Coastal Louisiana

Unlike most terrestrial environments, the ecosystems of coastal Louisiana experience rapid changes that are driven by changes in topographic relief, geological processes, and climate. In most terrestrial ecosystems, the underlying geology is stable within the period of ecosystem development and through many human generations: thousands or tens of thousands of years. Ecosystems of coastal deltas, though, are changed by water regimes and geological processes that operate in thousands, hundreds, and even tens of years. Coastal Louisiana, therefore, is an excellent laboratory in which to study ecosystems and their component species that have evolved in a rapidly changing environment. Because significant topographic and water regime change has taken place within the lifetimes of currently active scientists, the research record documenting these changes is unusually complete. The recent geological record for the coast of the Gulf of Mexico has been intensively studied because of the important fossil fuel resources in this region. In light of the knowledge gained, scientists have been able to interpret changes that are occurring in this century in the context of cycles that have been repeated since the last glaciation, some 6,000 years ago.

McNab and Avers (1994) classified coastal Louisiana in the Outer Coastal Plain Mixed Forest Physiographic Province, an extensive and diverse area that includes the Atlantic and Gulf of Mexico coastal plains from Maine to the Texas boundary with Mexico. The province includes the Louisiana coast prairies and marshes, which is an area of weakly dissected alluvial plain with poorly drained soils subject to flooding and high water tables and plant communities dominated by prairie grasses, marshes, and forested wetlands, including baldcypress (Fig. 1) and baldcypress–tupelo swamps.

Rapid Loss of Wetlands in Coastal Louisiana

The annual rate of loss in the area covered by Louisiana's coastal wetlands is currently about 66 square kilometers per year, down from a high of 107 square kilometers per year in the early 1980's (Dunbar et al. 1992; U.S. Geological Survey, National Wetlands Research Center, Lafayette, Louisiana, unpublished manuscript). Most of the change results from loss of vegetated marsh that reverts to open water. No other coastal areas of the United States experience such large-scale wetlands changes. Wetland scientists report additional large areas of coastal Louisiana that now appear to show the same visual pattern of stress that is exhibited by vegetated marsh before it disappears. These wetlands have always been dynamic systems, and the expansion and shrinking of deltas and subdeltas and their associated wetland and barrier systems have been in a fluctuating balance for millennia.

A combination of natural processes modified by humans is responsible for the present high rates of wetland degradation and loss along the Louisiana coast. The sea level relative to the land surface (*relative sea level*) is rising because the rates of coastal land lowering are very high. Large winter storms and hurricanes resculpt the coastline and rapidly change habitats. As the relative sea level rises, wetlands sink beneath the intertidal zone, and barrier island systems move shoreward and become thinner. Some barrier islands have submerged entirely in the last 50 years, and more are on the verge of total submergence.

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Fig. 1. Baldcypress in the Red-eye Swamp of the Atchafalaya basin; the cypress stumps are the remains of logging that occurred in the basin from the late 1880's to the late 1920's.

Human influences have helped tip the balance of growth and shrinking of coastal delta ecosystems. In particular, the levees and associated navigational works of the Mississippi River prevent the overflow of fresh water and sediments into the adjacent marshes during spring floods. These structures extend to the river's mouth, where fresh water and heavy, delta-building sediments enter deep water on the edge of the Gulf of Mexico Continental Shelf. The levees have eliminated almost all inflow to the marsh system from the Mississippi River, except in the Atchafalaya basin and at the very mouth of the river at the Balize delta. When levees were built to control flooding and aid navigation, no one anticipated their contribution to wetland loss. Canals built for oil and gas exploration, pipelines, well maintenance, and transportation have also contributed to wetland loss. Artificial canals and their associated spoil deposits are directly responsible for at least 10% to 30% of the loss, and an additional but unknown percentage of loss may be attributed to their indirect effects.

Ecosystems that are threatened by continued losses of coastal Louisiana wetlands provide habitat for internationally significant migratory waterfowl concentrations. The threatened habitats, which cover almost 3,000 square kilometers, also support large nesting concentrations of other birds, including threatened and endangered species such as the eastern brown pelican and the bald eagle. These areas also include 12 national wildlife refuges, Jean Lafitte National Park, and several state wildlife management areas, with land holdings totaling almost 300,000 hectares (National Park Service 1993; U.S. Fish and Wildlife Service 1996).

Cycles of Change in Coastal Ecosystems

Change in natural systems is fundamental and universal (see chapter on Natural Processes). The defining geomorphic processes acting upon the Louisiana coast are nearly all cyclic and thus, to some degree, predictable. These cycles range in length from the alternating marine–delta environments of the Tertiary (especially the Miocene, 20 million years ago, when the oil and gas reserves underlying the coast were formed) through the successive glacial–interglacial intervals of the Pleistocene, to the cycles of delta lobe formation and loss of the past 10,000 years that define the extent and present surface pattern of the Louisiana coast. The geomorphic cycles are linked to the flows of water down the Mississippi River and to long-term climatic events and cycles. Scientists have also described short-term cycles of wet and dry years that modify hydrology and directly affect animal and plant populations.

Although recent 100- to 5,000-year geomorphic cycles control the pattern of ecosystems on the landscape and its consequent change through time, all biotic processes also demonstrate seasonal cycles of growth and dormancy and respond to the seasonal flood cycle. Particularly important in the coastal region is the seasonal cycle of bird, fish, and shellfish migrations, which vary in space as well as time.

Coastal Ecosystems Are Open Systems

Coastal ecosystems in general, and Louisiana coastal ecosystems in particular, are open systems—they both gain and lose matter and organisms to other environments (Watzin and Gosselink 1992). Ecologically, they are defined as a type of *ecotone*, a transitional area that here is between the ocean and terrestrial uplands and is influenced by both. The Louisiana delta receives its enormous supplies of fresh water, sediments, and nutrients (as well as toxins) from the Mississippi River watershed, which covers about 41% of the conterminous United States. The delta's fate is thus controlled by events occurring all over this enormous watershed, including dam building (see chapter on Water Use), forest clearing (see chapter on Land Use), and heavy nutrient runoff from Midwest farmlands. It is also influenced by tides and marine storms that flood the coastal zone and deposit sea salt in coastal soils. Alterations to the Lower Mississippi River, including levees, blockages of former drainage systems, large and small water-control structures, canals, and channelization to support shipping, have all greatly influenced Louisiana's coastal wetlands. Biologically, the coast is also open and is dominated, at least seasonally, by migratory animals—fishes, shellfishes, and birds that move in and out of the coastal estuaries and wetlands.

Geology and Geomorphology of the Louisiana Coast

The Mississippi River Deltaic Plain

Geologically, the Louisiana coast consists of an eastern deltaic system and associated barrier islands built by the Mississippi River, and a geologically distinct Chenier Plain to the west, which is named for the linear, oak-dominated ridges that parallel this part of the coast (*chenier* is the French word for *oak*).

The Mississippi River, the largest river system in North America, drains an area of 4.76 million square kilometers. The average discharge of the river at the Mississippi River delta apex is approximately 15,400 cubic meters per second, with a maximum of 57,900 cubic meters per second and a minimum of 2,830 cubic meters per second. Sediment discharge is generally about 240 billion kilograms annually. The sediments brought by the river to the delta are 70% clay, mixed with silt and sand.

The river has had a pronounced influence on the development of the northern Gulf of Mexico. In the Tertiary (65–2.5 million years before the present), the large volumes of sediment carried by the Mississippi River created a major sedimentary basin, and many of the subsurface deposits, especially those that formed in localized centers of deposition, have been productive reservoirs of oil and natural gas. Faulting of these Tertiary sediments led to the migration and accumulation of hydrocarbons in fields below the coast, especially along the flanks of salt domes that were forced up through the sediments from the underlying rock strata (Roberts et al. 1989). These are sites of intensive oil and gas extraction, an activity that has strongly influenced the development of coastal ecosystems (Louisiana Coastal Wetlands Conservation and Restoration Task Force 1993).

In more recent geologic times, changing sea levels associated with the advance and retreat of inland glaciers during the Pleistocene ice ages greatly influenced sedimentary patterns off the coast. To understand the development of the present-day coastal wetlands, it is necessary to view the changes in the Mississippi delta and its adjacent coastal plains in relation to several time scales. These time scales range from those geologic periods associated with changing sea levels to recent changes in the past 100 years in the formation of minor subdeltas in the most recent deltaic lobe, the Balize delta. Sediments deposited by the river during the last several million years have caused excessive loading and resulting subsidence throughout the Mississippi River Deltaic Plain. To a large degree this loading has controlled the rate of coastal wetland addition and loss through much of recent geologic history (Gosselink 1984; Fig. 2).

