial, and political interest. Salt marsh accretion rates reported (DeLaune et al. 1978; Baumann 1980) indicate that accretion is less than the rise in estimated sea level (Swanson and Thurlow 1973), except in natural levee areas. This result, which is consistent with the ongoing submergence of marshlands in south Louisiana, has been attributed to a deficiency in fluvial sediment influx into many relict deltaic marshes. Accretionary processes in adjoining but physiographically distinct, brackish, intermediate, and freshwater marshes of the Mississippi River

Delta have not been adequately examined: Baumann (1980) found that visual particulate tracers (white feldspar clay) were not suitable for use in these low density substrates.

We here report rates of vertical marsh accretion and sediment accumulation calculated from ^{137}Cs profiles in freshwater, intermediate, brackish, and salt marsh soils of Barataria Basin, a delta-flank depression of the Mississippi River. Accretionary variations are discussed in relation to hydrology, sedimentation, subsidence, and vegetation with a view to further elucidation of the accretionary mechanism in marshes of each type.

Physiographic setting

Because an understanding of the cyclic nature of the Mississippi River Delta sedimentation is essential to the correct interpretation of our results, we review briefly the salient features of this deltaic system with specific reference to the study area. A detailed geologic description is given by Coleman and Gagliano (1964); vegetative characteristics have been described by Bahr and Hebrard (1976).

The coastal marshlands of south Louisiana comprise a series of recognizable physiographic units, uniquely defined by depositional history, hydrology, and vegetative distribution. Mississippi fluvial deposits form an extensive, seaward-

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thickening sequence of overlapping and contemporaneous delta lobes resulting from the process of primary channel switching at intervals of about 1,000 years (Frazier 1967). Periods of seaward progradation and fluvial dominance have alternated locally with periods of land loss and marine transgression. Rapid subsidence continues as a result of the concomitant processes of crustal downwarping caused by the sediment overburden, consolidation of the sediments of the Gulf Coast geosyncline, local consolidation, and tectonic activity; regional subsidence decreases with distance inland. Rates of subsidence and shoreline alteration generally diminish with increasing age of the delta lobe.

The modern deltaic system is partitioned by active and relict distributary channels bounding the lower interdistributary wetland basins which vary in age and state of deltaic alteration. Barataria Basin (Fig. 1) is the youngest such "interfluvial" entity, bounded by the present course of the Mississippi River, and its most recently abandoned channel to the west, Bayou Lafourche. Historically, spring overbank floods have maintained a supply of fluvial sediments to the interdistributary marshes, adding nutrients and contributing structurally to their stability. But progressive channelization of the Mississippi River over the past century for flood control purposes has prematurely terminated the fluvial phase of the basin's development. Secondary landward redistribution of earlier deltaic, marine, marsh, and bay sediments by tides, waves, and wind-induced water movements has replaced fluvial sources of inorganic sediments reaching the marsh surface. Hydraulic energy now decreases with distance from the Gulf of Mexico. Hydrologic alterations such as canals are believed to be responsible for accelerating the natural process of marsh deterioration during local interfluvial periods, resulting in a net loss of land along the historically advancing Louisiana coastline.

Kolb and Van Lopik (1966) recognized three major sedimentary marsh types which are generally correlated with hy-

drology, salinity, and distribution of vegetation. Freshwater floating marsh (or flotant) substrates comprise an extremely fibrous mat of roots and other plant remains admixed with a fine muck 0.1–0.35 m thick and underlain by 1–5 m of organic ooze that grades with depth to steel gray clay. Brackish-intermediate marsh soils comprise a vegetative mat with muck 0.1–0.2 m thick overlying 0.3–3.1 m of fibrous peat, underlain in turn by a blue-gray clay or silty clay containing lenses rich in organic matter. Saline to brackish marshes consist of a vegetative mat and muck 0.1–0.2 m thick underlain by 0.3–3.1 m of fibrous peat on a firm, blue-gray or black, coarse, silty clay. The seaward sequence from freshwater to salt marshes is characterized by an increase in grain size.

The four principal vegetative units examined in the present study have been described in detail by Bahr and Hebrard (1976) and are represented in Fig. 1. Freshwater marshes (salinity < 1‰), which cover roughly 19% of the basin, are characterized by dense stands of *Panicum hemitomon, Eleocharis* sp. and *Sagittaria falcata*. About 20% of the basin is termed brackish to intermediate marsh: the brackish system (salinity 5–10‰) is largely vegetated by *Spartina patens* with lesser amounts of *Distichlis spicata* and occasional intrusions of *Spartina alterniflora*. This predominance of *S. patens* increases into the intermediate marsh (salinity 10–15‰) where *S. alterniflora* is totally absent. Salt marsh vegetation covers some 14% of the basin and is widely interspersed with open water bodies; *Juncus romerianus* and *D. spicata* are secondary to *S. alterniflora* which represents about 60% of cover and up to 95% locally.

Methods

Representative sites in freshwater, intermediate, brackish, and salt marshes of the basin were selected on the basis of vegetation type, soil morphology, and hydrology. Ten cores were taken at known intervals on lateral transects from the stream or lake banks at each marsh type.
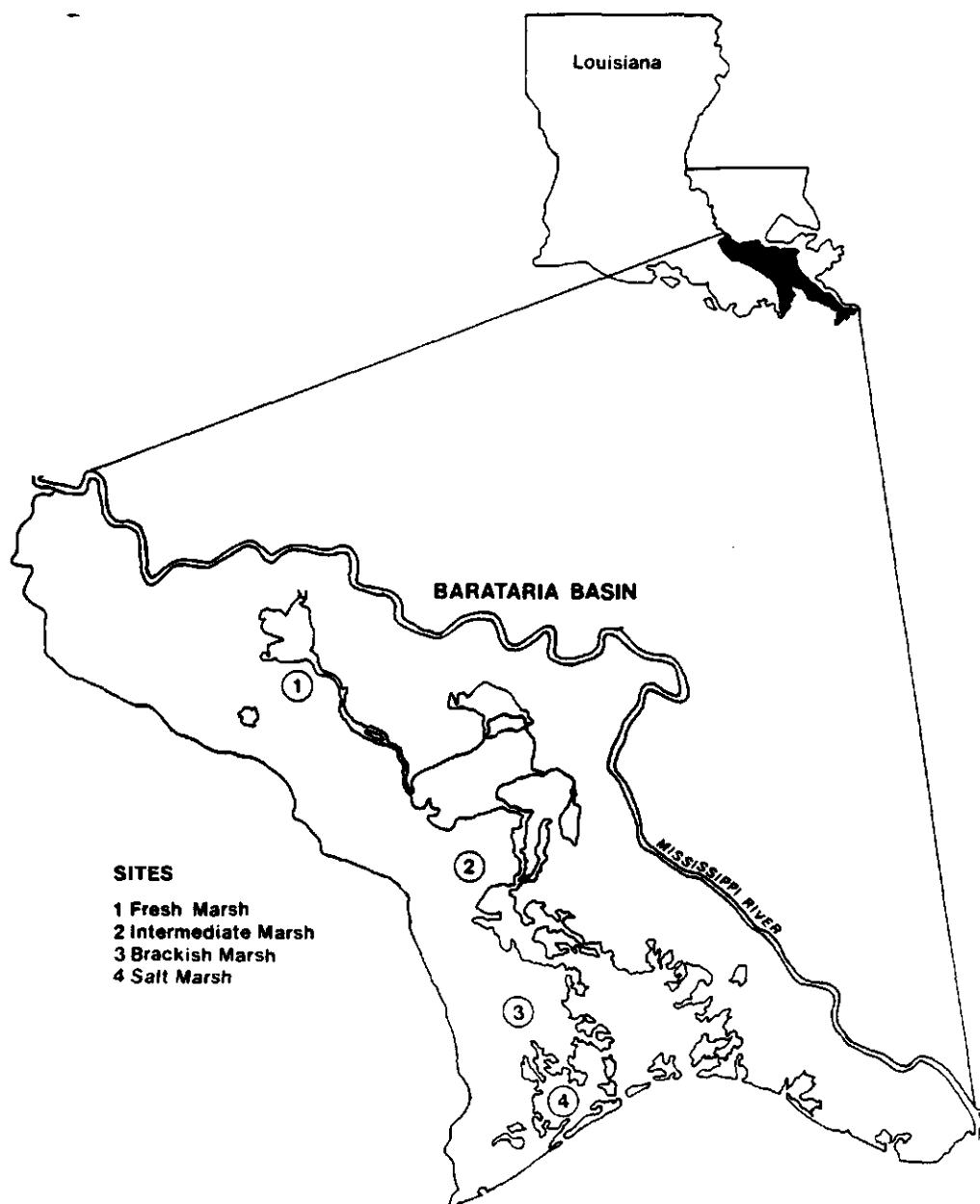
Fig. 1.   Map of Barataria Basin showing delineation of marsh types (after Bahr and Hebrard 1976) and location of study sites.

Due to the exceptionally low density and high water content of these soils, special procedures were necessary to prevent compaction either through direct compression or water loss. Broad (15 cm) diameter, thin-walled (0.2 cm) aluminum coreliners with a sharpened cutting edge were carefully twisted into the substrate to a depth of 50 cm. Cores were capped in situ before being raised to the surface
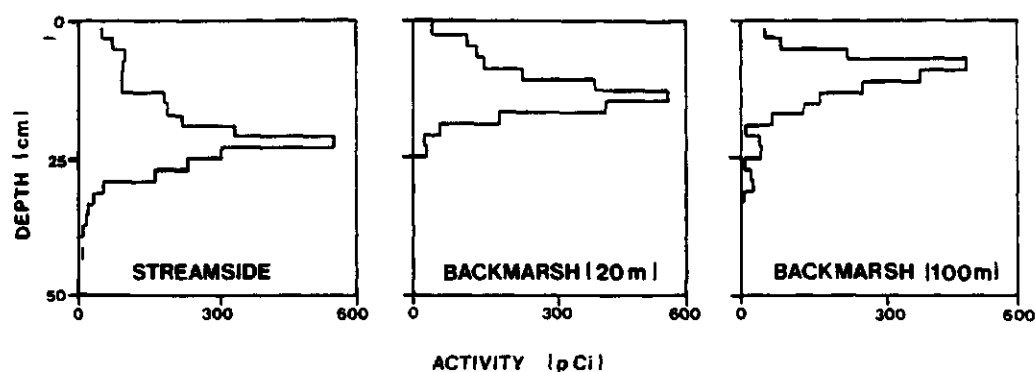
Fig. 2. ^{137}Cs profiles from the intermediate marsh illustrating levee effect. Values in parentheses indicate distance in meters from adjacent body of water.

and sealed with especially designed PVC caps and nylon straps. Entire cores were frozen and accurately sectioned into 2-cm horizontal subsamples with a bandsaw, allowing for blade thickness; freezing did not significantly alter the vertical distribution of sedimentary solids. Subsamples were weighed wet and again after drying to constant weight at 100°C. Bulk density was calculated from the dry weight and uniform sample volume.

^{137}Cs activity profiles were determined with an Ortec (model 8011-1620-S) coaxial, lithium-drifted germanium detector coupled to a multichannel analyzer (model 6240B). Entire sections were counted for a variable period determined statistically by the ^{137}Cs activity, but not exceeding 2×10^4 s. Vertical marsh accretion rates were computed directly from the depth of burial corresponding to 1963, the year of maximum ^{137}Cs fallout (De- Laune et al. 1978).

Selected cores were analyzed for organic carbon content; composite homogenized subsamples from alternate 2-cm intervals (0–2, 4–6, . . . , etc.) to a depth of 38 cm were analyzed by dry combus-

Table 1. Vertical accretion rates (*R*, mm·yr^{-1}), organic matter, and inorganic sediment data for marshes of Barataria Basin.

	R		Soil bulk density (g·cm^{-3})	Organic matter			Inorganic sediments			Mean ^{137}Cs activity (pCi·g^{-1})
Site*	Mean	Range		Dry wt (%)	Bulk density (g·cm^{-3})	A†	Dry wt (%)	Bulk density (g·cm^{-3})	A†	
Freshwater										
L	10.6	—	0.11 ± 0.03	41 ± 7	0.045	477	59	0.065	689	4.7
B	6.5	3.1–6.9	0.09 ± 0.01	52 ± 6	0.047	306	48	0.043	280	
Intermediate										
L	13.5	13.0–14.0	0.18 ± 0.04	33 ± 6	0.059	797	67	0.121	1,634	3.5
B	6.4	3.8–10.6	0.08 ± 0.01	52 ± 4	0.042	269	48	0.038	243	
Brackish										
L	14.0	10.6–16.9	0.27 ± 0.02	22 ± 3	0.059	826	78	0.211	2,954	1.3
B	5.9	3.8–8.1	0.14 ± 0.01	42 ± 3	0.059	348	58	0.081	478	
Salt										
L‡	13.5	—	0.35	20	0.050	675	80	0.200	2,700	0.9
B	7.5	5.9–9.4	0.29 ± 0.06	20 ± 3	0.058	435	80	0.232	1,740	

* L—Levee; B—backmarsh.
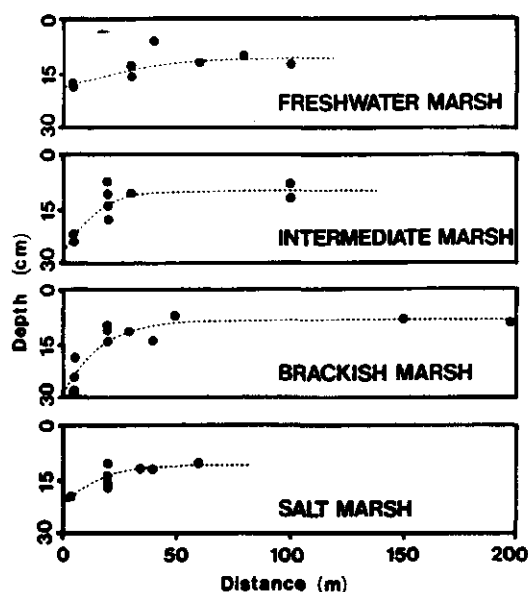† Accumulation rate (g·m^{-2}·yr^{-1}).
‡ From DeLaune et al. 1981.

Fig. 3. Projected ^{137}Cs horizons in marsh soils illustrating limited lateral extent of levee. Individual core samples—●.

Fig. 4. Variation of (a) bulk density and (b) sedimentation with marsh type. L—Levee; M—backmarsh; —●— —data from DeLaune et al. 1981. F—Freshwater; I—intermediate; B—brackish; S—salt.

tion. Organic matter content was calculated from the organic carbon value determined by dry combustion in a carbon train, using the multiplier of 1.724 derived by Wilson and Staker (1932).

The rate of accumulation (A, $g \cdot m^{-2} \cdot yr^{-1}$) of mineral and organic sediments was calculated from dry weight percentages (C_d) and the vertical accretion rate (R, $cm \cdot yr^{-1}$) using the formula

$$A = C_d \times R \times D \times 10^2 \ (g \cdot m^{-2} \cdot yr^{-1})$$

(where D is total sediment bulk density).

Results

^{137}Cs activity profiles showed, with few exceptions, extremely well defined 1963 maxima (Fig. 2). Circumstantial evidence suggests that physical disturbance of the vegetated marsh surface is negligible except in established animal (*Nutrea nutrea*) paths which were not sampled. Occasional disturbance by burrowing crabs was observed only in streamside areas of brackish and salt marshes.

Vertical accretion rates (Table 1) cal-

culated from 1963 ^{137}Cs activity maxima indicate that marsh accretion is an ongoing, but typically variable process in freshwater, intermediate, brackish, and salt marshes of the basin. Rates of vertical growth ranged from a maximum of 1.7 cm · yr^{-1} in streamside or natural levee deposits to as little as 0.31 in selected backmarsh areas; mean values were 1.3 and 0.7 cm · yr^{-1} in levee and adjacent backmarsh areas. Approximately similar accretion rates were identified in analogous areas of freshwater, intermediate, brackish, and salt marsh types (Table 1), within the limit of error of the determination.

Lateral transects from stream or lake banks consistently indicate the more rapid aggradation of levees than of backmarsh areas. The burial depth of the 1963 horizon (Fig. 3) attains a maximum at or near the waters edge, declining rapidly as the distance "inland" to attain a rela-

Table 2. Summary of available marsh accretion (R) data from North American Atlantic seaboard.

	Marsh type	R	Mean sea level rise	Method[*]	Source
		(mm·yr⁻¹)	(mm·yr⁻¹)		
Mass.	S. alterniflora	18.3 (1.5–51.8)	3.4	S	Redfield 1972
Conn.	S. alterniflora	8–10	2.5	P	Bloom (cited in Richard 1978)
Conn.	S. patens	2–5	2.5	P	Harrison and Bloom 1974
N.Y.	S. alterniflora	4.0	2.9	²¹⁰Pb	Muzyka 1976
N.Y.	S. alterniflora	4.7–6.3	2.9	²¹⁰Pb	Armentano and Woodwell 1975
N.Y.	S. alterniflora	2.0–4.2	2.9	P	Richard 1978
N.Y.	S. alterniflora	2.5	2.9	H	Flessa et al. 1977
Del.	S. alterniflora	5.1–6.3	3.8	P	Stearns and McCreary 1957
Del.	S. alterniflora (short)	5.0	3.8	²¹⁰Pb	Lord 1980
Ga.	S. alterniflora	3–5		¹³⁷Cs	Hopkinson pers. comm.
La.	S. alterniflora (Deltaic Plain)				
	i) streamside	13.5	9.2	¹³⁷Cs	DeLaune et al. 1978
	ii) inland	7.5	9.2	¹³⁷Cs	
La.	S. alterniflora (Chenier Plain)	4.7 (4.4–8.2)	9.2	¹³⁷Cs	DeLaune unpubl.
La.	S. alterniflora (Deltaic Plain)				
	i) streamside	15.2	9.2	P	Baumann 1980
	ii) inland	9.1			

[*] S—Stratigraphy; P—visual particulate, H—historic record.

tively uniform level at distances·≥40 m. Lateral variation is least apparent in the flotant freshwater marsh and most well defined in the brackish marsh.

Total soil bulk density showed a primary dependence on mineral sediment bulk density which decreased inland from the Gulf Coast; highest values occurred in the levee deposits (Fig. 4a). Organic carbon, by contrast, constituted an approximately constant mass in all soils. Inorganic sedimentation is therefore the principal determinant of variations in bulk density in this marsh system. Rates of mineral sediment and accumulation generally increased seaward from freshwater marshes toward the salt marshes, again with higher rates adjacent to natural bodies of water than in the distal backmarshes (Fig. 4b); organic carbon accumulation

rates showed similar local variation but regional differences were not significant.

Discussion

The freshwater, intermediate, brackish, and salt marsh accretion rates measured here approximate values reported previously from salt marshes in the basin (DeLaune et al. 1978; Baumann 1980). Together these studies are consistent in showing the relatively rapid accretion of Louisiana marshes as compared to those of the U.S. Atlantic Coast, some of which are listed in Table 2. This result is probably indicative of the relatively rapid subsidence of south Louisiana.

Local variations in accretion rate from levee to backmarsh areas have been documented in salt marshes by several investigators, including Redfield (1972),

Table 3.   Data for comparison of annual aboveground production with organic matter accumulating in brackish and salt marshes. Accumulation rates $(A, g \cdot m^{-2} \cdot yr^{-1})$ are expressed as a percentage equivalence $(E\%)$ of the annual aerial production (AP) calculated from peak standing crop (PSC, $g \cdot m^{-2}$) measurements from this study, and the ratio AP*:PSC* from Hopkinson et al. (1978) and White et al. (1978): $E\% = A \div PSC \times AP^*:PSC^* \times 10^2$.

Marsh type	PSC	A	AP*:PSC*		E%	
			Hopkinson	White	Hopkinson	White
Brackish	2,508	348	2.5	0.79	6	17
Salt	1,648	435	1.7	2.23	16	23

DeLaune et al. (1978), and Baumann (1980). Our data further illustrate the lateral and vertical expression of natural levee deposition in four distinct marsh types. Except in the freshwater marsh, the projected slope of the ^137Cs horizon declined sharply with distance from the streambank, attaining a relatively constant value at distances >40 m. The faster aggradation in the proximity of natural bodies of water forming levees is generally attributed to lateral hydraulic and associated inorganic sedimentation gradients extending from the streambank (Frey and Basan 1978). The observed distribution of mineral sediments (Fig. 4b) is consistent with this hypothesis. The relative uniformity of freshwater marsh accretion rates conforms to the lateral uniformity in mineral sediment distribution (Fig. 4a), which itself appears to result from the continuing erosion of the lake shoreline sampled.

The regional uniformity in vertical accretion rate of spatially predominant backmarshes is somewhat paradoxical in view of the apparent local relationship between inorganic sedimentation and accretion (Fig. 3) and the fact that the regional inorganic sedimentation gradient exceeds that expressed locally in each marsh type (Fig. 4). Inorganic sediment is thus clearly not the sole or principal determinant of the vertical growth rate of these marshes. By necessity, therefore, soil organic matter must be invoked as the controlling factor. Evidence to support this hypothesis includes the volumetric constancy of soil organic matter content (organic matter bulk density) shown in Fig. 4a and the structural role and buoyancy of macroorganic matter im-

mediately apparent on examination of these substrates. Especially in less saline systems, inorganic particles are clearly interstitial constituents of a primarily organic matrix; organic matter may comprise >50% of the dry weight of these soils (Table 2). These results support McCaffrey's (1977) concept of a "vegetative growth mechanism" whereby marshes deficient in inorganic sediments accrete as a result of plant growth in response to changing water level. The same concept is consistent with the levee effect, in that plant production is greatest in hydrologically dynamic streamside areas which would act synergistically with lateral hydraulic or depositional gradients to increase the aggradation rate locally. Interpretation of these data, however, is complicated by vegetative and hydraulic gradients which parallel the regional sedimentation gradient. Whereas organic materials clearly dominate freshwater marsh soils, the relative role and thus the necessity of the inorganic fraction appear to increase as the hydraulic energy increases seaward in the basin.

The species-specific response of marsh plants to inorganic sediment deficiency and their natural productivity are inadequately understood to assess fully their role in the accretionary process or how this varies from one marsh type to another. Calculations based on clip-plot production measurements made in our study and previous production data from Louisiana (Hopkinson et al. 1978; White et al. 1978), summarized in Table 3, suggest that organic matter equivalent to 6–23% of aerial production accumulates in brackish and salt marshes. However accumulated organic matter appeared to be primarily

root material, the production of which is not documented for the Louisiana marshes.

DeLaune et al. (1978) and Baumann (1980) have observed that except in natural levees, salt marshes in Barataria Basin have shown an accretionary deficit with respect to post-1959 rise in sea level. Figure 5 shows that the same is generally true of less saline marshes in the basin. If we assume a worldwide eustatic rise in sea level of 0.12 cm·yr⁻¹ (Gutenberg 1941; Swanson and Thurlow 1973; Belknap and Kraft 1977), the relative rise in the basin can be largely ascribed to subsidence, which is therefore estimated to be of the order of 1.0–1.2 cm·yr⁻¹. The current accretionary deficit responsible for the continuing loss of marshlands in the area is generally attributed to increased subsidence. However, channelization resulting in saline intrusion is also increasingly being implicated as accelerating the natural rate of marine transgression. It is also conceivable that, at least in the geologic short term, floating marshes may persist independently of the subsiding basement so that an accretionary deficit need not be an immediate result in land submergence.

¹³⁷Cs dating has been successfully applied to geochronological investigations of lacustrine (Pennington et al. 1973) and salt marsh environments (DeLaune et al. 1978). The technique is subject to the constraint that sedimentary ¹³⁷Cs profiles accurately reflect the yearly fallout pattern. With one exception (Alberts and Muller 1979), available data indicate that this element is not subject to significant postdepositional remobilization even under reduced conditions and in a variety of sediments (Eyman and Kevern 1975; Gardner and Skulberg 1964; Tamura 1964). Supportive evidence from our study and previous studies in the basin includes a well defined 1963 ¹³⁷Cs maximum in most of the profiles examined and the close agreement between salt marsh accretion rates reported here and independent estimates based on a visual particulate method (Baumann 1980). Field observations suggest that bioturbation by macrofauna is not significant.
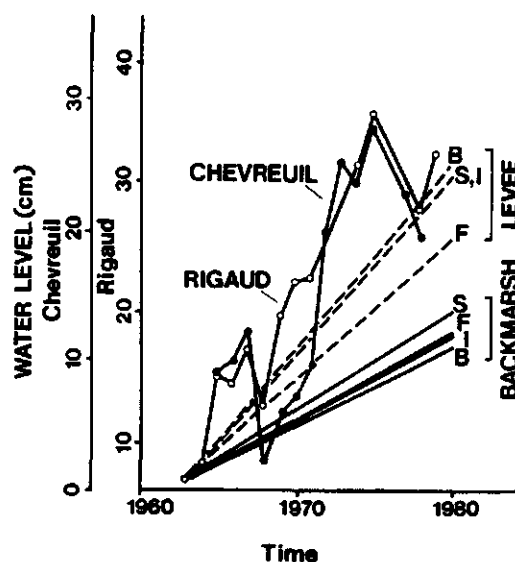
Fig. 5. Water level rise in Barataria Basin for 1963–1980 (from Baumann 1980) and marsh accretion projected from mean accretion rates in Table 2. Gauging stations at Chevreuil and Rigaud near freshwater and salt marsh sites indicated in Fig. 1.

Conclusions

Despite extensive loss of marshlands in the area, vertical marsh accretion is a rapidly continuing process in freshwater, intermediate, brackish, and salt marshes in the Barataria Basin. In general, accretion rates of levee marshes seem to be keeping pace with subsidence as measured by water level data. However, the spatially predominant backmarsh areas are accreting at about half the regional subsidence rate, a result which is consistent with continuing land loss by submergence. Substrate buoyancy may contribute to the persistence of marshes experiencing such an accretionary deficit in the geologic short term. Whereas the accretionary process is conventionally attributed largely to inorganic sedimentation, the regional independence of measured accretion rates from the inorganic sediment supply is testimony to the accretionary role of organic matter in this low-energy system, which is poor in inorganic sediments. However the structural necessity for inorganic particles seems to increase with increased hydraulic energy toward the

Gulf Coast. The production and accumulation of autochthonous organic matter, and its controls and consequences, deserve greater emphasis in considerations of the mechanism of marsh accretion, particularly in view of the accelerating marshland deterioration in south Louisiana. Management practices such as burning and channelization with salt water intrusion, which may retard the production and accumulation of organic matter, thus have serious consequences for marsh accretion and land loss.

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6. Sedimentation, Nutrient Accumulation, and Early Diagenesis in Louisiana Barataria Basin Coastal Marshes

by

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SEDIMENTATION, NUTRIENT ACCUMULATION, AND EARLY DIAGENESIS IN LOUISIANA BARATARIA BASIN COASTAL MARSHES

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Abstract: Vertical marsh accretion, along with sediment and nutrient accumulation, were examined using ^{137}Cs dating and chemical analysis of soil cores taken from various marshes in Louisiana's Barataria Basin. Vertical accretion averaged 1.3 cm yr^{-1} and 0.7 cm yr^{-1} in levee and backmarsh areas respectively. Inorganic sedimentation increased fourfold from freshwater through salt marshes along a transect perpendicular to the Gulf Coast. The accretionary role of inorganic sediments is variable according to marsh type. Mineral sediment being deposited in the marsh is the principle source of iron, manganese, and phosphorus, but not of organic carbon or nitrogen. Manganese and phosphorus appear to be subject to substantial post-depositional remobilization.

Introduction

The controls and consequences of material exchange between salt marshes and estuarine waters have been the subject of considerable interest in recent years. The flux of sediments and associated nutrients to the marsh surface from estuarine waters is an important determinant of fertility and macrophyte production (DeLaune et al. 1979). But marshes themselves appear to perform concurrently as a source of biologically accessible nutrients released from inorganic sediments by virtue of chemical and biochemical transformations below the marsh surface (Nixon 1980). Evidence of this aspect of the accretionary development (Letzsch and Frey 1980) and early diagenesis of marsh soils (McCaffrey 1977; Lord 1980; DeLaune et al. 1981) is limited primarily to saline marshes. The biogeochemical consequences of depositional and other physical processes which distinguish the spatially predominant brackish, intermediate, and freshwater marshes have been the subject of only limited study (Kolb and Van Lopik 1966; Chabreck 1972). Our purpose is to discuss vertical accretion, nutrient accumulation, and early diagenesis in each of four marsh types in the Barataria Basin, Louisiana.

Setting

The unique physiography of Louisiana marshlands is a direct result of

the cyclic nature of deltaic sedimentation of the Mississippi River. Due to the process of primary channel switching, periods of fluvial dominance have alternated locally with periods of land loss and marine transgression (Coleman and Gagliano 1964), giving rise to a seaward thickening sequence of overlapping and contemporaneous delta lobes. The modern deltaic plain is thus characterized superficially by a series of interdistributary wetland basins of varying age which are separated by active and relict distributary channels. Barataria Basin is the youngest such interdistributary basin, bounded by the present course of the Mississippi River and by its most recently abandoned channel to the west, Bayou Lafourche (Fig. 1).

Historically, flooding during high river stage has maintained a supply of fluvial sediments to the interdistributary marshes, contributing structurally and chemically to their stability. Progressive channelization of the Mississippi River over the past century for flood control has prematurely terminated the fluvial phase of the Basin's development. Secondary landward redistribution of earlier deltaic, marine, marsh and bay sediments by tides, waves, and wind-induced water movements has replaced fluvial sources of inorganic sediments reaching the marsh surface. Hydraulic energy decreases with distance from the Gulf of Mexico (Byrne et al. 1976). Together with improper land use practices, such hydrologic alterations are generally believed to be responsible for accelerating the natural process of marsh deterioration during local interfluvial periods, resulting in a net loss of land along the historically advancing Louisiana coastline.

The four principal vegetative units we examined in Barataria Basin have been described in detail by Bahr and Hebrard (1976) (Fig. 1). Freshwater marshes (salinity $<1^o/_{oo}$) which cover roughly 19% of the basin, are characterized by dense stands of Panicum hemitomon, Eleocharis sp. and
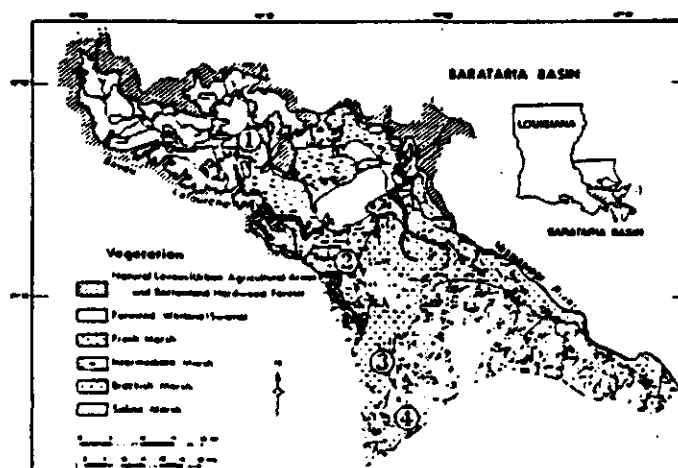

Figure 1. Barataria Basin, its location in Louisiana, vegetation distribution, and location of study sites. (Nos. 1-4).

Sagittaria falcata. Approximately 20% of the basin is termed brackish to intermediate marsh: the brackish system $(5-10°/oo)$ is largely vegetated by *Spartina patens* with lesser amounts of *Distichlis spicata* and occasional intrusions of *S. alterniflora.* This predominance of *S. patens* increases into the intermediate marsh $(10-15°/oo)$ where *S. alterniflora* is totally absent. Salt marsh vegetation covers some 14% of the basin, and is widely interspersed with open water bodies: *Juncus romerianus* and *Distichlis spicata* are secondary to *S. alterniflora* which represents approximately 60% of cover, and up to 95% locally.

Methods

Representative sites in each marsh type were selected on the basis of vegetation type, soil morphology, and hydrology. Cores for determination of vertical accretion rates were taken at known intervals laterally from the stream banks. Large diameter (15 cm), thin walled (0.2 cm) aluminum coreliners with a sharpened cutting edge were carefully twisted into the substrate to z depth of 50 cm. Cores were capped *in situ* before being raised to the surface, and sealed using specially designed PVC caps and PVC nylon straps. Entire cores were frozen and accurately sectioned into 2 cm horizontal subsamples using a band saw, allowing for blade thickness; freezing did not alter significantly the vertical disposition of sedimentary solids. Samples were weighed wet, and again after drying to constant weight at $100°C$. Bulk density was calculated from dry weight of each section of known volume.

Activity profiles of ^{137}Cs were determined using an Ortec (model 8011-1620-S) coaxial, lithium-drifted germanium detector coupled to a (model 6240B) multichannel analyzer. Entire sections were counted for a variable time period determined statistically by ^{137}Cs activity, but not exceeding 2×10^4 sec. Vertical marsh accretion rates were computed directly from depth of burial of the dated (1963) ^{137}Cs activity maximum (DeLaune et al. 1978).

Selected cores were analyzed for total organic carbon (TOC), Kjeldahl nitrogen, and total phosphorus, iron, and manganese as outlined by DeLaune et al. (1981). Organic carbon was determined by dry combustion and organic matter calculated from this value using a multiplier of 1.724 (Wilson and Staker 1932). Kjeldahl nitrogen content of accurately weighed 2-3 g samples was determined by the method of Bremner (1965). Total phosphorus, iron and manganese were extracted by perchloric-nitric acid digestion of 0.5 g soil samples (Standard Methods 1975, pp. 169-170). Iron and manganese analyses were performed on a Fisher (90-750, ICAP) emission spectrometer. Orthophosphate was determined by the standard molybdate blue method (EPA-625-/6-74-003, 1974).

