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Wetland loss dynamics in southwestern Barataria basin, Louisiana (USA), 1945–1985

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Abstract

We determined spatial associations of wetland loss rates in a 950-km² study area in the southwestern Barataria basin of Louisiana's Mississippi River delta plain for four intervals spanning 40 years, 1945–1985. A geographic information system was used to analyze spatial and temporal changes.

Annual wetland loss rates increased over the 40 years; the rate of increase in annual rates accelerated through 1980 and then began to decelerate. The average annual rate of wetland loss for the entire study area increased from 0.2%/yr during 1945–1956, to 1.2%/yr for 1956–1969, 1.9%/yr for 1969–1980, and 2.0%/yr for 1980–1985. Wetland loss was not uniform throughout the study area. Eight sub-areas were identified as having different densities and/or causes of loss. Processes implicated in the differing loss rates include sea level rise, shoreline erosion, accelerated subsidence along natural levees, canal modification of hydrologic flows, interference of dredged material with sheet flow, and saltwater intrusion. In some areas, several processes are believed to operate together to induce wetland degradation and wetland loss.

Introduction

We extend the study of Sasser *et al.* (1986) by reporting rates and locations of wetland loss* from 1945 to 1985 in a 950-km² area of the southwestern Barataria basin of Louisiana, USA. We hypothesize that different patterns of wetland degradation and loss result from different physical and biotic processes, including sea level rise, shoreline erosion, accelerated subsidence along natural levees, canal modification of hydrologic flows, interference of dredged material with sheet flow, and saltwater intrusion. 'Degradation' as used here describes the process over time, as observed on aerial photographs, of expanses of solid marsh progressively breaking up, with the appearance of small open water bodies which in time coalesce into larger lakes and bays.

The continuing break up and loss of Louisiana's coastal wetlands is a serious problem. These marshes constitute 41% of the coastal wetlands of the continental United States (Turner and Gosselink 1975). Wetland loss rates in Louisiana's Mississippi River delta plain may be as high as 100 km²/yr (Gagliano *et al.* 1981).

An important factor in the loss of coastal wetlands is rising sea level relative to the marsh surface. On a global scale, sea level is rising at a mean rate of about 0.1 cm/yr (Gornitz *et al.* 1982). Louisiana's current rate of relative sea level rise already

* By 'loss' we mean conversion of wetlands to other land forms. In coastal Louisiana most loss reflects conversion to open water as marshes degrade.

averages 1.1 cm/yr (Penland *et al.* 1988b), while on the US Atlantic coast it has been about 0.3 cm/yr for the past century (Hicks *et al.* 1983). Global warming models predict that sea level will rise 1.2–1.8 cm/yr from 1980 to 2100 (Titus 1987). Sea level rise will have a great impact on Louisiana's coast, which has a slope of about 0.2 mm/km (Byrne *et al.* 1976).

Delaune *et al.* (1983) showed that wetland loss to open water in a southwestern Louisiana estuary was directly proportional to changes in relative sea level. Since the magnitude of relative sea level rise depends on both eustasy and spatially varying local land subsidence, rates of wetland loss also vary both spatially and temporally, even within our study area. Reasons for wetland loss and its variation have been the subject of much research and speculation, and both natural and human-induced causes have been implicated (Craig *et al.* 1980, Scaife *et al.* 1983, Coleman *et al.* 1986, Walker *et al.* 1987, Cahoon and Turner 1988, Costanza *et al.* 1990).

Both aggradational and degradational processes occur in all marshes; their relative magnitudes determine whether a wetland will accrete rapidly enough vertically to remain subaerial or will submerge. The Louisiana delta plain is a conglomeration of overlapping delta lobes aggraded during Recent geologic times by the main distributary of the Mississippi River as it shifted to follow the most hydraulically efficient route to the Gulf of Mexico (Kolb and Van Lopik 1958). Delta lobes are cyclic geologic features that form when a river's distributary deposits its sediment load in the shallow water of an estuary (Coleman and Gagliano 1964). While the distributary follows one course, the delta continues to accrete. However, as the delta grows, the river's route becomes less efficient. Eventually, a new main distributary channel captures the flow and a new delta begins to grow. The former (abandoned) delta lobe then disintegrates over a period of several thousand years (Frazier 1967).

An aggradational deficit causes some of the wetland loss in abandoned delta lobes. For example, Baumann *et al.* (1984) showed that in interior delta plain marshes, aggradation of new sediments was not keeping up with relative sea level rise (eustasy plus subsidence), and wetlands deteriorated as they sank lower and lower in the intertidal zone.

Subsidence, one of the natural processes leading to degradation of the wetland surface, is caused by: dewatering, consolidation, and compaction of Recent sediments; downwarping of the underlying Pleistocene and Tertiary deposits; and tectonic activity. The importance of subsidence depends on the age of the Recent sediments; younger lobes subside faster than older deltaic sediments (Penland *et al.* 1988b). In undisturbed systems, sediment aggradation nearly balances subsidence, and marshes survive for centuries. On the Mississippi River's tributaries, however, wetland degradation has accelerated because dams have reduced the available sediment load and levees built along the river deprive the marshes of sediments by channeling sediments into deep coastal waters (Keown *et al.* 1980).

As a result of the confinement of the Mississippi River, new deltas (where aggradation is greater than relative sea level rise) are building in only 20% of the Louisiana delta plain (Penland *et al.* 1988a). In abandoned delta lobes, sediment supply for wetland aggradation comes primarily from local mineral sources and organic deposits from below- and above-ground plant growth (Hatton *et al.* 1983). Thus, sediment deposition in abandoned delta lobes is caused by reworking of bay-bottom sediments by hurricanes and winter storms, supplemented by organic production. In these abandoned delta lobes, sediment deposition rates are 0.7–1.3 cm/yr (Baumann *et al.* 1984), and in marshes experiencing the lowest of these sedimentation rates, aggradation is not keeping pace with subsidence.