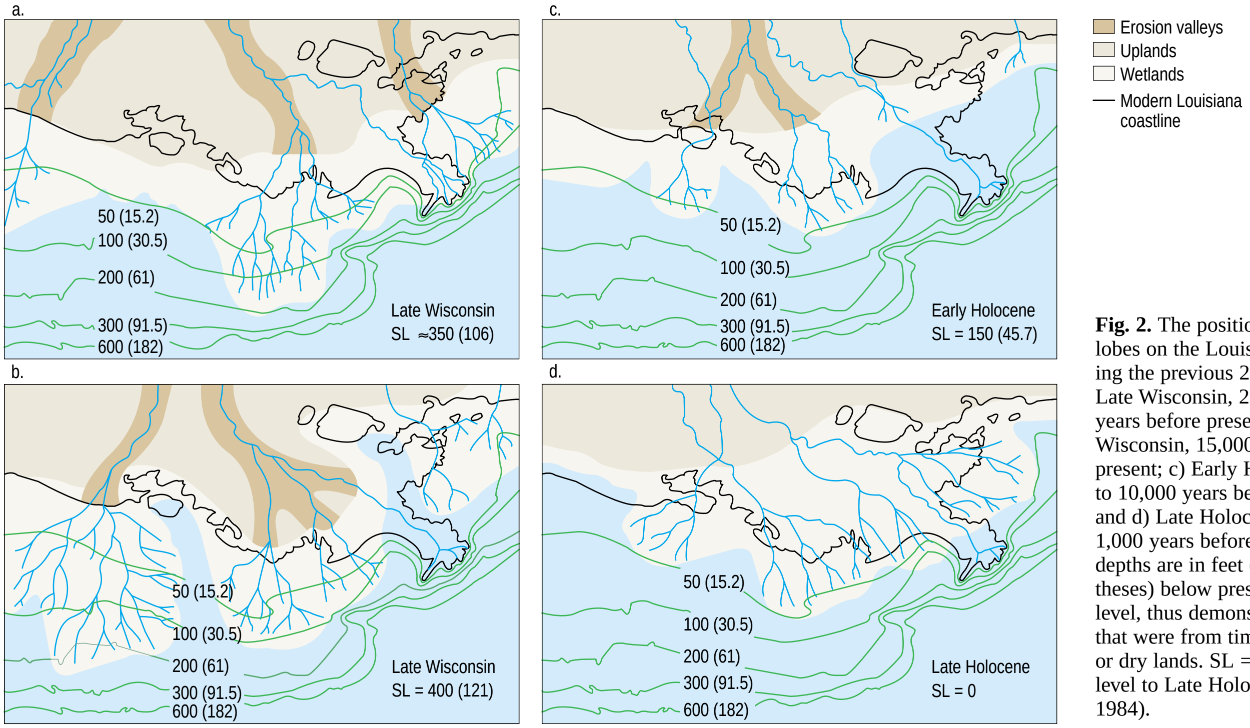


Fig. 2. The position of major delta lobes on the Louisiana coast during the previous 25,000 years: a) Late Wisconsin, 25,000 to 20,000 years before present; b) Late Wisconsin, 15,000 years before present; c) Early Holocene, 12,000 to 10,000 years before present; and d) Late Holocene, 5,000 to 1,000 years before present. Bottom depths are in feet (meters in parentheses) below present-day sea level, thus demonstrating areas that were from time to time marsh or dry lands. SL = relative sea level to Late Holocene (Gosselink 1984).

Recent Geomorphic Delta Cycles

The past 5,000 to 6,000 years have been characterized by relatively stable climates and small changes in sea level along the Louisiana coast. Most authorities agree that there are at least seven delta lobes (Fig. 3), which formed one after another. The result of the building and subsequent abandonment of these delta lobes by the river was the construction of a modern deltaic Coastal Plain with a total area of 28,000 square kilometers (Coleman 1976).

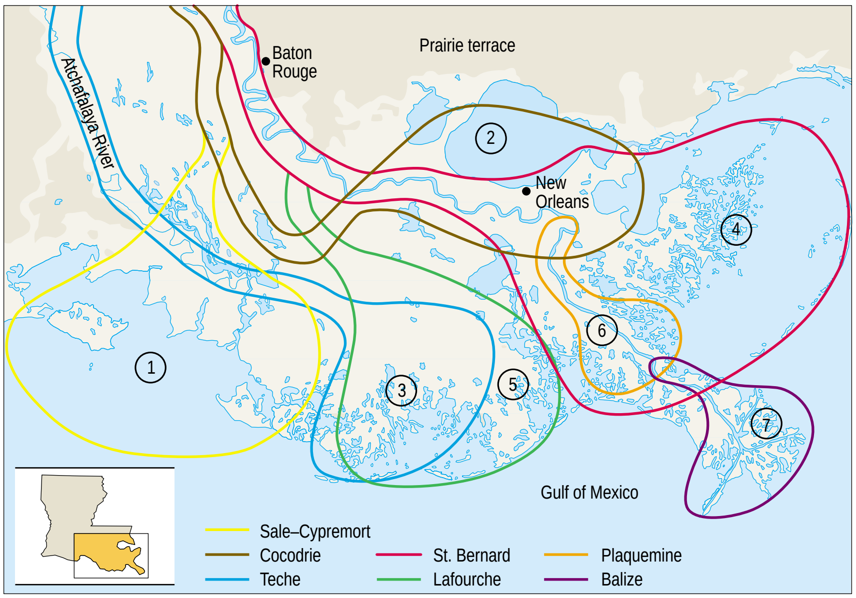


Fig. 3. Lobes of Mississippi River deltas, numbered in chronological order of formation (modified from Kolb and Van Lopik 1958). Light shading shows extent of current coastal marsh and bottomland forest.

One of the earlier deltas, the Sale–Cypremort delta, developed along the western flanks of the present Mississippi River Deltaic Plain (Fig. 3). In approximately 1,200 years, an extensive coastal marshland emerged before the river switched its course and began depositing sediments in another location, the Cocodrie system (Fig. 3). Over time this site of deposition was also abandoned, and a new delta lobe began to form. This process continues, each delta completing a cycle of expansion that lasts about 1,000 to 1,500 years. Over the last 600 years, the most recent delta cycle formed the modern birdfoot or Balize delta (Figs. 3 and 4). The modern Balize delta has nearly completed its expansion cycle, and in this century a new distributary, the Atchafalaya River, began drawing off a portion of the Mississippi River's water and sediment discharge. Thus, the new Atchafalaya delta is beginning its expansion phase (Van Heerden and Roberts 1980; Wells et al. 1982).

Broad coastal marshes form during each expansion phase of the delta cycle. Scruton (1960) referred to this as the *constructional phase*. However, once the river begins to abandon its major deposition site, the unconsolidated mass of rapidly deposited deltaic sediments is immediately subjected to reworking and subsidence, resulting in progressive flooding of the marshes, and within a few thousand years the delta lobe sinks beneath the sea. Scruton (1960) called this stage of the delta cycle the *destructional phase*. Thus, both land gain and land loss take place in the relatively short geologic period of 4,000–5,000 years.

A satellite image of the eastern portion of the Mississippi River Deltaic Plain shows several delta lobes in different stages of construction and destruction (Fig. 4). The oldest lobe shown is the St. Bernard delta, which was actively expanding some 3,000 years before present. This delta lobe remained active for approximately 1,200 years, forming a coastal marshland along the eastern Mississippi River Deltaic Plain (Gosselink 1984). Approximately 1,800 years ago, the Lafourche channel began its expansion. The St. Bernard delta, deprived of its sediment load, began to subside. The Lafourche distributary gradually increased its sediment yield, and within 1,000 years had built a major delta lobe west of the modern Balize delta. The sea began to intrude into the formerly freshwater marshes of the St. Bernard delta, and the marshland deteriorated rapidly. Coastal headlands and barrier islands formed at the mouths of the former distributaries. Eventually the Lafourche delta system reached its maximum development, while the modern delta lobes (Plaquemine and Balize) began their expansions. The Lafourche delta, abandoned by the river, was then subjected to marine reworking and compaction. During the past 800 years, this delta has lost land, mainly through saltwater intrusion and flooding of the marshland behind a coastal barrier still attached to the former distributaries.

Courtesy National Aeronautics and Space Administration (NASA)

Fig. 4. Satellite image of the Mississippi River delta region showing delta lobes of different ages (Gosselink 1984).

The Mississippi River has constructed a major delta lobe in the modern Balize delta. However, changes in river gradient and flow resistance now favor diversion of this flow to a more efficient path to the Gulf of Mexico. If artificial river-control structures did not limit diversion to about one-third of the Mississippi River's discharge, the river would soon abandon this lobe in favor of the Atchafalaya River course, diverging from the Mississippi River 480 kilometers upstream from the river's present mouth.

The Modern Mississippi River Delta

The modern Balize delta (Fig. 5) was constructed during the past 500 years. Because it is relatively young, it offers researchers an opportunity to evaluate the short-term processes responsible for delta building and inundation which mimic, on a smaller scale of time and space, the construction and destruction of the major delta lobes. When a break (or *crevasse*) occurs in the natural levee of one of the river distributaries, water rushing through the break deposits sediment into the adjacent bay (Fig. 6). After an initial break in the levee of a major distributary during flood stage, flow through the crevasse gradually increases through successive floods, reaches a peak of maximum deposition, then decreases and is cut off (Coleman 1976). As a result of compaction, the crevasse system is flooded by marine waters and reverts to a bay environment, completing its sedimentary cycle. Of the six recent crevasses (Fig. 5), four have bay fill sequences that have been dated from historical records, and much of their development during the past few hundred years can be traced by reviewing historical maps. Historical maps of Cubits Gap, for example, illustrate a cycle of delta building and abandonment (Fig. 7). The area shown on the 1838 map was surveyed before the break and shows a narrow, natural levee separating the Mississippi River from the shallow Bay Rondo. In 1862 the daughters of an oyster fisherman named Cubit excavated a ditch to allow passage by shallow draft boats. Although the original ditch was only about 120 meters wide, the flood of 1862 enlarged the opening, and by 1868 the break was 740 meters wide. By 1884 the initial development of a complex series of distributary channels had deposited relatively coarse sediment near the break, with shoaling in the bay caused by underwater deposition of the finer-grained deposits. A 1905 map shows that many of the major distributaries had developed and that rapid expansion had taken place since 1884. A major portion of the subdelta had been constructed by 1922; some small bays were already beginning to open up, indicating that some parts