Accumulation rates (A) of organic carbon, nitrogen, iron, manganese, and phosphorus were calculated from mean dry weight concentrations (C, %) and the vertical accretion rate $(R, cm\ yr^{-1})$ using the formula

$$A(g \ m^{-2} \ yr^{-1}) = (CRD)10^6$$

where D is the soil bulk density in g cm^{-3}.

Where appropriate, the extent of subsurface depletion (F) and the rate of depletion (LR) were estimated from nutrient profiles using the expressions

$$F = 1 - \frac{C_h}{C_s}$$

and

$$LR \ (g \ m^{-2} \ yr^{-1}) = C_s DFR$$

C_s and C_h denote the surface layer and "steady state" concentrations, respectively (%).

Results

Sedimentation and Vertical Accretion

Accumulation of inorganic sediment increased fourfold from freshwater through salt marsh systems. Organic matter comprised a progressively smaller weight fraction of soil solids seaward in the Basin and towards levee areas but organic matter content per unit volume was remarkably uniform regardless of marsh type or location (Table 1). A predictable curvilinear relationship was found between percentile dry weight organic carbon content (C) and bulk density (D), as

$$D = 0.091 + 1.027 \times e^{-1.78 \times C}$$

This function yielded a mean organic carbon bulk density of approximately 0.09 g cm^{-3} when extrapolated to C = 100.

Geochronologies of ^{137}Cs indicated considerable regional (between marsh types) uniformity in vertical accretion rate, but pronounced variation within specific marshes (Table 1). Accretion rates in the four study areas averaged 1.3 cm yr^{-1} and 0.7 cm yr^{-1} in levee and backmarsh areas respectively.

Total Nutrient Concentrations

Except for particularly high levels of manganese in the freshwater marsh, total iron and manganese concentrations increased progressively in the seaward direction (Table 2). Both metals were consistently more enriched in levee soils than in lower density backmarsh soils. Total iron profiles (Table 3) indicated considerable density-related variability. Correlation analysis yielded a statistically significant positive correlation between iron (Fe) and bulk density (D) over all marsh types and depths such that

$$Fe = 7168 + 4143D \qquad (r = 0.45; \ P<0.01)$$

Table 1. Vertical accretion, bulk density, and sedimentation data. Error limits represent two S.D. (L = levee; B = backmarsh; N = number of cores).

Marsh Type	Site	Vertical Accretion (mm yr⁻¹)		Bulk Density (g cm⁻³)	Organic Matter Accumulation		Inorganic Sediment Accumulation		N
		Mean	Range		%	(g m⁻² yr⁻¹)	%	(g m⁻² yr⁻¹)	
Freshwater	L	10.6	-	0.11 ±0.03	41 ±7	477	59 ±10	689	2
	B	6.5	3.1-6.9	0.09 ±0.01	52 ±6	306	48 ±6	280	7
Intermediate	L	13.5	13.0-14.0	0.18 ±0.04	33 ±6	797	67 ±12	1634	2
	B	6.4	3.8-10.6	0.08 ±0.01	52 ±4	269	48 ±4	243	7
Brackish	L	14.0	10.6-16.9	0.27 ±0.02	22 ±3	826	78 ±11	2954	4
	B	5.9	3.8-8.1	0.14 ±0.01	42 ±3	348	58 ±4	478	8
Salt	B	7.5	5.9-9.4	0.29 ±0.06	20 ±3	435	80 ±12	1740	7

Table 2. Total concentrations (Conc.) and accumulation rates (Acc.) of iron, manganese, phosphorus and nitrogen. Error limits represent two S.D. (L = levee; B = backmarsh; N = number of cores).

Marsh Type	Site	Iron Conc. (µg g⁻¹)	Iron Acc. (g m⁻² yr⁻¹)	Manganese Conc. (µg g⁻¹)	Manganese Acc. (g m⁻² yr⁻¹)	Phosphorus Conc. (µg g⁻¹)	Phosphorus Acc. (g m⁻² yr⁻¹)	Nitrogen Conc. (µg g⁻¹)	Nitrogen Acc. (g m⁻² yr⁻¹)	N
Freshwater	L	14729 ±3912	19	144 ±52	0.15	927 ±171	1.0	1.50 ±0.30	16	2
	B	9956 ±2007	7	114 ±12	0.07	944 ±82	0.5	1.80 ±0.20	9	7
Intermediate	L	18691 ±2672	46	69 ±12	0.17	648 ±88	1.5	1.23 ±0.18	28	2
	B	10079 ±1590	6	60 ±7	0.03	763 ±34	0.4	2.00 ±0.16	11	7
Brackish	L	20831 ±1251	79	100 ±12	0.38	624 ±135	2.4	0.66 ±0.04	25	2
	B	11830 ±1152	10	77 ±7	0.06	664 ±38	0.5	1.31 ±0.1	10	7
Salt	B	16857 ±854	29	83 ±16	0.14	668 ±112	1.1	0.69 ±0.2	11	7

Table 3. Bulk density and total nutrient profiles. Individual values represent means of two cores in levee areas and seven cores in backmarsh areas.

Depth cm	Bulk Density g cm^{-3}	Concentration C %	N %	P µg g^{-1}	Fe µg g^{-1}	Mn µg g^{-1}
Freshwater Marsh: Levee						
1	0.07	22.5	1.42	1100	15000	353
5	0.10	21.3	1.31	1196	12500	148
9	0.08	29.7	1.99	1221	7353	96
13	0.11	20.1	1.46	1083	11111	100
17	0.07	26.4	2.22	1063	8594	116
21	0.06	35.8	2.16	1063	9286	118
25	0.09	29.0	1.45	833	14103	115
29	0.18	14.6	0.94	694	20833	123
33	0.16	16.2	0.94	391	24219	129
37	0.14	17.7	1.10	641	24286	
Backmarsh						
1	0.05	33.0	2.00	1186	7678	169
5	0.07	33.6	1.99	1116	5632	82
9	0.07	33.6	2.18	1079	5641	73
13	0.05	37.0	2.16	1095	5318	93
17	0.05	37.4	2.22	990	5520	88
21	0.05	36.1	1.33	806	8049	104
25	0.06	32.2	1.78	838	12104	121
29	0.10	25.0	1.42	674	13653	126
33	0.19	11.0	0.86	714	18137	127
37	0.37	16.2	0.93	745	18623	148
Intermediate Marsh: Levee						
1	0.16	18.6	1.19	686	21760	113
5	0.18	16.2	1.16	769	19231	92
9	0.25	16.6	1.66	538	18396	72
13	0.16	15.1	1.27	666	19711	58
17	0.29	15.0	1.05	387	17653	59
21	0.21	14.5	0.87	510	20192	60
25	0.16	13.9	0.96	546	23039	73
29	0.12	22.7	1.36	720	24152	59
33	0.11	27.3	1.43	721	11441	56
37	0.09	27.9	1.52	702	11530	52
Backmarsh						
1	0.06	26.5	1.67	1012	12325	89
5	0.10	26.1	1.61	766	16421	74
9	0.08	27.9	1.70	726	12367	63
13	0.09	24.6	1.79	684	12675	61
17	0.07	29.5	2.15	725	8630	59
21	0.06	35.6	1.89	696	7616	46
25	0.07	33.6	2.18	766	6186	45
29	0.08	32.5	2.25	784	7177	55
33	0.08	29.6	2.22	755	8229	54
37	0.08	31.3	2.32	730	10634	54
Brackish Marsh: Levee						
1	0.25	14.1	0.73	1186	18275	150
5	0.26	17.6	0.74	759	18969	85
9	0.25	12.1	0.69	570	20313	108
13	0.29	8.8	0.66	604	21615	90
17	0.33	10.0	0.63	611	20779	83
21	0.26	14.7	0.65	546	20192	90
25	0.28	11.0	0.52	549	18339	91
29	0.29	11.9	0.66	520	24230	103
33	0.22	11.6	0.73	529	22449	100
37	0.26	13.4	0.67	369	23113	104
Backmarsh						
1	0.12	17.5	1.35	895	15769	100
5	0.18	18.3	1.07	772	16337	95
9	0.17	18.4	0.97	656	15716	89
13	0.13	26.5	1.26	689	11377	68
17	0.11	26.6	1.42	718	9656	61
21	0.11	25.9	1.30	619	9637	62
25	0.12	26.9	1.36	576	10130	66
29	0.12	22.7	1.24	647	11296	73
33	0.12	25.0	1.43	596	8595	69
37	0.11	32.9	1.81	567	7818	71
Salt Marsh: Backmarsh						
1	0.15	11.3	0.86	833	18666	97
5	0.22	11.1	0.77	733	18879	82
9	0.26	13.2	0.72	695	17303	77
13	0.27	11.6	0.57	642	16629	83
17	0.23	13.3	0.70	665	15443	73
21	0.31	14.3	0.81	671	16406	79
25	0.30	10.7	0.66	657	17169	87
29	0.30	13.5	0.77	631	15238	84
33	0.19	8.1	0.53	640	16698	83
37	0.45	5.4	0.38	511	15930	80

Table 4. Remobilization of phosphorus and manganese as indicated by soil profiles. (F = subsurface depletion index: LR = loss rate: L = levee: B = backmarsh).

Marsh Type	Site	Phosphorus F (%)	Phosphorus LR (g m⁻² yr⁻¹)	Manganese F (%)	Manganese LR (g m⁻² yr⁻¹)
Freshwater	L	25	0.33	72	0.30
	B	39	0.32	32	0.03
Intermediate	L	31	0.66	33	0.10
	B	28	0.14	41	0.02
Brackish	L	55	2.47	63	0.36
	B	30	0.22	33	0.03
Salt	B	24	0.44	17	0.04

in response to the parallel gradient in hydraulic energy and rate of sediment redistribution. This transgressive process of marsh soil development is characteristic of the cyclic sedimentation of the Mississippi River Delta. Similarly, local gradients in inorganic sedimentation follow directly from lateral hydraulic gradients extending inland from tidal streams and other water bodies.

Nutrient Concentrations and Accumulation Rates

The general parallel between concentrations and accumulation rates of iron and manganese and sedimentation patterns shows that inorganic sediments are the principal carriers of these metals within the Barataria system. This result is consistent with the general geochemistry of these metals (Carroll 1958). Correlation between iron and bulk density over all depths and marsh types is further evidence that iron remains closely associated with inorganic sediments and is not subject to substantial post-depositional mobility within this system. By contrast, lack of statistical correlation and distinct surface maxima observed in the case of manganese indicate substantial mobility, presumably due to release of soluble manganous ions upon reduction of manganic oxides.

Although iron and manganese display some geochemical similarity, their divergent behavior in the Barataria Basin marshes has sound chemical basis. Note that (1) natural oxides of manganese are more readily reduced than iron oxides, resulting in a proportionately greater release of soluble manganous ions into solution upon soil reduction (Gotoh and Patrick 1972, 1974); (2) whereas ferrous ions are subject to significant complexation by organic compounds in soil solution, soluble manganese appears to remain entirely in the unassociated and more mobile ionic form (Stevenson and

Ardakani 1972; Olomu et al. 1973); (3) the solubility of manganese sulfides is far greater than that of iron sulfides (Lisk 1972); (4) free iron but not manganese availability in reduced soils is strongly pH-dependent even under near-neutral conditions (Gambrell et al. 1977). These factors all contribute to an explanation of the lower mobility of iron as compared to manganese in flooded soil systems.

Significant post-depositional remobilization of iron has only been reported from a freshwater lake system (Gorham and Swain 1965), whereas manganese remobilization has been noted in freshwater lake (Robbins and Callendar 1975) and estuarine and tidal marsh deposits (McCaffrey 1977; Lord 1980).

The origin of exceptionally high levels of total manganese (and to a lesser extent, phosphorus) in freshwater marsh soils is not obvious from the data. Agricultural runoff is potentially important in this respect; Kemp (1975) has recorded enrichment of adjacent swamps by agricultural runoff containing phosphorus, although manganese was not examined.

Phosphorus accumulation is qualitatively in accord with sedimentation patterns and the concept that inorganic sediments are the principal carrier of phosphorus to this marsh system. The association of phosphorus with iron and thus the inorganic sediments has been suggested by several workers (Williams et al. 1971; Syers et al. 1973; Patrick and Khalid 1974). However, organic phosphorus may constitute up to 70% of total phosphorus in some lake sediments (Frink 1969; Sommers et al. 1972). It is possible therefore that as a result of plant uptake and slow mineralization under anaerobic conditions, a large proportion of phosphorus in marsh soils may be associated with the organic phase, especially in low density, highly organic substrates of freshwater marshes. Our data are inconclusive in this respect, and it is likely that additional effects, including differential remobilization, are involved.

Almost no data on total concentration and accretionary impoundment of nutrients are available from other marsh systems. McCaffrey (1977) measured iron and manganese flux to a New England brackish marsh of 36 g m^{-2} yr^{-1} and 0.78 g m^{-2} yr^{-1} respectively. These rates are comparable to our own values and those reported previously from Louisiana salt marshes (DeLaune et al. 1981). Organic carbon and total nitrogen concentrations reported for U.S. Atlantic marsh soils (Haines et al. 1977; Lord 1980; Nixon 1980) are generally lower than the Barataria values which we believe to be related to the low inorganic sediment content of these Louisiana marsh soils.

Nutrient Remobilization

Greater diffusive loss of nutrients from the soil surface to flood waters is anticipated in hydrologically dynamic streamside areas, first, because of the greater flow of water over the marsh surface and second, because of the higher concentration of available manganese and phosphorus in levee soils (Brannon 1973). Remobilization from levee soils would be further enhanced by plant uptake in proportion to productivity: not only is productivity greater,

but the manganese content of the streamside plants is proportionately higher than the backmarsh form (DeLaune unpublished data). The apparent seaward increase in remobilization rates may be explained similarly by a seaward increase in availability of these nutrients (Hatton 1981) and tidal flushing which would enhance both diffusive loss and loss through detrital export.

Because of the assumptions involved, calculation of remobilization rates from soil nutrient profiles is subject to a large uncertainty. For example, it must be assumed that concentration in incoming sediments has not altered in the time span of the soil section examined: whereas agricultural inputs are potentially important in some areas, the extent of this effect is not obvious from the data. It must be assumed that upper layer concentrations in soil profiles represent incoming sediments, rather than surface accumulations resulting from oxidative re-precipitation. Data from an adjacent Louisiana salt marsh (DeLaune et al. 1981) indicate that whereas this assumption may be true of phosphorus, it may not hold for manganese. The extent of the oxidative re-precipitation is also likely to vary between marsh type according to soil redox condition and flushing time. Finally, selection of a steady state concentration at depth is complicated by significant density-related variability which we have simplified by using a mean subsurface value. But despite these assumptions and the uncertainty that surrounds the calculated remobilization rates, our results appear to be similar to those of McCaffrey (1977) who suggested a manganese export rate of 0.1 ± 0.02 g m^{-2} yr^{-1} from a New England brackish marsh. However, short term direct flux measurements at the marsh surface (Lord 1980) yield values which range from zero to several orders of magnitude greater than indicated by the sedimentary record.

We can compare potential remobilization by plant uptake with export rates indicated by soil profiles. Annual aboveground production of *Spartina alterniflora* in Louisiana salt marshes appears to be of the order of 3×10^3 g m^{-2} yr^{-1} (Hopkinson et al. 1978; White et al. 1978). Together with our preliminary estimates of manganese (1×10^4 g/g) and phosphorus (7×10^{-4} g/g) in aerial components of this species, uptake by *Spartina* is estimated at 0.3 g Mn m^{-2} yr^{-1} and 2.1 g P m^{-2} yr^{-1}. These values are generally higher, but of the same order of magnitude, as the values calculated from soil profiles. This result is interpreted as indicating that there must be considerable recycling *in situ* of manganese remobilized by plants.

In conclusion, despite a pronounced regional landward decrease in inorganic sedimentation in the Barataria Basin, ^{137}Cs geochronologies indicate a remarkable uniformity in vertical accretion rates in analogous marsh areas. This uniformity appears to be sustained by the accumulation of autochthonous organic matter, especially roots. The accretionary role of organic matter increases from saline through freshwater marshes. Vertical marsh accretion in both levee (1.3 cm yr^{-1}) and backmarsh (0.7 cm yr^{-1}) deposits are relatively high compared to estimates from Atlantic coast marshes.

Inorganic sediment is apparently the principal source of iron,

manganese, and phosphorus to the Barataria Basin marshes. The general lack of correlation between bulk density and dry weight concentrations of manganese and phosphorus suggest significant influence of other factors which may include modern sediment source, contamination, and chemical and biochemical remobilization with release to estuarine waters. Calculations based on soil profiles and vertical accretion rates indicate (1) that remobilization of phosphorus and manganese from levee marshes exceeds that from backmarshes; and (2) there is a progressive increase from freshwater through salt marshes in phosphorus and manganese outflux rates. Considerable uncertainty surrounds the calculation of nutrient outflux rates from soil profiles; whereas remobilization processes appear to alter significantly the nutrient distribution of marsh soils, the quantitative significance in the fertility of estuarine waters cannot be estimated from the sedimentary record alone.

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7. The Use of δ ^{13}C Signature of C-3 and C-4 Plants in Determining Past Depositional Environments in Rapidly Accreting Marshes of the Mississippi River Deltaic Plant, Louisiana, U.S.A.

by

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THE USE OF δ^{13}C SIGNATURE OF C-3 AND C-4 PLANTS IN DETERMINING PAST DEPOSITIONAL ENVIRONMENTS IN RAPIDLY ACCRETING MARSHES OF THE MISSISSIPPI RIVER DELTAIC PLAIN, LOUISIANA, U.S.A.

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Abstract

DeLaune, R.D., 1986. The use of δ^{13}C signature of C-3 and C-4 plants in determining past depositional environments in rapidly accreting marshes of the Mississippi River deltaic plain, Louisiana, U.S.A. Chem. Geol. (Isot. Geosci. Sect.), 59: 315—320.

The stable carbon isotope compositions of vegetation and soils of marshes of Louisiana's Barataria Basin were determined. The δ^{13}C-values of organic soils taken from fresh, intermediate, brackish and salt marshes are similar to the δ^{13}C-value of its vegetation. The δ^{13}C of a sediment profile taken from a salt marsh in a rapidly subsiding distributary of the Lafourche delta, an older distributary of the Mississippi River, showed that the δ^{13}C signature of buried peats represents original organic sources (e.g., fresh marsh plant species). The δ^{13}C signature at depth representing a C-3 plant-dominated freshwater environment corresponded to reported depositional reconstruction using paleo-environmental techniques. Vertical accretion rates determined by ^{137}Cs dating support historical and measured δ^{13}C-values in the profiles corresponding to earlier freshwater environments.

1. Introduction

There is growing interest in the use of the stable carbon isotope composition of estuarine plant sources for determining carbon transformations and exchanges in coastal and marine sediments (Parker et al., 1972; Haines, 1976; Fry and Sherr, 1984; Torgersen and Chivas, 1985).

Carbon isotope fractionation is associated with photosynthesis (B.N. Smith and Epstein, 1971). Vascular plants segregate into two groups in relation to their δ^{13}C composition: (1) C-3 plants with low δ^{13}C-values; and (2) C-4 plants with high δ^{13}C-values. Algae have intermediate δ^{13}C-values.

Louisiana's Mississippi River deltaic plain contains extensive marshes extending along a salinity gradient from the Gulf of Mexico (Feijtel et al., 1985). Due to the compaction of the Recent alluvial sediment of the Mississippi River the area is rapidly subsiding (Hatton et al., 1933). The marshes remain intertidal via rapid vertical marsh accretionary processes. A large portion (up to 300 g m^{-2} yr.$^{-1}$ C) of annual organic-matter production of marsh macrophytes is fixed in these accretionary processes (C.J. Smith et al., 1983).
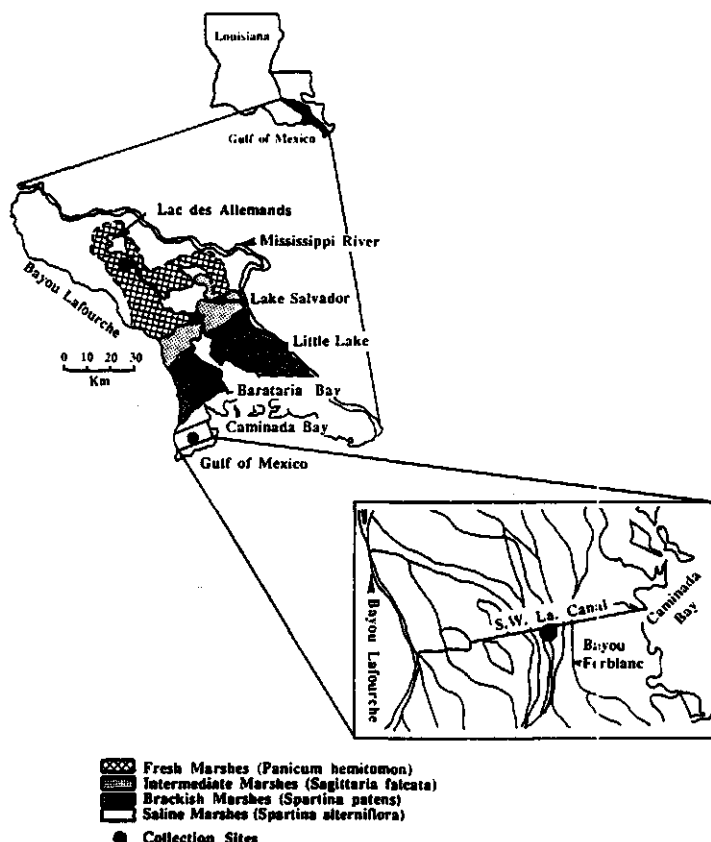
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Fig. 1. Location map of study area showing marsh type, predominant vegetation, and sites (•) at which vegetation and soil were sampled. Expanded portion of map shows lower Lafourche Delta where core was taken for determining $\delta^{13}C$ of buried peats representing earlier depositional environment.

Four vegetation types can be identified along a salinity gradient extending inland from the Gulf of Mexico (salt marsh, brackish marsh, intermediate marsh, and freshwater marsh) (Bahr and Hebrard, 1976). The distribution of predominant plant species is shown in Fig. 1. The fresh and intermediate marshes contain C-3 plants and the brackish and salt marshes have C-4 plants.

The purpose of this study was to: (1) determine carbon isotopic compositions of individual plant species representing the predominant vegetation of the fresh, intermediate, brackish and salt marshes of the Mississippi River deltaic plain; (2) determine if the $\delta^{13}C$-value in surface sediment of these marshes represents $\delta^{13}C$ of its vegetation;

and (3) evaluate if the $\delta^{13}C$ signature of organic material in a profile of a rapidly accreting marsh represents the $\delta^{13}C$ of vegetation from earlier depositional environments (e.g., fresh marsh).

2. Materials and methods

Vegetation and soil samples were collected in March 1984 from fresh, intermediate, brackish and salt marshes of the Barataria Basin (Fig. 1). Vegetation representing individual plant species was collected from 10 sites at each location covering an area of ~ 1 ha. The plant material was dried at 70°C, ground, and subsamples were taken for stable carbon isotope analysis. Surface

marsh soil samples were taken at 0—15-cm depth at approximately the same locations at which plant samples were taken from the individual marshes. Soil was composited, dried and ground, and subsamples were also taken for stable carbon isotope analysis.

In January 1985 a 10-cm diameter core was taken along an old distributary of Bayou Lafourche. The site was the same aforementioned salt marsh location from which vegetation and surface soil samples were taken. Bayou Lafourche received fresh water from the Mississippi River until 1904 and the earlier marshes were fresh. Since this time due to rapid subsidence and salt-water intrusion the area has changed into a salt marsh. The core was taken from a site at which paleo-environmental methods had previously been used to reconstruct earlier depositional environments in the marsh profile (Beckman, 1985).

The core was split and sectioned into 3-cm increments. Sections from one-half of the core were dried, ground, and subsamples taken for stable carbon isotope analysis. Each section was analyzed for ^{137}Cs activity to determine the rate of vertical accretion (DeLaune et al., 1978). ^{137}Cs is a man-made isotope and first entered the environment in the early 1950's as a result of fallout from atomic testing. Peak fallout occurred in 1963 (Pennington et al., 1973). The ^{137}Cs activity in the profile which represents 1963 was used to determine the rate of vertical marsh accretion.

The sections from the other half of the core were washed and passed through a sieve to remove macro-organic portions from the organic soil. The macro-organic portion from each section of the profile was dried, ground, and subsamples taken for carbon isotope analysis.

Carbon isotope analysis was performed with a double-collecting mass spectrometer on CO_2 from combusted plant or sediment samples. The sediment was pretreated with weak acid to remove any carbonate minerals. The $^{13}C/^{12}C$ ratio is expressed in parts per thousand (‰) relative to PDB standard.

3. Results

The $\delta^{13}C$ of marsh vegetation in the Barataria Basin ranged from −26.5 and −27.9‰ for *Panicum hemitomon* and *Sagittaria falcata* in fresh water and intermediate marshes in the upper region of the basin to −13.3‰ for *Spartina alterniflora*, the predominant vegetation in the salt marshes near the coast (Table I). The $\delta^{13}C$-value for sediment reflects that of the $\delta^{13}C$-values for vegetation present in the individual marshes. There was, however, a slight difference in $\delta^{13}C$-values between the soil and vegetation for the salt marsh. This was apparently due to appreciable organic-enriched sediment being deposited in salt marshes by tidal action. Hatton et al. (1983) reported greater amounts of mineral sediment in the salt marshes in the lower Barataria basins compared to the fresh and brackish marshes. When sediment was washed from salt soil the $\delta^{13}C$-value in the macro-organic portion was −14.1‰, which was closer to the $\delta^{13}C$-value of *Spartina alterniflora*. Sediment from an adjacent bay near the salt marsh is apparently enriched with either

TABLE I

The $\delta^{13}C$ composition of predominant plants and soils in marshes of Barataria Basin

	$\delta^{13}C$ (‰)
Fresh marsh:	
Panicum hemitomon plant material;	−26.5
marsh soil	−27.9
Intermediate marsh:	
Sagittaria falcata plant material;	−27.8
marsh soil	−26.6
Brackish marsh:	
Spartina patens plant material;	−13.5
marsh soil	−14.9
Saline marsh:	
Spartina alterniflora plant material;	−13.3
marsh soil	−16.5

organic material derived from upper estuaries or organic matter from phytoplankton both which have a different $\delta^{13}C$ signature than salt marshes. A bottom sediment sample taken from Caminada showed a $\delta^{13}C$ of —22.8‰. Such organic-rich sediment entering the salt marshes of lower Barataria Basin would alter its $\delta^{13}C$-value slightly.

The value of $\delta^{13}C$ in the profile taken from an old distributary channel of Bayou Lafourche decreases with depth (Table II). The surface portion of the profile represents the $\delta^{13}C$-value of salt marshes. The lower section of the profile contains $\delta^{13}C$-values of fresh marsh environments. Macro-organic material washed from the soil contained slightly higher $\delta^{13}C$-values than the soil itself, especially at the surface. As aforementioned, we attribute this to the enriched sediment content in the surface profile representing the saline marsh which receives greater mineral sediment inputs. The lower section of the profile, which was once a freshwater marsh, was highly organic with little sediment to alter its stable carbon isotope composition.

Stable carbon isotope composition of the profile compares favorably to paleo-environmental reconstruction methods reported by Beckman (1985). Using paleo-vegetation analysis (comparing seed assemblage) of

buried peats and Foraminifera assemblages, Beckman (1985) reconstructed the earlier depositional environments at the site. He showed the presence of freshwater systems at approximately the same depth where we report using $\delta^{13}C$ signature of the buried peats (Fig. 2).

^{137}Cs distribution indicated an accretion or sedimentation rate at the site of 0.86 cm yr.$^{-1}$ (Fig. 3). Previous sedimentation studies using ^{137}Cs dating have reported similar rapid accretion rates (DeLaune et al., 1978; Hatton et al., 1983). Extrapolating the sedimentation rate to 1904, when the Mississippi River was
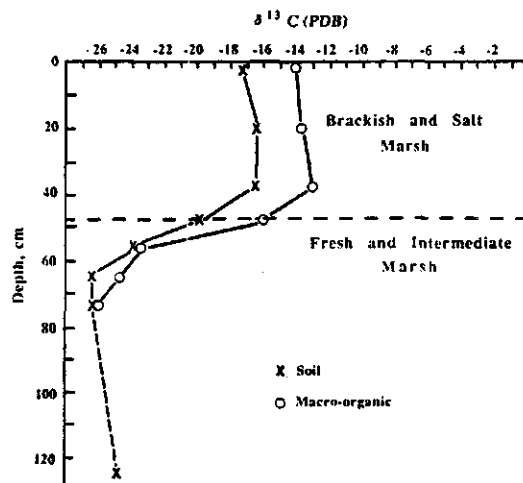

Fig. 2. Measured $\delta^{13}C$-values in marsh profile as compared to stratigraphic boundary (----) established between fresh and marine environments by Beckman (1985) using paleo-environmental techniques (seed assemblages).

TABLE II

The $\delta^{13}C$-value of organic matter in a sediment profile taken from a rapidly accreting salt marsh which in very late recent was a freshwater marsh

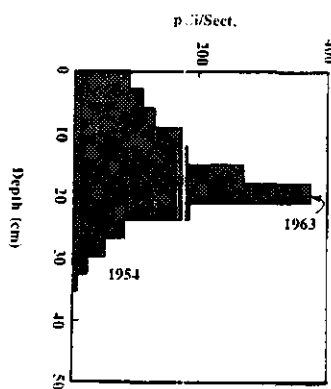| Depth (cm)	$\delta^{13}C$ (‰)		
	soil	macro-organic	$\Delta\delta^{13}C$ (soil—macro-organic)
0—3	—17.4	—14.1	—3.3
18—21	—16.5	—13.9	—2.6
36—39	—16.4	—13.0	—3.4
45—48	—19.9	—16.0	—3.9
54—57	—24.0	—23.8	—0.2
63—66	—26.5	—24.8	—1.7
72—75	—26.4	—26.1	—0.3
123—126	—24.9	—	—

Fig. 3. ^{137}Cs distribution in sediment profile.

prevented from flowing down Bayou La-fourche, indicates that the 60—70-cm depth in the profile was once a fresh marsh. These accretion rates also support values for $\delta^{13}C$ at this depth which are typical of a freshwater marsh.

4. Discussion

The difference in $\delta^{13}C$-values of C-3 fresh-water vegetation in a freshwater marsh in the upper portion of the basin and $\delta^{13}C$ of a C-4 *Spartina* species in the saline marsh in the lower basin bordering the Gulf of Mexico is very distinct. The $\delta^{13}C$ plant signature shows up in the organic soil or peats in these rapidly accreting marshes. Other investigators (Emery et al., 1967; Hunt, 1970; Brinson and Matson, 1983; Schell, 1983) have also re-ported that $\delta^{13}C$-values of peat beds and soils depend on the original C-4 or C-3 plant mate-rial contributing to their organic material.

We attribute the observed similar $\delta^{13}C$-values in the marsh soil and the vegetation of the individual marshes to the zonation of these marshes. In Louisiana's extensive coastal area, in contrast to the Atlantic coast, there are areas with monospecific vegetation types with sufficient distance to prevent mixing from upland coastal regions or between marsh types. In addition, the marsh soils are flooded almost continuously with very reducing or anaerobic conditions (C.J. Smith et al., 1983). Thus, decomposition of plant material is slow which limits microbial alter-ation of the soil organic matter under these anaerobic conditions.

Such $\delta^{13}C$ signature, as observed in this study, provides a method for determining past depositional environments in the rapidly subsiding Mississippi River deltaic plain. Parker et al. (1972), and Torgersen and Chivas (1985) have studied $\delta^{13}C$ composition in sediment profiles. These studies, however, were confined to marine sediment in which they investigated terrestrial input of organic carbon to near-shore zones. These investiga-tions did not measure a distinct change in

$\delta^{13}C$ in the sediment profile as reported in this investigation.

The work presented in this study suggests that $\delta^{13}C$ may be a useful tool in determining past depositional environments in rapidly accreting coastal regions such as the Missis-sippi River deltaic plain.

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8. Sedimentation Patterns in a Gulf Coast Backbarrier Marsh: Response to Increasing Submergence

by

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SEDIMENTATION PATTERNS IN A GULF COAST BACKBARRIER MARSH: RESPONSE TO INCREASING SUBMERGENCE

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ABSTRACT

The rate of vertical accretion was determined on two backbarrier marshes in the Mississippi River Plain, using ^{137}Cs dating techniques. An average accretion rate of 0·55 cm yr^{-1} was found on Grande Terre, and 0·78 cm yr^{-1} on Grand Isle. Analysis of mineral organic content of the marsh profile shows that the backbarrier marshes accrete through (1) accumulation of low density organic matter, and (2) episodic deposition of high density mineral sediment probably associated with major hurricanes or storm events. The rates of vertical accretion were two to three times less than the rate of submergence due primarily to rapid subsidence in the deltaic plain, and imply that these backbarrier marshes will progressively deteriorate.

INTRODUCTION

The barrier islands which fringe the Mississippi River Deltaic Plain on the Gulf Coast of Louisiana are important geomorphological features protecting some of the most valuable marshes and estuarine wetlands in the United States. Louisiana's barrier islands formed and evolved as a result of the past delta cycles of the Mississippi River (Penland and Boyd, 1981). However, unlike the wetlands whose initiation occurs during the progradational phase of the delta cycle, barrier island initiation begins during the destructional phase when delta transgression dominates. In the past when the Mississippi River abandoned a delta and sediment input diminished, subsidence became dominant over aggradation. As a result, the delta front becomes transgressive and delta sands are reworked and moved landward to form barrier islands. These barrier islands are backed by continuous marsh. The beaches along the barrier islands act as erosional headlands which provide the source of sand for downdrift spit accretion. Eventually the spits breach and flanking barrier islands (e.g. Grand Isle and Grande Terre) are formed. At present the deltaic barrier islands are undergoing severe erosion, thought to be a result of deltaic subsidence and a limited sand supply (Penland and Boyd, 1981).