Human activities influence wetland loss rates, both by directly destroying marshes and by accelerating natural submergence. These activities include canal dredging (Scaife *et al.* 1983, Turner *et al.* 1983, Cahoon and Turner 1988), fluid withdrawal (Gagliano *et al.* 1981), toxic pollution including brine introduction (Leibowitz 1989), and boat wakes (Johnson and Gosselink 1982). Wetlands are also drained and converted to agricultural, industrial, and urban uses.

Wetland plants are flood-adapted, but sensitive to changes in hydrologic conditions (Mendelssohn and McKee 1988). As relative sea level rises, species of emergent vegetation with roots poorly adapted to permanent submersion begin to die. Without roots to bind sediments, unvegetated areas are susceptible to erosion by factors such as wave action and tidal scouring. Herbivores, such as *Ondatra zibethicus* (muskrats), *Myocastor coypus* (nutria), and some waterfowl, can also cause wetland degradation by destroying plants (O'Neil 1949, Fuller *et al.* 1984).

Materials and methods

The study area lies in Lafourche Parish in the abandoned Lafourche delta in southeastern Louisiana, where aggradation is no longer keeping place with combined effects of eustasy and subsidence (Fig. 1). After the Mississippi River abandoned the Lafourche delta approximately 250 years ago (Frazier 1967), some flow continued through the abandoned Bayou Lafourche distributary until the U.S. Army Corps of Engineers dammed it north of the study area at Donaldsonville in 1904. The study area, located in the southwestern portion of Barataria basin, comprises 950 km^2 in Lafourche Parish. It is bounded on the west by Bayou Lafourche; on the east by Caminada Bay, Little Lake, and other connecting lakes and bayous; on the south by the Gulf of Mexico; and on the north by a canal north of Clovelly Farm. The area comprises marshes, open water, canal/spoil, natural levees and swamp-forests along Bayou Lafourche and its distributaries, and beaches along the Gulf of Mexico. Agricultural, urban, and industrial sites are located on and adjacent to the Bayou Lafourche natural levee. Although swamp-forests are also wetlands, they are rare in the study area and we only considered marshes in determining wetland loss. We use the terms 'marsh' and 'wetland' interchangeably. Sasser *et al.* (1986) reported that wetland loss rates in this area increased from 2.3 km^2/yr during 1945–1956 to 10.4 km^2/yr during 1969–1980.

We visually photo-interpreted 1:24000-scale color infrared aerial photographic transparencies taken in October 1985 (source: Gulf Coast Aerial Mapping, Baton Rouge, Louisiana, U.S.A.). We used a Bausch and Lomb Stereo Zoom Transfer Scope to correct for image distortions in the transparencies. Our minimum mapping unit of 1 ha was small enough to capture most linear features of interest, such as canals. The pixel (grid-cell) size was 0.25 ha. Following Dozier (1983), we differentiated visually among wetland, open water, canal/spoil, natural levees, developed areas, beaches, and LA Highway 1. The wetland category was subdivided into six classes according to the percentage of open water bodies within the marsh. Although there was no control for water levels in the photographs, the marsh-open water interface is sharp; even when the marsh surface is flooded, marsh vegetation is visible and can be differentiated from the open water areas. For some analyses and for reporting purposes, the six marsh and open water classes were merged into solid marsh (Class I), degraded marsh (Classes II–IV), and open water (Classes V and VI) (Table 1). ('Degraded marsh' refers to marsh fragmented by 10–60% open water bodies, as observed from aerial photographs; 'open water' refers to where marsh had degraded to less than 40% of the surface area). Data were digitized manually in vector format on an Intergraph mapping system (developed by Intergraph Corporation) at Louisiana State University's Remote Sensing and Image Processing Laboratory (RSIP). The vector format was converted into raster format in ELAS (Earth Resources Laboratory Applications Software), a software package developed by the National Aeronautics and Space Administration (NASA) and modified by RSIP. ELAS is both an image processing system and a geographic information system (GIS) – a computerized georeferenced mapping system designed to store, process, and analyze spatial data (Honeycutt *et al.* 1980). Raster data were added to an existing data base in ELAS that contained identically mapped and classified land-cover information from 1945, 1956, 1969, and 1980, as reported by Sasser *et al.* (1986). Two people photo-interpreted all of the imagery for both studies, and their classification results were comparable. Data were manipulated within