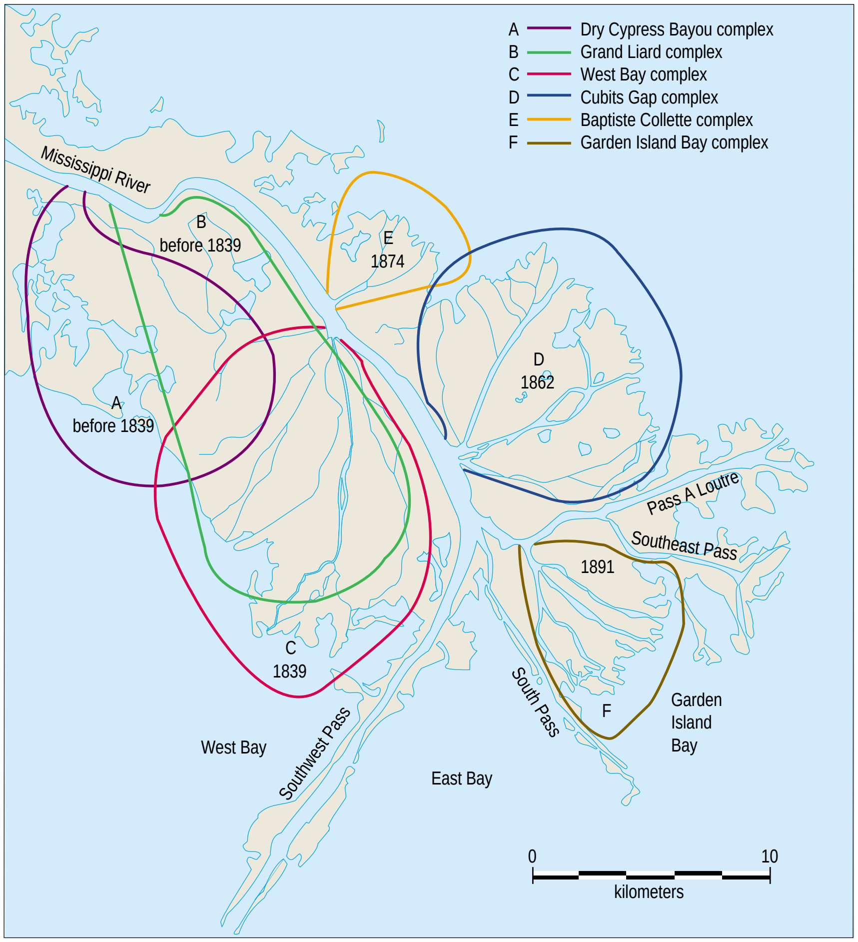
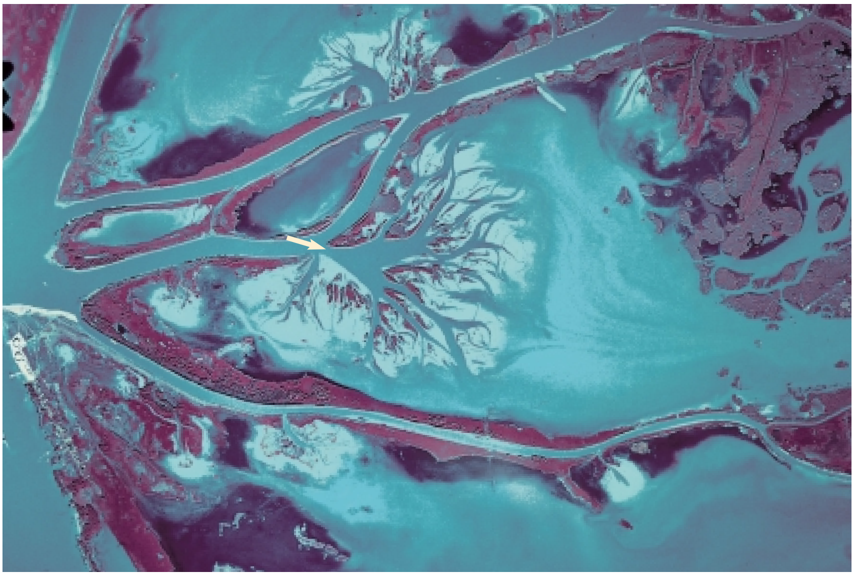


Fig. 5. Six subdeltas of the modern Mississippi Balize delta recognized from maps and sediment analysis. Dates indicate years of crevasse openings (Wells et al. 1982).



Courtesy D. White, Loyola University, New Orleans; modified from an original image from NASA

Fig. 6. The bird's foot formation in the center of this photo shows the early stage of formation of a subdelta lobe after a break (crevasse) occurred in the natural levee of the adjacent channel. Another delta lobe can be seen in the top center of the photo.

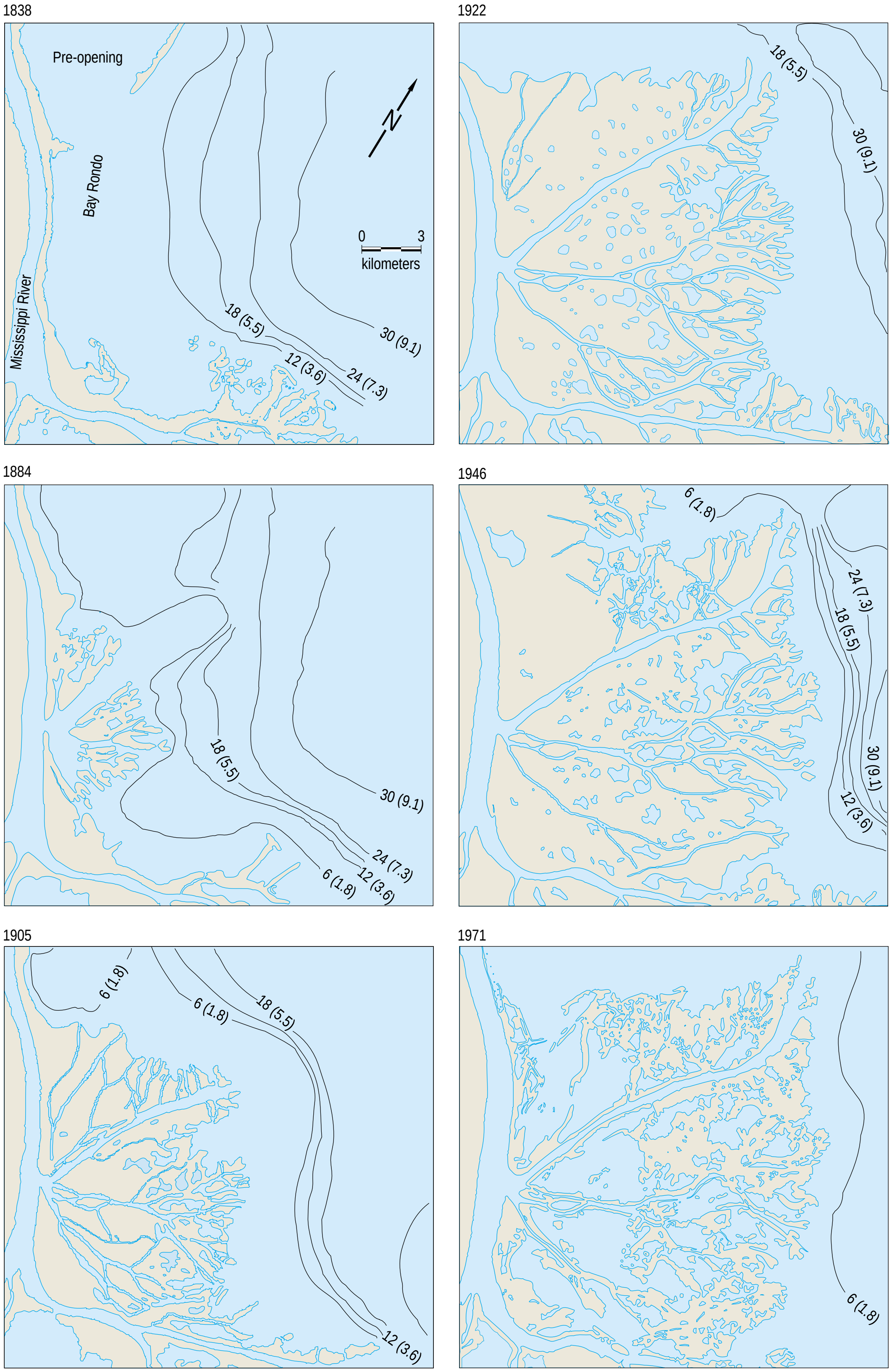


Fig. 7. Sequential development of Cubits Gap subdelta. Bottom depths are in feet (meters in parentheses) below sea level (Wells et al. 1982).

of the crevasse (subdelta) system were being deprived of sediments. The 1946 map shows sedimentation primarily at the seaward ends of selected distributaries; it also reveals that marshland loss was beginning. By 1971 a large part of the crevasse system was inundated by seawater, and marsh loss was becoming significant. The only sediment deposition occurring was at the seaward ends of some of the distributaries and underwater in the bay fill front. Note that land loss begins first near the crevasse break where sedimentation is extremely slow, depending only on overbank flooding, whereas higher sedimentation rates still prevail near the most remote parts of the crevasse system.

The growth and deterioration cycle of bay fills over a relatively short period of 50 to 100 years parallels the cycle of major delta lobes described previously. The growth period in a delta cycle approaches 800 to 1,000 years, and the deterioration period can be as long as 2,000 years. Bay fills provide an excellent model for evaluating the future growth of the newly formed Atchafalaya delta (Wells et al. 1982) and the deterioration of the former Mississippi River delta lobes.

Barrier Island Formation

The inactive delta lobes of the Mississippi River are fronted by a series of headlands and barrier islands. The sediments are derived from the reworking of formerly active distributary mouths, and they form erosional headlands with flanking barrier deposits after the distributary is abandoned (Penland et al. 1988). Sand deposits in the abandoned headland are reworked and dispersed along the shore into flanking barriers, thereby enclosing bays between major delta lobes (Fig. 8). Gradual submergence of the delta lobe separates the headland from the shoreline, creating a lagoon behind a barrier island. The island migrates landward but does not keep pace with the retreating mainland shoreline. Eventually, the island is left far from the mainland and deteriorates into a shoal (Reed 1995; Fig. 8).