Backbarrier marshes, dominated by *S. alterniflora*, develop in the lee of the island. The transgressive barrier island migrates over the backbarrier marsh as shown in Figure 1. The marsh vegetation on the backbarrier portion of the island helps bind sediment and contributes organic matter incorporated by accretion into the substrate. Backbarrier marshes presumably reduce the rate of landward barrier island migration and lessen the impact of waves on the bayside shoreline.

To date studies of Louisiana's barrier islands have been mainly descriptive in nature or dealt with longshore sand transport and beach face erosion. Little attention has been given to the backbarrier marshes. In this paper
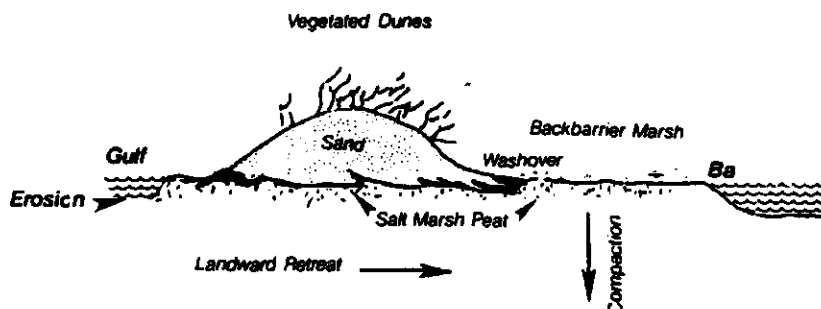
BARRIER ISLAND

Figure 1. Schematic of Barrier Island in relation to backbarrier marsh

we present findings on the rate of vertical marsh accretion in relation to changes in water level on the landward side of two of the barrier islands, Grand Isle and Grand Terre.

METHODS

Cores were taken at two locations on each of the two barrier islands (Figure 2). The cores were taken 50 m from the shoreline by twisting a thin aluminium cylinder 15 cm in diameter and 50 cm in length into the marsh surface. Compaction from sampling ranged from 2 to 3 per cent. The soil cores were sectioned into 3-cm increments, dried, and ground.

Vertical accretion was determined from the ^{137}Cs distribution in the soil profile (DeLaune et al., 1978). ^{137}Cs is a product of nuclear-weapon testing and does not occur naturally. Significant fallout levels first appeared in 1954, with peak quantities occurring in 1963 and 1964 (Pennington et al., 1973).

^{137}Cs activity in each section was determined by gamma counting of the oven-dried sample, using a lithium-drifted germanium detector and multichannel analyser (DeLaune et al., 1978). Organic carbon was determined by dry combustion. Bulk density was determined from oven-dried sediment and the known volume of each section.

Water level increase was determined from linear regression analysis of existing Corps of Engineers water level data at its Bayou Rigaud gauge.

RESULTS

^{137}Cs profile distribution in the four cores taken in 1982 showed that the backbarrier marsh has vertically accreted over the past twenty years at an average rate of 0·55 cm yr^{-1} for Grande Terre and 0·78 cm yr^{-1} for Grande Isle using 1963 as the peak year of ^{137}Cs fallout (Figure 3). Submergence as measured by the nearby Bayou Rigaud gauge has averaged 1·83 cm yr^{-1} since 1963 (Figure 4). In comparison sea level has been rising at a rate of 0·14 cm yr^{-1} along the stable west Florida coast (Hicks, 1978) and on a global basis at an average rate of 0·12 cm yr^{-1} for the past century (Gornitz et al., 1982). Thus eustatic and steric rise in sea level comprise less than ten per cent of the total submergence rate for these two Gulf Coast barrier islands.

Bulk density and carbon analysis of the cores used in the ^{137}Cs dating showed that the marsh accreted through the accumulation of both mineral sediment and organic material (Figure 5). Results suggest that these backbarrier marshes are accreting at a rate similar to more inland *Spartina alterniflora* marsh (DeLaune et al., 1978; Hatton et al., 1983). However, in the backbarrier marshes there are substantial variations in bulk density, and periods of inorganic sediment accumulation (high bulk density) are believed to relate to major high energy events. These results suggest that during storm events the marshes serve as a significant trap for mineral sediment. Under normal conditions the marsh accretes through accumulation of low density organic material.
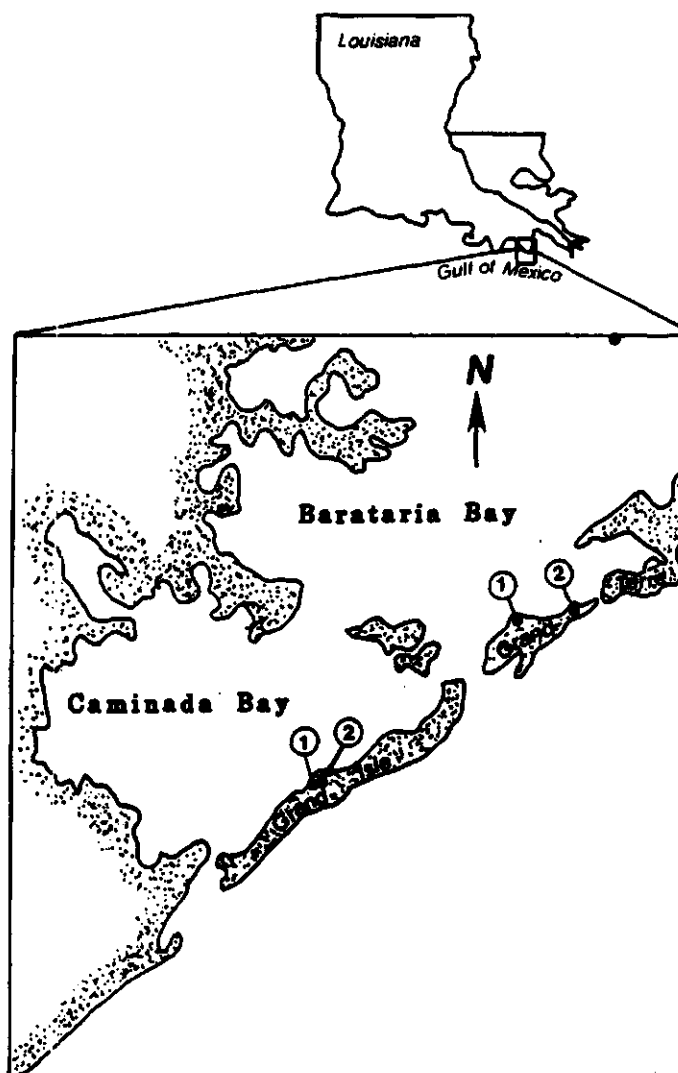
Figure 2. Map of study area showing site where cores were taken

DISCUSSION

Backbarrier marshes comprise 54 per cent of the total area of Louisiana's barrier islands versus 12 per cent area coverage by the dune communities, therefore, marsh management would have a greater impact than dune management (Mendelssohn et al., 1985). In a transgressive barrier island system, the type found in Louisiana, the backbarrier marsh forms the foundation over which the island migrates.

The results presented show that backbarrier marshes are actively accreting and may function in reducing barrier island erosion and landward migration. These marshes provide a platform on which overwash material can be deposited. Dune or marsh communities may develop on this overwash material depending on the depth of deposits relative to the intertidal zone. The marsh infill of the backbarrier reduces the void that has to be filled by the washover. Thus a similar volume of displaced material has a greater horizontal spread when a marsh is present. Also the marsh outcrop on the seaward side reduces or delays erosion. A barrier island is much more likely to be breached by storms where there is little marsh bracing the beach (Leatherman, 1983).
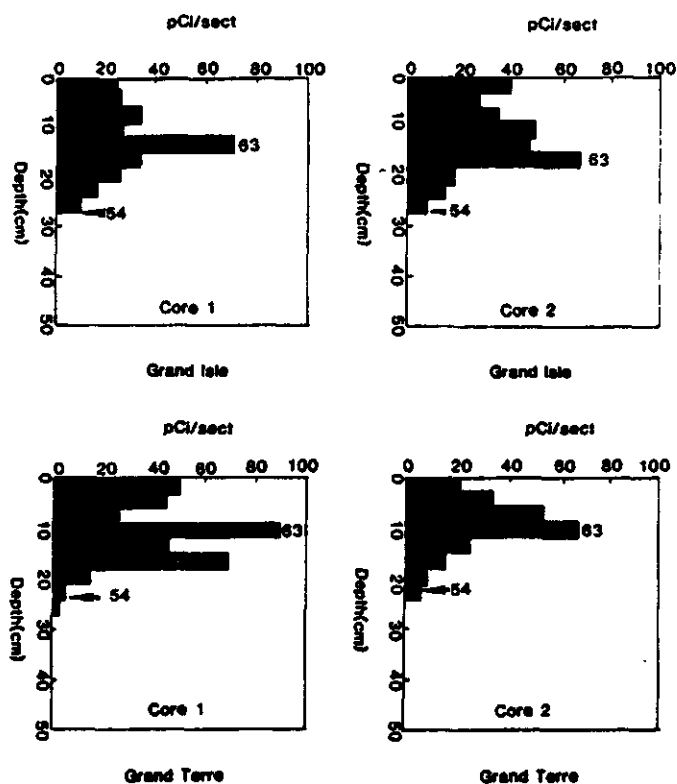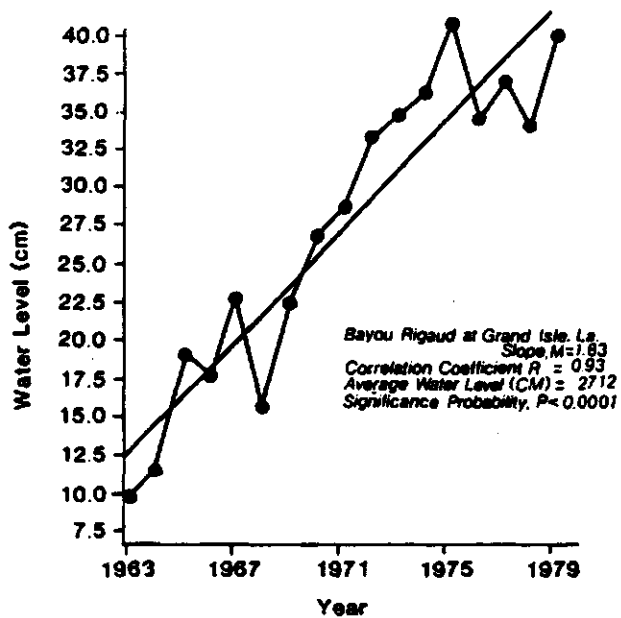
SEDIMENTATION PATTERNS

Figure 3. ^{137}Cs distribution in marsh soil profiles

Figure 4. Rate of water level increase at Bayou Rigaud gauge

During hurricanes the backbarrier marshes trap sediments which otherwise may have been lost from the system. In 1965, Hurricane Betsy passed over Grand Isle and Grande Terre destroying most structures on the island. This surge is believed to correspond with the mineral sediment and bulk density peaks above the 1963 ^{137}Cs peak in the sediment profile of backbarrier marshes from both barrier islands (Figure 5).

The rapid rate of local increase in water level ($1 \cdot 83$ cm yr^{-1}) is attributed mainly to subsidence. Local relative sea level rise includes eustatic and local components. By subtracting a rate of $0 \cdot 14$ cm yr^{-1} for eustatic sea level rise (Hicks, 1978) one arrives at a subsidence rate of approximately $1 \cdot 69$ cm yr^{-1} for these barrier island marshes. The rate of subsidence is more than 10 times greater than the average rate of eustatic sea level rise for the last century.

Since there is a large aggradation deficit between submergence and backbarrier marsh accretion, it is likely that these marshes will rapidly deteriorate. The increase in water level will put stress on plant growth which is the primary source of the organic material incorporated in the sediment processes of maintaining backbarrier marshes intertidal. As aggradation deficit continues the marshes will become more vulnerable to storms.

Submergence and subsequent marsh deterioration have been reported in other coastal regions of Louisiana. Submergence rates in marshes of the Louisiana Chenier Plain (or the southeastern edge of Lake Calcasieu)
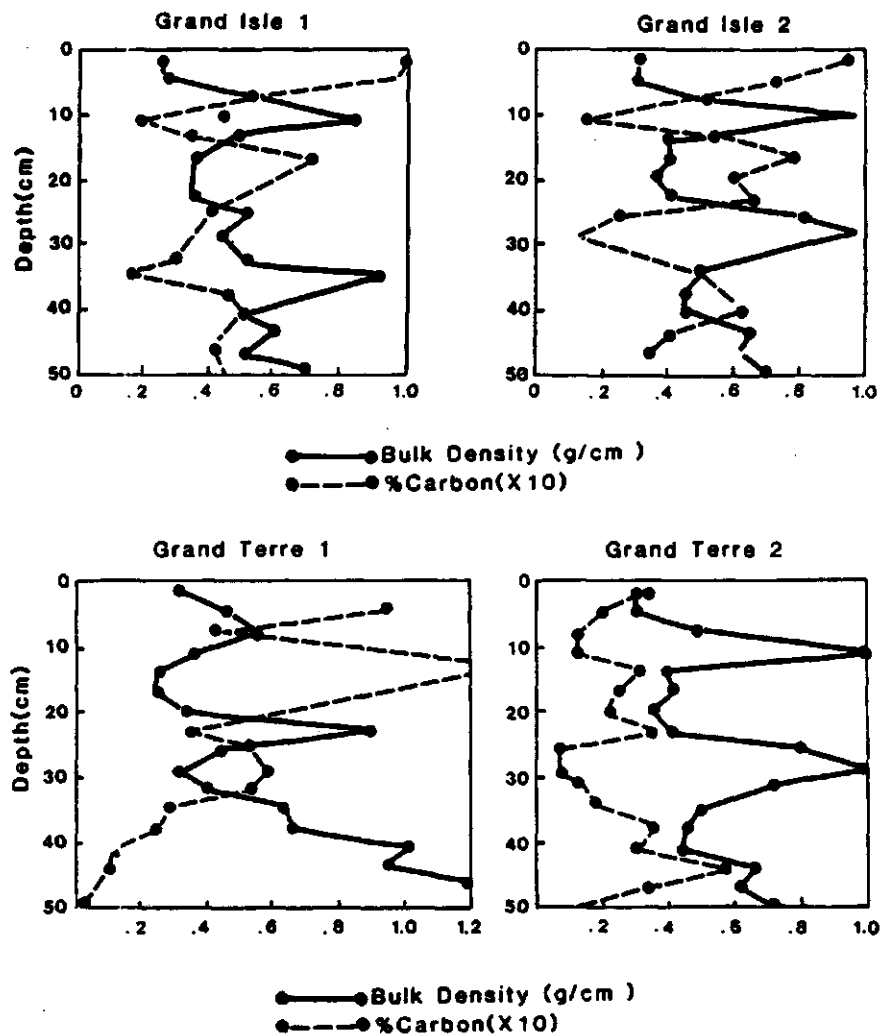

Figure 5. Bulk density and organic carbon distribution in the marsh soil profiles

were 1·5 times greater than rates of vertical marsh accretion (DeLaune *et al.*, 1983). Hatton *et al.* (1983) measured sedimentation rates in fresh, intermediate, brackish, and saline marshes of Louisiana's Barataria Basin and found that rates of vertical accretion ranged from a maximum of $1·7$ cm yr^{-1} on natural levees to as little as $0·31$ cm yr^{-1} in certain marsh areas. Sedimentation at many of the sites was not keeping pace with submergence. Aggradation deficits were greater near the coast. Peat accumulation occurring in fresh and brackish marshes are maintaining inland marsh elevation in close proximity to submergence rates (DeLaune *et al.*, 1984).

The extensive loss of wetlands occurring in Louisiana due to aggradation deficits imparts added significance to the processes involved in marsh accretion including processes presently occurring along the barrier islands. Assuming the measured aggradation deficit reported in this study holds for the entire Barrier Island system along the Louisiana coast, the life span of these islands is only of the order of several hundred years at the most. Barrier islands often migrate landward and build upward as sea level rises. However, in Louisiana it appears that rapid submergence rates may result in the islands breaking up rather than continually migrating landward. Within the projected life of these barrier islands there will be reworking of sands by wave action maintaining remnants of barrier islands but ultimately they will be subjected to the rapid submergence occurring along the Mississippi River Deltaic Plain. The rate of backbarrier marsh deterioration will be even greater if the predicted greenhouse warming effect contributes to an accelerated worldwide sea level rise.

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9. Rejuvenated Marsh and Bay- bottom Accretion on the Rapidly subsiding Coastal Plain of U.S. Gulf Coast: a Second-order Effect of the Emerging Atchafalaya Delta

by

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Rejuvenated Marsh and Bay-bottom Accretion on the Rapidly Subsiding Coastal Plain of U.S. Gulf Coast: a Second-order Effect of the Emerging Atchafalaya Delta

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Sedimentation processes in marshes and bays under the influence of the emerging Atchafalaya delta are described. The Atchafalaya delta is a major geological event in the Holocene history of the Mississippi River delta system because it represents the initial stages of a new delta cycle. The delta has resulted from the capture of the Mississippi River flow by the hydraulically more efficient Atchafalaya River. Using ^{137}Cs and ^{210}Pb dating techniques, maximum sedimentation of delta-flanking environments was found to occur in the bay bottoms and marshes closest to the emerging delta. Marshes directly under the influence of the emerging delta were accreting at rates as great as $1·4$ cm y^{-1} with appreciable mineral sediment inputs. In addition to increasing shoreline progradation, the added sediment is providing nutrients for increased net plant productivity which provides the organic source needed for vertical marsh accretion. Results show that the major area of coastal progradation will be in the immediate vicinity of the delta and along down-drift coasts. Updrift marshes (East Terrebonne marshes) away from the delta are accreting at a slower rate with smaller mineral sediment input and a larger percentage of organic material. These marshes are likely to continue experiencing rapid rates of deterioration.

Introduction

Louisiana's coastal area has been formed by the deposition of successive series of deltas resulting from significant changes in the course of the Mississippi River over the past 7000 years (Kolb & Van Lopik, 1966). These deltas alter the configuration of the coastal zone as they progress from growth through abandonment and finally continued deterioration until they are part of the subsurface record.

Growth of the Atchafalaya delta is a major geologic event in the Holocene history of the Mississippi River delta system because it represents the initial stages of a new delta cycle. The delta has resulted from the steady diversion and capture of the Mississippi River flow by the hydraulically more efficient Atchafalaya River (Van Heerden & Roberts, 1980).

Figure 1. Major delta lobes of the Mississippi River (including the emerging Atchafalaya Delta) which has formed the Mississippi River Deltaic Plain (Roberts & van Heerden, 1982, which was modified from Kolb & Van Lopik, 1966).

The Atchafalaya River, a distributary of the Mississippi River, carries about 30% of the total flow of the Mississippi and the majority of the Red River flow. Sedimentation commenced in the early 1950s in Atchafalaya Bay which marked the initiation of a new major delta lobe in the Mississippi River Delta Complex (Figure 1). Over the past ten years, the Atchafalaya River has built a new delta of about $40 \ km^2$ in Atchafalaya Bay. Subaerial exposures first appeared in 1973 and the new delta lobes have grown rapidly since then.

Marshes associated with the Atchafalaya River delta are in the most actively building delta in the United States and represent one of the few areas along the Louisiana coast where land loss is not a problem. Near the rapidly prograding distributary network, large areas of marsh have changed from brackish to freshwater. The opposite condition has occurred in the older deltas of the Mississippi River deltaic plain, where abandonment and subsidence results in invasion of marine water. Wetlands are rapidly disappearing in older delta lobes of the Mississippi River deltaic plain (Salinas et al., 1986). With an estimated overall net land loss of $100 \ km^2 \ y^{-1}$, land loss is of critical concern for most of coastal Louisiana (Gagliano, 1981).

Wetlands developing in the Atchafalaya delta are evolving under conditions similar to earlier delta lobes of the Mississippi River. Emergence of the Atchafalaya delta has caused dramatic changes in the wetlands, inland waters, and in the nearshore of central Louisiana. Such spatial sedimentation or accretion patterns must be clearly understood if changes in such a dynamic coastal system are to be accurately predicted.

In this paper the authors describe sedimentary processes in marshes and bays under the influence of the emerging Atchafalaya delta. Rates of carbon accumulation as well a accumulation of other elements as a product of sedimentation processes are quantified.

Figure 2. Location of sampling sites. For other place names mentioned in text, see Figure 4.

Materials and methods

Sedimentation rates were determined at key coastal areas which were selected on the basis of proximity to, and likely influence of, the emerging delta system. Representative sites at each marsh location were selected on the basis of vegetation type, soil morphology, and hydrology. These sites include: (1) the Terrebone marsh complex, (Bayou Penchant), (2) Four League Bay and adjacent marshes, (3) Plumb Palmetto and Creole Bayou marshes and Wax Lake Outlet marshes which flank the eastern and western sides of the river mouth, respectively, (4) Marsh Island, and (5) the water bottom west of the Atchafalaya River where Atchafalaya Bay extends into Vermillion Bay (Figure 2).

Sedimentation rates were determined from the ^{137}Cs distribution in marsh soil or lake bottom cores (DeLaune *et al.*, 1978). Cesium-137 is a product of nuclear-weapon testing and does not occur naturally. Significant fallout levels first appeared in 1954, with peak quantities occurring in 1963 and 1964 (Pennington *et al.*, 1973). Marsh soil profiles thus

show a maximum ^{137}Cs activity at the depth corresponding to 1963 deposits, tailing off at a depth equivalent to 1954 when ^{137}Cs first entered the environment. Although there some migration of ^{137}Cs in sediment is reported, peak concentrations do not shift substantially because ^{137}Cs is strongly adsorbed by clay (Robbins & Edington, 1975). Vertical accretion rates determined from ^{137}Cs dating are comparable to rates determined using artificial marker horizons (DeLaune et al., 1983).

Samples for determination of sedimentation or vertical accretion rates in marshes were taken with large-diameter (15 cm), thin-walled (0·2 cm) aluminium coreliners with a sharpened cutting edge. The coreliners were carefully twisted into the substrate to a depth of 50 cm. Cores were capped in situ before being raised to the surface, and sealed using specially designed PVC caps and nylon straps. Entire cores were accurately sliced into 3-cm across-core sections. Samples were dried at 70 °C. Bulk density was calculated from the dry weight of each section of known volume. Cylinders (10 cm diameter) were used to take cores from the bottom sediment of the bay. The same procedure as described above was used on these samples.

Activity profiles of ^{137}Cs were determined using an Ortex (Model 8011-1620-S) coaxial, lithium-drifted germanium detector coupled to a (Model 6240B) multichannel analyser. Each 3 cm thick core section was counted for a variable time period determined statistically by ^{137}Cs activity, but not exceeding 2×10^4 s. Vertical marsh accretion rates were computed directly from the depth of burial of the dated (1963) ^{137}Cs activity maximum (DeLaune et al., 1978, 1983).

Several cores were also dated using ^{210}Pb techniques. Lead-210 was measured via its daughter [210]Po which is assumed to be in secular equilibrium with [210]Pb (Flynn, 1968).

Selected cores from several locations were analysed for total organic carbon (TOC), Kjeldahl nitrogen, and total phosphorus, iron, and manganese as outlined by DeLaune et al. (1983). Organic carbon was determined by dry combustion and the organic matter content was calculated from this value using a multiplier of 1·724 (Wilson & Staker, 1932). The Kjeldahl nitrogen content of accurately weighed (2–3 g) samples was determined using the method of Bremner (1965). Total elements were extracted by perchloric–nitric acid digestion of 0·5-g samples (Standard Methods 1975, pp. 169–170). Metal and phosphorus analyses were performed on a Fisher (90–750, ICAP) emission spectrometer following nitric–perchloric acid digestion of 0·5-g subsamples (DeLaune & Smith, 1985).

Accumulation rates of organic carbon, nitrogen, and other elements were calculated using bulk density, element composition of sediment and sedimentation rates determined from ^{137}Cs dating.

Results

The ^{137}Cs profile distribution was used to document sedimentation rates and vertical marsh accretion in the bays and in peripheral marshes under the influence of the emerging Atchafalaya delta and showed rapid accretion rates (Table 1). Typical ^{137}Cs distribution in marsh and sediment profiles, which are used to calculate sedimentation rates in marsh and bay bottoms, are shown in Figure 3. Sedimentation rates determined from ^{210}Pb dating were similar to those determined using ^{137}Cs-dating techniques.

Maximum sedimentation rates occur in the bay bottoms and in the marshes closest to the emerging delta. Marshes between the lower Atchafalaya River and Wax Lake Outlets, which receive annual flood water by overbank flow, are accreting at an average rate of 1·4 cm y^{-1}.

TABLE 1. Sedimentation (^{137}Cs dating) and bulk density of marsh and bay-bottom studies

Site	Bulk density (g cm^{-3})	^{137}Cs sedimentation rate (cm y^{-1})	No. cores	^{210}Pb sedimentation rate (cm y^{-1})
Four League Bay (marsh)	0·40	0·65	5	
Terrebonne Marsh Complex (bayou penchant)	0·15	0·81 ± 0·28	5	0·76 ± 13
Palmetta Bayou/Bayou Creole/Plumb Bayou Marsh Area	0·35	0·92 ± 0·15	3	
Wax Lake Outlet Marsh	0·29	1·4 ± 0·4	4	
Marsh Island	0·36	0·70 ± 0·14	5	
Four League Bay (bottom sediments)	0·55	>1·5	5	
Atchafalaya Bay Bottom	0·70	>2·0	5	2·6[a]
East Cote Blanche Bay	0·69	2·0	5	1·5[a]
West Cote Blanche Bay	0·75	0·90	2	1·6[a]

[a]Only one core analyzed.
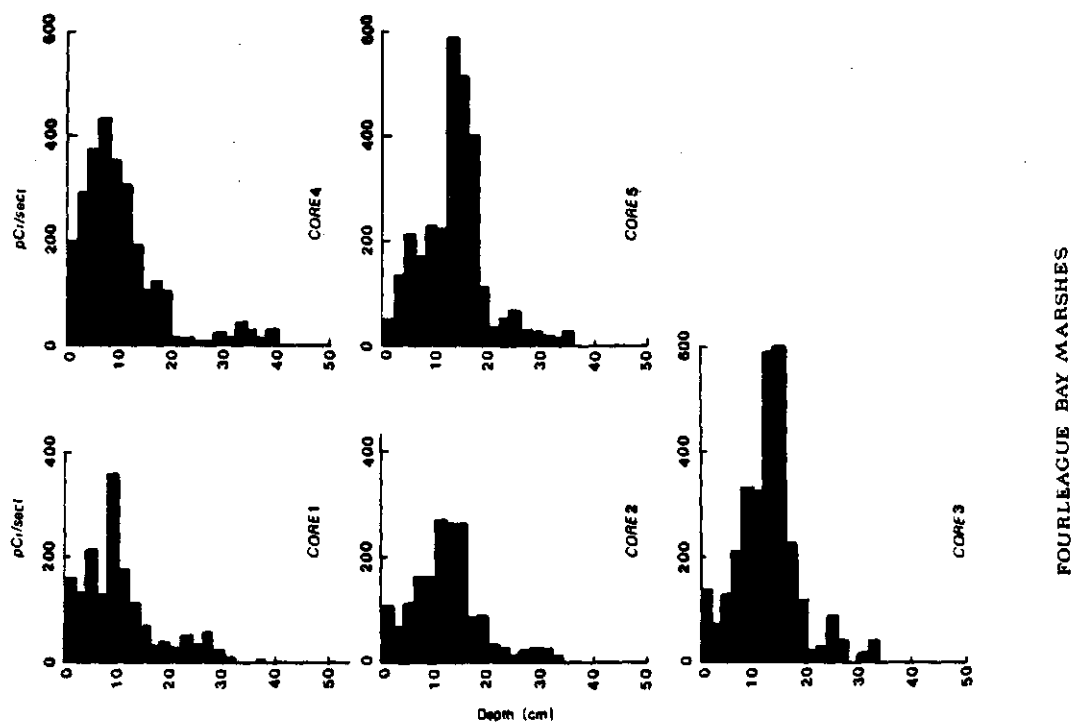
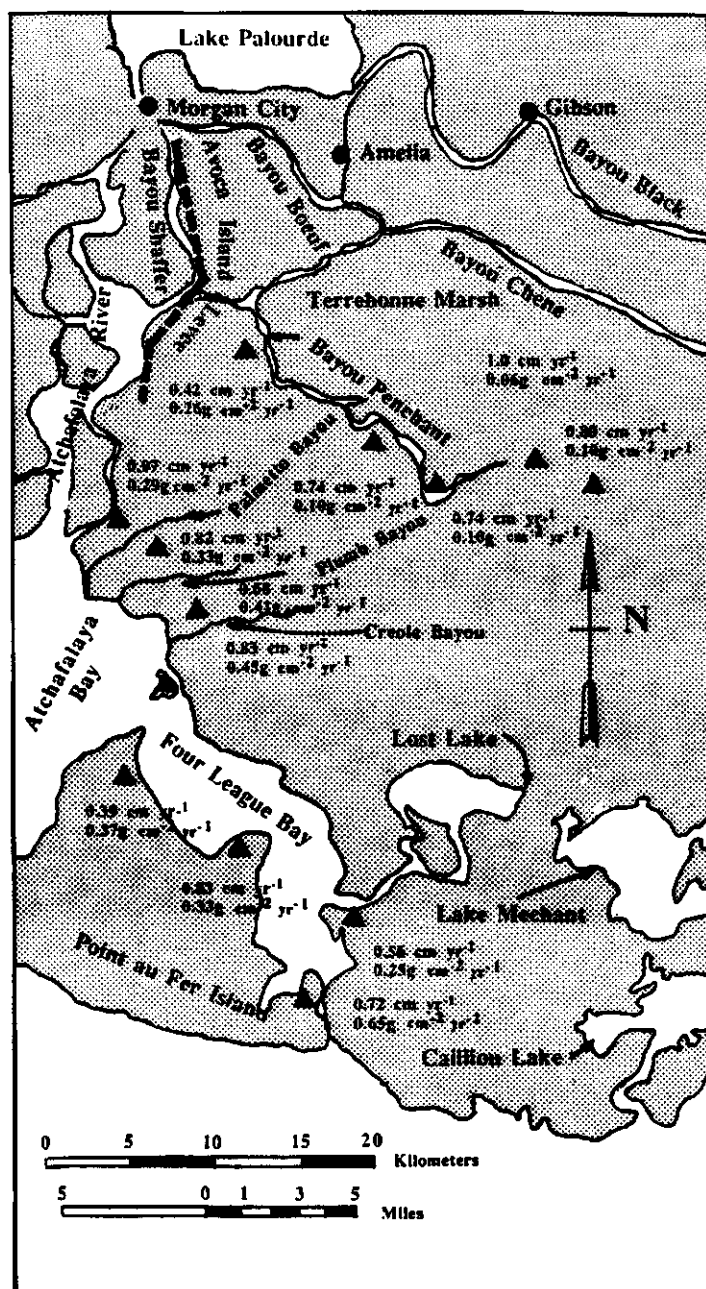Figure 3. Typical ^{137}Cs profile used for determining the sedimentation rate in marsh soil.

Figure 4. Terrebonne marsh showing rates of sedimentation and amount of sediment accumulation.

Marshes in the Terrebonne complex (Bayou Penchant) behind the Avoca Island levee (Figure 4) are accreting at an average rate of 0.81 cm y^{-1}. (The Avoca Island levee is a flood protection structure that prevents overbank flooding to the east of the lower Atchafalaya River.) The marshes were found to be accreting primarily through organic matter accumulation rather than by terrigenous sediment input. A density analysis of Bayou Penchant marshes in Terrebonne Parish showed low densities (Table 1) indicating

TABLE 2. Elemental accumulation rates (g m^{-2} y^{-1})

Element	Four League Bay (marsh)	Terrebonne Marsh (Bayou Penchant)	Four League Bay (bottom sediment)
C	152·0	181·0	55·0
N	12·0	16·8	5·8
P	2·6	1·6	4·5
Fe	88·0	32·0	58·0
Mn	0·7	0·3	4·3
Al	185·0	81·0	267·0
K	57·0	14·0	56·0
Cu	0·20	0·04	0·12
Ni	0·13	0·05	0·19
Pb	0·21	0·21	0·80
Zn	0·15	0·15	0·19

that little inorganic mineral sediment is entering the marsh and that organic content is high compared to marshes near the mouth of the Atchafalaya.

The rate of subsidence or region compaction and sea-level rise also affect accumulation rates of surficial sedimentation. Although general agreement has been reached on an acceptable range of values for recent global sea-level rise (Gornitz *et al.*, 1982), determining a value for subsidence, especially for the Mississippi deltaic plain, is much more difficult. It is difficult to separate the various components that contribute to subsidence in a coastal region which is as dynamic as the one in south Louisiana. The combined subsidence (local compaction) and eustatic rates of sea-level rise for the Atchafalaya delta have been estimated to be 1·61 cm y^{-1} from long-term tide gage data at Eugene Island seaward to Atchafalaya Bay (data compiled by Louisiana Geological Survey). Other data sets based on ^{14}C dating of peats from deep cores (> 30 m) through the Terrebonne marshes around Atchafalaya Bay (Roberts, unpubl. data) suggest that the Eugene Island data are much too high and may be anomalous. However, the authors estimate sedimentation rates to be equal to, or greater than, the subsidence rates close to the active delta. These results correspond with those obtained by Baumann and Adams (1981) who showed that land gain was occurring in marshes near the river mouth. The Terrebonne marsh complex, where there are apparent aggradation deficits, will probably continue to lose land area until bay filling is complete and a larger and more elevated delta is built with a distributary network which can distribute more sediment-laden water to surrounding marshlands.