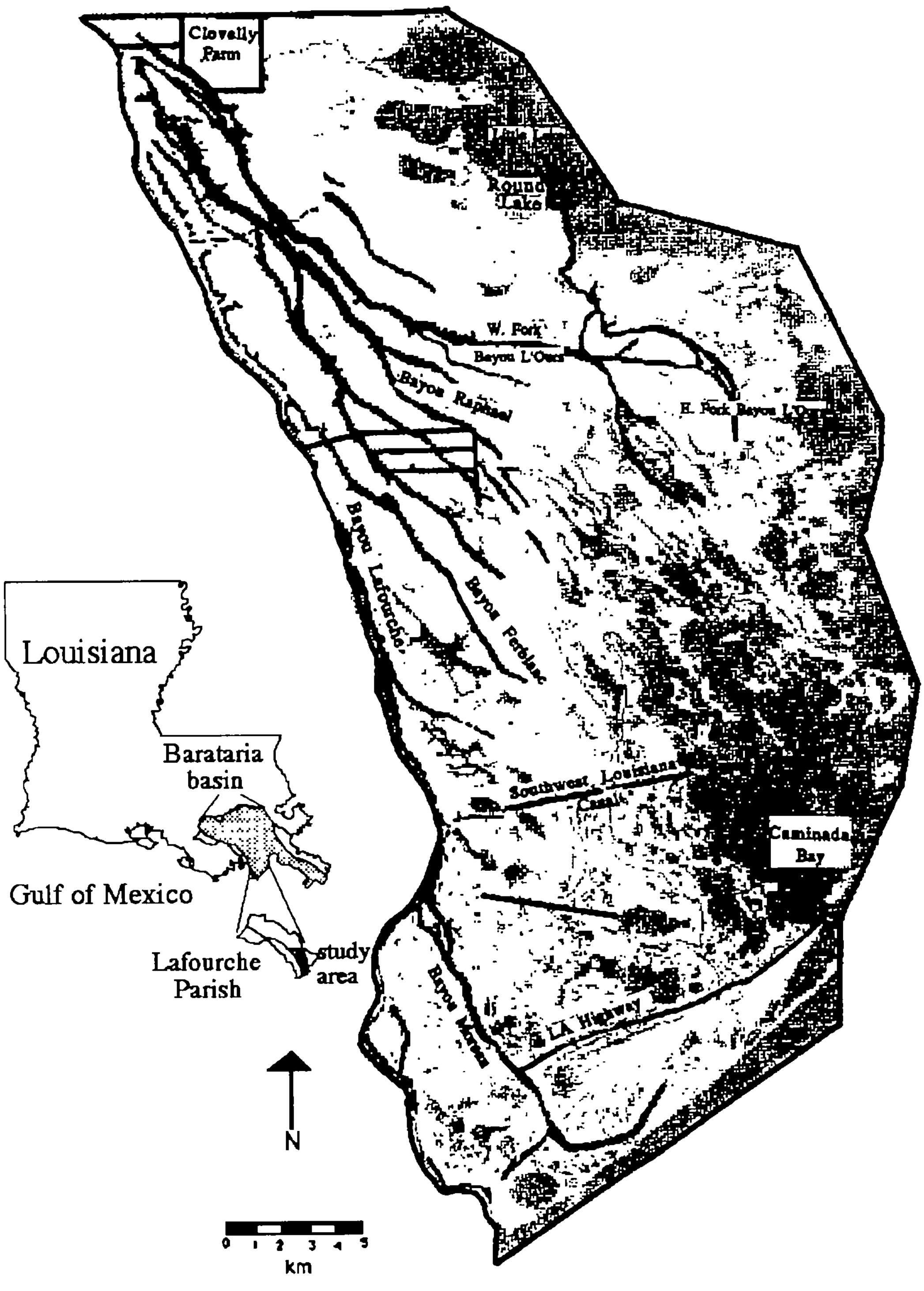


Fig. 1. The study area.

the GIS system to determine temporal and spatial patterns of wetland change in the study area.

Results

Temporal patterns of wetland loss

Change analysis, 1945–1985
Over the 40-year period, solid marsh (Class I) steadily decreased, and degraded marsh (Classes II, III, and IV) and open water (Classes V and VI) increased (Table 1; Fig. 2). Only 59% of the 1945 total marsh area (solid and degraded marsh, Classes I–IV) remained as marsh in 1985.

More detailed analysis of changes in wetland status over the period 1945–1985 revealed that the overall percentage change underestimates the extent of marsh degradation. Although the total marsh area (solid and degraded marsh, summarized in bold print in Table 2) in 1985 was 59% of that existing in 1945, only 10% of it remained qualitatively unchanged from 1945 to 1985 (the underlined values in Classes I–IV, Table 2). Of the total marsh area in 1945, 90% was solid marsh. In 1985, only 9% of this solid marsh was still classified as solid marsh; 7% was converted to canal/spoil, and the rest to open water or degraded marsh. Total canal/spoil area increased from 3.9 km^2 in 1945 to 49.5 km^2 in 1985. Canal length increased from 66.8 km in 1945, to 501.9 km in 1980, and to 516.9 km in 1985; additions in the last five years were mostly spurs off existing canals (Fig. 3).

Change analysis, 1980–1985
Between 1980 and 1985, the rate of marsh degradation increased. During this interval, 34% of the total marsh area remained unchanged (underlined values in Classes I–IV, Table 3). Overall, 6% of the study area was solid marsh in 1985 (Class I, Table 1), a decrease from 12% in 1980. Most of the change (45%) from solid marsh was to degraded marsh classes, but 12% of the solid marsh became open water, and 5% was dredged and entered the canal/spoil class (Table 3). The total area of degraded marsh (Classes II, III, and IV) remained essentially unchanged during the five-year period because as the solid marsh degraded, the degraded marsh further disintegrated to open water. Of the natural levee category, 21% was reclassified to solid marsh in 1980, and 32% to degraded marsh; both changes are believed to be due to subsidence.

Spatial patterns of wetland loss

Within the study area, wetland loss patterns differ spatially. A change-detection image shows that more than 60% of the area classified as wetlands in 1945 had been converted to open water by 1985 (Fig. 4). The pattern of loss was complex. Dozier (1983) and Sasser *et al.* (1986) divided the area into five zones of varying patterns of wetland loss. We expanded these basic categories to describe eight wetland loss zones based on density, location, and pattern of loss (Fig. 4, inset; Table 4). The area labeled 'developed' in Figure 4 consists mainly of natural levees, swamp-forests, and other land used for agricultural, urban, and industrial purposes.

Discussion

Wetland loss rates

The absolute rate of wetland loss in the study area increased from 1.4 km^2/yr during 1945–1956 to a maximum of 9.3 km^2/yr during 1969–1980, and decreased to 7.7 km^2/yr during 1980–1985.