Geomorphology of the Chenier Plain

West of the Mississippi River delta, the Louisiana coastal zone was created by forces related to the sediment supply of the river but not by direct sediment deposition, as in the delta. Pleistocene deposits, which form the geologic substrate of the Chenier Plain region, are found at the surface a few kilometers inland from the coast and dip gently seaward to include the slope of the Continental Shelf. When the last continental glaciers lowered sea level to 135 meters below its present level (Fisk and McFarlan 1955; Gould and McFarlan 1959) and the shoreline was about 200 kilometers seaward of its present position (Russell and Howe 1935), coastal streams cut valleys into the exposed Pleistocene deposits. As the level of the Gulf of Mexico rose during the subsequent glacial melt, layers of sediments were deposited on the eroded Pleistocene surface (Saucier 1974), including in the open gulf, bays, lakes, marshes, and swamps. In contrast to the deep Holocene sediments of the Mississippi River Deltaic Plain, on the Chenier Plain Holocene sediments form a thin veneer, except in the eroded river valleys. Today, the Chenier Plain supports an extensive marshland interspersed with large inland lakes formed in river valleys that were drowned after the last glaciation.

When the sea reached its present level, the shoreline was landward of its present location. During periods when the course of the Mississippi River was at the western edge of the Deltaic Plain, sediments from the river were carried westward by currents along the shore, forming mudflats along the Chenier Plain

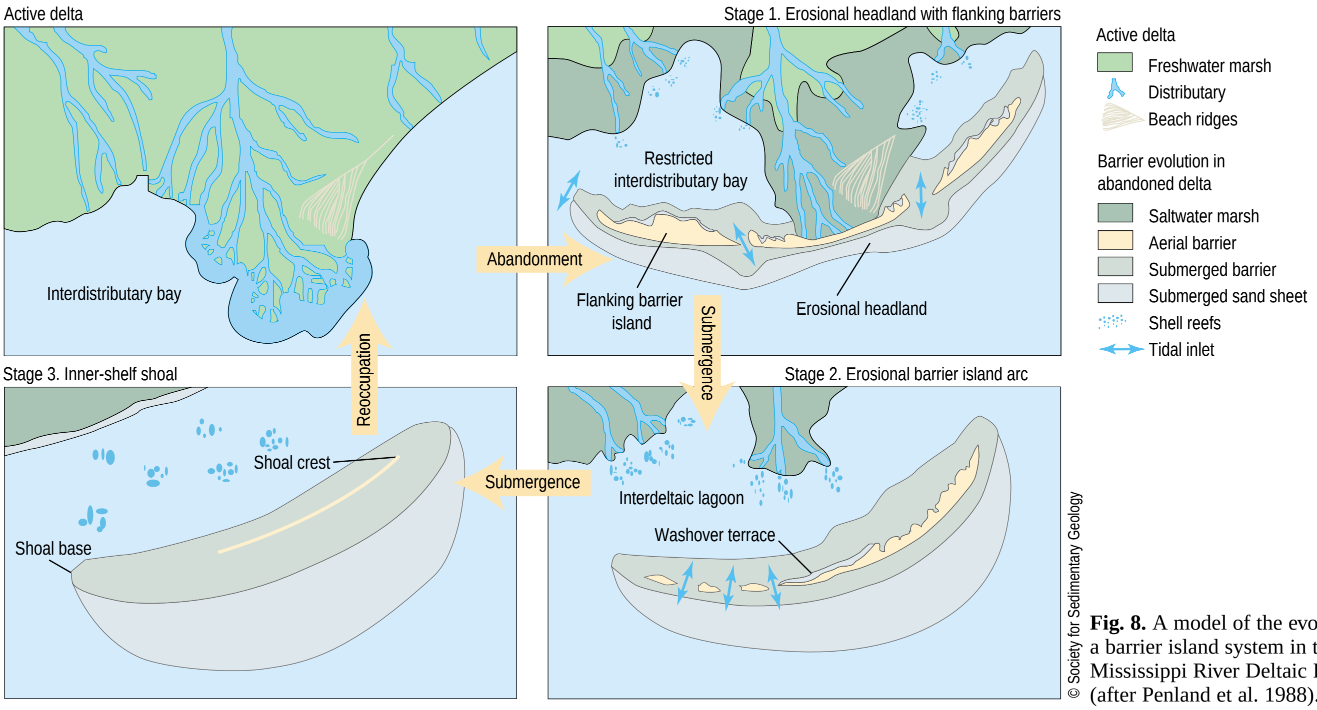


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Fig. 8. A model of the evolution of a barrier island system in the Mississippi River Deltaic Plain (after Penland et al. 1988).

shoreline (Kemp 1986). When the active channel of the river moved eastward and the Chenier Plain lost most of its sediment supply, erosion reworked the mud deposits, winnowing out the finest materials and forming beachfront ridges (cheniers) along the coast, with the remnants of the old mudflats (now marshes) behind them. The present topography reflects multiple river-mouth ridges converging to form a single beachfront ridge between the river inlets (Gosselink et al. 1979a,b,c; Fig. 9).

With the increase in this century of flow in the Atchafalaya River close to the western edge of the delta, fluvial processes are again dominating the Chenier Plain, and mudflat development is occurring along its eastern coast (Kemp 1986).

Accretion and Subsidence

The only active deltaic areas on the coast today are the Balize delta at the mouth of the Mississippi River and the actively expanding Atchafalaya River delta. Even within the Balize delta, much of the heavy sediment load of the Mississippi River is entrained by levees and navigational structures and is deposited in deep water on the edge of the Continental Shelf. Today, destructional processes far outweigh constructional processes over the Mississippi delta as a whole. The Chenier Plain, although protected on the marine edge by chenier ridges, is also rapidly losing wetlands, probably as an indirect result of human activities that have altered hydrology and allowed saltwater to invade freshwater marshes.

Net submergence is a dominant process in this destructional phase. It is a complex process with three components: subsidence, sea-level rise, and accretion of the surface through mineral sediment deposition and organic matter production (for example, see Cahoon et al. 1995). Subsidence of the substrate and eustatic sea-level rise lead to submergence of the land surface. Vertical growth via mineral sediment deposition and underground plant growth counter the effect of submergence. Net submergence occurs when subsidence and sea-level rise exceed vertical growth. Net submergence is taking place in most of the marshes in this destructional phase of the delta cycle, where submergence rates average about 1 centimeter per year, whereas vertical growth averages only about 0.6 centimeters per year. These subsidence estimates may actually be underestimates for many areas because they do not include subsidence that is occurring in the upper few meters of the substrate (Cahoon et al. 1995).

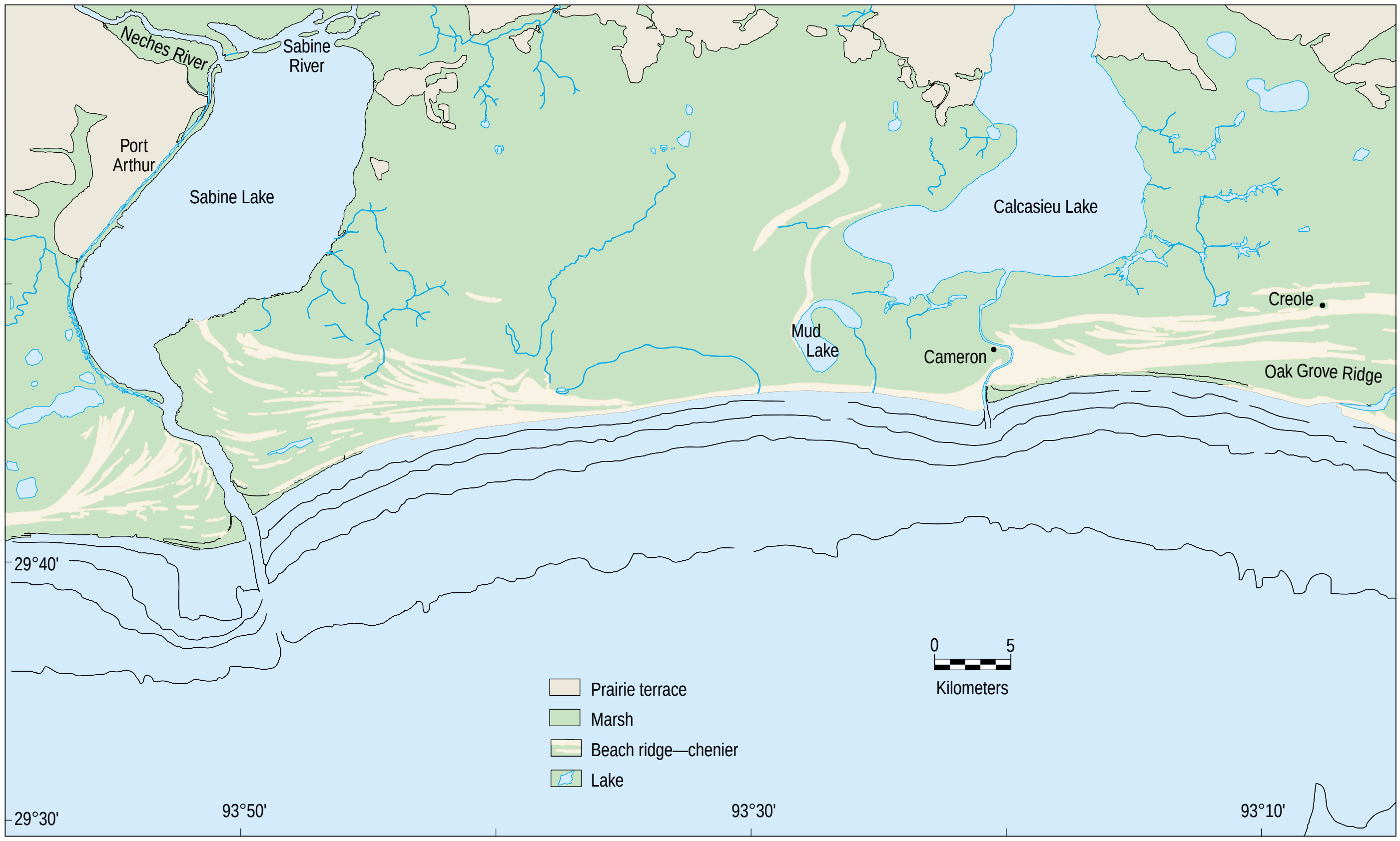

Fig. 9. The regional geomorphology of the Mississippi River Chenier Plain (after Penland and Sutter 1989). Bottom depths are in feet (meters in parentheses).