A management plan currently under consideration by the U.S. Army Corps of Engineers, involves the extension of a levee along the east bank of the Atchafalaya River from Avoca Island to the mouth of Four League Bay (Figure 4) to improve navigation and control backwater flooding. This project would cause sediment-laden floodwaters to be transported more efficiently into the Gulf and reduce water-sediment inputs to the Terrebonne marshes. A further restriction of sediment input into the Terrebonne marsh complex would thereby accelerate marsh deterioration and land loss.

Chemical and physical analyses of the cores used for the measurement of sedimentation rates show the relative importance of sediment from the Atchafalaya as a source of nutrients near the river mouth (Table 2). Phosphorus is accumulating at the rate of 2·6, 1·6, and 4·5 g m^{-2} y^{-1}, in the Four League Bay marshes, Terrebonne marshes, and in the bottom of Four League Bay, respectively. These areas also serve as large sinks of carbon

and nitrogen with as much as $181 \cdot 0 \text{ g C m}^{-2} \text{ y}^{-1}$ and $16 \cdot 8 \text{ g N m}^{-2} \text{ y}^{-1}$ accumulating in the organic-rich Terrebonne marsh sediment.

Sedimentation-associated nutrient inputs for the marsh site are dependent on sediments which are similar to those reported for the Barataria Basin (Hatton et al., 1983). Sedimentation rates are assumed to be similar between the two areas because accretion rates were found to be very similar.

Bay-bottom sediment with relatively high deposition rates received larger amounts of phosphorus, iron, and aluminium. Carbon and nitrogen accumulations were less in bay bottoms than in marshes, which illustrates the role of marsh macrophyte production and nitrogen fixation in supplying carbon and nitrogen to marsh surfaces in addition to carbon and nitrogen received from sediment input.

Discussion

Diversion of Mississippi River fresh water and sediment to the central coast of Louisiana via the Atchafalaya River will steadily influence the future character of the coastal environments in the immediate vicinity of Atchafalaya Bay. First-order effects of direct sedimentation in the delta-building process are resulting in rapid land-building opposite both the lower Atchafalaya and Wax Lake Outlets. Bay-bottom accretion peripheral to the subaerial deltas, as determined from ^{137}Cs dating, shows rapid aggradation.

In addition to simply supplying sediment for delta-building, secondary-sedimentation effects are influencing the hydrography and accretion of the surrounding marshlands. The emerging delta is affecting water levels of areas surrounding Atchafalaya Bay, as evidenced by analyses of local tide and flood level records. For example, flood levels at Morgan City and in adjacent marshes average over $0 \cdot 3$ m ($1 \cdot 0$ ft) higher than in pre-delta years (U.S. Army Corps of Engineers, 1974). This change has resulted from the inefficient dispersal of flood waters because of the obstructive effects of the rapid delta growth at the mouths of both the Lower Atchafalaya River and Wax Lake Outlet (Roberts & Van Heerden, 1982). Elevated flood levels have the net effect of putting additional stress on marsh vegetation with the result that a greater rate of accretion is required to maintain vegetation within a mean water level. Backwater effects and increased overbank flooding may cause an increased increment of yearly sedimentation which results in aggradation of the marsh surface at a higher rate than in pre-delta years.

As deltas from both Lower Atchafalaya River and Wax Lake Outlet continue to fill the bay and build onto the shallow continental shelf, delta lobes will merge to form extensive new marshlands that will protrude into the marine environment. At the present growth rate, nearly 3 km^2 ($1 \cdot 16$ mile^2) of new marshland is added above mean sea level to the Atchafalaya deltas yearly (average 1975–81). It is estimated that by the end of this century bay filling will be complete and the subaerial delta will be prograding onto the continental shelf. Marshes in the vicinity of the actively forming delta will probably receive enough sediment to maintain their elevation irrespective of any increase in water level due to subsidence and sea-level rise.

Marshes some distance away from the active delta (for example, East Terrebonne Marsh) will probably continue to experience a rapid rate of deterioration, especially if man-made control structures are implaced so as to restrict intrusion of flood water into these areas. The mean drift system, as well as the wave-induced longshore drift, in this part of the northern Gulf of Mexico favors an east-to-west transport direction. It is safe to

assume that the major areas of coastal progradation will be in the immediate vicinity of the delta and along the down-drift coasts while updrift marshes will continue to deteriorate.

In summary, diversion of Mississippi River water and sediment to the coast through the Atchafalaya system will provide additional sediment and nutrients to delta flanking environments. The sediment will increase shoreline progradation and nutrients, which will in turn increase plant productivity which is the source of organic matter for vertical marsh accretion of marsh soils.

Acknowledgements

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10. Accumulation of Plant Nutrients and Heavy Metals Through Sedimentation Processes and Accretion in a Louisiana Salt Marsh

by

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ABSTRACT: The accumulation of selected plant nutrients and heavy metals in a rapidly accreting Louisiana salt marsh was examined. Sedimentation processes were shown to be supplying large amounts of plant nutrients to the marsh. Accumulation of heavy metals was low and appeared to be associated with the natural heavy metal content of incoming sediment rather than from a pollution source. A large portion of organic carbon from primary production remained in the marsh, contributing to the aggradation process of vertical marsh accretion. Nitrogen accumulated in the marsh at rates as great as 21 g per m² per yr.

Introduction

There is little information on the relationship between nutrient cycling and vertical marsh accretion in Louisiana's coastal zone. Tide gauge records reveal rising water level trends over the last 20 years (Swanson and Thurlow 1973). Much of this rise is attributed to regional sinking of land rather than to eustatic sea level rise.

Even though there is a net land loss along the coast, vertical accretion apparently compensates for a portion of the subsidence. The marsh surface is maintained within the intertidal zone through plant growth, organic detritus accumulation and sediment deposition (DeLaune et al. 1978). As a result of plant growth both organic detritus and sediment particles are entrapped, resulting in the gradual aggradation of the surface. This process is governed by tides and wind driven currents sufficiently strong to transport sediments from stream and open water areas onto the marsh surface. Deposition of nutrient-rich sediment is an important fertilization mechanism for marsh plants. This work examines the amount of plant nutrients and other elements transported and accumulated in a Gulf coast salt marsh through sedimentation and accretion processes.

Methods

Cores were taken from a streamside and inland *Spartina alterniflora* salt marsh and from an adjoining shallow water lake in Barataria Basin in Louisiana (29°13'N, 90°7'W). The topography of the area is characterized by slightly elevated natural levees bordering streams and water bodies which gradually slope into inland depressions where marsh grass is sparse or completely absent (Kirby and Gosselink 1976; DeLaune and Patrick 1979). From the streamside location two sediment cores were taken 7 m inland and 5 m apart parallel to Bayou Ferblanc (Fig. 1). Another set of two cores was taken 45 m inland and 5 m apart parallel to the same stream. A third set of two cores was taken 350 m apart in adjacent Airplane Lake, a shallow 19 ha lake. The cores were collected from the same location where sedimentation rates were determined using ¹³⁷Cs distribution through sediment profile (DeLaune et al. 1978). Cores were obtained by twisting a thin-walled aluminum cylinder 15 cm diameter and 53 cm depth into the marsh soil

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or lake bottom. Compaction was minimal using these relatively large diameter thin-walled cylinders. The sediment was sectioned into 3-cm layers, dried, ground, and well mixed. Bulk density was determined from oven-dry sediment weight in the known volume of each section.

Shallow porcelain pans (37 cm length × 23 cm width × 6.5 depth) were used for capturing sediment which was being transported by tidal water or wind driven currents across the marsh surface. The sediment traps were placed at each location on the marsh from which the sediment cores were taken. The pans were pushed 3.5 cm into the marsh surface allowing the sides of the pans to extend 3 cm above the surface. Only suspended sediment from the water column was trapped. The traps were left on the marsh for 3 months (March thru May). Water currents were not strong enough to remove the lighter material from the traps over this period. The collected sediment was first passed through a 35 mesh sieve to remove any macro organic material, then dried and analyzed for total plant nutrients and heavy metals.

Organic carbon content of sediment from the cores and sediment traps was determined by dry combustion in a carbon train and trapping carbon dioxide. Total nitrogen was determined by the Kjeldahl method. Total elemental content of the samples was determined after digesting the dry sediment samples in nitric-perchloric-hydrofluoric acid mixture (Jackson 1958) using teflon beakers. Reagent blanks were carried out to determine the contamination from glassware, reagents and sample handling. Copper, Fe, K, Mn, and Zn were analyzed by flameless atomic absorption spectrophotometer (Perkin Elmer Model 360). Cadmium and Pb were analyzed by flameless atomic absorption spectrophotometer equipped with a background corrector (Perkin Elmer Model #360) utilizing graphite furnace (Perkin Elmer Model 2100). Phosphorus was determined by the molybdate blue method using ascorbic acid (Watanabe and Olsen 1965). Duplicate analyses of all elements were determined for each section of duplicate cores. For the average values obtained from each corresponding section of duplicate cores taken at each of three
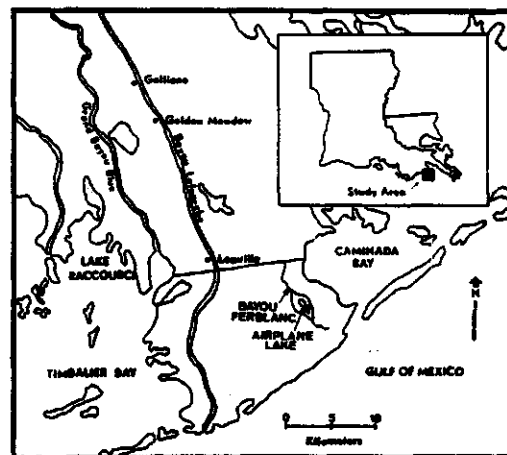

Fig. 1. Location map of study area.

locations, simple correlation coefficients were calculated between N, P, K, Fe, Mn, Zn, Cu, Cd, Pb, organic carbon, mineral matter, depth and bulk density. Mineral matter was determined from difference between organic matter content and weight of sediment. Analytical results for streamside and inland marsh and Airplane Lake, including standard deviations for the 0–3 cm section, are reported in Tables 1–3, respectively.

Results and Discussion

Sedimentation rates determined by ^{137}Cs dating have shown that the study area is vertically accreting at a rapid rate (DeLaune et al. 1978). The marsh nearer the stream is accreting at a rate of 1.35 cm per yr. The inland marsh is accreting at a slower rate (0.75 cm per yr) and the lake is accreting at a rate of 1.10 cm per yr. The accretion rates for the marsh approximately equal the subsidence rate of 1.28 and 1.12 cm per yr reported by Swanson and Thurlow (1973).

Bulk density of the marsh soils ranged between 0.3 g per cm³ and 0.10 g per cm³ depending on depth and location. The streamside marsh which is receiving more mineral sediment had an average soil density of 0.25 g per cm³ as compared to 0.20 g per cm³ for the inland marsh (Table 1). Regression analysis showed that there was no statistically significant change in bulk density with depth at both marsh locations. Density of the lake sediment significantly

TABLE 1.   The vertical distribution of plant nutrients and heavy metals in a streamside marsh.

Depth (cm)	N	P	K	Fe	Mn	Cd	Pb	Cu	Zn	% Organic Carbon	% Mineral Matter	Bulk Density (g per cm³)
		mg per g					µg per g					
0–3	6.31	0.67	3.01	20.9	125	1.9	30	20	65	9.4	83.8	0.25
3–6	6.09	0.54	3.03	18.8	111	1.9	24	19	61	9.0	84.6	0.27
6–9	5.99	0.54	3.04	18.21	108	1.9	26	22	63	10.3	82.4	0.24
9–12	6.20	0.52	2.99	17.63	103	2.0	29	21	61	11.5	80.2	0.24
12–15	6.57	0.47	2.82	16.72	99	2.0	30	21	65	12.0	79.3	0.23
15–18	5.06	0.47	2.99	17.38	106	2.5	30	19	65	8.7	85.0	0.34
18–21	5.63	0.44	3.05	18.84	111	2.1	30	19	73	9.6	83.6	0.27
21–24	5.97	0.45	3.06	18.74	115	2.0	29	18	68	10.4	82.2	0.27
24–27	5.99	0.43	3.09	18.74	113	2.0	30	17	66	11.0	81.1	0.28
27–30	6.12	0.44	2.83	18.74	113	1.6	26	16	68	11.5	80.3	0.26
30–33	6.50	0.44	2.95	17.63	110	1.8	24	16	58	11.9	79.6	0.23
33–36	5.41	0.44	2.91	15.66	113	1.6	24	15	51	10.9	81.3	0.27
36–39	7.57	0.49	2.69	15.03	108	1.8	26	16	50	14.4	75.3	0.21
39–42	7.03	0.51	2.78	16.19	115	2.0	26	17	56	14.1	75.8	0.22
42–45	6.94	0.50	2.46	16.91	111	1.8	24	17	50	13.0	77.3	0.23
Average	6.23	0.49	2.91	17.74	111	1.9	27	18	61	11.2	80.8	0.25
SD (0–3 cm)	±0.03	±0.04	±0.06	±0.28	±1.41	±0.07	±0.71	±0.71	±1.41	±0.14	±0.21	±0.00

(r = 0.756**) (**stands for significance at 1% level; where * stands for 5% level of significance) increased from 0.45 g per cm³ at the surface to approximately 0.65 g per cm³ at 45 cm depth. From density and carbon content of the sediment profile, along with vertical accretion rates determined by ^{137}Cs dating it is shown that the area has vertically accreted through organic detritus accumulation and sediment input. The lake is receiving a larger amount of mineral sediment than the adjacent marsh (Table 4).

The inland marsh contained an average carbon content of 15.6% compared to 11.2% for the streamside marsh (Tables 1, 2, and 3). There was significant increase in organic carbon content with depth at both inland and streamside locations (r = 0.752**; 0.722**). Airplane Lake sediment contained 3.8% organic carbon which was uniformly

TABLE 2.   The vertical distribution of plant nutrients and heavy metals in an inland marsh.

Depth (cm)	N	P	K	Fe	Mn	Cd	Pb	Cu	Zn	% Organic Carbon	% Mineral Matter	Bulk Density (g per cm³)
		mg per g					µg per g					
0–3	6.97	0.71	2.92	17.91	120	1.8	28	18	67	8.9	84.8	0.24
3–6	7.23	0.54	2.45	15.18	104	1.9	28	17	63	10.1	82.7	0.25
6–9	6.47	0.51	2.77	13.75	87	1.9	27	15	55	11.6	80.1	0.23
9–12	6.80	0.49	2.64	14.78	86	1.6	25	15	61	11.1	80.9	0.26
12–15	7.33	0.45	2.50	16.56	87	1.7	25	16	60	13.5	76.7	0.25
15–18	8.95	0.46	2.67	16.26	87	1.9	25	15	59	15.9	75.2	0.22
18–21	9.80	0.44	1.98	11.44	72	1.6	22	12	45	16.7	71.3	0.18
21–24	12.13	0.47	2.35	12.35	87	1.8	22	12	40	20.7	64.3	0.13
24–27	8.41	0.48	2.69	13.59	101	1.6	24	13	44	15.6	73.1	0.16
27–30	3.07	0.42	3.11	11.56	95	2.0	21	9	40	5.4	90.7	0.46
30–33	8.54	0.50	2.45	12.16	87	1.8	22	13	48	16.9	71.0	0.17
33–36	8.26	0.45	2.66	12.10	85	1.8	21	12	49	16.7	71.4	0.18
36–39	12.55	0.38	1.55	8.24	61	1.5	16	11	35	23.9	59.4	0.12
39–42	12.03	0.50	1.92	10.98	78	1.6	21	13	42	21.8	62.5	0.12
42–45	12.66	0.51	1.83	9.48	73	1.5	19	12	36	25.4	56.4	0.13
Average	8.75	0.49	2.43	13.09	87	1.7	23	13	50	15.6	73.4	0.20
SD (0–3 cm)	±0.05	±0.01	±0.02	±0.06	±2.12	±0.07	±0.71	±0.71	±0.71	±0.14	±0.35	±0.01

TABLE 3. The vertical distribution of plant nutrients and heavy metals in Airplane Lake.

Depth (cm)	N	P	K	Fe	Mn	Cd	Pb	Cu	Zn	% Organic Carbon	% Mineral Matter	Bulk Density (g per cm³)
		mg per g						μg per g				
0–3	3.53	0.58	3.12	22.19	193	1.5	30	16	69	4.4	92.6	0.46
3–6	3.16	0.55	3.01	21.50	224	2.0	24	16	67	4.2	92.9	0.51
6–9	3.04	0.56	3.10	22.84	226	1.8	27	17	71	4.0	93.1	0.47
9–12	2.81	0.55	3.19	22.84	227	2.5	27	16	69	4.0	93.2	0.47
12–15	2.53	0.49	3.11	22.84	267	2.3	27	14	69	3.7	93.6	0.56
15–18	2.42	0.49	3.00	20.88	276	2.0	27	14	67	3.7	93.6	0.52
18–21	2.15	0.52	3.13	22.19	258	2.3	27	13	67	3.6	93.9	0.60
21–24	2.02	0.51	3.14	22.84	258	2.3	30	12	66	3.4	94.2	0.64
24–27	1.93	0.51	3.16	20.88	253	2.0	30	13	63	3.3	94.4	0.67
27–30	1.98	0.49	3.12	19.63	239	1.8	27	11	62	3.4	94.3	0.62
30–33	2.14	0.49	3.14	19.63	244	1.8	27	12	63	3.6	93.9	0.63
33–36	2.18	0.53	3.09	20.88	246	2.0	30	12	65	3.8	94.4	0.61
36–39	2.16	0.53	2.81	20.88	262	2.0	27	12	65	4.3	92.6	0.58
39–42	2.51	0.49	3.19	18.44	235	2.0	27	11	58	3.5	93.2	0.61
42–45	2.26	0.47	2.89	19.63	244	1.5	30	12	62	3.6	93.8	0.62
Average	2.46	0.52	3.08	21.20	243	2.0	28	13	66	3.8	93.4	0.57
SD (0–3 cm)	±0.02	±0.01	±0.01	±0.01	±2.12	±0.00	±0.71	±0.00	±2.12	±0.00	±0.14	±0.01

distributed throughout the profile. Organic matter the lake was more decomposed than that of the marsh which contained identifiable remains of dead plant material.

The inland marsh also contained more nitrogen than the streamside marsh (8.75 mg per g compared to 6.23 mg per g). The higher nitrogen level was associated with higher organic matter content at the inland location. There was a significant increase (r = 0.564*) in nitrogen with depth in the inland marsh which corresponded to the greater organic matter content found at lower depths. Sediment from the lake contained less nitrogen (2.46 mg per g) than the adjacent marsh, which reflected a lower organic carbon level.

Phosphorus concentrations were approximately the same at each location with 0.49, 0.49, and 0.52 mg per g respectively for the streamside, inland marsh, and Airplane Lake. A significant decrease (r = 0.517*; 0.543*; 0.700**) in phosphorus concentration with depth was observed at each location. Phosphorus concentrations in the profiles of both the streamside and inland marsh were not correlated with either organic carbon or mineral matter. The dominant mechanism of most nutrient removal from marsh soils is the uptake of nutrients by marsh grasses through their root systems followed by release of some of these nu-

trients to water through excretion from stem and leaves of living marsh plants and through microbial decompositions of dead plant material. Pomeroy et al. (1969) reported Spartina removes phosphorus from the marsh sediment which is removed from the system through detrital export. Reimold (1972) has also shown that Spartina can serve as a nutrient pump and translocate measurable quantities of phosphorus from a salt marsh sediment. Then tidal inundation leaches phosphorus from the leaves. Sediment at the lower depths of the streamside and inland marsh has had more time for

TABLE 4. Accumulation of selected elements and mineral matter.

	Streamside	Inland	Airplane Lake
	———— g per m² per yr ————		
Mineral Matter	2,725.0	1,111.0	5,856.0
C	393.0	237.0	231.0
N	21.0	13.4	15.3
P	1.7	0.8	3.2
K	99.0	32.0	193.0
Fe	60.0	20.0	1,327.0
Mn	3.7	1.3	15.0
	———— mg per m² per yr ————		
Cd	6.0	3.0	12.0
Pb	90.0	35.0	170.0
Cu	60.0	20.0	81.0
Zn	210.0	70.0	400.0

Spartina to remove phosphorus than has the more recently deposited sediment nearer the marsh surface. This observed decrease in phosphorus suggests that phosphorus is being pumped from the system by *Spartina*.

Phosphorus concentrations of the sediment in Airplane Lake decreased with depth (Table 3). Phosphorus concentrations in the sediment were highly correlated (r = 0.751**) with the organic carbon content of the sediment. The decrease in phosphorus with depth is explained by the corresponding decrease in organic carbon content even though the decrease was not statistically significant at the 5% level of probability.

The analytical data for Fe, Mn, Cd, Pb, Cu, and Zn are listed in Tables 1, 2, and 3. Heavy metal concentrations in the streamside and inland marsh as well as Airplane Lake sediment were low indicating a relatively pristine salt marsh. Khalid et al. (1978) also found low concentrations of these metals in sediment from this estuary. The area is apparently 50 km from any heavy industrial activity and five km from the only major road in the area.

Streamside marsh soil with greater densities and more mineral matter contained more Fe and Mn than the lower density inland marsh. Cores taken from Airplane Lake contained slightly more Fe and two to three times more Mn than the cores taken from the adjacent marsh. The low Mn content, on the order of 100 μg per g, in the inland marsh soils cannot be attributed to dilution by the greater organic matter content of the soil. This suggests that the anaerobic condition existing in the marsh soils is conducive to Mn loss. Carpenter et al. (1975) observed that Mn is released from sediment when pH and dissolved oxygen levels decline in the water column. Reduced forms of Mn are more soluble than oxidized forms (Gotoh and Patrick 1972), and Mn is also more soluble at lower pH. Patrick and DeLaune (1977) have measured soil pH as low as 4.5 in the marsh soil zone of maximum root activity. They attributed the low pH to oxidizing conditions in the *S. alterniflora* root rhizosphere. Appreciable amounts of Mn are taken up by *S. alterniflora*. A significant relationship has been observed between concentrations of Mn in

S. alterniflora plant tissue and *S. alterniflora* biomass (R. D. DeLaune unpublished data). More productive stands of *S. alterniflora* contained greater plant tissue concentrations of manganese. Detrital export thus would tend to remove appreciable Mn from the marsh soils.

Statistically, lesser amounts of Cu (r = −0.858**; −0.759**) and Zn (r = −0.596*; −0.858**) were found in the lower portion of the streamside and inland marsh soil profiles. Larger amounts of Pb were observed only in the surface of the inland marsh soil profile. There was no gradient in the vertical distribution of Cd. The decrease in Zn and Pb with depth is attributed to less mineral material at lower depth and removal through plant uptake rather than to an added input of these elements resulting from the activities of man. The relatively low Pb concentrations compare to Pb concentrations observed by Siccama and Porter (1972) in the preautomotive environment in the deeper profiles of a Connecticut salt marsh. Zinc concentrations were positively correlated with mineral matter content (r = 0.652**; 0.677**) and inversely correlated (r = −0.650**; −0.652**) with organic carbon. Lead was also associated with the sediment's mineral fraction which decreased with depth. The observed decrease in Cu with depth could not be related to changes in mineral or organic carbon with depth in the sediment.

Regression analysis of cores taken from Airplane Lake showed a highly significant decrease only in Cu (r = −0.900**) and Zn (r = −0.846**) with depth. The Cu (r = 0.608*) and Zn (r = 0.547*) were correlated to sediment organic carbon which decreased with depth even though the decrease was not statistically significant (r = −0.464).

Using accretion rates obtained from ^{137}Cs dating and the average elemental concentration in each sediment profile, the annual accumulation of these elements was determined for each location (Table 4). The values reported represent sediment chemical composition after the sediment has been expanded by plant roots and subjected to possible loss through biological and chemical transformations.

The marsh is undoubtedly a sink for nitrogen. Nitrogen is accumulating at rates of

TABLE 5. Nutrient and heavy metal content of sediment caught in sediment traps.

Location	N	P	K	Fe	Mn	Cd	Pb	Cu	Zn	% C
			mg per g				μg per g			
Streamside	6.86	0.69	3.08	18.90	219	2.5	32	24	69	14.8
Inland	6.90	0.68	29.90	16.40	178	2.5	31	22	69	14.3

21 g per m² per yr, 13.4 g per m² per yr, and 15.3 g per m² per yr in the streamside marsh, inland marsh, and Airplane Lake, respectively. The original source of most of this accumulated nitrogen is from the deposited sediment which is rich in organic nitrogen. The organic nitrogen undergoes mineralization releasing NH_4^+ which can be taken by S. alterniflora.

A large portion of the inorganic nitrogen taken up by S. alterniflora remains on the marsh in the organic form. Decomposition of dead plant material is slow in these soils because they remain anaerobic throughout the year. Organic carbon is accumulating at rates of 393 g per m² per yr, 237 g per m² per yr, and 231 g per m² per yr at the streamside marsh, inland marsh, and Airplane Lake, respectively. Using the factor 1.724 to convert organic carbon to organic matter (Wilson and Staker 1932), the equivalent of 678 g per m² per yr, 409 g per m² per yr, and 398 g per m² per yr of organic matter is accumulating. Most of the organic matter exists as an approximately one m thick layer of peat overlying recent Mississippi alluvial mineral sediment.

Net production of S. alterniflora in the marsh surrounding Airplane Lake was estimated to be equivalent to 510 g carbon per m² per yr and productivity by phytoplankton in the lake itself was 198 g carbon per m² per yr (Stowe et al. 1971). This productivity estimate for the marsh is conservative because productivity of belowground plant biomass was not included. Comparison of productivity to the amount of carbon accumulating in the system, shows that a significant portion of the carbon from primary production is remaining on the marsh.

Phosphorus was accumulating at rates of 1.7, 0.8, 3.2 g per m² per yr in the streamside marsh, inland marsh, and Airplane Lake, respectively. Sedimentation processes are supplying adequate amounts of phosphorus for plant growth. A portion of the phosphorus associated with the incoming sediment with time becomes available to S. alterniflora.

Large amounts of potassium are accumulating in this estuarine ecosystem. Levels of potassium present in the marsh soil are adequate for plant growth. The streamside marsh is accumulating more potassium than the inland marsh because of a faster deposition of mineral material. Potassium was associated with the mineral component of the sediments. Sediment in Airplane Lake which had a higher bulk density and more mineral material than the marsh soil was accumulating potassium at a rate of 193 g per m² per yr (see Table 4).

Greater iron and manganese accumulation were associated with locations receiving larger mineral sediment inputs. Only small amounts of manganese were accumulating in the streamside and inland marsh. Manganese content of the sediment in these organic marsh soils was low compared to concentrations in recent Mississippi alluvial sediment which was the original source of sediment to the salt marsh.

Nitrogen and phosphorus content of sediment retained in the sediment traps placed on the marsh showed that sedimentation can be an important source of nutrients (Table 5). The equivalent of 23 g per m² per yr of nitrogen and 2.3 g per m² per yr of phosphorus is being supplied to the streamside marsh through sedimentation processes at the streamside marsh. These figures were calculated from the N and P content of the incoming sediment caught in the traps and the bulk density of the marsh soil at the 0–3 cm depth along with the vertical accretion rate of 1.35 cm per yr obtained from ^{137}Cs dating. Sedimentation is also supplying a large amount of nutrients to the inland marsh. The phosphorus concentrations of the incoming sediment at both the streamside and inland marsh were greater than the average phosphorus concentration in the local sediment profile.

Sediment retained in the traps placed on

the streamside and inland marsh also contained more Mn, Cd, Pb, Cu, and Zn than did sediment in lower sections of the soil profile. This suggests that these elements are being mined by *S. alterniflora* and released into the ecological food web. For example, concentrations of Cu and Zn in *S. alterniflora* plant tissue at these locations are 4.4 μg per g and 12.8 μg per g respectively (R. D. DeLaune, unpublished data). Using aboveground dry matter productivity of 1,509 g per m^2 per yr aboveground biomass (Stowe et al. 1971) for the streamside marsh, the equivalent of 6.6 mg per m^2 Cu and 19.3 mg per m^2 Zn would annually be incorporated into *S. alterniflora* plant tissue. Assuming 50% of primary production is annually exported from the marsh in the form of detritus, the equivalent of 3.2 mg per m^2 of Cu and 9.7 mg per m^2 per yr of Zn would annually be removed by this process. This loss is equal to approximately 3% and 5% respectively of the annual Cu and Zn accumulating in the marsh.

Sediment input contributes to vertical marsh accretion which is important in keeping the marsh intertidal. The most probable source of the nutrient enriched sediment being deposited on the marsh surface is resuspended sediment from other environments within Barataria Basin, because the basin receives no significant riverborne sediment supply. The resuspended sediment is rich in plant nutrients which supplies nutrients for marsh plants which in turn enhance further sediment entrapment and stabilization. Productivity of *S. alterniflora* is greater in soils with greater bulk density, a result of greater mineral sediment input (DeLaune et al. 1979). A portion of the inorganic nitrogen and phosphorus incorporated in plant tissue is recycled and made available to succeeding years' plant growth. A large portion of the organic matter from primary production remains on the marsh, contributing to the aggradation processes of vertical marsh accretion. This helps compensate for a rapid subsidence rate due to compaction and dewatering of a several hundred-foot layer of recent Mississippi River alluvial sediment underlying the marsh surface.

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11.   Methane Release from Gulf Coast Wetlands

by

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Methane release from Gulf coast wetlands

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ABSTRACT

A seasonal study of methane release from adjoining salt, brackish and fresh marsh sediment and the adjacent open water areas in Louisiana's Barataria Basin indicates that methane emission is a significant process in the carbon and energy flow of the ecosystem. Methane emission was inversely related to salinity and sulfate concentration, with methane increasing and salinity and sulfate decreasing with increasing distance from the coast. The annual amounts of methane evolved were 4.3, 73 and 160 g C m^{-2} for the salt, brackish and fresh marshes, respectively. In vitro experiments show that methane production is sensitive to the addition of sulfate, high concentrations (10 mM SO_4) inhibiting methane evolution.

1. Introduction

Louisiana's coastal zone comprises more than 3.2×10^6 hectares of marshes and estuaries, representing 41% of the total coastal marsh area of the United States (Turner and Gosselink, 1975). Barataria Basin, in which this study was conducted, is an interdistributary basin bounded on the east by the Mississippi River and on the west by Bayou Lafourche. In recent years the basin has been deprived of riverine deposits through natural stream diversion and flood control measures. Barataria Basin is thus a well-defined hydrologic unit containing more than 371.914 hectares of marsh and open water area (Day *et al.*, 1973). Salinity decreases with increasing distance from the coast. Freshwater marsh covers 19% of the basin. Brackish and intermediate marsh cover approximately 20% of the basin. Salt marshes near the coast cover approximately 14% of the basin and are widely interspersed with open water bodies.

Recently there has been increased interest in the role coastal marshes play in the overall global carbon cycle. Methane production in anaerobic environments such as coastal wetlands and subsequent release to the atmosphere is an important process which needs to be quantified. It has been suggested that the oxidation of methane may provide a source of water for the upper atmosphere and may regulate ozone concentration to some extent as a result of its interaction with the OH radical and carbon monoxide cycles (Sze, 1977). Methanogenesis is also a significant process with respect to carbon and energy flow in wetland ecosystems (King and Wiebe, 1978; Rudd and Taylor, 1979).

Over 80% of the methane in the atmosphere is reported to be produced by microbial activity in anaerobic environments. It is estimated that 280×10^{12} g CH_4 yr^{-1} is produced annually in flooded rice soils (Ehhalt, 1973). Global methane production of swamps and marshes have been estimated to be relatively few in situ measurements of methane production published.

In this paper we present data quantifying seasonal fluxes of methane from Barataria Basins fresh, brackish and salt marshes and adjoining water bodies along a salinity gradient perpendicular to Louisiana's Gulf coast.

2. Materials and methods

The emission of methane was measured from the three predominant marsh types found within Barataria Basin (Fig. 1). Properties of the sediment
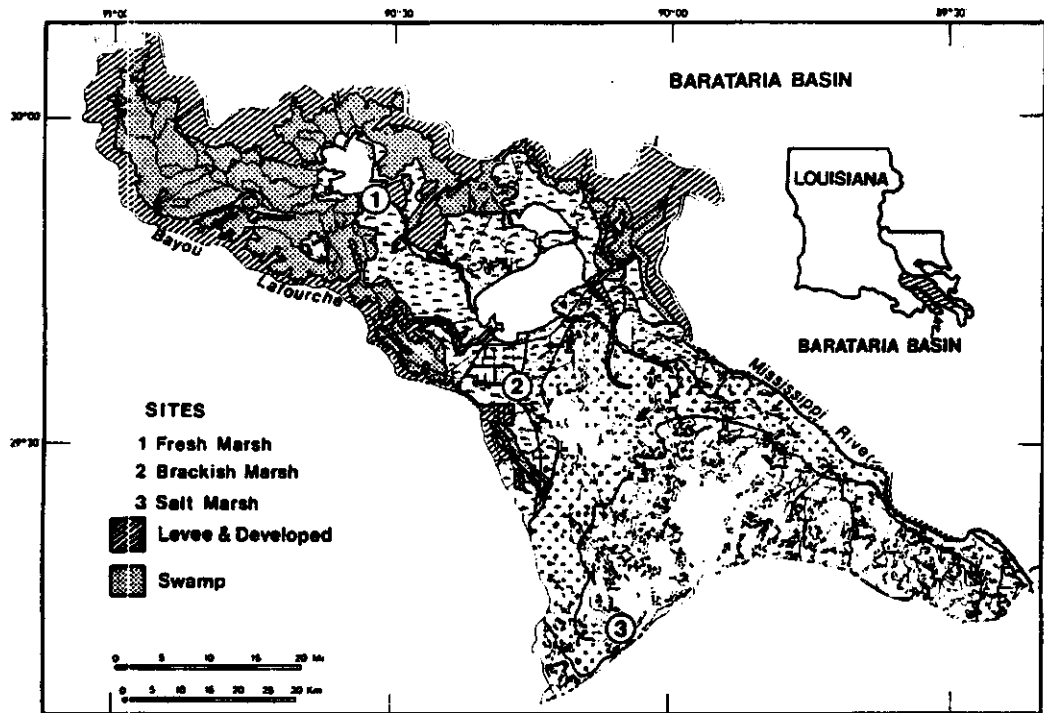
Fig. 1. Location of study area.

are shown in Table 1. *Spartina alterniflora*, *Spartina patens* and *Panicum hemitomon* are the most abundant plant species found in the salt, brackish and fresh marshes, respectively. These marshes have been described extensively elsewhere (Kolb and Van Lopik, 1966; Day et al., 1973). Methane emissions from each marsh environment and their adjacent open water areas were determined at approximately 6-week intervals during 1980 and 1981.