The annual percentage wetland loss rate is standardized as follows:

$$\text{Annual Percentage Loss} = \frac{\text{Area changed from marsh to nonmarsh}}{\text{area of marsh at beginning of interval} * \text{years in interval}} \times 100 \quad \text{(eq. 1)}$$

For our study area the standardized annual loss rate shows an acceleration from 0.2 to 1.9% from 1945 to 1980. The annual rate from 1980 to 1985 was 2.0%, the greatest rate of the 40-year period (Fig. 5). Results of other studies (Table 5) generally support our conclusions that the annual rate of wetland

Table I. Marsh area in 1945, 1956, 1969, 1980, and 1985, and rates of change during 1945–1956, 1956–1969, 1969–1980, and 1980–1985 in southwestern Barataria basin marshes. Bold values are wetland (classes I, II, III, and IV) and open water (classes V and VI) totals, respectively

	area by Year					1945–1956	1956–1969	1969–1980	1980–1985	1945–1985
category	1945 (km^2)	1956 (km^2)	1969 (km^2)	1980 (km^2)	1985 (km^2)	rate of change (km^2/yr)	rate of change (km^2/yr)	rate of change (km^2/yr)	rate of change (km^2/yr)	rate of change (km^2/yr)
class I[a]	527.4	470.4	246.4	119.2	59.3	−5.2	−17.2	−11 6	−12.0	−11.7
class II	45.9	73.9	179.5	147.0	120.4	2.6	8.1	−3.0	−5.3	1.9
class III	10.7	23.2	37.2	76.4	107.4	1.1	1.1	3.6	6.2	2.4
class IV	1.1	2.6	24.2	42.7	59.9	0.1	1.7	1.7	3.4	1.5
wetland total	**585.1**	**570.1**	**487.3**	**385.3**	**347.0**	**−1.4**	**−6.3**	**−9.3**	**−7.7**	**−5.9**
class V	2.6	3.4	0.2	27.4	48.3	0.1	−0 2	2.5	4.2	1.1
class VI	281.0	294.2	323.1	382.8	403.4	1.2	2.2	5.4	4.1	3.1
open water total	**283.6**	**297.6**	**323.3**	**410.2**	**451.7**	**1.3**	**2.0**	**7.9**	**8.3**	**4.2**
natural levees	53.1	41.0	44.0	31.3	18.6	−1.1	0.2	−1.2	−2.6	−0.9
canals	3.9	15.7	48.9	42.8	49.5	1.1	2.6	−0.6	1.3	1.1
developed	19.3	20.8	39.4	71.7	75 8	0.1	1.4	2.9	0.8	1 4
other	7.3	6.3	9.2	9.0	8.8					

[a]class I: solid marsh, 0%–10% open water.
class II: degraded marsh, 10%–25% open water.
class III: degraded marsh, 25%–40% open water.
class IV: degraded marsh, 40%–60% open water.
class V: open water, 60%–80% open water.
class VI: open water, 80%–100% open water.
[b]includes Bayou Lafourche, beach, and LA Highway I.

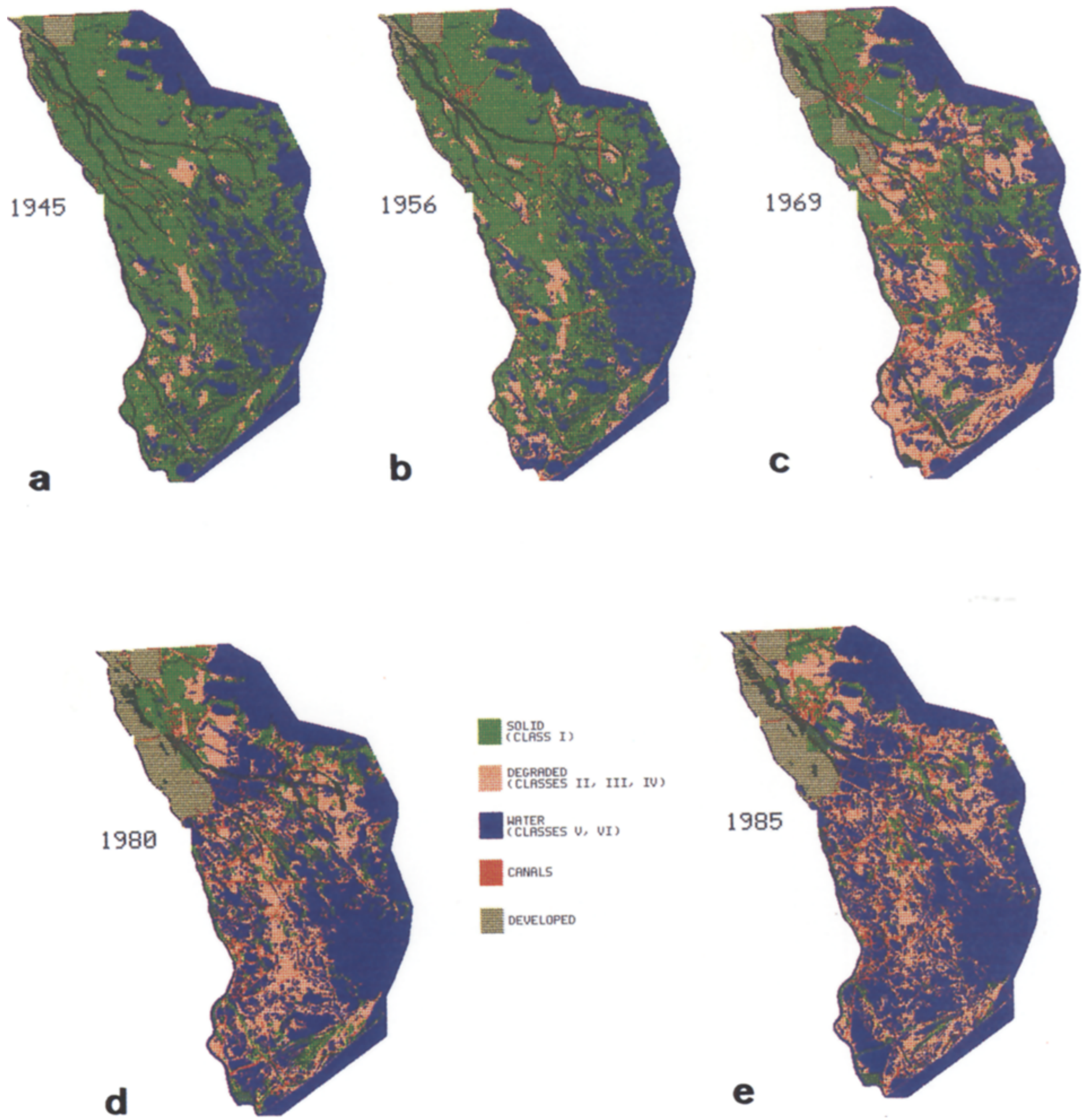


Fig. 2a–e. Maps of the study area in 1945, 1956, 1969, 1980, and 1985 as represented in aggregated classes Part *a* represents study area as it appeared in 1945; *b*, in 1956; *c*, in 1969; *d*, in 1980; and *e*, in 1985.