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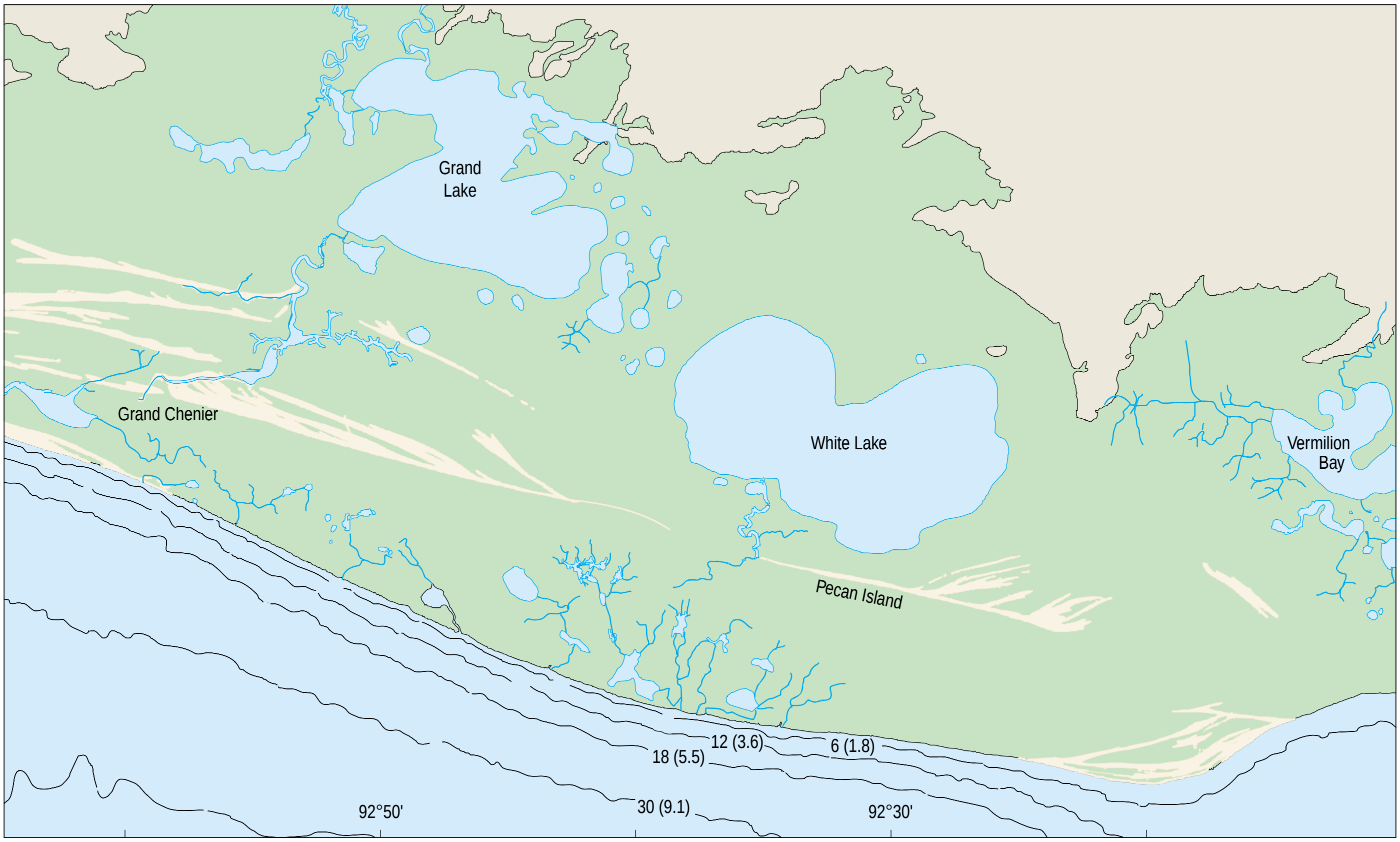
Along the northern gulf coast, eustatic sea-level rise is a minor component of submergence, about 0.23 to 0.24 centimeters per year (Gornitz et al. 1982; Penland et al. 1989), less than 10% to 50% of the total submergence rate. Most observed submergence is thus related to subsidence (Penland et al. 1994), and the subsidence rate is extremely variable across the coast (Fig. 10). The age and thickness of Holocene (recent) deposits are a contributing factor to the subsidence rate because thick deposits have more potential for compaction than thin ones and because younger deltaic deposits subside faster than older deposits, reflecting the progressive consolidation of sediments. The thickest Holocene sediments (nearly 100 meters; Penland et al. 1994) are within the incised valley of the Mississippi River; this valley spans the area between the Atchafalaya River on the west and New Orleans on the east, the largest portion of the coast. Thus, this part of the coast is generally subsiding faster than other sections. Peats, organic-rich sediments, prodelta clays, and bay clays have the greatest consolidation potential (Kuecher et al. 1993).

Most of the compaction occurs in the upper 2 meters of the sediment profile, reflecting the biological process of peat decomposition during the first few years after production. After that, sediment compaction and soil dewatering appear to dominate (Turner 1991).

Until recently, most of the emphasis on accretionary processes that counterbalance subsidence has focused on the introduction of mineral sediments by fluvial and marine processes, which occurs during the constructional phase of a delta cycle. However, in the destructional phase of a delta, organic material—primarily live and dead plant roots still in place—is the major structural component of the substrate, and plant underground production is the major expansion force (Nyman et al. 1990; Nyman et al. 1993a). Inadequate organic matter accumulation results from a decrease in root production of flood-stressed plants as a marsh subsides. Mineral sediments counteract this flooding stress, as shown by the positive relationship between soil bulk density and plant biomass (DeLaune et al. 1979; Nyman et al. 1994; Fig. 11). The role of sediments, however, is not structural but is indirect through stimulation of plant growth by mineral nutrients (Broome et al. 1975; DeLaune and Pezeshki 1988), precipitation of toxic sulfides (King et al. 1982; Mendelssohn and McKee 1988), and buffering of low reduction/oxidation potentials (Ernst 1990).



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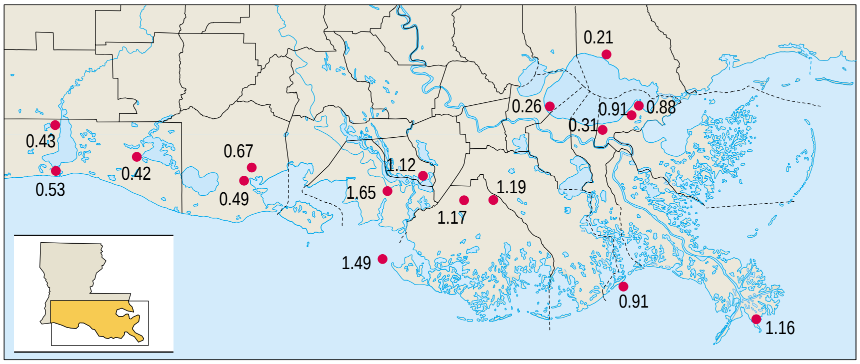


Fig. 10. Coastal Louisiana subsidence rates, centimeters per year (modified from Ramsey and Penland 1989; Penland and Ramsey 1990).

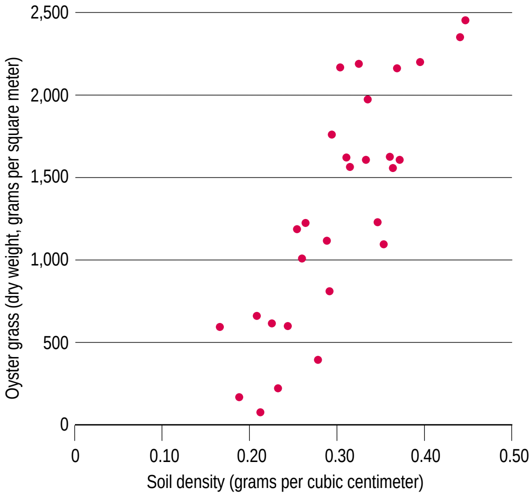


Fig. 11. Relationship between soil bulk density and aboveground biomass of smooth cordgrass in saltwater marshes (after DeLaune et al. 1990). Reprinted courtesy Elsevier Science, Catena, Volume 17, p. 282 (DeLaune et al. 1990). Processes governing marsh formation in a rapidly subsiding coastal environment. © 1990, Elsevier Science N L, Sara Burgerhartstraat. 25, 1055 KV Amsterdam, The Netherlands

The Present Environment of Coastal Louisiana

Climate

In the Mississippi River delta region, at about 30° north latitude, solar energy reaching the Earth's surface varies from about 200 calories per square centimeter per day during the winter to a peak of nearly 600 calories per square centimeter per day in June and July. During the summer, insolation at this latitude is higher than anywhere else on the globe; it falls off both northward toward the Arctic and southward toward the Equator. Therefore, midsummer growth potential in terms of solar energy is as high in the Mississippi delta as it is anywhere else on Earth.