The vertical methane flux density was estimated by monitoring accumulation of the gas beneath chambers placed over the water or sediment surface, for a maximum of 2 hours. A similar chamber technique has been used by King and Wiebe (1978) and Oremland (1975) to estimate methane emission. Triplicate determinations were made in the fresh and salt marshes and duplicate determinations in the brackish marsh on each sampling date. The chambers were fabricated from

Table 1. *Sediment properties of the three predominant marshes of Barataria Basin*

| | | | | | | Sulfide | |
| | | | | | | Free | Combined |
Marsh type	pH	Organic C %	Density g cm^{-3}	Chlorinity %	Sulfate μg cm^{-3}	μg cm^{-3}	μg cm^{-3}
Spartina alterniflora (Salt)	7.2	8.6 ± 1.8	0.3	10	20*	20	16
Spartina patens (Brackish)	7.1	18.6 ± 3.4	0.1	1	<1	6	4
Panicum hemitomon (Fresh)	6.3	23.1 ± 4.2	0.1	0.2	<1	0.8	1.0

* Average concentration from 0–50 cm.

aluminum cylinders, 41 cm internal diameter and had an effective internal height of 10 cm above the water or sediment surface. If water was covering the marsh, chambers 15 cm tall were used. These chambers were supported by styrofoam collars positioned such that 5 cm extended below the air-water interface. When the marsh was drained the chambers were placed on permanent bases previously installed in the marsh to minimize the physical disturbance of the sediment. The permanent bases were constructed from p.v.c. pipe (5 cm length, 36 diameter) pushed into the sediment and a top plate (washer shaped) which had a 2 cm × 1 cm deep U-shaped groove. Water was placed in this groove to provide a seal between the chamber and the base.

The chambers were shaded at all times thereby minimizing the air temperature increase within the chamber during the flux measurement. The chamber used on the open water bodies was insulated with liquid foam and covered with a reflective space blanket. The tops of the chambers were fitted with an air sampling port constructed from a 0.6 cm Swagelok bulk-head union modified for gas-chromatographic septum penetration, and a vent port constructed from a 1.2 cm Swagelock bulk-head union. An open-ended tube (0.6 cm o.d. × 100 cm L) was attached to the vent port, thereby allowing pressure equilibration without entry of outside air during sampling. Aliquots (10 cm³) of the atmosphere within the chamber were withdrawn at 10 min intervals (0–120 min) into glass syringes, greased with Apeizon N and sealed with Pharmaseal Teflon 3-way plastic valves (Dowdell et al., 1972). The samples were collected by passing an 8 cm hypodermic needle through the air sampling port.

The methane content of the gas samples was measured on a Varian 3700 gas chromatograph equipped with a flame ionization detector. The air samples were injected using a heated gas sampling valve (40 °C) with a 0.25 cm³ sampling loop onto a Porapak N column (80/100 mesh; 5 m, L. by 0.2 cm, i.d.) maintained at 50 °C. The carrier gas was dinitrogen and the flow rate was controlled at 30 cm³ min⁻¹. Peaks were integrated on a Varian CDSIII integrator and compared to standards. Methane fluxes were computed from the concentration increase within the headspace of the chamber (Smith et al., 1981).

Methane production as affected by sulfate concentration cf the floodwater was determined by incubating sediment samples in the laboratory. Cores (15 cm diameter) were collected from the brackish marsh October 7, 1980 and the upper 15 cm of each core transferred to plexiglass cylinders (15 cm i.d., 30 cm L.) closed at one end. The cores were returned to the laboratory and incubated at 25 °C. The floodwater was drained after a 2-week preincubation period and duplicate cores were flooded with 500 cm³ either of distilled water, 1 mM Na_2SO_4 or 10 mM Na_2SO_4. The plexiglass cylinders were sealed and laboratory air passed through the headspace at 50 cm³ min⁻¹. After 720 hours the floodwater was removed and the corresponding fresh solutions re-applied. Dextrose was added to all cores at the rate equivalent to 27 mmoles C/core.

The emission of methane was determined by monitoring the incoming and outgoing air stream. Air samples (10 cm³) were taken in all glass syringes twice daily. The methane evolution was computed by integration of the difference between the incoming and outgoing concentration with time and shown as the cumulative carbon production.

Salinity measurements were obtained using a YSI model 33 SCT meter. Sulfate was determined by the turbidiometric method (Tabatabi, 1974) and sulfide by the procedure outlined by Connell and Patrick (1966). Organic carbon was determined by dry combustion trapping the carbon dioxide evolved.

3. Results

The seasonal emission of methane from the three marshes studied are shown in Figs. 2, 3 and 4. The average daily methane emissions from the salt, brackish and fresh marshes were 12, 200 and 440 mg C cm⁻², respectively. Not shown in Figs. 2, 3 and 4 is the spatial variability of the CH_4 flux measurements. Points plotted in the figures represent the mean of three individual determinations having coefficients of spatial variability averaging 58, 70 and 62 over the 13 sampling dates for the salt, brackish and fresh marsh respectively. Similar diversity in field flux measurements has been reported for CH_4 (King and Wiebe, 1978) and N_2O (Mosier and Hutchinson, 1981; Bremner et al., 1981).

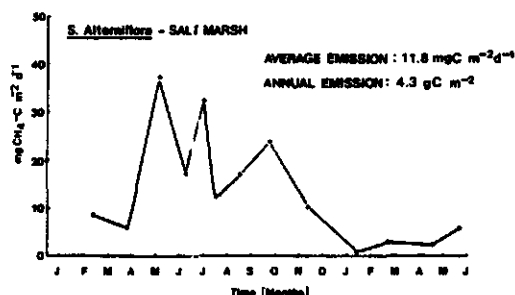The methane emission increased with increasing

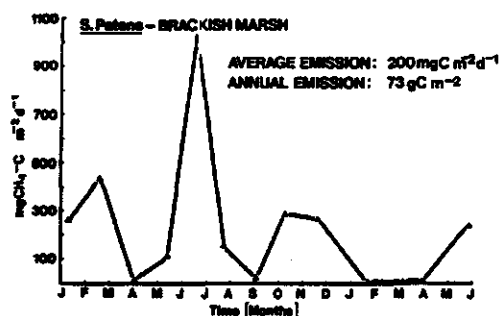Fig. 2. Seasonal methane release from salt marsh during 1980-1981.

Fig. 3. Seasonal methane release from brackish marsh during 1980-81.
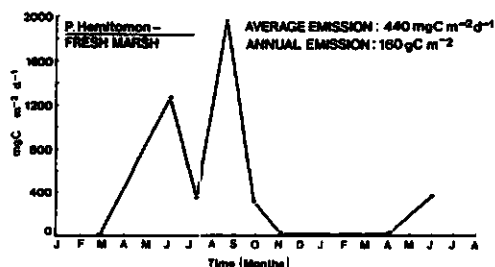

Fig. 4. Seasonal methane release from fresh marsh during 1980-1981.

distance from the coast and was equivalent to an average annual loss of 4.3, 73 and 160 g C m^{-2} respectively for the salt, brackish and fresh marshes. The evolution from the fresh and brackish marsh during the summer period was significantly greater than the evolution from the salt marsh. Although the average evolution from the fresh marsh was greater than the evolution from the brackish marsh the difference was not significant ($P \leq 0.05$). There was however an apparent seasonal trend in the methane evolution from all three marshes, which was found to be statistically

significant. Methane emission from the marsh sediment to the atmosphere was greater during the summer months as compared to the winter months (Figs. 2–4). Other investigators have also reported the flux of methane to be a function of temperature both in situ and in vitro (King and Wiebe, 1977; Baker-Blocker et al., 1977; Koyama, 1963).

There was considerably less methane evolution from the open water bodies adjacent to the three marsh sites (Table 2). The open-water bodies adjacent to the marshes had a depth of approximately 100 cm as compared to an average depth of less than 10 cm of water overlying the marsh. Thus potentially a greater amount of methane escaping from the bottom sediment could have been oxidized to carbon dioxide because of this greater depth. The methane fluxes from the open water sites also increase with distance from the coast ranging from 3.6 mg C m^{-2} d^{-1} at the salt water site near the coast to 37 mg C m^{-2} d^{-1}. Average chlorinity levels at each site range from 10% in the salt marsh to 1% and 0.2% for the brackish marsh and freshwater marsh. Calculations using soil density data and percent organic carbon shows the organic carbon content in the three marsh sites studied are essentially the same, ranging between 19 and 23 mg C cm^{-3}. Volume expression of organic carbon is more realistic as allowance is made for variation in mineral sediment content between the three marsh environments. Both soil sulfide and sulfate levels were greatest in the salt marsh nearer the coast which contained the higher salinity levels (Table 1). The salt marsh soils contained a total of 36 μg cm^{-3} of acid soluble (combined) and free sulfide. In contrast the fresh water marsh contained a total of 1.8 μg cm^{-3} of free and combined sulfide. Sulfate was present throughout the salt marsh soil profile whereas the brackish marsh contained only a trace amount of sulfate in the profile. Sulfate could not be detected in the fresh water marsh soil. The large supply of sulfate in the water overlying the salt marsh apparently was not all reduced to sulfide as it diffused into the soil profile as indicated by the presence of sulfate throughout the sediment profile. In contrast there was less sulfate in the water inundating the brackish and fresh marshes. For these areas the sulfate was removed by sulfate-reducing bacteria as it diffused down the soil profile.

Results of the laboratory studies on the effect of sulfate concentration on methane production from

Table 2. *Diffusive evolution of methane from the open water bodies found within the Barataria Basin*

Location	Measurement period (days)	CH₄ evolution		
		Total mg C m⁻²	Average mg C m⁻² d⁻¹	Annual mg C m⁻²
Salt	507*	1854	3.6	1.3
Brackish	516	6731	13	4.8
Fresh	495	18,550	37	14

* Methane flux determined 13 times during 1980–1981.

cores taken from brackish marshes with and without added dextrose are shown in Figs. 5 and 6. Small additions of sulfate (1 mM) stimulated methane production; however high concentrations of sulfate (10 mM) reduced the methane evolution. The addition of 1 mM sulfate stimulated methane evolution approximately threefold compared to the
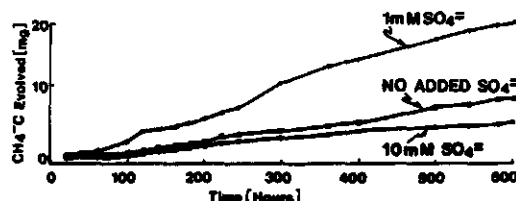
Fig. 5. Effect of added sulfate on methane release from soil cores.
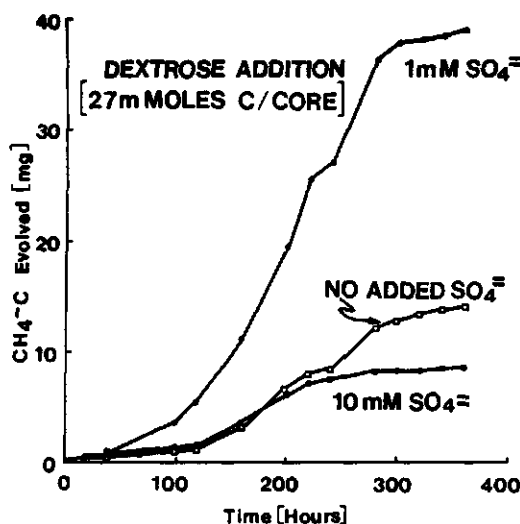
Fig. 6. Effect of added dextrose on methane release from soil cores.

cores that were not amended with sulfate. Dextrose additions increased methane emissions from all treatments. The methane evolution from the 1 mM sulfate treatment averaged 33.3 µg C h⁻¹ and was increased to 108 µg C h⁻¹ following the addition of dextrose. A maximum methane evolution of 412 µg C h⁻¹ was observed between 100 and 280 hours after the addition of dextrose.

The addition of sulfate to pore water has been shown to inhibit methane production in laboratory studies (Winfrey and Zeikus, 1977). Sulfate concentrations of 2 mM inhibited methanogenesis for 10 hours, but 10 mM sulfate caused inhibition for up to 100 hours. The stimulation of methane production from cores amended with 1 mM sulfate could be due to the stimulatory effect low sulfide concentrations have on methanogenesis (Winfrey and Zeikus, 1977). However, high concentrations of sulfide (>100 µg cm⁻³) are inhibitory to sediment methanogensis (Winfrey and Zeikus, 1977; Rudd and Taylor, 1979). Another plausible explanation could be increased carbon dioxide formation, following the addition of sulfate. The carbon dioxide then diffuses to an environment depleted of sulfate where it is converted to methane.

4. Observations

Methanogens are terminal organisms in the anaerobic microbial food chain and utilize potentially toxic compounds produced during anaerobic fermentation. Methane, the final product of their energy metabolism, is a non-toxic relatively mobile substance, and an important component of the carbon cycle in anoxic environments. The methane which is not recycled (Rudd and Taylor, 1979) is

returned to the aerobic biosphere by diffusion or ebullition. Methane can also escape to the atmosphere through plants. In this study the marsh vegetation was clipped prior to placing the diffusion chamber over the marsh. We do not believe methane fluxes were significantly affected since methane would still have direct passage from the marsh soil through the cut plant stems. Cicerone and Shatter (1981) reported no significant difference in methane flux between cut rice plants and intact rice plants. However, this loss of methane-C has not been included in the carbon balance for Barataria Basin developed by Day et al. (1973).

Methane emission was considerably greater at the marsh site farthest from the coast. We attribute the greater emission to lower sulfate concentrations in the fresh water environment. It has been reported that methane production in sediment is inhibited by sulfate (Martens and Berner, 1974; Cappenberg, 1974). King and Wiebe (1980) also investigated the effect of sulfate depletion in a salt marsh on methane production and found that the production was increased when sulfate was depleted. In this study, environments were selected which exhibited a range in sulfate concentrations. Methane production increased approximately 17 to 38 fold from sulfate depleted environments. However, it should be noted that methane production still occurred in the salt marsh. This is postulated to occur in microzones depleted of sulfate within the sediment (King and Wiebe, 1980; Winfrey and Zeikus, 1977; Whelan, 1974; Sansone and Martens, 1981). Methane release from Georgia salt marshes have been reported to range from 1.0 g CH_4 m^{-2} yr^{-1} (Atkinson and Hall, 1976) to a maximum of 53 g CH_4 m^{-2} yr^{-1} from the higher elevated areas where lower sulfate concentrations exist (King and Wiebe, 1978). Cicerone and Shatter (1981) reported an average methane flux of 0.28 g CH_4 m^{-2} yr^{-1} from a southern California salt marsh. The annual methane evolution from the salt marsh in Barataria Basin is similar to the evolution reported from areas of high sulfate concentrations.

Evolution from the open water bodies to the air was lower than that observed from the marsh itself. The total evolution from the bottom sediment could have been greater than the measured atmospheric evolution due to bacterial methane oxidation within the aerobic water column (Rudd et al., 1974; DeBont et al., 1978; Rudd and Hamilton, 1978). Methane oxidation may also have occurred on the marsh itself; however, King and Wiebe (1978) and Atkinson and Hall (1976) have shown that this process appears to be insignificant at the marsh surface. The possibility of anaerobic methane oxidation by sulfate reducers (Reeburgh, 1976; Davis and Yarborough, 1966) and/or aerobic methane oxidation in the root rhizosphere cannot be excluded.

The methane evolution from the fresh water areas is similar to the methane evasion estimated for Lake Mendota for the 90-day stratified period between June 14–September 14, 1977. The methane evasion to the atmosphere was reported to be 181.7 mmol C m^{-2} which is equivalent to a daily atmospheric emission of 24 mg C m^{-2} (Fallon et al., 1980). The average daily atmospheric emission from the fresh water lake within Barataria Basin was calculated to be 37 mg C m^{-2}. Maximum emissions of 250 mg C m^{-2} d^{-1} and minimum emissions of 5 mg C m^{-2} d^{-1} were measured. Similarly daily emissions ranging from 69–383 mg C m^{-2} have been observed from Michigan wetlands (Baker-Blocker et al., 1977). These reported fluxes possibly overestimate the atmospheric emission because the gas collector was positioned below the air-water interface, thus possibly reducing methane oxidation within the water column.

5. Concluding remarks

Louisiana's Barataria Basin is apparently an important source of atmospheric methane. Total release is a function of the area of the various marsh types and open water bodies. The portion of Barataria Basin covered by marsh plants evolved considerably more methane than open-water area. The 371,914 hectares (3.71914 × 10⁹ m²) of the basin is composed of 19% fresh marsh (0.71 × 10⁹ m²); 20% brackish marsh (0.74 × 10⁹ m²) and 14% salt marsh (0.52 × 10⁹ m²) (Day et al., 1973). Thus the total annual emission from the fresh, brackish and salt marshes are 2.236 × 10⁹, 5.4 × 10¹⁰ and 1.14 × 10¹¹ g CH_4-C yr^{-1}. respectively. The open water areas of the hydrologic unit totals 1.75 × 10⁹ m² of which 0.73 × 10⁹ m² (41.6%) are in the saline area. The area of the brackish and fresh water bodies is estimated to be 1.022 × 10⁹ m². Thus, the total emission from the open water bodies of the basin is 0.95 × 10⁹ g CH_4-C yr^{-1}. respectively. The total methane emission from the Barataria hydro-

logic unit (marsh + open water) is 1.8×10^{11} g C
yr⁻¹. The flux of methane represents a loss equiv-
alent to approximately 0.6% (0.3–1.4) of the
reported annual carbon fixed (Kirby and
Gosselink, 1976; White et al., 1978; Hopkinson et
al., 1978) in the aboveground portion of the plants
in the salt (S. alterniflora) marsh. The emission of
methane from the brackish (S. patens) marsh
represents a loss of carbon equivalent to 3 to 10%
of the reported fixed carbon, depending on the
productivity estimate used. No published estimate
of the productivity of P. hemitomon is available for
Barataria Basin. These losses compare with the 5%
conversion reported by Ehhalt (1974) for swamps.

The global methane production of swamps and
marshes has been estimated to be 143–225 $\times 10^{12}$
g C yr⁻¹ (Freyer, 1979). Thus the methane
emission from the Barataria hydrologic unit repre-
sents approximately 0.1 ± 0.02% of the global
methane emission. Extrapolation of the data for
the Barataria Basin as typical of methane emission
from the wetland areas of the northern Gulf Coast
marshes (Turner and Gosselink, 1975), with the
assumption that the ratio of water bodies to marsh
is constant, indicates that the annual methane
evolution is equivalent to 1.5×10^{12} g CH₄–C or
0.9 ± 0.1% of the global methane emission.

6. Acknowledgement

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12. Carbon Dioxide Emmission and Carbon Accumulation in Coastal Wetlands

by

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Carbon Dioxide Emission and Carbon Accumulation in Coastal Wetlands

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Direct measurements of CO_2 fluxes were made in salt, brackish and freshwater marshes and parallel adjacent open water areas in Barataria Basin, Louisiana. Vertical flux density was determined by monitoring the accumulation of CO_2 in aluminum chambers placed over the water or sediment surfaces. Annual CO_2 fluxes were 418, 180 and 618 g C m^{-2} from the salt, brackish and freshwater marsh, respectively. Water bodies adjacent to the marsh evolved 103, 54 and 242 g CO_2-C m^{-2} yr^{-1} to the atmosphere from saline, brackish and freshwater lakes, respectively. The role these marshes play in serving as a major carbon sink was determined from the carbon content of the sediment, vertical accretion rates and the bulk density of the sediment. Accretion rates were calculated from the depth in the sediment of the 1963 horizon, the year of peak ^{137}Cs fallout. Net carbon accumulation was essentially the same in all three marshes; 183, 296 and 224 g C m^{-2} yr^{-1} from the salt, brackish and fresh marsh, respectively. Data presented suggest a limited net export of carbon from these coastal marshes. A large percentage of fixed carbon remained on the marsh, being immobilized in accretionary processes or lost to the atmosphere as CO_2.

Introduction

There is considerable interest in the role carbon plays in the detritus based food chain of estuarine ecosystems. Carbon dioxide production and subsequent release to the atmosphere are important processes in the overall carbon budget in coastal wetlands and need to be quantified. Carbon dioxide is a product of the biological oxidation of organic carbon by oxygen and/or other electron acceptors such as NO_3^-, and SO_4^{2-}. It includes three biological processes, namely, microbial respiration, root respiration and faunal respiration and a non-biological chemical oxidation, which may be pronounced at high temperatures (Bunt & Rovira, 1954). In waterlogged marsh soils the diffusion of oxygen into the soil is restricted resulting in the formation of a largely anaerobic environment with small aerobic zones at the surface and around roots (Teal & Kanwisher, 1966). Much of the metabolism occurs anaerobically and involves the oxidation of organic carbon to carbon dioxide using the oxygen contained in the SO_4^{2-} ion as the electron acceptor (Jorgensen, 1978).

Respiration or decomposition has been estimated by indirect techniques in marsh soils. The approaches used include the measurement of the disappearance of particulate matter, the consumption of the electron acceptors oxygen or sulfate and the turnover of specific dissolved organic compounds (Christian and Wiebe, 1978; Hackney & de la Cruz, 1980;

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Jorgensen, 1978). Most reports on carbon dioxide evolution are from upland agricultural soils and forest ecosystems (Gupta & Singh, 1981; Reinke *et al.*, 1981). To date there have been few *in situ* carbon dioxide flux measurements from coastal marshes.

Barataria Basin, in which this study was conducted, is an interdistributary basin bounded on the east by the Mississippi River and on the west by Bayou Lafourche. In recent years the basin had been deprived of riverine deposits through natural stream diversion and flood control measures. Barataria Basin is thus a well defined hydrologic unit containing more than 371 914 hectares of marsh and open water (Day *et al.*, 1973). Salinity decreases with increasing distance from the coast. Freshwater marshes cover 19% of the basin and brackish marshes cover 20% of the basin. Salt marshes near the coast cover approximately 14% of the basin and are widely interspersed with open water bodies.

In this paper we present data quantifying seasonal fluxes of carbon dioxide from Barataria Basin fresh, brackish, and salt marshes and adjoining water bodies located along a salinity gradient perpendicular to the Gulf Coast. In addition we identify the role of the aggradation process of vertical accretion in serving as a large carbon sink in Louisiana Gulf Coast marshes.

Materials and methods

The emission of carbon dioxide was measured from the three predominant marsh types found within Barataria Basin (Figure 1). *Spartina alterniflora, Spartina patens,* and
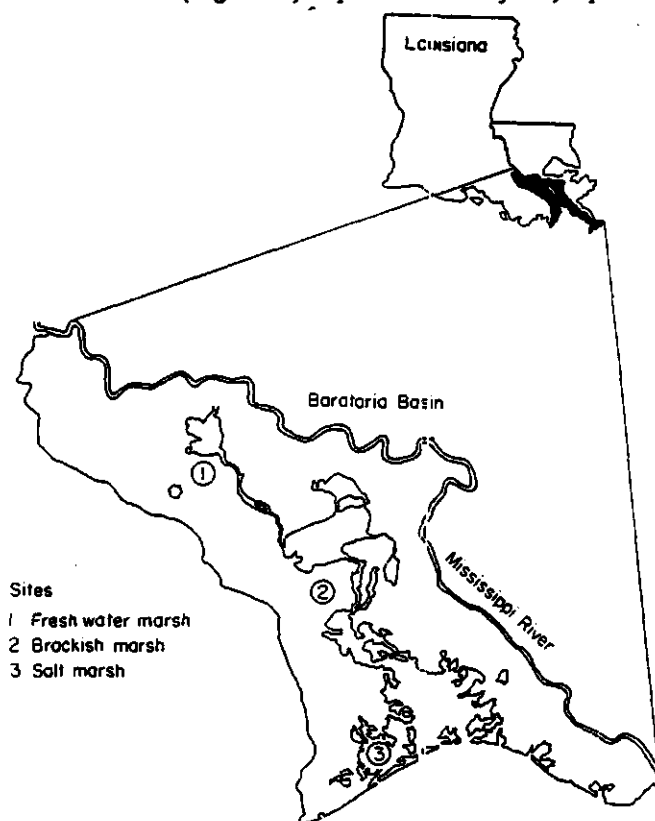

Figure 1. Location of study area.

Panicum hemitomon are the most abundant plant species found in the salt, brackish and freshwater marshes, respectively. These marshes have been described extensively elsewhere (Kolb and Van Lopik, 1966; Day *et al.*, 1973; DeLaune *et al.*, 1982). Carbon dioxide emissions from each marsh environment and their adjacent open water areas were determined at approximately six week intervals during 1980 and 1981.

The vertical carbon dioxide flux density was estimated by monitoring accumulation of the gas beneath chambers placed over the water or sediment surface, for a maximum of one hour (DeLaune *et al.*, 1982). The chambers were light proof which prevented any photosynthesis. A similar diffusion chamber technique has been used by King & Wiebe (1978) and Oremland (1975) to estimate methane emission. Triplicate determinations were made in the freshwater and salt marshes and duplicate determinations in the brackish marsh on each sampling date. The marsh vegetation was clipped and removed prior to making the measurements. The chambers were fabricated from aluminum cylinders, 41 cm internal diameter and had an effective internal height of 10 cm above the water or sediment surface. Chambers 15 cm tall were used for flux determination on the open water bodies and when water was covering the marsh. These chambers were supported by styrofoam collars positioned such that 5 cm extended below the air–water interface. When the marsh was drained the chambers were placed on permanent bases previously installed in the marsh to minimize physical disturbance of the sediment. The permanent bases were constructed from P.V.C. pipe (5 cm length, 36 cm diameter) pushed into the sediment and a top plate (washer shaped) which had a 2 cm × 1 cm deep U-shaped groove. Water was placed in this groove to provide a seal between the chamber and the base.

The chambers were shaded at all times, thereby minimizing the air temperature increase within the chamber during flux measurements. The chambers used on the open water bodies were insulated with liquid foam and covered with a reflective space blanket. The top of the chambers were fitted with an air sampling port constructed from a $0 \cdot 6$ cm Swagelock bulk-head union modified for gas-chromatographic septum penetration and a vent port constructed from a $1 \cdot 2$ cm Swagelock bulk-head union. An open ended tube ($0 \cdot 6$ cm outside diameter × 100 cm long) was attached to the vent port, thereby allowing pressure equilibration without entry of outside air during sampling. The vent port was capped on the chambers used on the open water bodies. Aliquots (10 cm^3) of the atmosphere within the chamber were withdrawn at 10 min intervals (0–60 min) into glass syringes which were greased with Apeizon N and sealed with Pharmaseal Teflon 3-way plastic valves (Dowdell *et al.*, 1972). The samples were collected by passing an 8 cm hypodermic needle through the air sampling port.

Carbon dioxide content of the gas samples was determined on a Varian 3700 gas chromatograph equipped with a flame ionization detector (FID) operated at 340° C and a catalytic conversion unit operated at 400° C (Williams *et al.*, 1972). The catalyst oven was added between the column exit and the FID inlet (Smith *et al.*, 1981). The air samples were injected using a heated gas sampling valve (40° C) with a $0 \cdot 25$ cm^3 sampling loop onto a Porapak N column (80/100 mesh; 5 m long × $0 \cdot 2$ cm internal diameter) maintained at 50° C. The carrier gas was dinitrogen and the flow rate was controlled at 30 cm^3 min^{-1}. Peaks were integrated on a Varian CDSIII integrator and compared to standards. Carbon dioxide fluxes were computed from the concentration increase within the headspace of the chamber (Smith *et al.*, 1981).

Vertical marsh accretion and sedimentation rates in the bottom of adjoining shallow water lakes was determined using ^{137}Cs dating technique (DeLaune *et al.*, 1978). Sedimentation or accretion rates were calculated from the depth in the soil or sediment of the 1963

horizon, the year of peak ^{137}Cs fallout, a result of atomic weapon testing. Cores were taken at each site, sectioned into 3 cm increments, dried and ground, and each sample well mixed. The ^{137}Cs activity in each section was determined by γ counting of the oven-dried sample using a Lithium-drift germanium detector and multichannel analyser. Total carbon content of the sediment was determined by dry combustion. Density was determined from oven-dry sediment in the known volume of each section. The net carbon accumulation was calculated from the carbon content of the sediment, the accretion rate, and the bulk density of the sediment.

Results

Accretion on sedimentation rates in marshes and lake bottoms are shown in Table 1. Net accretion was essentially the same for all marsh types studied, ranging between 0·76 and 1·1 cm yr^{-1}. Calculations using soil bulk density data, accretion rates and organic carbon content show that annual carbon accumulation was essentially the same in all three marshes studied, ranging between 183 and 296 g C m^{-2} yr^{-1}. The annual rates of carbon accumulation was less in the freshwater bottom sediment than in the saline bottom sediment (Table 1). In these computations allowance was made for the variation in the mineral sediment content of the marshes.

TABLE 1. Accumulation rates of carbon and net accretion rates

Marsh type	Site[a]	Accretion rate (cm yr^{-1})	Bulk density (g cm^{-3})	Organic carbon (mg g^{-1})	Carbon accumulation (g C m^{-2} yr^{-1})
Spartina alterniflora	M	0·76 ± 0·12	0·28 ± 0·06	86 ± 16	183
(salt)	B	1·1 ± 0·1	0·57 ± 0·01	38 ± 12	238
Spartina patens	M	0·95 ± 0·05	0·13 ± 0·02	240 ± 32	296
(brackish)	B				
Panicum hemitomon	M	0·85 ± 0·02	0·10 ± 0·04	263 ± 14	224
(fresh)	B	0·52 ± 0·2	0·26 ± 0·05	45 ± 16	60

[a]M—Marsh surface; B—bottom sediment from open water areas.

The seasonal emissions of carbon dioxide for the three marshes are shown in Figures 2, 3 and 4. The average daily carbon dioxide emissions from the salt, brackish and freshwater marshes were 1150, 490 and 1690 mg C m^{-2}, respectively. Not shown in Figures 2, 3, and 4 is the spatial variability of the CO_2 flux measurements. Points plotted in the figures represent the mean of three individual determinations having coefficients of spatial variability averaging 60, 55 and 72 over the 12 sampling dates for the salt, brackish, and freshwater marsh, respectively. Similar diversity in field flux measurements has been reported for CH_4 (King & Wiebe, 1978; DeLaune et al., 1982) and N_2O (Mosier & Hutchinson, 1981; Bremner et al., 1981). The carbon dioxide emission was equivalent to an average annual loss of 418, 180 and 620 g C m^{-2}, respectively, for the salt, brackish, and freshwater marshes (Table 2).

There was an apparent seasonal trend in the carbon dioxide evolution for all three marshes which was found to be statistically significant. Carbon dioxide evolution was directly related to the sediment and air temperature ($P < 0·05$). Generally the carbon
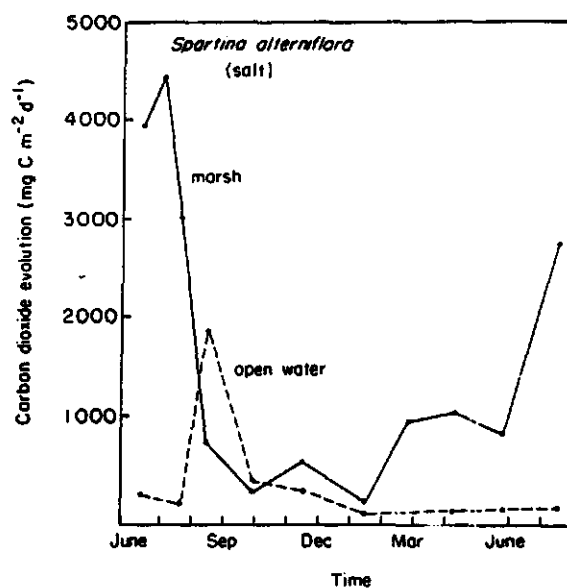
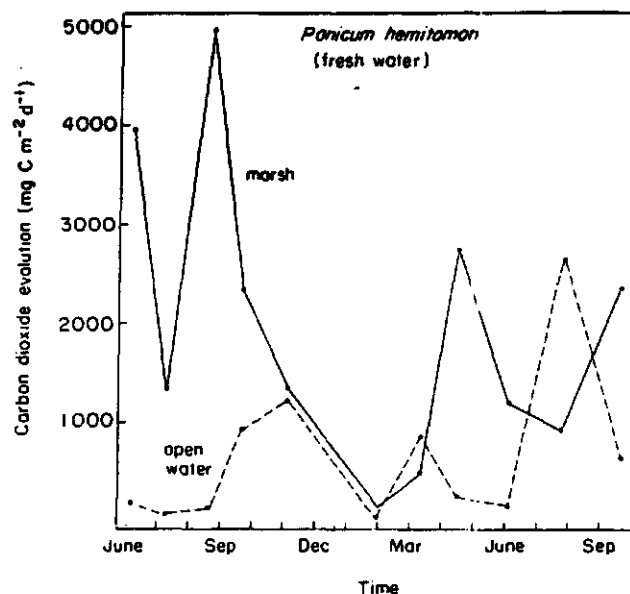Figure 2. Seasonal carbon dioxide release from salt marsh.