Table 2. Change detection for 1945–1985 land categories (km^2). Values in the matrix are areas of the indicated 1945 class (rows) that were classed as shown in 1985 (columns). Underlined values represent no change in the category. Bold values are wetland (classes I, II, III, IV) and open water (classes V and VI) totals, respectively. Last column and row are the area totals for each class, in 1945 and 1985, respectively.

	1985												
1945	class I[a]	class II	class III	class IV	wetland total	class V	class VI	open water total	natural levees	canals	developed	other[c]	1945 totals
class I	48.2	96.8	85.7	46.3	**277.0**	35.9	125.2	**161.1**	5.3	36.6	44.9	2 2	527.1
class II	1.7	5.7	7.8	6.4	**21.6**	6.1	13.7	**19.8**	b	3.8	0.5	b	45.9
class III	0.2	1.1	2.2	1.8	**5.3**	1.4	3.0	**4.4**	0	0.8	1.0	b	11.5
class IV	b	b	0.2	b	**0.2**	0.2	0.4	**0.6**	b	b	b	0	1.1
wetland total	**50.1**	**103.6**	**95.9**	**54.5**	**304.1**	**43.6**	**142.3**	**185.9**	**5.3**	**41.2**	**46.4**	**2.2**	**585.1**
class V	b	0.3	0.4	b	**0.7**	0.3	1.2	**1.4**	b	b	b	b	2.6
class VI	2.9	9.1	6.4	3.5	**21.9**	2.6	253.4	**256.0**	b	2.0	0.5	0.6	280.9
open water total	**2.9**	**9.4**	**6.8**	**3.5**	**22.6**	**2.8**	**254.6**	**257.4**	**b**	**2.0**	**0.5**	**0.6**	**283.6**
natural levees	5.7	6.9	4.1	1.7	**18.4**	1.6	4.5	**6.1**	12.0	3.4	11.2	2.0	53.1
canals	0.2	b	0 3	b	**0.5**	0.2	0.3	**0.5**	b	2.0	0.7	b	3.9
developed	b	b	b	b	**b**	b	b	**b**	1.0	b	17.4	0	19.2
other[c]	b	0.4	0.2	b	**0.6**	b	1.7	**1.7**	b	b	0.4	3.2	6.2
1985 totals	59.3	120.4	107.4	59.9	**347.0**	48.3	403.4	**451.7**	18.6	49.5	76.6	8.9	

[a]class I: solid marsh, 0%–10% open water.
class II: degraded marsh, 10%–25% open water.
class III: degraded marsh, 25%–40% open water.
class IV: degraded marsh, 40%–60% open water.
class V: open water, 60%–80% open water.
class VI: open water, 80%–100% open water.
[b]represents <0.01% of the study area.
[c]Includes Bayou Lafourche, beach, and LA Highway 1.

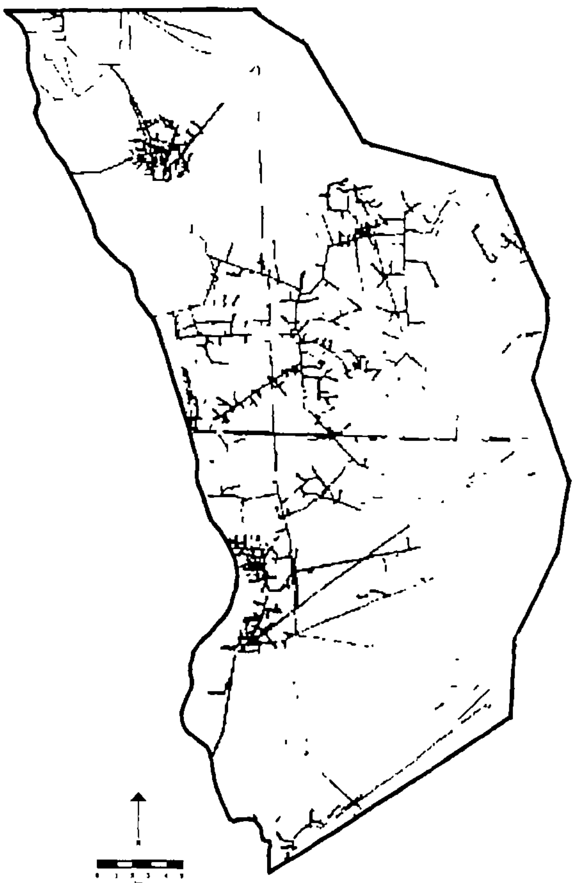


Fig. 3. Canal network in the study area, 1985.

loss in the Barataria hydrologic unit accelerated until 1980. Although the annual rate was higher during 1980–1985 than previously, the rate of increase in the rate had decelerated. We found wetland loss rates for southwestern Barataria basin about equal to those Gagliano and van Beek (1970) calculated for the entire Barataria basin and greater than Gagliano *et al.* (1981) calculated for the entire basin. They were also greater than the average rates Adams *et al.* (1976) calculated from representative samples of the three marsh types in the Barataria basin (Table 5). This was expected because our study area primarily comprised rapidly degrading brackish and saline marsh, whereas the two other studies included more inland freshwater marshes of the northern Barataria basin.