As one might expect, seasonal air temperatures closely follow insolation. Mean monthly temperatures range from a December–January low of about 14°C to a midsummer high of about 30°C. Because of the moderating effect of the water bodies and high humidity, midday temperatures seldom exceed the low 30's (Celsius) despite the high insolation. Frost is infrequent; the annual average number of frost-free days on the coast is about 300. Because most of the inshore waters are less than 1 meter deep, water temperature closely follows air temperature.

Each of the components of the *water budget* (rainfall, evapotranspiration, river inflow, and tides) varies in both time and space. Annual precipitation, usually as rain, averages about 150 centimeters (Fig. 12). October tends to be the driest month and July the wettest, but torrential rains are common at any time. Wax et al. (1978) analyzed the atmospheric circulation of the Louisiana coast and found that high pressure systems moving in from the north and west bring cool, dry air. These systems are easily recognized during the winter as cold fronts but occur throughout the year. The fronts are typically followed by atmospheric conditions that bring warm air in from the coast, usually with heavy cloud cover and rain. About two-thirds of the coastal rainfall is associated with frontal activity of this kind. Ten to fifteen percent of the rainfall is from infrequent, severe tropical storms and hurricanes.

The effect of precipitation depends not so much on absolute amount but on the relationship between rainfall and evaporation from water and plant surfaces. Excess water occurs during the winter, a balance during the summer, and occasional deficits from May through August (Fig. 12), with an annual rainfall surplus of about 75 centimeters. This surplus is important for maintaining salinities well below seawater strength in the estuaries.

Hurricanes and severe winter storms play a major role in ecosystem maintenance and development (see box on Hurricane Andrew in the Natural Processes chapter). These severe events overturn floating marsh mats, decimate forests, kill large areas of vegetation through inundation with saltwater, and account for most of the

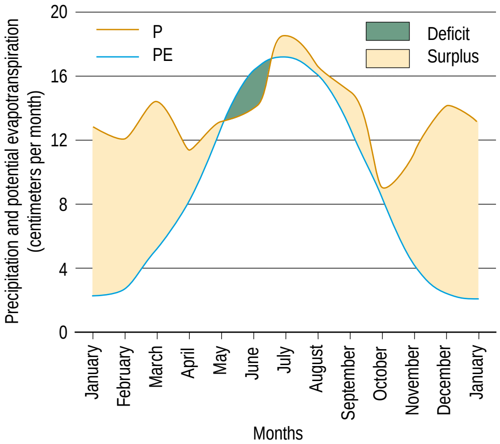


Fig. 12. Average water budget for the upper Barataria estuary, 1914–1978 (modified from Gosselink 1984; Sklar 1983). P = precipitation, PE = potential evapotranspiration.

sediment deposition in interior destructional phase marshes (Baumann et al. 1984; Reed 1995; Guntenspergen and Vairin 1996).

Fluvial Processes

The largest source of fresh water to the Louisiana coast is the Mississippi River and its major distributary, the Atchafalaya River. The combined annual flow of these two rivers averages about 15,400 cubic meters per second. Other, smaller rivers contribute additional water from local watersheds. Flow is strongly seasonal, peaking in late spring, fed by melting snow and spring rains in the Upper Mississippi watershed. River flow can be nearly independent of local rainfall because of the size of the Mississippi River watershed but is often reinforced by spring rains along the coast.

The inactive delta of the Mississippi River (the part that has been abandoned by the river) is isolated from direct riverine input by natural and artificial levees. The Mississippi and Atchafalaya rivers discharge into the Gulf of Mexico through the active Balize and Atchafalaya delta lobes. Most of their waters are carried westward along the coast, freshening the gulf waters that move in and out of the Barataria, Terrebonne, and Vermilion estuaries. Thus, although these three estuaries have almost no direct freshwater inflow except from local runoff, the rain surplus and the moderated salinities offshore keep estuarine salinities much lower than that of seawater.

Marine Processes

Water fluxes in the coastal marshes are driven by the water-level differences across the estuary. These change over the long term, seasonally, and daily (Fig. 13). Since the ocean reached its present level about 6,000 years ago, it has been rising relative to the land at a rate measured in centimeters per decades (Fig. 13a). Superimposed on this long-term trend is a mean water level that varies seasonally by 20 to 25 centimeters, with peaks in the spring and late summer (Fig. 13b). Part of this seasonal variation is related to the dominant variable wind regime over the Gulf of Mexico (Chew 1962). Maximum east and southeast winds in spring and fall move water toward the shore. During winter and summer, westerly winds (southwest in summer, northwest in winter) strengthen the Mexican Current and draw a return flow of water from the estuaries (Baumann 1980).

Superimposed on the seasonal water level change is a diurnal tide (Fig. 13c), which averages about 30 centimeters at the coast. Because of the broad, shallow expanse of the coastal estuaries, the tides decrease inland. The normal tide range decreases from saltwater to freshwater marshes (Fig. 13c); in the example in Fig. 13c, tides are still perceptible 50 kilometers inland from the tidal passes because of the extremely gradual slope of the land.

Water levels do not always follow predictable daily and seasonal cycles; they are modified strongly by unpredictable weather fronts with winds that push water in or out of the estuaries. Such effects are clearly shown in Fig. 13c, where gradually decreasing water levels are associated with a cold front beginning on 12 October 1972. The water levels suddenly rose on 19–22 October, when the wind changed to the south. The magnitude of these wind effects is often 40–50 centimeters, which, when combined with astronomical tides, can result in water-level shifts of more than a meter within

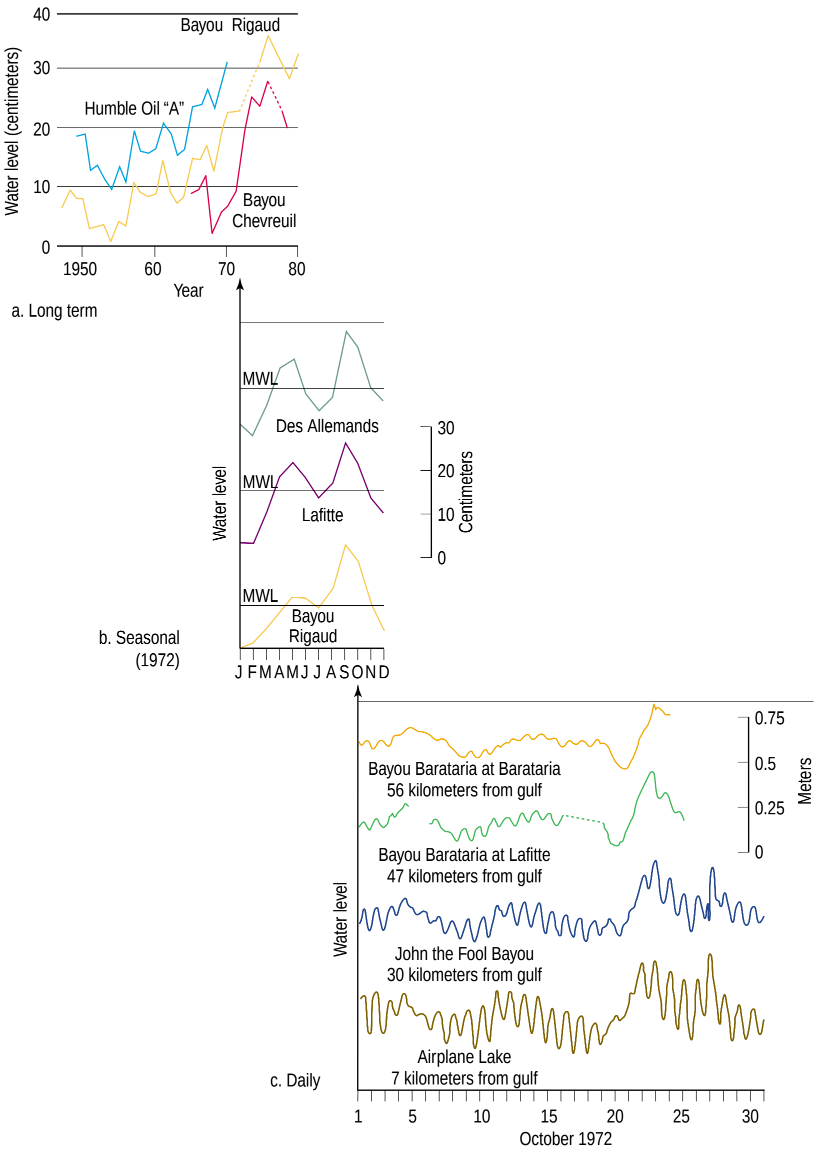


Fig. 13. Water-level trends in Louisiana coastal marshes: a) long term, b) seasonal, and c) daily. MWL = mean water level (Gosselink 1984).

12 hours. Such meteorologically driven changes in water level are common events. Tropical storms are much more unusual and may elevate water levels dramatically. The water-level height/frequency curve for Shell Beach, southeast of New Orleans, for example, shows that wind tides as high as 3.5 meters have been recorded and that 1.5-meter tides occur about once every 8 years. On a coast with a slope of about 0.2 centimeters per kilometer (Byrne et al. 1976), a 1.5-meter tide can flood hundreds of kilometers inland.

Human Effects

Before European settlement along the Mississippi River, the Coastal Plain gradually increased in area and elevation, supporting a wetland area of about 16,000 square kilometers. Dominant fluvial processes not only built new delta lobes but also nourished the deteriorating lobes through overbank flooding during high water in spring. During this century, though, the balance between land-building processes and destructional processes has tipped in the direction of land loss, resulting in a net conversion of 4,000 square kilometers of wetland to open water.