Figure 3. Seasonal carbon dioxide release from brackish marsh.

dioxide evolution was greater during the summer period when temperatures were high as compared to the winter months. However, the vertical flux of carbon dioxide to the atmosphere was found to have an inverse relationship with depth of water inundating the marsh ($P < 0.05$). Multiple correlation of carbon dioxide flux *vs* temperature and water depth improved the correlation coefficient, which become highly significant ($P \leq 0.001$).

There was considerably less carbon dioxide evolution from the open water bodies adjacent to the three marsh sites (Table 3). The open water bodies adjacent to each marsh had
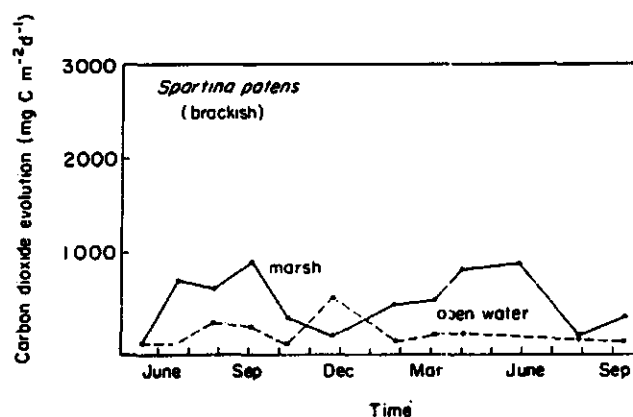
Figure 4. Seasonal carbon dioxide release from freshwater marsh.

TABLE 2. Carbon dioxide emission from the three predominant marsh soils found within Barataria Basin

Marsh type	Measurement[a] period (days)	Carbon dioxide emission		
		total g C m^{-2}	average g C m^{-2} d^{-1}	annual g C m^{-2}
Spartina alterniflora (salt)	396	453	1·15	418
Spartina patens (brackish)	486	239	0·49	180
Panicum hemitomon (fresh)	452	762	1·69	616

[a]Mean of three determinations from each marsh, and the flux determined 12 times during 1980–1981.

TABLE 3. Diffusive emission of carbon dioxide from the open water bodies found within Barataria Basin

Location	Measurement[a] period (days)	Carbon dioxide evolution		
		total g C m^{-2}	average g C m^{-2} d^{-1}	annual g C m^{-2}
Spartina alterniflora (salt)	396	112	0·28	103
Spartina patens (brackish)	486	72	0·15	54
Panicum hemitomon (fresh)	452	300	0·67	242

[a]Carbon dioxide flux determined 12 times during 1980–1981.

an average depth of approximately 100 cm as compared to an average depth of less than 10 cm of water overlying the marsh. Thus potentially a greater amount of carbon dioxide escaping from the bottom sediment would have been dissolved in the relatively deeper water. The average pH of the water ranged from 7·0 in the freshwater lake to 7·5 in the

salt water lake. The carbon dioxide fluxes from the open water sites ranged from 103 mg C m^{-2} d^{-1} at the salt water site near the coast to 242 mg C m^{-2} d^{-1} from the freshwater site. The dissolved carbon dioxide content of the open water was not significantly different among the three sites and ranged from 2 to 14 mg CO$_2$ l^{-1} throughout the year. The total carbon dioxide content of the water ranged from 0·5 to 3·8 g CO$_2$-C m^{-2}.

Discussion

Carbon dioxide is not necessarily the only respiratory product in anaerobic marsh soils and sediments. Under intensely anaerobic conditions carbon dioxide can be further reduced to methane by methanogens. Thus some of the carbon dioxide produced in the anaerobic sediment can be reduced as it diffuses through the sediment. Methane, the terminal product of metabolism is a non-toxic mobile substance and an important component of the carbon cycle in anoxic environments. The carbon dioxide which is not utilized as an electron acceptor is returned to the atmosphere by diffusion or ebullition or could be conducted through the continuous gas spaces from shoots to rhizomes and roots. Oxygen diffuses through these spaces into the sediment (Teal & Kanwisher, 1966), and carbon dioxide could also diffuse to the atmosphere. Although the marsh vegetation was clipped prior to placing the diffusion chamber over the marsh we do not believe the carbon dioxide fluxes were significantly affected since carbon dioxide would still have direct passage from the marsh soil through the cut stems. Cicerone & Shatter (1981) reported no differences in methane flux measured from cut and intact rice plants.

Earlier carbon budgets developed for coastal marshes have not included gaseous carbon fluxes. Gaseous evolution of carbon dioxide and methane was not included in a carbon budget developed for Barataria Basin by Day *et al.* (1973). Similarly, Woodwell *et al.* (1977) did not include gaseous carbon emission in a carbon study of a Northeastern US Flax Pond ecosystem. Data presented in this study show that a significant amount of fixed carbon in the various marshes found in Louisiana Barataria Basin is returned to the atmosphere (Table 2). However not all the carbon dioxide evolved from marsh soil is lost from the soil/plant system, a portion of carbon dioxide evolved is taken up by marsh plants via photosynthetic processes. The contribution of soil carbon dioxide flux to plant photosynthesis has been estimated for various submerged and nonsubmerged plants (Yoshida *et al.*, 1974; Monteith *et al.*, 1964; Nixon, 1980). Soil CO$_2$ contribution to the gross photosynthesis in various upland crops (Monteith *et al.*, 1964) ranged between 10 to 40% and contributed 6% of the CO$_2$ fixed by rice grown under flooded conditions (Yoshida *et al.*, 1974). Nixon (1980) cites 40% of the plant biomass as being produced from carbon dioxide evolved from the surface of a Flax Pond marsh. He reported annual plant production was 500 g C m^{-2}; 200 g C m^{-2} coming from the carbon dioxide evolved from the surface, and 300 g C m^{-2} from new atmospheric carbon dioxide. No value was reported for the total carbon dioxide evolution from the marsh surface and it is not known what fraction of the soil flux this represents. For the marshes under study the total gaseous carbon emission as carbon dioxide and methane can be calculated by summation of the annual fluxes for the two gases. Previously reported annual methane flux for these Barataria Basin salt, brackish, and fresh marshes was 4·3, 73 and 160 g CH$_4$-C m^{-2}, respectively (DeLaune *et al.*, 1982). Thus the total annual gaseous carbon evolution as CO$_2$ and CH$_4$ is equivalent to 422, 253 and 776 g C m^{-2} for the salt, brackish and freshwater marshes, respectively.

Evolution from the open water bodies to the air was lower than that observed for the marsh itself. The total evolution from the bottom sediment was very likely greater than

the measured atmospheric evolution due to the formation of inorganic carbon compounds in the water. Carbon dioxide flux was also less from the marsh when it was inundated with water. The bottom sediment in open water adjoining the marshes are also a sink for organic carbon, the magnitude of which is shown in Table 1. However, significantly more carbon accumulates in the marsh than in the bottom sediment of open water bodies.

Carbon dioxide evolution during the summer months in this study was similar to that reported for flooded rice soils (Yoshida *et al.*, 1974). They found the flux to range from $1 \cdot 6$ to $2 \cdot 4$ g C m^{-2} d^{-1}, whereas emission from the marshes in this study ranged from 1 to 5 g C m^{-2} d^{-1}. The carbon content of the marsh soil in this study was significantly greater than the paddy soil which would result in the increase in the carbon dioxide release. Emissions from forest soils varied from 400 to 510 g C m^{-2} (Reinke *et al.*, 1981) which was greater than the annual evolution from the marsh sediment. Respiration from grasslands has been reported to be 360, 420, and 470 g C m^{-2} y^{-1} (Coleman, 1973; Gupta & Singh, 1981).

Carbon evolution in the salt marsh has been previously estimated by measurement of oxygen consumption (Hopkinson, 1973). The streamside consumption was equivalent to 395 g C m^{-2} y^{-1} and inland consumption equivalent to 260 g C m^{-2} y^{-1} based on measurements in the vicinity of our study site (Hopkinson, 1973). These calculated estimates are similar to the CO$_2$ fluxes reported (418 g C m^{-2} y^{-1}). The net annual marsh production in the vicinity of our site has been calculated to be 1175 g dry wt m^{-2} or 590 g C m^{-2} (Kirby & Gosselink, 1976). Happ *et al.* (1977) used this productivity figure and the carbon emission based on oxygen consumption measurements to estimate organic carbon available for export. They estimated 290 g C m^{-2} y^{-1} to be flushed from the marsh. However, the amount of carbon accumulating during the process of vertical accretion was not included in the calculation. Due to rapid subsidence large amounts of organic material formed from primary production remain on the marsh mainly as peats as part of aggradation processes involved in keeping the marsh intertidal.

The annual carbon accumulation obtained by ^{137}Cs dating and the gaseous evolution data reported in this paper strongly suggests a limited net loss of fixed organic carbon from the Louisiana salt marsh. Marsh accretion processes serve as a sink for 183 g C m^{-2} y^{-1} and an additional 418 g C m^{-2} y^{-1} is evolved from the marsh surface as CO$_2$ and CH$_4$ and a major portion of the CO$_2$ is returned to the atmosphere. These two carbon fluxes closely approximate the net production reported by Kirby & Gosselink (1976) for this particular salt marsh. There is limited productivity data for the fresh and brackish marshes thus it is not possible to make similar estimates of net carbon export from the marsh. The carbon fluxes presented question the traditional view of marshes as large net exporters of fixed carbon. A large portion of carbon fixed in Louisiana Barataria Basin either remain on the marsh mainly as peat deposits or is degraded and released to the atmosphere as carbon dioxide and/or methane. Woodwell *et al.* (1977) showed a tidal marsh on the north shore of Long Island to be a net consumer of chlorophyll throughout the year and a strong heterotrophic system in summer which does not support the conventional view of marshes as a net source of fixed carbon to coastal waters. Haines (1977) studies of δ ^{13}C ratio of organic matter in Georgia estuaries also supports the data presented that fixed carbon is not exported with each tidal inundation.

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13. Carbon Flow in Coastal Louisiana

by

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Carbon flow in coastal Louisiana

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ABSTRACT: Carbon flux data was synthesized to estimate carbon flow along a salinity gradient in Louisiana's Barataria Basin, a major Gulf Coast estuary (USA). Using a mass balance approach, we found an estuarine carbon surplus of 150 to 250 g m^{-2} yr^{-1}, which originated primarily in the tidal salt marsh. Carbon export from marshes to adjacent water bodies decreases with distance from the Gulf of Mexico. The Barataria Basin marshes function as important global carbon sinks within this export gradient. High community respiration, methane emission, and carbon accretion resulting from annual carbon fixation reduce carbon export from the northern part of the basin. Higher primary production, low community respiration, and low methane evolution make the southern part of the basin a source of aquatic carbon.

INTRODUCTION

Many studies and discussions address the export or outwelling of nutrients and organic carbon in Gulf and Atlantic coast estuaries (e.g. Haines 1976, Nixon 1980, Pomeroy & Wiegert 1981, Day et al. 1982, Gosselink 1984, Teal 1984). Direct flux measurements, stable carbon isotope ratios, and marsh carbon budgets have been used to assess the carbon flow.

Recent work on carbon fluxes in fresh, brackish, and saline marshes along Louisiana's Gulf Coast (Hatton et al. 1983, Smith et al. 1983, DeLaune & Smith 1984) provides a basis for increasing understanding of different interconnections between marsh habitats and adjacent water bodies. The mass balance approach previously used to calculate the carbon budget for the Barataria Basin (Day et al. 1982) was subject to high background noise. Using extrapolated data, Day et al. (1977, 1982) estimated wetland export from freshwater and brackish marshes. Numerous studies conducted during the past few years in Barataria Basin make it possible to approach the annual organic carbon budget from a source-sink point of view, considering the adjacent water bodies as transport media (e.g. Day et al. 1982, Smith et al. 1983 DeLaune & Smith 1984, Stow et al. 1985).

Barataria Basin, the area for this study on major carbon fluxes, is an interdistributary Louisiana Gulf Coast estuarine basin (400,000 ha) with well-defined vegetative units bounded on the east by the Missis-

sippi River and on the west by its most recently abandoned channel, Bayou Lafourche (Fig. 1). Several primary vegetative marsh units that generally corre-
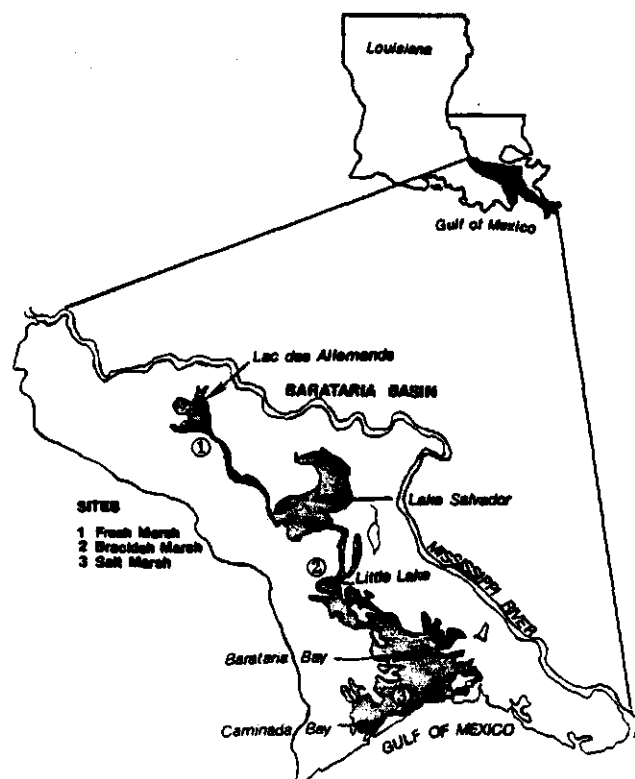

Fig. 1. Fresh, brackish and salt marshes in study area, Barataria Basin

late with substrate type and salinity can be identified within the basin: saltwater marsh, brackish-intermediate marsh, and freshwater marsh (Bahr & Hebrard 1976). Freshwater marsh (salinity ≤ 1 ‰) covers 19 % of the basin and is characterized by *Panicum hemitomon* Schult., *Eleocharis* spp., and *Sagittaria falcata* Pursh. Brackish and intermediate marshes (1 to 10 ‰) together cover approximately 20 % of the basin. The brackish marsh is vegetated largely by *Spartina patens* (Ait.) Muhl., *Distichlis spicata* (L.) Green, and small amounts of *Spartina alterniflora* Lois. The intermediate marsh is characterized by the dominance of *S. patens* and the absence of *S. alterniflora*. Saltwater marsh (> 10 ‰) covers approximately 14 % of the basin; *S. alterniflora* is the dominant vegetation.

Water bodies in the upper basin (Lac des Allemands) are characterized by high primary productivity, pronounced seasonality, and net heterotrophy (Day et al. 1982). The tidal range is 3.2 cm (Byrne et al. 1976), and waters are fresh. The lower basin has a tidal range of 12 cm (Marmer 1948) in the brackish area (Little Lake) and up to 30 cm in the bay (Day et al. 1982), with salinity up to 35 ‰. Autotrophic saline areas are less productive and lack consistent seasonality (Day et al. 1982).

Table 1. Production of major marsh macrophytes in the Louisiana Mississippi River deltaic plain

Species	Peak biomass (g org. matter m^{-2})	Productivity (g org. matter m^{-2} yr^{-1})	Method	Source
Spartina alterniflora	1018	1410	a	(1)
		2645	b	
	754	2658	b	(2)
	1070	1527	a	(3)
		2895	b	
	1080	2160	c	
Spartina patens	1376	2000	a	(2)
		5812	b	
	1350	1342	a	(3)
		1428	b	
	1248–2466	2605–4411	a	(4)
		3056–3464	b	
	1100	1350	c	(5)
Panicum hemitomom	1160	1700	d	(6)
	1200	1500	c	(5)

a Smalley 1958
b Wiegert & Evans 1964
c Barataria Basin study-site estimate
d Lomnincki et al. 1968

(1) Kirby & Gosselink 1976
(2) Hopkinson et al. 1978
(3) White et al. 1978
(4) Cramer & Day 1980
(5) DeLaune & Smith 1984
(6) Sasser & Gosselink 1984

Marsh carbon flows

Primary production

Researchers have reported aboveground production estimates for dominant marsh macrophytes in the Mississippi River deltaic plain over the past decade (Table 1). Aboveground production estimates varied from 1,410 to 2,895 g organic matter m^{-2} yr^{-1} for saline habitats (Kirby & Gosselink 1976, White et al. 1978). Brackish marshes exhibited the highest range of productivity, with values of 1,342 to 5,812 g organic matter m^{-2} yr^{-1} (Hopkinson et al. 1978, White et al. 1978), and freshwater marshes produced between 1,500 and 1,700 g organic matter m^{-2} yr^{-1} (Hopkinson et al. 1978, White et al. 1978, DeLaune & Smith 1984, Sasser & Gosselink 1984). (Spatial variability and the inherent difficulty of measuring net production make it difficult to determine true net primary production, which indicates the need for standardization of productivity techniques.) Hopkinson et al. (1978) pointed out that this higher production rate in brackish marshes is associated with the high biomass turnover rate of *Spartina patens*. Production estimates in Louisiana suggest that the turnover rates are a factor of 1.5 to 4.4 greater than peak standing crop (Kirby & Gosselink 1976, Hopkinson et al. 1978, Sasser & Gosselink 1984). Little data exists in belowground productivity estimates;

estimates of belowground biomass range from 25 % to 90 % for the main delta marsh plant species (Gosselink 1984).

Gaseous carbon emission

Smith et al. (1983) used diffusion chambers to obtain direct seasonal measurements of CO_2 fluxes in salt, brackish, and freshwater marshes in Barataria Basin. They determined vertical flux density by monitoring the accumulation of CO_2 in aluminum chambers placed over the water or sediment surfaces. Annual CO_2 fluxes were 418, 180, and 618 g C m^{-2} from the saltwater, brackish, and freshwater marshes, respectively.

DeLaune et al. (1983) used diffusion chambers in a seasonal study of methane release in sediment from the saltwater, brackish, and freshwater marshes adjoining the basin and the adjacent open water areas, and found that methane emission is a significant process in the carbon and energy flow of the ecosystem. Methane emission is inversely related to salinity and sulfate concentrations; methane increases and salinity and sulfate decrease with increasing distance from the coast. The annual amounts of methane evolved were 4.3, 73, and 160 g C m^{-2} for the saltwater, brackish, and freshwater marshes, respectively.

Carbon sinks

The role of these marshes as a major carbon sink has been determined from the carbon content of the sediment, vertical accretion rates, and the bulk density of the sediment (Smith et al. 1983). Accretion rates were calculated from depth in sediment of the horizon for 1963, the year of peak ^{137}Cs fallout (DeLaune et al. 1978). Net carbon accumulation was essentially the same in all 3 marshes: 183, 296, and 224 g C m^{-2} yr^{-1} from the saltwater, brackish, and freshwater marshes, respectively. A large percentage of fixed carbon, immobilized in accretionary processes, remained on the marshes. Hatton et al. (1983) found similar carbon accumulation rates in these marshes.

Aquatic carbon flows

Primary production

Most water bodies adjacent to the Gulf of Mexico have been well described and primary production estimates well documented (e.g. Allen 1975, Hopkinson & Day 1979, Day et al. 1982).

Day et al. (1982) divided the water portion of the basin into 2 regions based on temporal patterns, degree of eutrophy, and degree of heterotrophy. Water bodies in the upper basin are quite heterotrophic and eutrophic, but in the lower basin the ratio of production to respiration is close to one. The carbon fixation rate of 10 g C m^{-2} yr^{-1} in Little Lake is low compared to the fixation rate of 73 g C m^{-2} yr^{-1} in the freshwater lake and 123 g C m^{-2} yr^{-1} in the saline (Hopkinson & Day 1977). Only the saline lake showed a net community production (20 g C m^{-2} yr^{-1}); the freshwater lake consumed 169 g C m^{-2} yr^{-1} and the brackish 44 g C m^{-2} yr^{-1} (Day et al. 1977, Day et al. 1982).

Gaseous emission

Water bodies adjacent to the major marsh types found in Barataria Basin evolved 103, 54, and 242 g CO_2-C m^{-2} yr^{-1} to the atmosphere from saltwater, brackish, and freshwater lakes, respectively (Smith et al. 1983).

There was considerably less methane evolution from open water than from the marshes (DeLaune et al. 1983). The open-water environment adjacent to the marshes had a depth of approximately 1 m, compared to an average depth of less than 10 cm of water overlying the marsh. This deeper water column can allow more methane (escaping from the bottom sediment) to be oxidized to carbon dioxide. Reported methane fluxes from open-water sites increase with distance from the coast (DeLaune et al. 1983). Annual methane emissions were 14 mg C m^{-2} in fresh water, 4.8 mg C m^{-2} in brackish, and 1.3 mg C m^{-2} in the salt water nearer the coast.

Sinks

Stow et al. (1985), using ^{137}Cs dating, found organic carbon sinks in a freshwater lake in the upper end of the basin (Lac des Allemands) of approximately 60 g C m^{-2} yr^{-1}. Rates of carbon accumulation are similar in brackish and saline waters (Feijtel unpubl.).

DISCUSSION

The studies of carbon transformations in Barataria Basin make it possible to estimate carbon budgets for each part of the basin, based on major carbon flows (Table 2). Gaseous carbon emissions (CO_2 and CH_4) and sinks formed by accretion and sedimentation pro-

Table 2. Mean organic carbon data used in mass balance of Barataria Basin (g C m^{-2} yr^{-1})

	Fresh	Brackish	Salt
Marsh			
Net primary production	600[a]	550[a]	860[a]
CO_2 fixation	700[b]	400[b]	–
CO_2 emission	618[c]	180[c]	418[c]
CH_4 production	160[d]	73[d]	4.3[d]
Sedim. C accumulation	224[c,e]	296[c,e]	183[c,e]
Open water			
Net community production	– 600[f]	– 44[g]	20[g]
CO_2 emission	242[c]	54[c]	103[c]
CH_4 production	0.014[d]	0.005[d]	0.001[d]
Sedim. C accumulation	60[h]	60[i]	60[i]

[a] Estimation based on study sites where flux determinations were made (Table 1)
[b] DeLaune & Smith (1984): triplicate determinations, 10 times during 1981–82
[c] Smith et al. (1983): triplicate determinations, 12 times during 1980–81
[d] DeLaune et al. (1983): triplicate determination in fresh and salt marsh; duplicate in brackish marsh; 13 sampling dates during 1980–81
[e] Hatton et al. (1983): ^{137}Cs dating on 10 cores from streamside on lateral transects
[f] Day et al. (1977): monthly sampling during 1975–76
[g] Hopkinson & Day (1979): monthly sampling from Dec 1976–Feb 1978
[h] Stow et al. (1985): ^{137}Cs dating on 5 cores
[i] Feijtel (unpubl.): duplicate determination 1984–85

cesses account for the major carbon outputs from the system.

The major inputs are CO_2 fixation and aquatic C import from upper-basin drainage. Although we have no direct measurements of water movement, the general basin drainage direction is south to southeast. The aquatic carbon input from upland drainage was estimated to be approximately $165 \text{ g C m}^{-2} \text{yr}^{-1}$ in the freshwater marshes (Hopkinson & Day 1979, Day et al. 1982). We incorporated aquatic net production, marsh/water-body exchange, sedimentation, and drainage pattern into a mass-balance approach to estimate carbon transport to nearshore Gulf Coast areas (Fig. 2).

The volumetric approach taken by Happ et al. (1977) is based on monthly measurements of dissolved and particulate organic carbon. They applied average annual concentration gradient to a first-order mixing model to estimate the annual flux. Considering the magnitude of errors involved in the assumptions upon which the calculations were based, they reported an organic carbon export of 25 to 540 g C m^{-2} inshore water yr^{-1}, with the most probable value around $150 \text{ g C m}^{-2} \text{yr}^{-1}$ (Happ et al. 1977).

A mass balance of average annual flux measurements approximates the net effects of global processes, such as net sedimentary carbon accumulation or net gaseous losses to the atmosphere. Atmospheric carbon dioxide fluxes decrease when the marsh is inundated. Gaseous evolution from the bottom sediment is very likely to be greater than the measured atmospheric evolution because inorganic carbon compounds form in the water column. The contribution of CO_2 in flood-
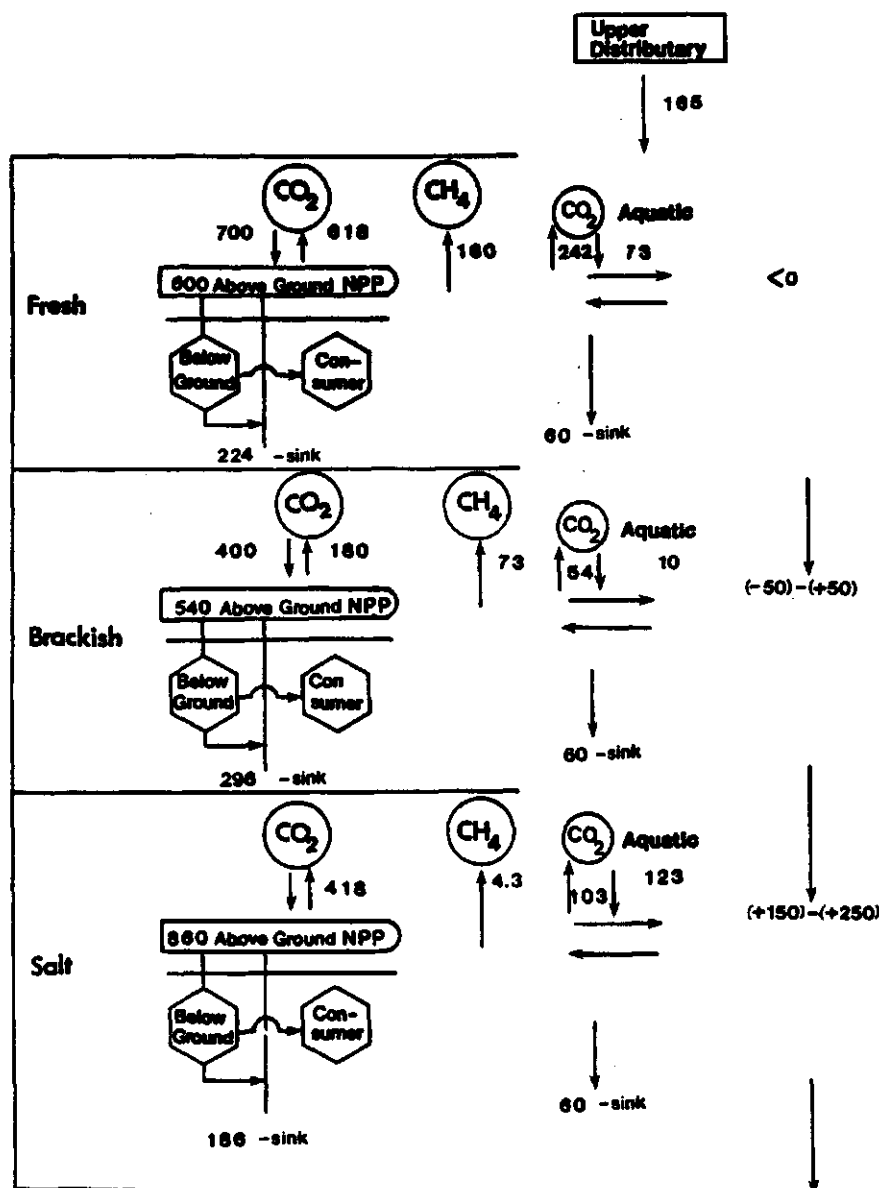

Fig. 2. Integrated carbon budget for Barataria Basin, showing flow pattern of carbon (g C $\text{m}^{-2} \text{yr}^{-1}$) from freshwater marshes into brackish and saline marshes

waters is difficult to assess because it can be consumed by primary producers or leave the system in the tidewaters as bicarbonates and dissolved CO_2. Gaseous carbon emissions may account for the major portion of the net gaseous loss from the marsh canopy.

Data obtained with ^{137}Cs dating indicates that marsh accretion processes fix carbon on the marshes as peat deposits or degrade and release it to the atmosphere as gaseous carbon. Because the carbon contribution apparently remains constant, we did not incorporate the previous year's contribution in calculating the carbon budget.

Belowground productivity of Gulf Coast marshes has not been estimated, and previously published carbon budgets were based on aboveground production studies and respiration of submerged marshes only (Day et al. 1973, Hopkinson & Day 1977). Belowground biomass accounts for 25 % of the total biomass of *Spartina alterniflora*, 57 % of *S. patens*, and up to 90 % of *Panicum hemitomon* (Gosselink 1984).

Productivity estimates made with CO_2-fixation measurements include carbon translocation to belowground portions of the marsh (which equals gross primary production). Annual fixation rates were found to be 5 % higher than clip-plot estimates of aboveground production in the freshwater marsh. Low turnover rates of belowground biomass in the freshwater marsh suggest a significantly lower productivity than in the aboveground portions. Belowground productivity estimates were not included in this mass balance. Burning freshwater and brackish marshes for management purposes (Hoffpauer 1968) is thought to balance the majority of the ignored annual belowground input. We estimated that 25 % to 35 % is burned every year.

Annual fixation rates in the brackish marshes were found to be lower than the aboveground production estimates, indicating the importance of CO_2 recycling and CO_2 in floodwaters (Table 2). The lack of information on belowground production warrants future investigation for any refinement of the carbon budget presented.

Freshwater marshes were reported to import 165 g C m^{-2} yr^{-1} from the upper distributary (Hopkinson & Day 1979), and fairly high aquatic carbon fixation rates probably balance the C deficit in these marshes. Comparative aquatic productivity studies in Barataria Basin showed that although the highest gross production is Lac des Allemands (1,231 g C m^{-2} yr^{-1}), there was also a net community consumption of -169 g C m^{-2} yr^{-1} (Day et al. 1977). This suggests an allochthonous input of nutrients and organic matter. This heterotrophic characteristic decreases as the tidal influence increases, with a net community production of 14 g C m^{-2} yr^{-1} in the brackish water bodies and 0 g C m^{-2} yr^{-1} in the saline. The freshwater marsh

budget (Table 2) indicates a similar heterotrophy, and very little or no import is expected from the fresh water into the brackish wetlands.

The brackish marsh can be thought of as a transition zone on a hydraulic gradient where export or import occurs. The associated water body (Little Lake) is slightly heterotrophic and receives allochthonous carbon from surrounding marshland. Brackish CO_2 fixation is apparently underestimated and carbon export probable. Soil CO_2 flux accounts for the underestimation of atmospheric CO_2 fixation. The contribution of soil CO_2 to gross photosynthesis in various upland crops ranges between 10 % and 40 % (Monteith et al. 1964). Nixon (1980) reported that 40 % of the plant biomass was produced from CO_2 evolved from the surface of a Flax Pond marsh. Restricted diffusion in the grass canopy within the chambers and recycling of the evolved CO_2 limits CO_2 loss on the marsh surface. The integrated budget suggests a zero balance, but with net primary production and respiration correction factors, C excess can be expected.

Southward transport and increased tidal range create C exchange in the saltwater marsh. The lower-basin water bodies are either balanced or slightly autotrophic up to about 20 g C m^{-2} yr^{-1} (Hopkinson & Day 1979). Low methane evolution and low accretion make the saltwater marsh a source of aquatic carbon.

CONCLUSIONS

Marshes and bottom sediments of the water bodies within Barataria Basin function as an important global carbon sink, with marshes accumulating significantly more carbon than bottom sediments (Table 2). Freshwater, brackish, and saline marshes accumulate an equivalent of 37, 54 and 21 %, respectively, of the aboveground productivity. Carbon accumulation in bottom sediments remains constant over the hydraulic gradient, 60 g m^{-2} yr^{-1}. The carbon contribution of the upper portion of Barataria Basin is minor, and the majority of the carbon export in the basin originates in the tidal saltwater marsh. The overall C budget for Barataria Basin indicates an excess of around 150 to 250 g C m^{-2} yr^{-1}. A large part of this 150 to 250 g m^{-2} yr^{-1} is thought to be exported into the Gulf of Mexico.

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14.   Changes Occurring Along a Rapidly Submerging Coastal Area: Louisiana, U.S.A.

by

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Changes Occurring Along A Rapidly Submerging Coastal Area: Louisiana, USA[1]

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ABSTRACT

SALINAS, L.M.; DeLAUNE, R.D., and PATRICK, W.H., Jr., 1986. Changes occurring along a rapidly submerging coastal area: Louisiana, USA. *Journal of Coastal Research*, 2(3), 269-284. Fort Lauderdale, ISSN 0749-0208.

Within the last century the Louisiana coastline began an accelerated rate of retreat primarily due to rapid subsidence. Implications of changes occurring along the rapidly subsiding Louisiana coast could be of concern worldwide, because of similar situations that may be encountered in the future if the predicted global rise in sea level occurs. The lack of sediment deposition with respect to rapid coastal subsidence cause increased submergence which in turn causes numerous habitat changes. Various human (canal cutting, leveeing, dredging, etc.) and natural processes (hurricanes, tropical storms, etc.) conjunctively influence the rate of deterioration. Landward retreat of the wetlands, in addition to causing land loss, promotes secondary effects such as saltwater intrusion, aquifer contamination, loss of freshwater marshes and disappearance of the present biota. Flooding will cause increases in salinity, waterlogging, and anaerobiosis, killing native vegetation and eventually resulting in open bodies of water.