Looking beyond overall marsh loss rates to the temporal dynamics of different marsh degradation classes was instructive. For example, more than 50% of the marsh in 1945 was classified as solid, and virtually the only other class was open water (Tables 1, 4). By 1956, however, more of the marsh was classified as degraded (Table 1). As solid marsh continued to decrease, the degraded classes continued to increase, until in 1969 as much marsh was classified degraded as solid. By 1969 more hectares of marsh were classified as open water than solid marsh. To the extent that other studies considered degraded marshes simply as 'marsh', without considering degree of degradation and the presence of small open water bodies within the marsh, they underestimated the rate of marsh loss.

The dense network of canals in the study area (Fig. 3) affects wetlands and must be considered in wetland loss studies. Adams *et al.* (1976) estimated that, including associated spoil banks, as much as 10% of the wetland area in the Barataria basin had been converted to canals by 1974. Of the 950 km^2 in the southwestern Barataria basin study area (a subportion of the basin), 5.2% (49.5 km^2) was canal/spoil in 1985. Because canals and their associated spoil banks are actually dredged in the marsh itself, they represent a direct loss of wetlands. The indirect loss of wetlands caused by canals is difficult to determine, but important (Scaife *et al.* 1983). For example, canals widen at appreciable rates as their banks erode (Craig *et al.* 1980, Johnson and Gosselink 1982). Canals also alter the hydrologic regime in marshes. By restricting overland flow, their spoil deposits increase flooding stress by decreasing the number but lengthening the periods of marsh inundation and by changing the below-surface water regime (Swenson 1983, Swenson and Turner 1987). The sheet flow of water across marshes, which nourishes the marsh with nutrients and sediments, is impeded by canal spoil banks (Scaife *et al.* 1983). Canals that connect high- and low-salinity marshes may also cause saltwater intrusion (Wang 1988), which can stress the plants. Although determining the total impact of canals on wetlands is difficult, their direct and indirect impacts are believed to have caused 30–59% of Louisiana's coastal wetland losses from 1955 to 1978 (Cahoon and Turner 1988).

Between 1945 and 1985, 74% of agricultural, ur-

Table 3 Change detection for 1980-1985 land categories (km²). Values in the matrix are areas of the indicated 1980 class (rows) that were classed as shown in 1985 (columns). Underlined values remained unchanged in the time interval. Bold values are wetland (classes I, II, III, IV) and open water (classes V and VI) totals, respectively. Last column and row are the area totals for each class, in 1980 and 1985, respectively.

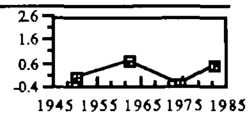
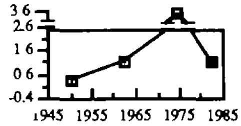
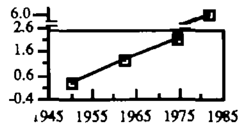
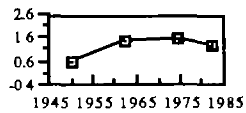
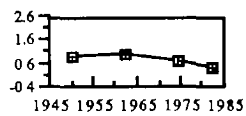
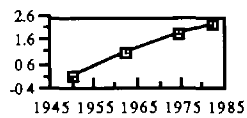
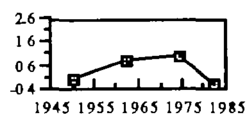
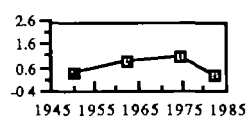
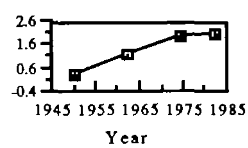
	1985												
1980	class I[a]	class II	class III	class IV	wetland total	class V	class VI	open water total	natural levees	canals	developed	other[c]	1980 totals
class I	36.0	31.0	17.2	5.6	**89.8**	3.8	10.6	**14.4**	5.1	6.0	3.5	0.5	119.3
class II	8.2	51.3	39 7	15.0	**114.2**	8.6	16 9	**25.5**	0.5	5.6	0.9	0.3	147.0
class III	1.5	8.5	28.0	13.5	**51.5**	9.9	12.1	**22.0**	0 4	2.4	0.3	0.2	76.8
class IV	0.4	4.1	5.0	15 3	**24.8**	9.0	7.7	**16.7**	b	1 2	b	b	42 7
wetland total	**46.1**	**94.9**	**89.9**	**49.4**	**280.3**	**31.3**	**47.3**	**78.6**	**6.0**	**15.2**	**4.7**	**1.0**	**385.8**
class V	0.4	1.9	2.4	2.1	**6.8**	9.3	10.0	**19.3**	b	1.2	0.2	b	27.5
class VI	3.9	14.0	9.9	6 0	**33.8**	5.5	337.1	**342.6**	b	4.5	1.2	0.4	382.6
open water total	**4.3**	**15.9**	**12.3**	**8.1**	**40.6**	**14.8**	**347.1**	**361.9**	**b**	**5.7**	**1.4**	**0.4**	**410.1**
natural levees	6.7	6.5	2.5	1.1	**16.8**	0.6	1.5	**2.1**	9.0	1.2	2.2	b	31.3
canals	2.2	2.8	2.7	1.2	**8.9**	1.5	3.9	**5.4**	0.4	26.6	1.2	b	42.5
developed	b	b	0.3	b	**0.3**	b	0.7	**0.7**	3.0	0 8	66.0	0.7	71.6
other[c]	b	0.2	0 1	b	**0.3**	b	0 6	**0.6**	b	b	0 1	6.3	7.5
1985 totals	59.3	120.4	107.8	59.9	**347.2**	48.3	403.4	**451.7**	18.6	49 5	75.8	8.9	

[a]class I: solid marsh, 0%–10% open water
class II: degraded marsh, 10%–25% open water
class III: degraded marsh, 25%–40% open water
class IV: degraded marsh, 40%–60% open water
class V: open water, 60%–80% open water.
class VI: open water, 80%–100% open water.
[b]represents <0.01% of the study area.
[c]Includes Bayou Lafourche, beach, and LA Highway 1.