Continental-scale manipulation of the Mississippi River and its tributaries for flood control and hydropower has significantly influenced coastal ecosystems. After a major flood occurred in 1927, the U.S. Congress initiated a massive effort to levee the river, seal off the crevasses, and cut off long meanders to increase the gradient and accelerate runoff. Because of the levees, the river has built its present active delta to the edge of the Continental Shelf, where most of the sediments are lost in deep water and can no longer build land. A control structure constructed 480 kilometers above the mouth of the river has halted the imminent capture of the main flow of the Mississippi River by the Atchafalaya River; this structure limits the diversion to one-third of the combined flow of the Mississippi and Red rivers. The levee systems on both rivers limit overbank flow during spring floods to the lower Balize delta and to the Atchafalaya bay and its adjacent marshes (Louisiana Coastal Wetlands Conservation and Restoration Task Force 1993).

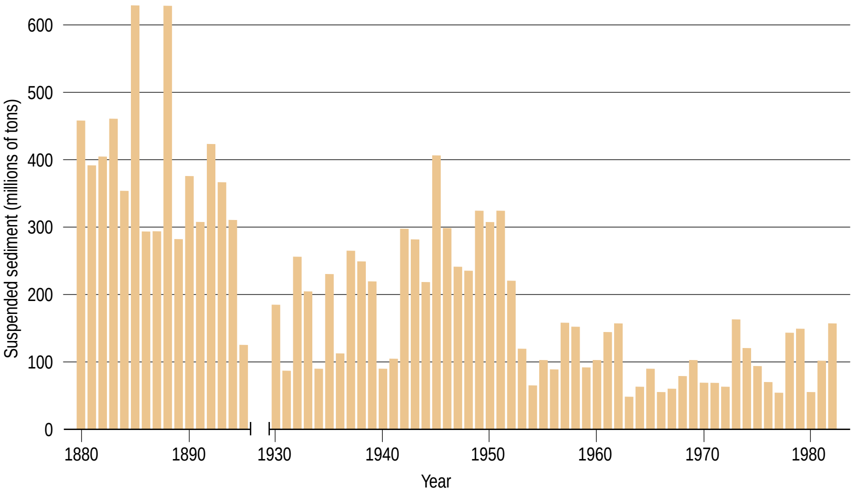


Fig. 14. Historical record of the suspended sediment load of the Mississippi River at New Orleans (Kesel 1987). Historical period = before 1900, pre-dam period = 1930–1952, and post-dam period = 1963–1982.

Before these artificial modifications, the Lower Mississippi River had an estimated average annual sediment discharge of 270 million cubic meters per year of suspended load, and bedload that may have been as high as 130 million cubic meters per year (Kesel et al. 1992). Since 1850, however, the sediment supplied by the Mississippi River and its tributaries has decreased by almost 80%. This reduction can be divided into three phases: a historical period before 1900, a pre-dam period (1932–1952), and a post-dam period (1963–1982). The suspended sediment load declined by 43% from the historical to the pre-dam periods and by 51% from the pre-dam to the post-dam periods (Fig. 14). At the same time, the particle size of the suspended sediment load has decreased. At 170 kilometers above the mouth of the river, the sand fraction decreased by 72% from the late 1800's to 1983 (Kesel 1989). The particle size distribution in the bedload also declined during this period. Presumably, dams on the tributaries, particularly the Missouri River, act as sediment traps, especially for the heavier sediment fraction, and are partly responsible for the decrease in both load and coarse fraction delivered to the delta. Clearing of the watershed for agricultural and urban development undoubtedly contributed to the suspended load during the last century, but clearing may have occurred before there were good records of sediment loading rates. Efforts to reduce erosion from agricultural fields in recent years are not reflected in the record.

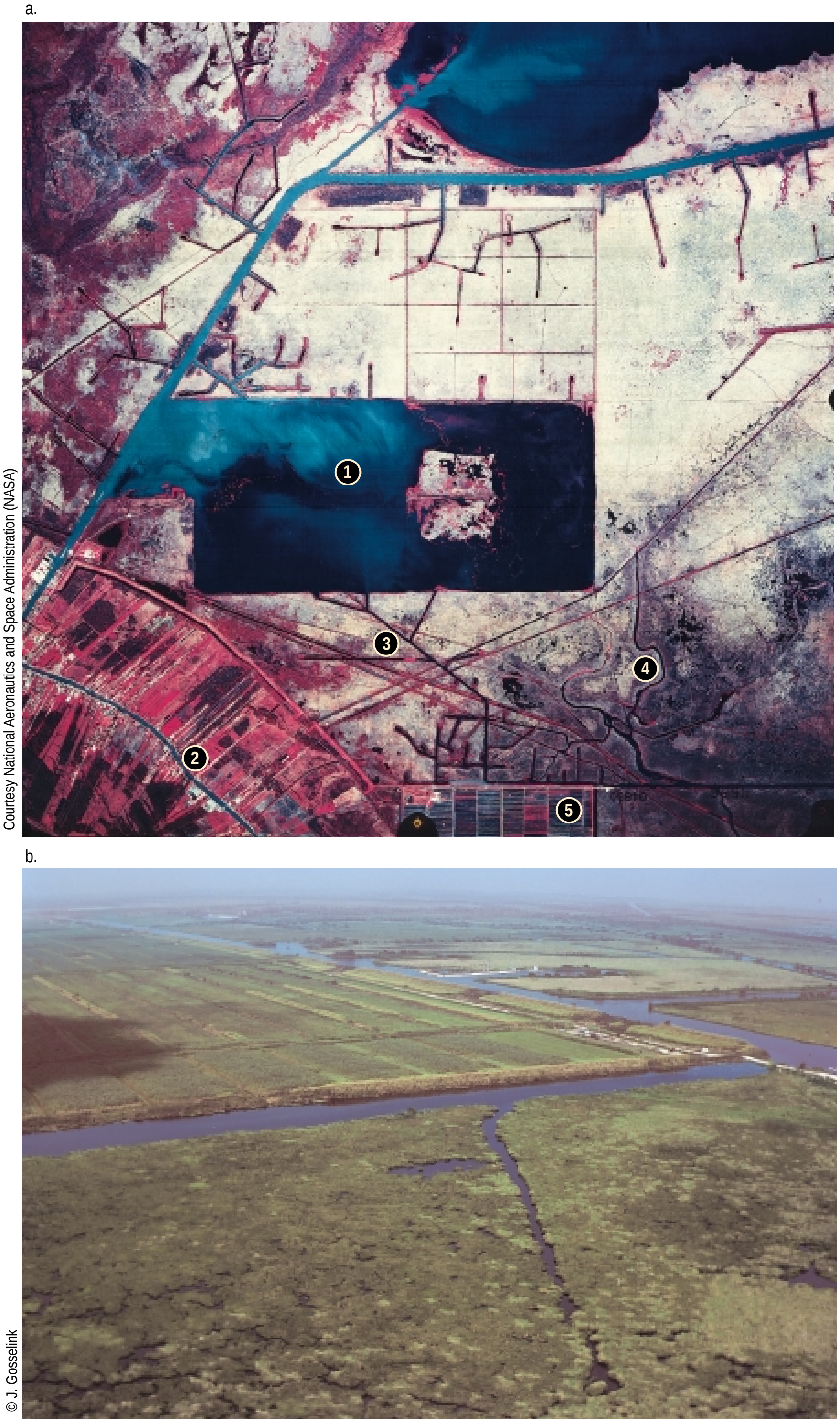
Development projects within the coastal basins themselves also affect the rates of wetland loss. Early in this century more than 800 square kilometers of wetland were cleared, leveed, and pumped out to create agricultural and suburban lands (Harrison and Kollmorgen 1947). Draining the organic wetland soils resulted in rapid oxidation, subsidence, and reversion to open water when subsequent storms breached the levees. Many of these "reclamation" projects are still visible as large rectangular lakes (Fig. 15). More recently, structural management for marsh restoration has controlled the exchange of water through levees and control structures such as flumes and gates, which are typically managed to reduce flooding frequency and duration and to restrict saltwater input. The effectiveness of this type of management is a source of considerable controversy.

Artificial canals also significantly affect coastal wetlands. Formerly, rain runoff from adjacent uplands flowed across the wetlands, dropping its load of sediment and nourishing the marshes. Now a network of drainage canals along the marsh–upland interfaces of the coastal estuaries carries this runoff directly into estuarine lakes and bays, bypassing the swamps and marshes (Conner and Day 1982). If runoff flowed across the wetlands, the trapped sediment would allow the vertical accretion of the marsh surface and would help minimize wetland subsidence. Additionally, the quality of the runoff water would be improved before it entered the lakes and bays because wetlands act as natural filters. Instead, the portions of the estuaries near urban areas are becoming increasingly turbid and enriched by nutrients (Craig et al. 1977; Gael and Hopkinson 1979).

At the seaward edge of the estuaries, navigation canals, especially those that cross the shoreline, disrupt water circulation. These canals are straight and deep in estuaries where the average depth is otherwise only 1 or 2 meters. They capture flow from smaller channels and allow the intrusion of saltwater deep into the estuary. Saltwater accelerates the conversion of freshwater and low-salinity marshes to saline marshes. When salt increases are sudden, salt-intolerant vegetation is often killed, and the marsh may erode before other vegetation can become established (Reed 1995).