ADDITIONAL INDEX WORDS: *Barrier islands, Louisiana, saltwater intrusion, sea-level rise, subsidence, wetland.*

INTRODUCTION

Levels of inundation and salinity in coastal marshes worldwide are predicted to rise. The relative elevation of the sea and of the coastal marshes has changed throughout time in response to two fundamentally different groups of factors, global and local. Global factors include changes in the volumes of the ocean basins due to tectonic processes and increases in the total amount of ocean water resulting from the melting of continental glaciers. The main local factor is subsidence, which primarily results from the compaction of recently deposited sediments, fluid withdrawal, and changes in sedimentation patterns. Recent global climatic modeling indicates that we are probably about to begin a period of rapid warming due to increased levels of carbon dioxide in the atmosphere (REVELLE, 1983). This climatic warming would increase melting of glaciers,

leading to eustatic sea level rise. The U.S. Environmental Protection Agency estimates that the sea level will rise from 50 to 200 cm in the next century, a large increase over the 10 to 15 cm rise observed in the last century (HOFFMAN *et al.*, 1983). Little information exists on the probable response of coastal vegetation to the increased inundation and salinity that would result from this predicted rise in sea level. Louisiana's coast, especially the Mississippi River delta plain, is rapidly subsiding, both locally and regionally. Basement sinking stems from a decreasing sediment load, sediment consolidation, and tectonic activity. The meandering of the Mississippi River has created a series of overlapping lobes in the delta plain that, combined with natural levee ridges, form an elevated embankment bounding the lower interdistributary basins. Most of the research regarding coastal subsidence has been conducted in one section of this area, Barataria Basin. This basin is bound on the east by the Mississippi River and on the west by the river's most recently abandoned channel, Bayou Lafourche. The basin has been deprived of sediment by natural stream diversion and flood control measures. The water level is rapidly
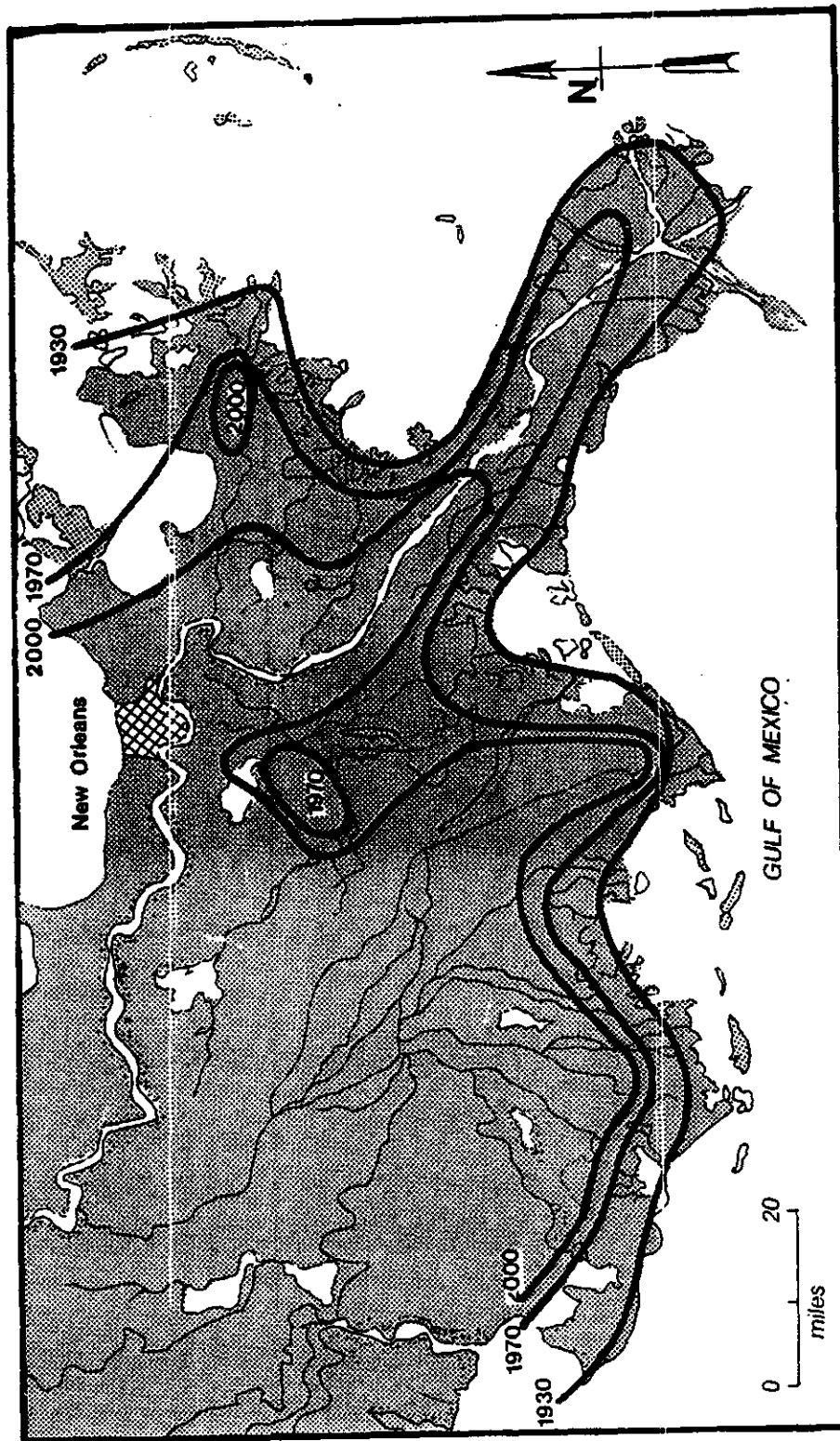
Figure 1. Fifty percent land-water isopleth over a 70-year period in the Mississippi River delta plain (GAGLIANO *et al.*, 1970).

rising in the wetland habitats of Louisiana's Mississippi River delta, primarily because of rapid subsidence (Figure 1). Salinity and water level are currently increasing in coastal marshes here, as they will soon be in coastal marshes worldwide if the sea level rises as rapidly as predicted. This paper summarizes the changes resulting from the rapid increase in apparent sea level along the Mississippi River delta plain and other portions of coastal Louisiana. These changes may be seen as a preview of the effect of the predicted increase in true sea level on other coastal regions.

LAND LOSS

Historically, the Mississippi River has undergone major natural diversions every 1,000 to 2,000 years, resulting in the formation of new delta systems. Human interaction forcing the Mississippi River flow down the current channel halted this process, causing sediment to be deposited off the continental shelf, instead of allowing the natural meander down the Atchafalaya River. This loss of sediments is a primary factor in the loss of Louisiana wetlands. GAGLIANO (1981) recently estimated that these wetlands, which cover approximately 3.2 million ha and represent 41% of all U.S. wetlands (TURNER

and GOSSELINK, 1975) are disappearing at rates as high as 130 km²/yr. Studies show that brackish marshes are deteriorating faster than any of the other wetland habitats (GAGLIANO and VAN BEEK, 1970; ADAMS et al., 1976; CHABRECK et al., 1968). The rate of land loss reported for brackish marshes is 1,355 ha/yr, whereas it is 701 ha/yr for saline marshes, 499 ha/yr for freshwater marshes, and 223 ha/yr for the swamp forest (CRAIG et al., 1979). CRAIG et al. (1979) found that the wetlands in Barataria Basin are receding more rapidly than those in any other area of the Louisiana coastal zone (Figure 2). In addition, the rate at which the land is subsiding has accelerated greatly since 1940 (Figure 3). In other coastal regions of the United States, however, marsh aggradation has kept pace with increases in water level and with coastal submergence (LETZSCH and FREY, 1980). These results apply to the areas where the supply of available sediment is adequate and sea level rise is not rapid. If aggradation is less than the increase in relative sea level, the marshes will deteriorate, and land loss and marine transgression will usually occur. In Louisiana's Mississippi River delta plain, marshes are deteriorating because the sediment deposition falls below coastal submergence rates. The relative sea level is estimated to increase at a rate of increase of 1 m per century along the coast of
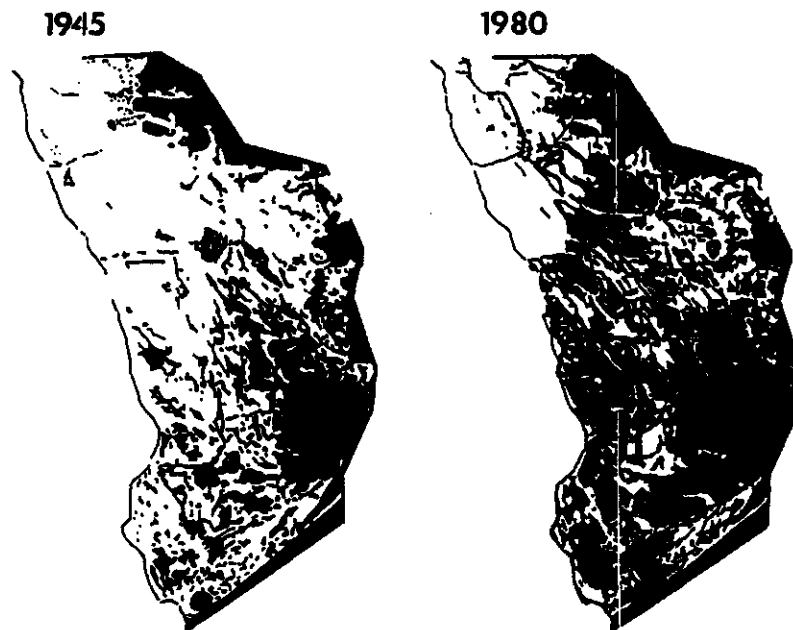

1945   1980

Figure 2.   Change in Barataria Basin wetland area between 1945 and 1980; black is open water (after DOZIER, 1983).
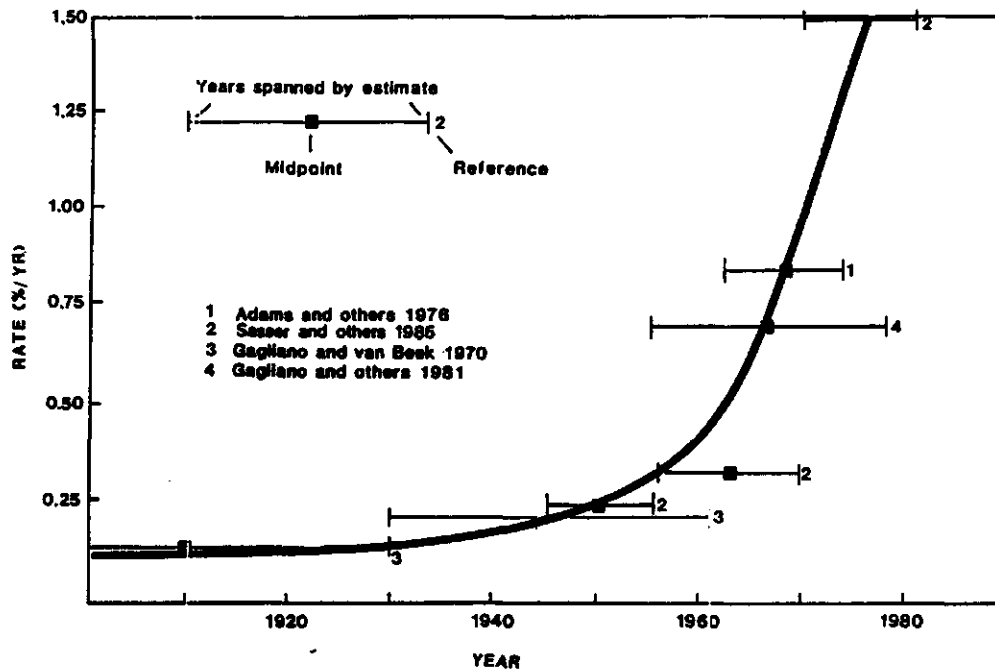
Figure 3. The accelerated wetland loss rate in the Mississippi River delta (SASSER *et al*, 1985).

Louisiana (HICKS *et al*., 1983), primarily because of rapid subsidence. Deterioration of the coastal wetlands began in the early nineteenth century in approximately the same period that the Mississippi River was leveed; before this, the net balance was positive (during the Holocene). Subsidence and subsequent marsh deterioration are now evident in sections of coastal Louisiana. DELAUNE *et al.* (1983a) found that the present submergence rate of 1.2 cm/yr in the East Cove area (Figure 4) of the Chenier Plain (on the southeastern border of Lake Calcasieu) is substantially greater than the average rates throughout the late Holocene. DELAUNE *et al.* (1983a) used Cs[137] dating to establish that the submergence rate is substantially greater than the accretion rate of 0.8 cm/yr. This discrepancy is a recent phenomenon; the increases in the subsidence rate have not been fully compensated for by increases in the aggradation rate of the marsh. If the trends of the past 25 years continue, the East Cove marsh could complete its transformation to open water within 40 years (DELAUNE *et al.* 1983a). Several factors contribute to this above-average submergence rate. Along flat coastlines such as this, any conversion of marsh to open water directly relates to the balance

between submergence and vertical marsh accretion. In this region, changes in degradation appear to be correlated with human activities, particularly the construction of the Calcasieu ship channel. An additional hindrance has been the dredging and canal cutting for petroleum operations. The occurrence and rate of subsidence in Louisiana's coastal marshes directly relates to the proximity of the marshes to the rivers or streams. Streamside marshes have higher sedimentation rates than inland marshes do because they are closer to the source of sediment. DELAUNE *et al.* (1978) observed Cs[137] profile distributions in Barataria Bay (Figure 5) and found that the accretion rate of the marsh closest to the stream was 1.35 cm/yr, whereas the inland marsh was accreting more slowly at a rate of 0.75 cm/yr. This inland marsh is slowly deteriorating into an open-water area. The distribution of Cs[137] in a proximate lake (Airplane Lake), however, showed an accretion rate of 1.1 cm/yr. BAUMANN and DELAUNE (1981) compared rates of sedimentation in inland marshes and streamside marshes to the apparent sea-level rise and found that the streamside marshes were maintaining their relative elevation, whereas the inland marshes were not. HATTON
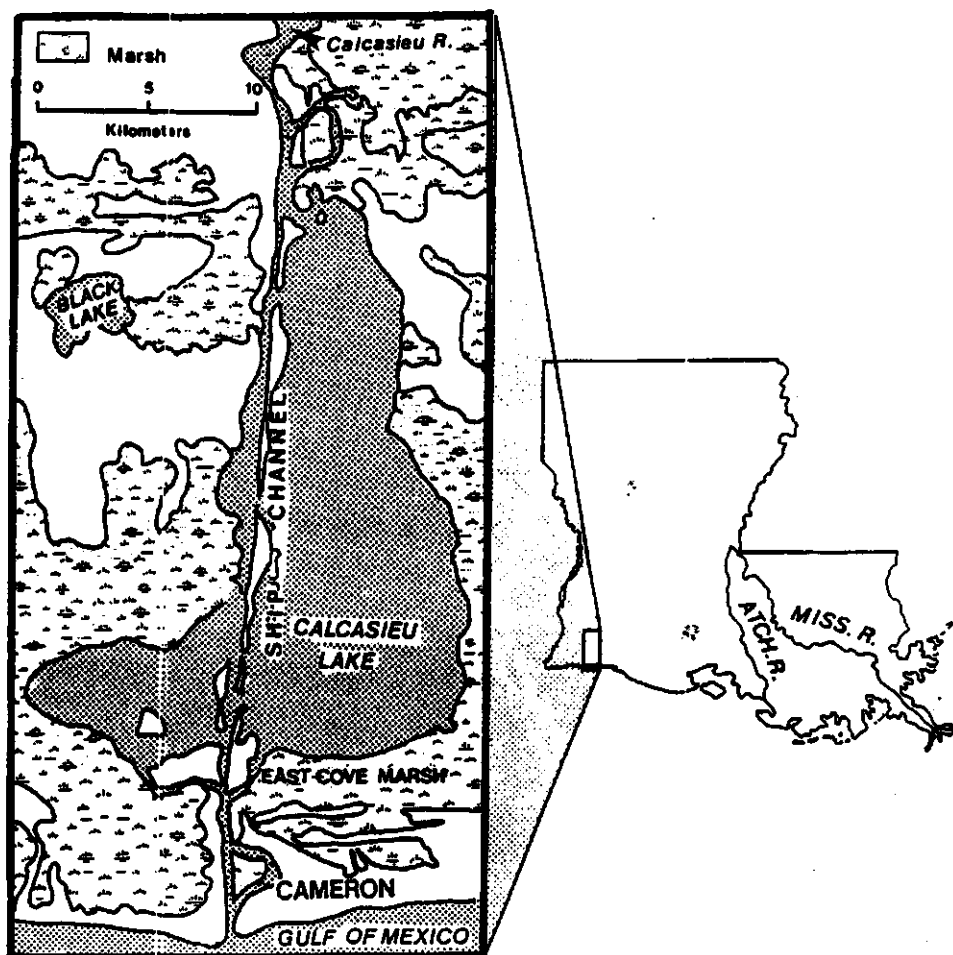
Figure 4. Location of the East Cove marsh study area (DELAUNE et al, 1985).

et al (1983) conducted a study of four different marsh types (fresh, intermediate, brackish, and saline) and found that the rates of vertical growth ranged from a maximum of 1.7 cm/yr in streamside and natural levee deposits to as little as 0.31 cm/yr in selected back-marsh areas. Mean values were 1.3 cm/yr in levee areas and 0.7 cm/yr in adjacent back-marsh areas. Thus, although there is extensive loss of marshlands in coastal Louisiana, vertical accretion is a rapidly continuing process. In general, water level data shows that the accretion rates of levee marshes are keeping pace with subsidence. The predominant back-marsh areas, however, are accreting at half the regional subsidence rate (Figure 6).

HATTON *et al* (1983) also showed that inorganic sedimentation is the main determinant of the vertical growth rate of these marshes, although organic carbon constitutes an approximate constant mass in all soils. Mineral sediments generally accumulate at faster rates in the freshwater marshes than in the saltwater marshes; the sedimentation rates in areas adjacent to natural bodies of water are higher than in the back marshes.

An increase in apparent sea level not only affects the marshlands of coastal Louisiana, it also has an impact on the coastal wetland forest. Excluding the upper Barataria and Atchafalaya basins, there are approximately 159,800 ha of bald-cypress/water-tupelo swamps and 59,800 ha of bottomland

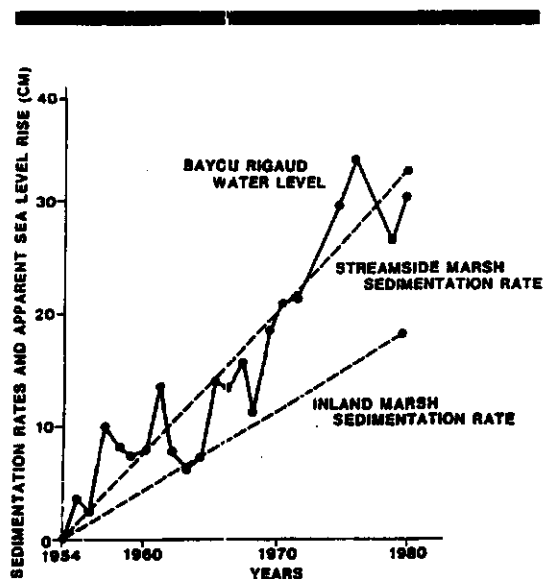Figure 5.   Barataria Basin (DAY et al. 1982).

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Figure 6. Apparent sea-level rise and mean sedimentation rates from streamside and inland saline marshes in the lower Barataria Bay (BAUMANN and DELAUNE, 1981).

hardwood forests in the Louisiana coastal zone (WICKER *et al.*, 1980, 1981; SCS, 1978). As the water level rises, the upland forests will eventually be replaced by bottomland hardwoods and then, as the water level continues to rise, by the more flood-tolerant bald-cypress/water-tupelo swamps. The final stage in this progression will be an open body of water (DELAUNE and PATRICK, 1985).

The impact of an increase in water level is evident in the Verret drainage basin (Figure 7). For a wetland forest to survive, it must maintain a mean elevation relative to the changing water level. DELAUNE and PATRICK (1985) determined the relationship between sedimentation, submergence, and seedling growth in the Lake Verret watershed. The tree species in the area range from bald cypress and water tupelo in the wetter areas to bottomland hardwood species in the drier areas (primarily located on natural ridges). Cs^{137} profiles of the region show that the vertical accretion rate of the swamp forest bordering Lake Verret averages 0.33 cm/yr, whereas the water-level increase averages 1.36 cm/yr (DELAUNE and PATRICK, 1985); the water level in the region is rapidly rising. The survival rates of overcup oak (*Quercus lyrata*) and bald cypress (*Taxodium distichum*) ranged from 0 to 60 %; the greatest survival rates were at the highest elevations. Neither of these species survived in a flooded area.

This indicates that the increase in water level will restrict the regeneration of new species to the higher areas and ridges, which will be decreasing rapidly.

Work in Louisiana has shown that the seasonally flooded bottomland hardwoods are very productive (CONNER and DAY, 1982). The Lake Verret forest area, however, remains flooded for most of the year because of the recent rapid increase in water level. Other studies show that bottomland hardwood species are not very flood tolerant (DICKSON *et al.* 1972; GILL, 1970). Even cypress, noted for its ability to survive under flooded conditions, degenerates and gradually dies under floods of greater than 60 cm (BROWN and LUGO, 1982; HARMS *et al.* 1980; EGGLER and MOORE, 1961). The high water levels lead to anaerobiosis, which causes a variety of stresses and adversely affects many physiological activities (TESKEY and HINCKLEY, 1977).

BARRIER ISLANDS

Any alteration in the coastal barrier island system can indirectly threaten the existence of the interior wetland ecosystem. Louisiana wetlands are protected along the Gulf coast from Trinity Shoal to the Chandeleur Islands by a series of Holocene-age barrier islands, spits, and beaches. These originate from abandoned delta formations built up by an influx of coarse sediments. The Louisiana coastal Plain consists of six major delta complexes. The only two still active are the Atchafalaya and the modern Mississippi deltas; the other four are abandoned. Subsidence and marine reworking of the sediments of the abandoned deltas cause the various formations of the coastal barriers (PENLAND and BOYD, 1981).

Relative sea-level rise, coupled with subsidence and a decreasing supply of sediments, has caused extensive erosion of the barrier islands. Louisiana has lost 41% of the land area of its barrier islands since 1887; barrier island erosional rates are as high as 65 ha/yr, and the islands are migrating landward at a rate of 20 m/yr (PENLAND and BOYD, 1981; MENDELSSOHN *et al*, 1983a,b). Figure 8 shows shoreline changes in the Isles Dernieres barrier system over an 85-year period. The erosion of this island chain and others like it has accelerated the loss of coastal marshes, contributed to the destruction of coastal property, and allowed saltwater intrusion farther inland. Sand dunes, the first line of protection against erosion, are poorly developed on Louisiana's barrier islands because of limited accumulations of eolian sands and frequent overwash.
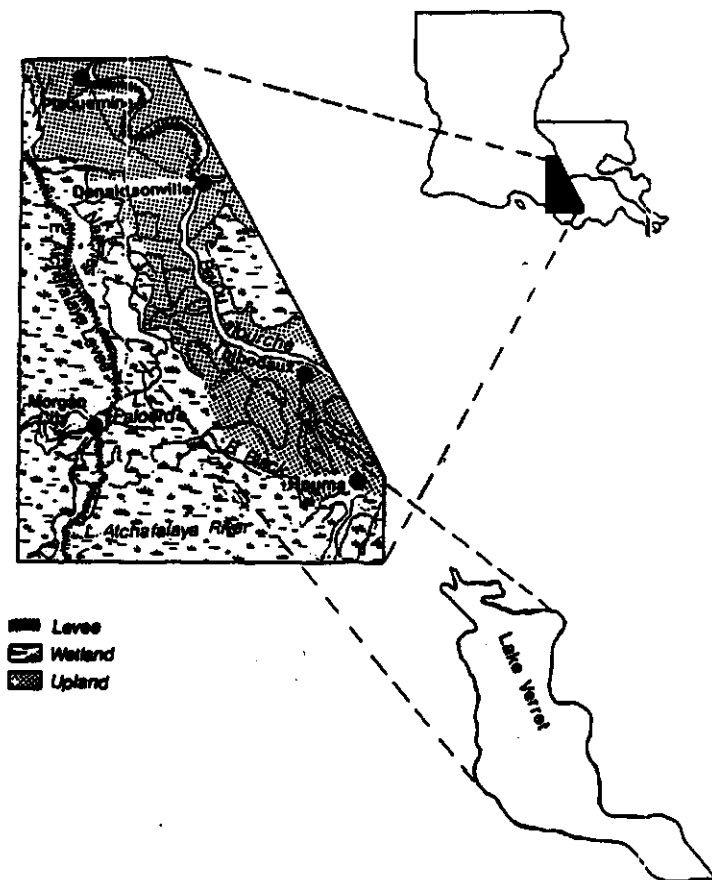
Figure 7. The Lake Verret area (DELAUNE and PATRICK, 1985).

Only 12% of these barrier islands is covered by dunes, whereas backbarrier marshes compose 54% of the total area. Marsh vegetation on the back-barrier portions of the islands binds sediment and provides organic matter for accretionary processes in addition to protecting the bayside shoreline from erosion. Backbarrier marsh vegetation may also reduce the landward migration of the barrier islands (Figure 9). DELAUNE et al., (1985) verified, by measuring organic C content and bulk density, that sediments bound by the backbarrier marshes form a platform that traps additional sediment during storms that might otherwise be lost from the system. These marshes act as a foundation for the islands and a platform for sediment deposition and dune building. Thus, marsh management may more

effectively reduce erosion than dune management (MENDELSSOHN et al., 1985).

DELAUNE et al. (1985), using Cs^{137} profiles, discovered that the backbarrier marshes on Grand Terre and Grand Isle have been vertically accreting over the last 20 years at rates of 0.55 and 0.78 cm/yr, respectively, whereas submergence was an average of 1.83 cm/yr (Figure 10). These measurements and the observed relative sea-level rise of 0.14 cm/yr (HICKS, 1978) indicate that the back-barrier marshes are subsiding at a rate of 1.69 cm/yr. The aggradation deficit suggests that these marshes will become increasingly vulnerable to storms, and plant growth, the source of organic material for the marshes and the main stabilizing agent, will be subject to increasing water stress.
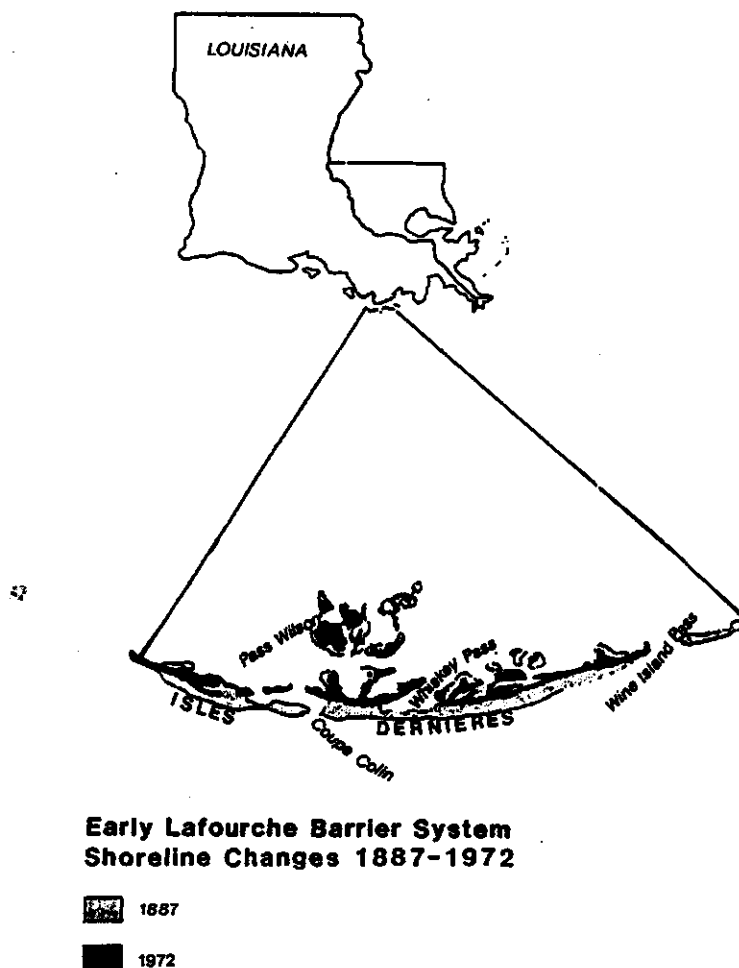
Early Lafourche Barrier System
Shoreline Changes 1887-1972

▦ 1887

■ 1972

Figure 8. Shoreline changes on the Isles Dernieres (after PENLAND and BOYD, unpublished).

SALINITY AND OTHER CONSEQUENCES OF INCREASED SUBMERGENCE

As the sea level rises, salt water will extend farther upstream and inland, especially during droughts Much of the marshland vegetation, such as bald cypress, cannot tolerate salt water and will die under these conditions. Saltwater intrusion, a major problem in the wetlands, affects wetland vegetation, fauna, and freshwater supplies, and accelerates wetland loss.

DELAUNE et al (1983b) observed that any modification of the natural freshwater flow could influence submergence by promoting saltwater intrusion, which degrades freshwater macrophytes and other plants not saltwater tolerant. They observed no evidence of toxic-salinity effects on marsh vegetation at that time. The salinities are well within the range tolerated by one of the dominant plants of the East Cove marsh, *Spartina patens*. Several researchers have concluded that salinity levels are partially responsible for the variation in *S. alterniflora* growth in Atlantic Coast marshes (ADAMS, 1963; BROOME et al., 1975; NESTLER, 1977). The growth of *S. alterniflora* was found to decrease as salinity increased (HAINES and DUNN, 1976). All of these studies have pertained to salt-tolerant marshland species. Other inland species would also be affected by saltwater intrusion,
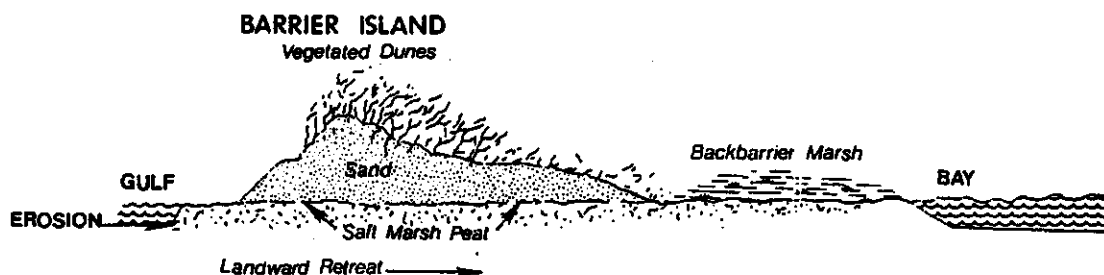
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Figure 9.   Cross-sectional schematic of a barrier island (DELAUNE *et al.*, 1985).

and significant dieback would result.

In a study of the effect of salinity change on oyster distribution, VAN SICKLE *et al.* (1976) discovered that oyster leases, which existed mainly in the outer Barataria Bay area in 1947, had encroached as far north as Little Lake in 1975, indicating a substantial increase in salinity over a 28-year period. In 1910 Little Lake was fresh enough to be a haven for largemouth bass (MOORE and POPE, 1910); Little Lake is now considered brackish, with salinities ranging from 4-10 ppt. VAN SICKLE *et al.* (1976) monitored St. Marys Point (in the northern part of Barataria Bay) and observed a definite increase in salinity levels; salinity increases averaged 0.009 ppt per month. Figure 11 shows changes in salinity in this area from 1894 projected through the year 2000. The presence of live *Rangia* clams in the bottom sediments of Bayou des Allemands indicates that saline waters have on occasion reached that far north (CRAIG *et al.*, 1977). A consistent drop in nutrient concentration observed along Bayou des Allemands may be due to precipitation of nutrients caused by the influx of increasingly saline waters. The oyster yield will eventually be affected by this northern migration because of the increased predation and disease accompanying Gulf waters. Increased pollution and toxic wastes could also seriously threaten the oyster harvest from this area.

Previously, water was distributed in Barataria Basin slowly and indirectly through small bayous and lakes as well as by overland flow. Recently, many straight, deep canals have been cut throughout the basin to facilitate petroleum exploration and to aid navigation. These canals create straight and direct connections between waters of different salinities and may therefore be a major factor in the landward advance of salt water. Large canals that link the saline waters of the Gulf directly with the

inner marshes are particulary efficient in promoting saltwater intrusion.

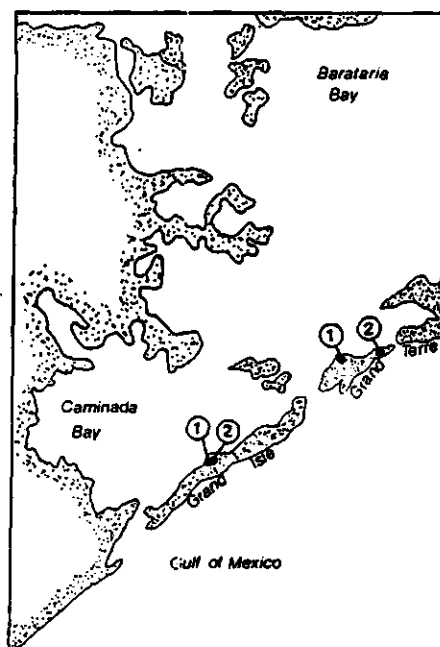Figure 10.   Barrier island study area (DELAUNE *et al.*, 1985).