Fig. 4. A change detection of the study area depicting, in shades of gray, pixels (grid cells) that were less that 60% open water in 1945 and more than 60% open water in 1985 (i.e., a change from 'marsh' to 'open water'). The darker the pattern, the greater the density of water pixels in the area. Horizontal stripes indicate areas that were more than 60% open water in 1945 White represents all other categories. Numbers on the inset depict eight different loss rate areas, and pertinent values for each are presented in Table 4.

ban, and industrial development in the study area occurred on natural levees and solid marshes (Table 2). Agricultural areas are found mostly in the northwestern section of the study at the divergence of distributaries from Bayou Lafourche (Fig. 1), where natural levees are suitable for farming and

Table 4. Descriptions and conditions of the marsh in 1945 and 1985 for the total study area and eight discrete areas, along with average rates of wetland loss for the intervals 1945–1956, 1956–1969, 1969–1980, and 1980–1985. See Figure 4 for the locations of the different areas.

area	marsh degradation type	description of area	1945 solid marsh (%)	1945 degraded marsh (%)	1985 solid marsh (%)	1985 degraded marsh (%)	wetlandloss (%/yr)
1	stable	solid marsh area	93.7	3.0	38.9	51.2	
2	rapidly degrading marsh	very high density wetland loss containing large, contiguous areas of open water	80.5	8.2	10.5	31.1	
3	Rapidly degrading impounded marsh	Very high density wetland loss containing large, contiguous areas of open water	58.4	16.7	3.5	27.6	
4	steadily retreating lake-edge marsh	shoreline wetland loss primarily through lake-edge erosion	71.5	7.9	10.7	36.6	
5	steadily degrading beachfront	shoreline wetland loss through beach and chenier erosion	81.1	12.9	6.1	62.2	
6	degrading marsh	high density of wetland loss and smaller areas of open water	72.8	5.5	2.0	46.3	
7	degraded stable marsh	not solid in 1945, but stable throughout 1945–1985	67.8	22.0	15.8	56.9	
8	degraded marsh	saline/brackish marsh characterized by areas of low-density wetland loss	43.0	2.3	5.0	28.6	
total study area			55.5	6.1	6.2	30.3	

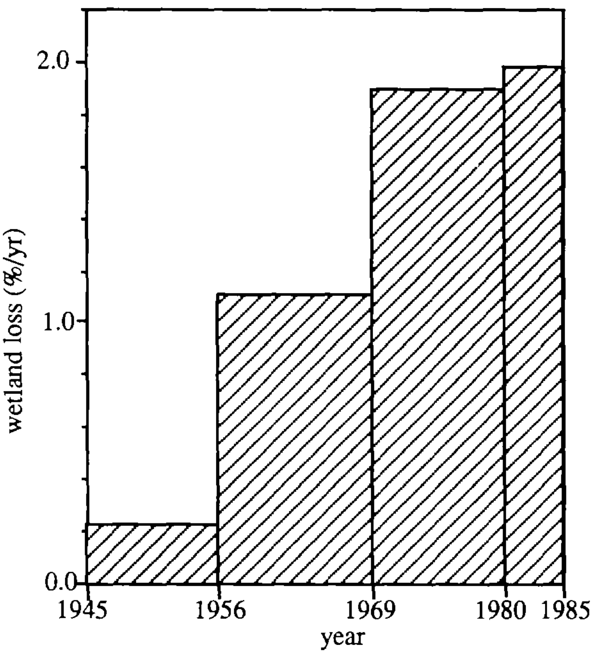


Fig. 5. Wetland loss rates since 1945 in the southwestern portion of Barataria basin.

marshes along levees were solid and fresh enough in the early 1900s to farm when drained. Urban and industrial areas lie along the Bayou Lafourche natural levees.

Spatial trends of wetland loss

The eight subareas show different rates and patterns of loss (Fig. 4; Table 4) and appear to be responding to differing intensities or combinations of physical and biotic processes. Area 1 corresponds to marsh that Sasser *et al.* (1986) classified as stable. O'Neil (1949) classified this area east of Clovelly Farm as an oligohaline floating three-corner-grass (*Scirpus olneyi*) marsh. In 1985, this area was still oligohaline. It was mostly solid marsh from 1945 to 1969, and loss rates were less than those for the entire study area throughout the 40-year period (Table 4). The marsh has begun to degrade in the last few years, however, though relatively little has been converted to open water.

Dozier (1983) characterized area 2 as rapidly degrading. Leibowitz (1989) also noted it as a 'hot spot' of wetland loss in a regional study of land change between 1956 and 1978. He found no definitive cause for the very rapid loss rate here, but suggested that a combination of factors, such as fluid (oil and gas) withdrawal, sediment deficit, salinity stress, and oil and gas canals, might have worked together to cause this anomaly. Area 2 is enclosed on the north and south by natural levee ridges and is intersected by north-south canals. From 1945 to 1956, it remained stable as 80% solid marsh. Most of the present canals were in place by 1956. Between 1956 and 1980, the solid marsh degraded and eventually became open water (Table 4). The peak rate of wetland loss (3.6%/yr) occurred between 1969 and 1980. From 1980 to 1985, marsh degradation continued and solid marsh decreased to 10% of the area. Salinity increases, cited as contributing to marsh loss (Gagliano and Wicker 1988), have been gradual in the remaining solid marsh area, which already contains salt-tolerant plant species (Gosselink *et al.* 1988).

Another area of rapid degradation, area 3, is located along the southwestern edge of Lafourche Parish (Fig. 4). The marsh was 60% solid in 1945. The rate of loss in this area has been consistently higher than for the total study area and accelerated to 6.8%/yr from 1980 to 1985 (Table 4). Approximately 85% was degraded marsh or open water by 1985. The area is cut off from most natural water flow by natural levees, LA Highway 1, and various canals and roads. The high loss rate probably resulted from impoundments created before 1969.