The continued northward saltwater encroachment in coastal Louisiana will cause drastic changes in the less saline brackish and freshwater marshes. Substantial changes in the flora and fauna will occur, along with decreases in the fishing yield. Present coastal wildlife habitats will be damaged, and some of the local groundwater aquifers will be
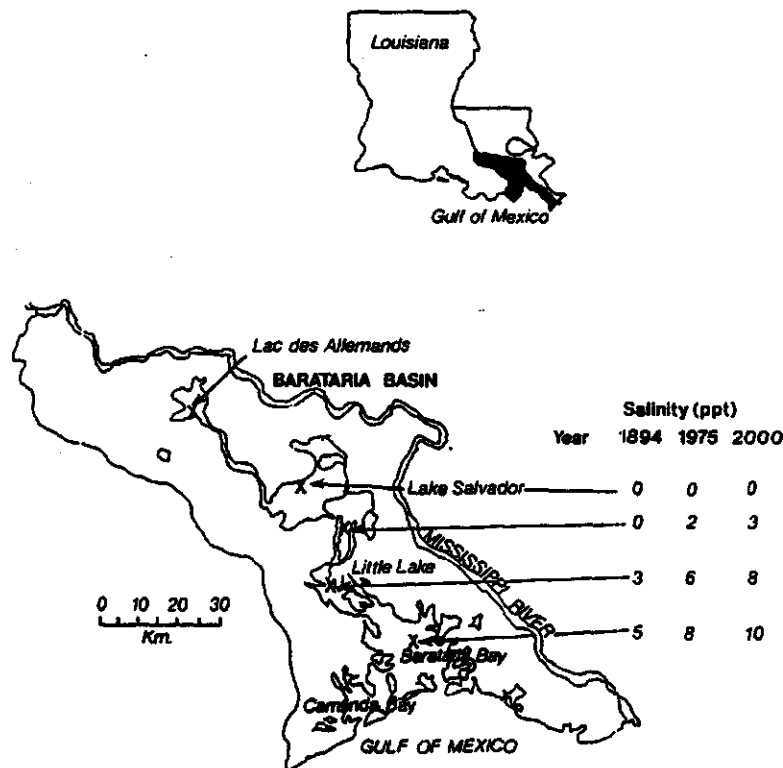
Figure 11. Saltwater intrusion in Barataria Basin (based on data from VAN SICKLE *et al.*, 1976 and CRAIG *et al.*, 1977).

contaminated with salt water. These trends, now apparent on the Louisiana coastline, are beginning to occur on a smaller scale in other parts of the United States; therefore, these studies and their recommendations for management measures should be kept in mind as similar situations must be dealt with.

Projects implemented to increase the influx of fresh water by diverting it from the Mississippi and local freshwater bayous would provide an additional source of sediment to the marshes and somewhat counterbalance saltwater intrusion. These projects would include building flood control structures resembling small-scale versions of the structure that contols freshwater influx to the Atchafalaya River (this structure was built to prevent the Mississippi River from flowing down the present course of the Atchafalaya and not as a freshwater diversion project). The Atchafalaya delta has increased from 0.51 km² in 1973 to 11.68 km² in 1979 (VAN HEERDEN and ROBERTS, 1980). Delta building

resulting from freshwater diversion projects, however, would be on a smaller scale than the delta building in the Atchafalaya. DAY and CRAIG (1982) estimated that marsh restoration would only create 1-3 km² of marsh a year.

TURNER *et al.* (1982) hypothesized that much wetland loss in Louisiana is due to canal construction. DEEGAN *et al.* (1983) found that 25% to 39% of marsh loss over a 23-year period was related to canal and spoil construction (they also found that 9%-13% of marsh loss was due to agricultural development). Management techniques for minimizing the impact of canals on wetland loss include prohibiting unnecessary canal building, backfilling canals with previously stripped spoils, designing canals to flow down naturally occurring channels, and distributing the canal spoils evenly instead of building spoil banks. When canals cross natural streams, they should be barricaded efficiently so that they do not divert waters from them. Directional drilling may be an alternative to digging canals

for the petroleum and gas industry. Also, using different types of vehicles that do not require trails or canals, such as those that ride on air cushions, should be considered.

EFFECT OF ANAEROBIOSIS ON MACROPHYTES

Two of the main factors controlling plant growth in marshes are the type of soil and its degree of anaerobiosis. Little or no free oxygen exists in flooded marsh soils, and facultative and strict anaerobic microorganisms use alternate compounds as terminal electron acceptors. Therefore, a waterlogged soil differs substantially from a well-drained soil. The amount of oxygen consumed in the sediment is greater than the amount entering the sediment through diffusion, resulting in the formation of a thin, oxidized layer overlying an anaerobic environment in the sediment. If the oxygen demand in the soil is great enough, the oxygen in the overlying water column may be depleted, and the aerobic layer will not be formed. The redox potential in these sediments is the most diagnostic parameter in measuring the degree of anaerobiosis. The following compounds, listed with their reduced forms and in sequence used, are utilized as electron acceptors when the redox potential decreases: nitrate to ammonium, manganic form to manganous, ferric to ferrous, sulfate to sulfide, and carbon dioxide to methane.

One effect of waterlogging on marsh soils, a decrease in sediment redox potential, is especially important because of the direct relationship between redox potential and the productivity of the streamside, inland, and dieback zones of *Spartina alterniflora* (DELAUNE et al, 1976; MENDELSSOHN et al, 1981). The sediment underlying the tall varieties of *S. alterniflora* found along the creek banks is more oxidized than that underlying the short variety found at least 2 m landward of the creek (HOWES et al, 1981). DELAUNE et al (1983b, 1984) found that anaerobic root respiration of *S. alterniflora* grown in a laboratory environment increased with decreasing sediment redox potential without a reduction in plant growth.

The decomposition of organic compounds under anaerobic conditions usually results in the formation of several incompletely oxidized and some potentially toxic intermediates, such as ethylene, lactic acid, ethanol, acetaldehyde, and some aliphatic acids. The organic acids are toxic in order of

increasing molecular weight (RAO and MIKKELSEN, 1977). One of the toxic compounds most frequently produced under strong anaerobic conditions is hydrogen sulfide. GOODMAN and WILLIAMS (1961) observed that *Spartina* dieback was caused by sulfide toxicity, and FORD (1973) found that concentrations as low as 2.5 ppm are toxic to root growth. DELAUNE et al (1983b) concluded that in a Louisiana Gulf Coast marsh, the productivity of *S. alterniflora* is mainly controlled by the accumulation of free sulfide, although the accumulation of other toxic, reduced materials (ethanol, aldehyde) produced under anaerobic conditions should not be disregarded. Sulfides are neutralized in the soil in many cases by available ferrous iron, which precipitates with sulfides as nontoxic iron sulfides.

Even though iron is sometimes beneficial, other studies show that growth in macrophytes may be affected differently by the presence of iron and other elements. *Erica cinerea* rapidly developed waterlogging symptoms in a high-iron medium, whereas *E. tetralix* grown in the same medium was unharmed. *E. cinerea* took up more iron than the other plant (JONES and ETHERINGTON, 1970), which shows a difference in resistance to iron between two species of heath plants. In another study, JONES (1972) concluded that *Festuca rubra* was adversely affected by applications of up to 200 ppm of manganese, whereas the growth of *Carex nigra* was stimulated under the same conditions. Except in isolated studies such as these, the toxicity of these soil-produced phytotoxins and their effect on *Spartina* and other marshland flora have not been researched. Many of the elements that were harmless under oxidized conditions may prove to be toxic when reduced.

Root oxygenation is an important factor in the growth of macrophytes in the wetlands. Wetland plants use a few major mechanisms to adapt to anaerobic respiration. One is a well-developed aerenchyma cell system, which serves as an oxygen conduit to the root system in plants such as *Spartina* (ANDERSON, 1974). Another mechanism wetland plants use is ethanol diffusion out of the roots when alcohol fermentation exists, such as in rice under reduced conditions (BERTANI et al, 1980). In 1971, McMANMON and CRAWFORD proposed a theory explaining how flood-tolerant plants could avoid an accumulation of lethal ethanol. They suggested that nontoxic malate accumulates in the plants instead of ethanol. The malic enzyme is missing; therefore, malate is not converted to pyruvate, and ethanol production is precluded. LINHART and

BAKER (1973) found that within a single population of *Veronica peregrina* differential accumulation of malate under flooded conditions corresponded to microhabitat distribution. It has been hypothesized that other substances, such as lactic acid, pyruvic acid, succinic acid, glycerol, shikimic acid, glycolic acid, glyoxalic acid, a-ketoglutaric acid, olanine, ethylene, g-amino butyric acid, glutamic acid, serine, and proline, may serve as nontoxic alternatives to ethanol (CRAWFORD, 1978; MENDELSSOHN et al. 1981). Although this hypothesis seems to be a valid one, many researchers have found evidence to contradict it (HOOK et al, 1971; KEELEY and FRANZ, 1979; DAVIES, et al. 1974; SMITH and APREES, 1979).

In addition to the reduction of soil compounds and the anaerobic environment, wetland macrophytes must also adapt to different concentrations of salinity. In experiments on tillers of *Agrostis stolonifera*, AHAMAD and WAINWRIGHT (1976) observed no difference in the response of inland and spray-zone plants to salt treatments and an anaerobic environment, whereas these were significantly repressed in salt marsh plants. The responses of each ecotype to salinity and anaerobiosis paralleled the relative intensities of these in their natural habitats. ROZEMA and BLOM (1977) found that although *Agrostis stolonifera* and *Juncus gerardi* had depressed malate dehydrogenase levels when subject to NaCl treatments, their activities under saline conditions were significantly higher when flooded than when aerobic. ROZEMA and BLOM (1977) found that *Glaux maritima* has a similar inverse relationship with salinity and Positive one with flooding. The growth of *Spartina alterniflora* was found to decrease when the salinity in a nutrient solution was increased (GOSSELINK, 1970; HAINES and DUNN, 1976). NESTLER (1977) observed that the growth of *S. alterniflora* was inversely related to interstitial water salinity in a salt marsh in Georgia, and that elevated interstitial salinity in the high marsh zone can reduce transpiration and increase respiration in *Spartina*, thereby reducing photosynthesis and forming a weaker plant. LINTHURST and SENECA (1980) discovered that aeration enhanced uptake of certain nutrients, especially at higher salinities.

Plants have different mechanisms of responding to salt stress. The glycophytes (salt-intolerant plants) tend to exclude Na from the xylem by sequestering it in their roots and stems. Halophytes (salt-tolerant plants) accumulate ions in their vacuoles in order to maintain the necessary osmotic adjustment for life

under saline conditions. When the control mechanism of glycophytes is overloaded, Na concentration increases in the leaves and growth decreases (FLOWERS et al., 1977).

In the Louisiana marshes, saltwater intrusion greatly impacts the fresh, intermediate, and brackish marshes (to different degrees). Saltwater intruding from the Gulf of Mexico has changed the distribution of vegetation in the marshes: saline vegetation has expanded greatly, brackish and intermediate vegetation have shifted farther inland, and freshwater vegetation has been greatly reduced (CHABRECK, 1981). The exact mechanics of the impact that saltwater has on the different marsh types are not fully understood, but two results that often follow saltwater intrusion are (1) death of the original macrophyte population and, in cases where saltwater intrusion is too rapid to allow revegetation by more salt-tolerant plants (2) marsh degradation into open water.

SUMMARY

In the past century, the Louisiana coastline has been retreating at rates estimated as high as 130 km^2/yr (GAGLIANO, 1981), and this rate of deterioration is accelerating. This situation, currently unique to Louisiana, provides a good case study and opportunity to gather valuable information that can be applied to other regions that may be subject to this kind of deterioration in the future. The main factor causing the rapid rate of retreat in Louisiana is the low level of sedimentation, which has resulted from efforts to force the Mississippi River down its present channel, depriving wetlands of sediment needed to maintain their elevation relative to sea level. Human activities, such as canal cutting, dredging, and water table depletion have further accelerated degradational processes. Environmental factors impeding marshland maintenance are tropical storms, hurricanes, and other highly erosional natural phenomena. These forces are also rapidly deteriorating the Louisiana barrier islands, which presently provide the coast protection from the erosional forces of the sea and storms. The rapid deterioration of the barrier islands is exposing mainland marshes to more of the erosional power of the sea.

As the eustatic sea level rises, and problems similar to those in Louisiana become more widespread, landward retreat of wetlands in other coastal areas around the world will also increase. And, as in Louisiana, the submergence of coastal marshes

and wetland forests wil. cause secondary effects, such as saltwater intrusion, aquifer contamination, loss of freshwater marshes, disappearance of the present biota, and land loss.

In addition to land loss, the accompanying influx of salt water into previously fresh, intermediate, and brackish marshes greatly impacts wetland ecosystems. Salinity increases in the marshes may kill native vegetation, and if the change is too abrupt to allow revegetation, open bodies of water may result. As salt water intrudes farther inland, the brackish marshes will be pushed farther landward, and the freshwater marsh areas will be reduced. Many locations in Louisiana, such as the New Orleans metropolitan area, are surrounded by levees for flood protection because of their minimal relative elevation above sea level. This leveeing will halt the landward migration of the receding marshes, thus accelerating the rate of wetland disappearance. Water-level increases will affect the higher wetland forest areas that are not seasonally subject to flooding, causing waterlogging, anaerobiosis, changes in redox potential, and other consequences. This Louisiana case study illustrates how coastal wetlands with submerging marsh areas are adversely affected by interrelated primary and secondary factors.

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15. SUMMARY

Many factors influence the rate of formation of marsh soils in coastal Louisiana. In the subsiding environments of coastal Louisiana, continued existence of marsh habitat is particularly dependent on the ability of marsh to maintain its elevation within some specific tidal range through the process of vertical marsh accretion. As documented, many Louisiana Gulf Coast marshes are not accreting or aggrading rapidly enough in relation to increases in water level to keep the marshes intertidal (Table 1). The net result is the loss of viable coastal marsh. As shown in preceding chapters, accretion is accomplished through a combination of mineral sediment accumulation and peat formation. The two are interrelated since the influx of sediments also supplies nutrients for plant growth. Increased plant growth results in greater peat formation and increased stem density, allowing an enhanced ability to further entrap and stabilize sediment.

From a coastwide view, it is evident that vertical marsh accretion rates on the order of 0.6-0.8 cm per year are not sufficient to maintain the elevation of marshes which are being subjected to water level increases at rates as great as 1.5 cm per year. A continual decrease in relative elevation of the marsh with respect to water level results in the eventual conversion of marsh to an open water body. Streamside salt marsh accretion rates are greater or are almost equivalent to the water level increase along the coast. However, streamside marsh represent a small portion of total salt marsh area.

Comparison of water level increases along the Louisiana Gulf Coast to gauging stations at other Gulf Coast states reported by Penland et al. (1986) show that Louisiana is experiencing the greatest water increase of all

Table 1. Relationship between apparent water level increases and vertical marsh accretion at selected sites along the Louisiana Gulf Coast.

Area	Water level increase cm yr^{-1}	Vertical accretion cm yr^{-1}
Coastal Salt Marsh (Chapters 2, 3, 5)	1.2 cm	0.7 to 0.8
Atchafalaya Delta (Chapter 9)	1.64 to 2.11	0.65 to 1.40
Cameron-Chenier Plain (Chapter 4)	1.17	0.57 to 0.70
Lower Barataria Basin (Chapter 3)	1.83	0.7 to 1.35
Barrier Island (Chapter 9)	1.83	0.55 to 0.78

coastal wetlands bordering the Northern Gulf of Mexico. The faster rate of water level increases in coastal Louisiana is attributed primarily to subsidence resulting from compaction of recently deposited sediment associated with the Mississippi River Deltaic Plain. Penland et al. (1987) reported relative sea level rise along the Texas Coast of 0.33 cm yr^{-1} (Port Isabel) to 0.62 cm yr^{-1} (Galveston). In Gulf coastal regions east of Louisiana he reported rates of 0.15 cm yr^{-1} (Biloxi), 0.23 cm yr^{-1} (Pensacola), 0.17 cm yr^{-1} (Ceda Key), 0.10 cm yr^{-1} (St. Petersburg) and 0.22 cm yr^{-1} (Key West). Assuming that the eustatic sea level increase is 0.23 cm yr^{-1} (Barnett, 1984) for the Gulf based on the Key West Station (which is located in a geological stable area), it is obvious that the Louisiana Coast is experiencing water level increases several times greater than eustatic changes.

The relative contribution of mineral and organic matter to the total marsh profile vary with marsh type. Bulk density, an indication of sediment content, is greatest in salt marsh and progressively lower in inland fresh and brackish marshes. Mineral sediment constitutes a progressively greater fraction of marsh soil solids in the salt marshes. This is a consequence of the hydrological regime. Tidal action near the coast provides reworked mineral sediments to the salt marshes. The mineral sediment content of the salt marsh directly influences productivity by supplying plant nutrients. When bulk density of the root zone in salt marshes falls below 0.20 g cm^{-3}, salt marshes will not support appreciable growth of <u>Spartina alterniflora</u>.

Organic matter is an important component of marsh soil formation. Organic matter on a dry weight basis constitutes an increasing fraction of soil solids as the marine influence diminishes inland from the coast.

Organic matter is of greatest structural significance in low density, fresh, and brackish marsh environments. However, on a unit volume basis, the organic matter occupies the same volumes in fresh, brackish, and salt marshes.

Wetlands develop in dynamic depositional environments in which subsidence, eustatic changes, oxidation, rate of mineral and organic matter accumulation and local hydrology influence the marsh surface/water surface relationship. Aggradation or vertical accretion rates depend on the quality as well as the quantity of material available and are influenced by particle size, source, distance from source, and local hydrology and topography. Such complexity makes it difficult to model or budget aggradation processes. In an attempt to quantify some of the processes that influence coastal marsh formation in coastal Louisiana, a sediment budget was developed for Barataria Hydrologic Basin (Figure 1). The budget was developed for a single hydrologic unit rather than the entire coast to reduce complexity, where a relatively larger data base was available.

Table 2 shows the area of fresh brackish-intermediate and salt marshes in Barataria Basin. Using measured accretion rates, bulk densities and mineral-organic content of soil profiles an estimate of the yearly sediment supply to individual marsh units is presented. The source of the sediment is not known, but may be mainly reworked sediment from within the Basin. Currently little sediment enters the basin as a result of leveeing of the Mississippi, so that most sediment is directed offshore.

In developing a marsh building model, several important fluxes or processes as shown in Figure 2 were quantified for fresh, brackish, and salt marshes of Barataria Basin. Rate of water level increase are greater in salt

Figure 1. Louisiana's Barataria Basin.

Legend:
- Levee & Developed
- Swamp
- Fresh Marsh
- Intermediate Marsh
- Brackish Marsh
- Salt Marsh

GULF OF MEXICO

Table 2. Accretion Rate and Annual Mineral Sediment Deposition for Barataria Basin Marshlands

Marsh	Area[a] (hectare) 1978	Average Accretion Rate cm²/yr 1963-1985	Bulk density[b] g/cm³	% Mineral solids (mass base)[b]	sediment deposited kg/hectare/yr 1963-1985	yearly supply kg marsh unit area 1963-1985
Fresh	19,388	0.85	0.10	50	4,250	8.2×10^7
Brackish & Intermediate	79,483	1.0	0.15	60	5,500	4.4×10^8
Salt	65,358	1.1	0.30	75	24,750	1.6×10^9

[a] Gosselink, J. G. 1984.

[b] Hatton et al. 1983, DeLaune et al. 1978 (Average values representing individual marsh habitats.)

marshes of lower Barataria Basin with subsidence being the primary cause (Table 3). Subsidence in general is 3 to 5 times faster than the increase in eustatic sea level, which is estimated to be a 0.23 cm yr^{-1} change for the Gulf of Mexico (Barnett, 1984). Vertical marsh accretion rates were greater in the salt marsh in the lower basin than in the brackish and freshwater marsh. Rate of water level increase in general was greater than accretion in the brackish and salt marsh. Fresh marsh in the northern portion of basin is apparently maintaining elevation with respect to water level increase.

Also, as shown in the budget, organic matter is important in marsh aggradation at all marsh locations. Organic carbon accumulation is appreciable with 200-300 g C m^{-2} yr^{-1} being tied up in accretionary processes. Plant production, the source of the organic matter, is a very important factor in maintaining viable marshes. However, salt water intrusion and increased waterlogging can reduce primary production of marsh macrophytes. This, in turn, would reduce the organic source used in marsh building resulting in increased rates of marsh deterioration. Decomposition of soil organic matter and release of CO_2 and methane to the atmosphere also affects the stability of coastal marshes.

In summary, wetland loss rates are accelerating along the Louisiana coast, which can be attributed in many areas to the inability of the marsh surface to keep pace with water level increase. Understanding these relationships in Louisiana's coastal plain is even more difficult because of the multitude of natural and man-influenced processes that directly and/or indirectly affect marsh surface stability. These relationships, in many instances, may not be direct and simple. The combined effect of rapid subsidence, eustatic sea level rise and accompanying salt water intrusion
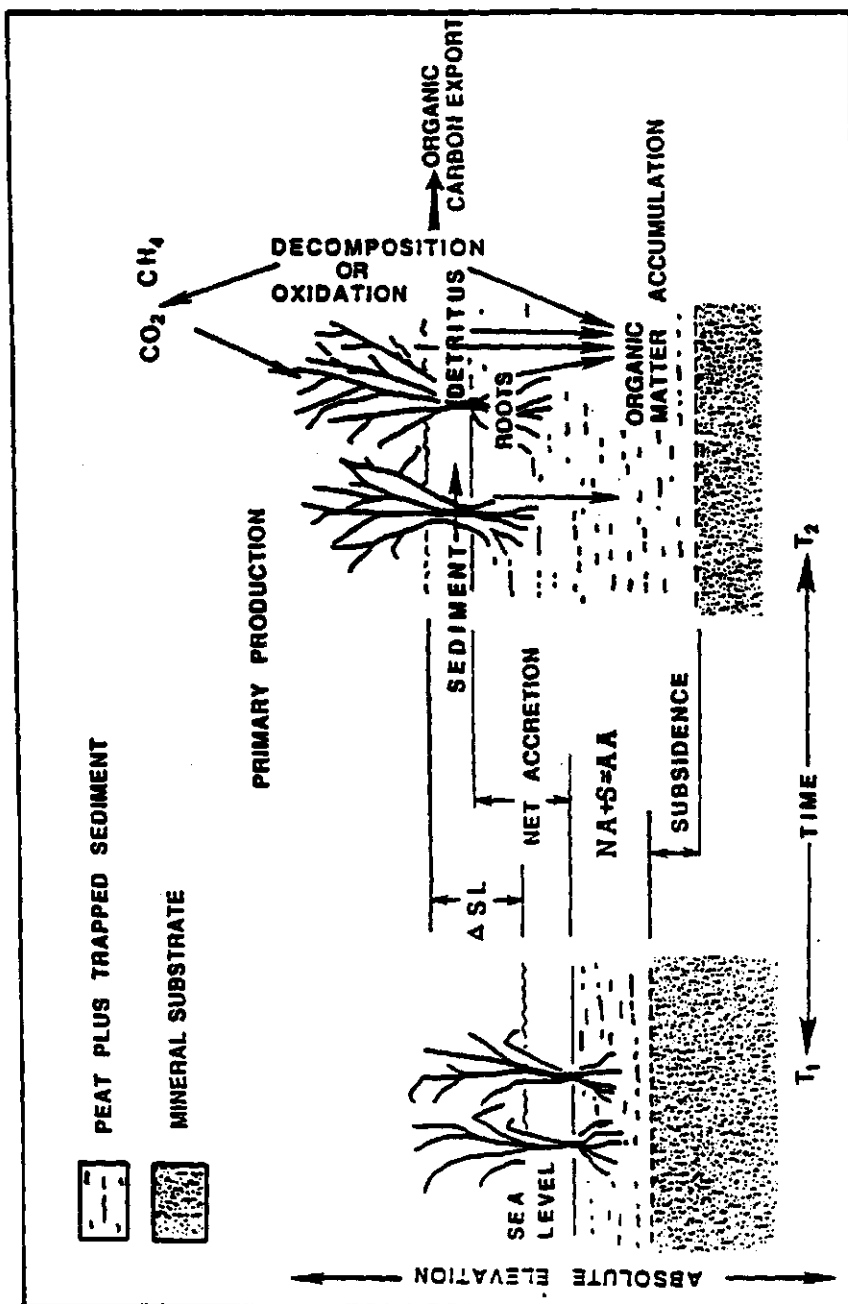
Figure 2. Schematic model of processes governing marsh accretion showing relation to organic carbon cycle (ΔSL = Eustatic Sea Level Change, NA = Net Accretion, S = Subsidence, AA = Absolute Accretion).

Table 3. Budget of marsh aggradation processes for Barataria Basin fresh, brackish and salt marsh showing role of mineral sediment and organic carbon. (The mineral sediment and organic carbon accumulation represents that accumulating for the respective vertical marsh accretion rates reported for each marsh type. This relationship can be used in accessing the significance of other carbon fluxes).

| Marsh Type | Submergence | | | Material Accumulation | | Oxidation $gCm^{-2}yr^{-1}$ | Plant Production $gCm^{-2}\ yr^{-1}$ | Export $gCm^{-2}\ yr^{-1}$ |
	Eustatic $cm\ yr^{-1}$	Subsidence $cm\ yr^{-1}$	Vertical marsh Accretion $cm\ yr^{-1}$	Mineral sediment $g\ cm^{-2}yr^{-1}$	Organic carbon* $gCm^{-2}yr^{-1}$			
Fresh	.23[a]	0.6-0.8[b]	.65-1.1[c]	.03-.07[c]	200-300[e]	760[e,f]	720[g]	<0[g]
Brackish-Intermediate	.23[a]	0.6-0.8[b]	.59-1.35[c]	.03-.15[c]	250-300[e]	250[e,f]	660[g]	(-50)-(+50)[g]
Salt	.23[a]	1.0-1.6[b]	.75-1.35[c,d]	.15-.30[c]	200-300[e,h]	420[e,f]	1030[g]	(+150) - (+250)[g]

[a] Barnett, 1984.
[b] DeLaune, R. D., Smith, C. J., and Patrick, W. H., Jr. 1986.
[c] Hatton, R. S., Delaune, R. D., and Patrick, W. H., Jr. 1983.
[d] DeLaune, R. D., Buresh, R. J. and Patrick, W. H., Jr. 1978.
[e] Smith, C. J., DeLaune, R. D., and Patrick, W. H., Jr. 1983.
[f] DeLaune, R. D., Smith, C. J., and Patrick, W. H., Jr. 1983.
[g] Feijtel, DeLaune, and Patrick, 1985.
(modified to include below ground production which was estimated to be 20 percent of reported aboveground primary production.)
[h] DeLaune, R. D., Reddy, C. N., Patrick, W. H., Jr. 1981.

will likely destroy much of these marshes. The marshes will likely continue disappearing at a rapid rate unless means are implemented for distributing Mississippi River sediment to the marshes. Results presented may represent future conditions for many coastal regions of the world, which may experience a rapid rise in water-level as a result of the predicted "greenhouse" warming and resultant accelerated worldwide sea-level rise.

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16. SAMENVATTING

Dit onderzoek betreft de processen die een rol spelen bij de opbouw en afbraak van moerasbodems in het kustgebied van de staat Louisiana in het Zuiden van de Verenigde Staten van Amerika. Vele factoren spelen een rol bij de vorming en afbraak. In het kustgebied van Louisiana vertoont de zeespiegel een (schijnbare) stijging. Onder zulke omstandigheden hangt het voortbestaan van moerassen af van de verticale opbouw door sedimentatie en vorming van organisch materiaal. Sedimentatie wordt bevorderd door aanwezigheid van vegetatie die in staat is zwevend slib uit het water in te vangen. Sterke vegetative groei bevordert de verticale opbouw dus zowel door vorming van organisch detritus als door versterkte invang van sediment. Op zijn beurt levert sediment plantevoedende stoffen, en kan zo de plantengroei weer bevorderen, zodat er sprake is van wederzijdse beïnvloeding.

Wanneer deze opbouwprocessen niet in staat zijn de stijging van de zeespiegel bij te houden gaat het moeras over in open water. Tabel 1 van hoofdstuk 15 laat zien dat de gemiddelde verticale aangroei (0.6-0.8 cm/jaar) de gemiddelde zeespiegelstijging (1.5 cm/jaar) niet bijhoudt. Lokaal, en met name langs stromend water (rivierarmen en getijdekreken), is de verticale opbouw echter groter of gelijk aan de zeespiegelstijging.

Vergelijking met literatuurgegevens laat zien dat de zeespiegelstijging langs de kust van Louisiana (1.5 cm/jaar) sneller is dan in andere kustgebieden langs de Golf van Mexico (0.22-0.62 cm/jr). De eustatische zeespiegelstijging wordt geschat op 0.23 cm/jr (waarde voor de schijnbare stijging bij het station Key West, dat in een tektonisch stabiel gebied ligt), zodat met name in de kustmoerassen van Louisiana de

landdaling belangrijk bijdraagt aan de sterke (schijnbare) stijging van de zeespiegel. Deze daling kan in de eerste plaats worden toegeschreven aan inklinking als gevolg van compactie van de dikke paketten waterrijk sediment in de Mississippi delta.

De relatieve bijdragen van mineraal en organisch materiaal tot het totale moeraspofiel varieert met het moerastype. Het volumegewicht van de moerasbodem is het hoogste in de zoutwatermoerassen, en lager in brak- en zoetwatermoerassen. In zoutwatermoerassen is het aandeel van mineraal materiaal ook groter dan in de andere moerastypen. Dit is een gevolg van de met getijdenwerking samenhangende grotere aanvoer van (geresuspendeerd) sediment nabij de kust.

Als het volumegewicht van het materiaal in de wortelzone door onvoldoende aanvoer van sediment lager wordt dan 0.2 g/cm^3, kan Spartina alterniflora zich in de zoutwatermoerassen niet handhaven. Organische stof gehalten, betrokken op de massa fractie van het gedroogde materiaal, nemen toe met afnemende marine invloed, gaande van de kust naar het binnenland. Op volume basis (van het sediment in situ) is de verhouding organisch tot mineraal materiaal echter ongeveer gelijk in zoet-, brak- en zoutwatermoerassen. In de zeer waterrijke bodems van zoet- en brakwatermoerassen draagt organisch materiaal overigens in belangrijke mate bij aan de (geringe) stevigheid van het materiaal.

Moerassen ontwikkelen zich in dynamische depositie milieus waar inklinking, eustatische zeespiegelveranderingen, de snelheid van de netto accumulatie van mineraal en organisch materiaal, en lokale hydrologie de relaties tussen het moerasoppervlak en het wateroppervlak bepalen. De snelheid van verticale opbouw van het moerasoppervlak hangt af van de aard en de hoeveelheid materiaal die daarvoor beschikbaar is, die op z'n

beurt wordt beïnvloed door deeltjesgrootte, bron, en afstand tot die bron van het sediment, alsmede door de lokale hydrologie en topografie. Door zijn complexe karakter is het opbouwproces moeilijk te modelleren of in een budget te vangen. In een poging om de belangrijkste van de genoemde processen toch te kwantificeren, is getracht een sedimentbudget van het Barataria Basin op te stellen. (Fig. 1, Hoofdstuk 15). Barataria Basin is uitgekozen omdat het hier een relatief eenvoudige, hydrologische eenheid betreft, waarover relatief veel bekend was.

Tabel 2 (Hoofdstuk 15) toont de oppervlakten aan diverse moerastypen binnen Barataria Basin, bestaande uit moerassen en open water. Op grond van via ^{137}Cs gemeten verticale aangroeisnelheden, volume gewichten, en de gehalten aan organisch en mineraal matriaal, is de jaarlijkse sediment toevoer geschat. De oorsprong van het sediment is onbekend, maar is waarschijnlijk voornamelijk geresuspendeerd materiaal vanuit gebieden met open water binnen Barataria Basin. Door kanalisatie van de Mississippi komt er op het ogenblik weinig sediment Barataria Basin binnen, en het meeste rivierslib komt verder van de kust in zee terecht.

Verschillende belangrijke fluxen die een rol spelen bij de vorming van moerassen (Fig. 2, Hoofdstuk 15) binnen Barataria Basin zijn gekwantificeerd voor zoet-, brak- en zoutwatermoerassen (zie Tabel 3, Hoofdstuk 15). De inklinking is in het algemeen 3 tot 5 maal sneller dan de eustatische zeespiegelstijging. De verticale aangroeisnelheid is groter in de zoutwatermoerassen dan in de zoet- en brakwatermoerassen. Desondanks is, als gevolg van de snellere inklinking aldaar, de verticale aangroeisnelheid in de zoutwatermoerassen onvoldoende om de schijnbare zeespiegelstijging bij te houden, terwijl het oppervlak van zoetwatermoerassen de zeespiegelstijging wel bij lijkt te houden. De

bijdrage van dode organische stof aan de verticale aangroei is in alle moerastypen 200-300 $gm^{-2} jr^{-1}$ aan C. Deze organische stof is voornamelijk afkomstig van plaatselijke plantaardige productie. De primaire productie van de moerasvegetatie kan negatief worden beïnvloed door intrusie van zout water en door toenemende inundatie. Afbraak van organische stof tot CO_2 en CH_4 tast ook de stabiliteit van de kustmoerassen aan.

Het toenemend verlies aan moerasland langs de kust van Louisiana kan op vele plaatsen worden toegeschreven aan onvoldoende verticale aangroei ten opzichte van zeespiegelstijging. De processen die daarvoor verantwoordelijk zijn, zijn zeer complex, mede omdat een groot aantal natuurlijke en door de mens beïnvloedde factoren daar direct of indirect een rol bij spelen. De kustmoerassen van Louisiana zullen in de toekomst waarschijnlijk in toenemende mate verdwijnen, tenzij maatregelen worden genomen om Mississippi sediment naar de moerassen te leiden. De hier gepresenteerde resultaten en inzichten kunnen van belang zijn voor vele kustgebieden in de wereld, als gevolg van de voorspelde klimaatsopwarming en daarmee verbandhoudende wereldwijde stijging van de zeespiegel.

Curriculum Vitae

Ronald D. DeLaune was born June 16, 1943 in Baton Rouge, Louisiana. He attended Louisiana State University from 1961 to 1965 and received a B. S. degree in Agronomy (soils). He attended graduate school at the same university from 1965 to 1968 receiving a M. S. degree also in Agronomy (soils).

Since graduating he has been employed by the Laboratory for Wetland Soils and Sediments, Louisiana State University. He has conducted and supervised research dealing with coastal wetland and is author or co-author of approximately 100 technical referenced publications.

His thesis research, a series of recent studies over past several years, was conducted along the Louisiana Gulf Coast and Mississippi River deltaic plain. He is presently a candidate for his Doctoral degree.