Table 5. Comparison of average annual rates of wetland loss from spatial studies of the Barataria basin.

Time interval	Average annual rates (%/yr)	Studies
1890–1930s	≅0.1	Gagliano and van Beek (1970)[a]
1930–1960s	≅0.2	Gagliano and van Beek (1970)[a]
1945–1956	0.2	this study[b]
1955–1978	0.7	Gagliano *et al.* (1981)[a]
1956–1969	1.2	this study[b]
1962–1974	0.8	Adams *et al* (1976)[c]
1969–1980	1.9	this study[b]
1980–1985	2.0	this study[b]

[a] Study area is Barataria basin.
[b] Study area is a 950 km^2 subsystem of the Barataria basin.
[c] Study area comprised representative samples from all three marsh types within Barataria basin.

Other studies (Swenson 1983, Swenson and Turner 1987) have shown that impoundment decreases the sediment supply to an area and, because of increased inundation periods, increases sediment waterlogging.

The shoreline in the Little Lake area (area 4) has eroded slowly throughout the 40 years of the study. Most solid marsh has disappeared, while open water and degraded marsh have steadily increased. Wetland loss rates in area 4 have been less than average rates from the total study area (Table 5), and loss in area 4 appears to be caused mainly by wave fetch from the lake.

Adams *et al.* (1976) reported that the Lafourche Parish coastline had the greatest rate of retreat in the state, averaging 14 m/yr between 1954 and 1969. The erosion rate is greatest in an area referred to as the Lafourche erosional headlands (Penland *et al.* 1988a), a portion of area 5. Peterson *et al.* (1988) reported shoreline retreat rates in the erosional headlands west of Bayou Moreau averaging 30 m/yr from 1980 to 1987. The energy of waves breaking on the beach erodes sand deposits, and nearshore currents carry the sand eastward to other locations (Adams *et al.* 1976). There was an increase in open water as the beach retreated. The marsh behind the beach is degrading in spite of an infusion of sand carried over the beach during storms. Table 4 shows that the rate of loss of solid and degraded marsh has been decreasing since 1956.

Area 6 lies over levee-flank depressions along the natural levee of Bayou Lafourche and other smaller distributaries that were active during the delta-building sequence. The weight of natural levees caused the adjacent marsh to subside at a greater rate than the marshes farther removed from the levees, resulting in shallow linear lakes parallel to the levees (Fisk 1955, Kolb and Van Lopik 1958). Both open water and degraded-marsh categories increased in this zone during the study period, and by 1985 no solid marsh remained. Rates of wetland loss were approximately equal to those for the whole study area, except that the loss rates here did not level out during 1980–1985, as they did for the total study area (Table 4).

Area 7, corresponding approximately to what Dozier (1983) and Sasser *et al.* (1986) referred to as the transitional area between a degrading marsh (area 6) and a stable marsh (area 8), had the lowest density of wetlands lost to open water (peak loss of 1.0%/yr during 1969–1980; Table 4). Although already degraded in 1945 (Fig. 2a), area 7 still had little open water in 1985 (Fig. 2e). This brackish-to-saline marsh may receive resuspended sediments from the bay through tidal channels.

Sasser *et al.* (1986) refer to area 8 as degraded marsh. Except for cheniers, this area has been saline marsh since at least 1978 (Chabreck and Linscombe 1978) and perhaps since 1949 (O'Neil 1949). Saucier (1963) concluded that saline marshes represent an advanced stage of degradation and have already passed the stage of maximum wetland loss. The high proportion of open water (>50%) in 1945 supports this description. Marshes in area 8 degraded between 1945 and 1985, but open water did not increase appreciably, and loss rates have been below the average for the study area (Table 4). These wetlands are, in a sense, remnants of former marshes, and as such either are more resistant to erosion or are in a steady state in which deposition of resuspended bay sediments on the marsh surface is sufficient to balance relative sea level rise. The digitate shoreline on the bay side of area 8, with its fingerlike projections, has the common configuration of a marsh with a barrier island fronting it (Morgan 1967, Boesch *et al.* 1983). The barrier island protects it from the direct effects of wave action. Possibly the most important erosive force affecting this area is tidal scour.

Barataria basin is presently nearing the end of the deteriorating phase of the delta cycle, and wetland loss is rapid. The whole marsh is submerging, although not at a uniform rate. Shoreline erosion occurs around the aquatic periphery. Riverine sediments formerly spread outward from distinct linear streams to blanket the marsh and counteract degrading forces. More recently, resuspended bay-bottom sediments have contributed to marsh aggradation, primarily in the protected saline marsh and to a lesser extent landward. The resulting complex natural topography and marsh breakup pattern reflect the interaction of these processes in space and time. Humans have complicated patterns and rates of change by: (1) constructing levees along major distributaries and preventing overbank introduction of sediments, mostly along the lateral peripheries of the coastal basin; (2) randomly interjecting canals and associated dredged material deposits, which create new, efficient paths of water, sediment, and salt movement, and at the same time inhibit overbank flows and isolate marshes from surface-water exchange; and (3) withdrawing subsurface fluids (oil, gas, water), which may accelerate subsidence. The dominant process contributing to marsh degradation is discernable in most of the eight subareas, although the effects of interactions among processes needs further elucidation. The extremely high loss rate in area 2 remains an enigma and may represent a convergence of several processes.

Documenting wetland loss in Louisiana's coastal region has been relatively easy. When coupled with insufficient sediment supplies, a general correlation between sea level rise and wetland loss over large areas is expected, but local patterns of loss are complex. If predictions are to be made for management, they must include an understanding of processes, such as substrate geology and human-induced effects, acting in discrete areas of interest. For example, although beach nourishment projects may slow beach erosion, they will help the interior marshes only indirectly; solutions to the problems associated with wetland loss are thus complex and site-specific.

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