An extensive network of medium-sized canals, dredged to provide access to oil and gas well sites (Fig. 16), links the navigation canals to the inner marsh and to the elaborate system of drainage canals constructed to drain floodwaters from the adjacent uplands. The canals themselves act in the same manner as the navigation canals and, in combination with them, change circulation patterns. For example, in the Leeville oil field (Terrebonne basin), the density of natural channels declined as dredged channels captured the flow of water. The canals also allow saltwater intrusion into formerly freshwater marshes and brackish-water marshes. In addition, the spoil banks of these canals block the flow of water across marshes, depriving them of sediments and nutrients, an effect that is especially noticeable where canals intersect and their spoil banks interlock to impound or partially impound an area (Turner 1987; Turner and Cahoon 1987a,b,c; Turner and Rao 1987, 1990; Reed 1995).

A linear relationship exists between canal density and marsh loss rate (Turner et al. 1982; Turner and Cahoon 1987a,b,c), although there is considerable unexplained variation in the



Courtesy National Aeronautics and Space Administration (NASA)

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Fig. 15. Freshwater wetlands were drained for residential and agricultural development in the early part of the century. The infrared aerial photograph a) depicts: (1) Delta Farms, now a large, rectangular lake that was the result of such agricultural development along (2) Bayou Lafourche, an abandoned distributary of the Mississippi River; (3) artificial canals that are straight and deep; (4) natural channels that are meandering and shallow; and (5) Clovelly Farms, sugarcane fields that are still in production. At Delta Farms, levees were breached by a severe storm and the reclamation was abandoned. The soil surface inside the levees at Delta Farms is now about 2 meters below the surrounding water level as a result of compaction and oxidation of the organic substrate. At Clovelly Farms, however, levees are still intact and water is continually pumped out to allow agricultural production. b) The northeast corner of Clovelly Farms is shown at a lower altitude in this aerial view; the sugarcane fields in the background are contrasted with the adjacent natural marsh in the foreground.

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Fig. 16. An oil field in the Louisiana coastal wetlands. The extensive network of artificial canals provides access to oil and gas wells. The canals are bordered by elevated deposits of dredged materials that block the natural flow of water to the remaining wetlands.

data, and therefore, considerable controversy surrounds the effect of canals on marsh loss. The rate of loss per unit of canal is higher in recently formed deltas where the sediments are less consolidated (Deegan et al. 1983), and it seems to be highest where freshwater marshes experience salt intrusion (Dozier 1983). Turner et al. (1982) found that in places where canal density was zero, marsh loss was always less than 10% of the total loss and was usually nearly zero. This finding indicates that if there were no canals, the marsh loss rate would be less than 10% of the present rate. The area actually dredged out of the marsh for a canal is less than 10% of the total loss. If the spoil area is three to five times the size of the canal area (Johnson and Gosselink 1982), the direct loss of marsh due to canals is less than half of the total loss. The rest of the loss is attributed to indirect effects of circulation disruption by the canal and its spoil deposits, unintended impoundment of wetlands, and saltwater intrusion into freshwater wetlands (Turner 1987; Turner and Cahoon 1987a,b,c).

Land Loss Rates

A recent study conducted by the U.S. Army Corps of Engineers Waterways Experiment Station (Britsch and Kemp 1990; Dunbar et al. 1990; Dunbar et al. 1992) analyzed wetland loss rates over the entire Louisiana Coastal Plain for four periods, from the early 1930's to 1990 (Table 1). These results show that loss rates were relatively low, about 38 square kilometers per year from the 1930's to 1958, before major human effects were detected on the coast. A peak loss rate of about 108 square kilometers per year occurred during the 1958–1974 period; the loss rate has fallen off since to a 1990 rate of about 66 square kilometers per year. A concurrent mapping study by the National Wetlands Research Center of the U.S. Geological Survey, in cooperation with the Louisiana Department of Natural Resources (Barras et al. 1994), generally supports this trend (Fig. 17), although the absolute values are different because of overlap in census dates in the late 1970's and 1980's, different scales of photographic coverage, and differences in methodologies of map interpretation and boundaries. In both studies, however, most wetland loss occurred because of degradation to open water, rather than by drainage for human use.

Table 1. Wetland loss rates in the Louisiana coastal zone, 1930's to 1990.

Interval	Loss rate (square kilometers per year)
1930's–1958	38[a]
1958–1974	108[a]
1956–1978	102[b]
1974–1983	79[a]
1978–1988/1990	90[b]
1983–1990	66[a]

[a] Dunbar et al. (1992).

[b] USGS, Biological Resources Division, National Wetlands Research Center, Lafayette, Louisiana.

Pattern of Loss

Wetland loss does not occur uniformly across the Louisiana coast. Local loss rates are determined by the interaction of several processes and characteristics, including the thickness of recent sediments; the pattern of distributaries of earlier delta lobes; the withdrawal of oil, natural gas, and other minerals; subsurface faulting; the type of marsh vegetation present; the intrusion of marine waters into the estuary; and the size of water bodies relative to wind direction and intensity, fetch, and tide surges.

There are two categories of marsh loss, shoreline loss and interior marsh loss (Wayne et al. 1993, 1994). Shoreline loss due to erosion by storms and boat wakes represents only about 31% of the total loss. Nearly all the rest (67%) is associated with interior marsh loss. Although dredging channels through marsh is a significant source of interior marsh loss (Craig et al. 1979; Turner et al. 1982; Scaife et al. 1983), most loss is associated with the development of small ponds that gradually coalesce into large shallow lakes (Wayne et al. 1994). The most rapid wetland losses occur in the low-salinity interior marshes (Lee and Turner 1987), possibly because the influences of subsidence and saltwater intrusion stress the marsh vegetation beyond its ability to survive.

Status and Trends of Ecosystems and Associated Biota of the Louisiana Coast

The cyclic geological development of the Louisiana coast leads to plant associations or communities that are determined by the stage of development or degradation of each delta lobe (Gagliano and Van Beek 1975; Fig. 18). Following a period of rapid wetland formation during the progradational phase of a delta lobe, a longer period of lobe degradation follows the shift of the river to another location. Overlapping natural environments develop and decline as the lobe ages. The sequence begins

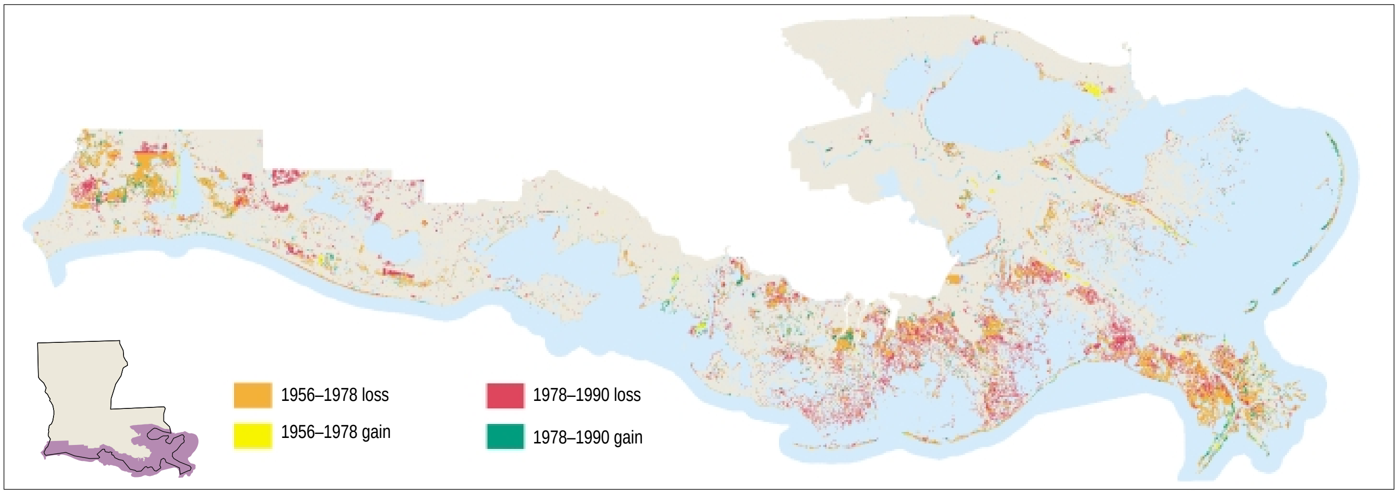

Fig. 17. Coastal land loss and gain in Louisiana, 1956–1990 (from Johnston et al. 1995).

with a shallow open bay into which the river begins to pour sediments. Infilling of the bay results first in subaerial mudflats, which later become freshwater marshes and swamps (Fig. 19). The natural levees along the major distributaries are elevated by sediment deposition during the largest floods and form a skeletal network of high ground that becomes terrestrial habitat amid the wetlands and lakes.

As the delta lobe expands and the river's course is channelized, portions of the lobe that receive little direct freshwater input come under the influence of marine forces, and freshwater marshes slowly change to brackish and then to saline marshes. The river abandons the lobe slowly over many years, and the system becomes progressively more saline. The compaction of recently deposited sediments and the loss of a mineral sediment supply begin a period of net subsidence, during which time the land surface gradually sinks beneath the water, the plant cover dies, the substrate disperses, and the area reverts to a shallow bay. At the marine interface, reworking of the shoreline by waves, longshore currents, and storms forms beaches and headlands that become detached from the mainland when the interior marshes are lost. Thus, a barrier island system is one of the last expressions of a degrading delta lobe.

Neill and Deegan (1986) showed that habitat diversity increases with age of a delta lobe. Gagliano and Van Beek (1975) speculated that biological diversity also increases (Fig. 18), with maximum diversity occurring during the middle of the destructional decay phase. As oceanic forces impose a strong salinity gradient, the landscape pattern increases in complexity, creating more and more habitat types (Fig. 20). Of a total of about 16,000 square kilometers of wetlands in Louisiana, marshes occupy about 10,000 square kilometers and forested wetlands about 6,000; of this 6,000, about 600 are shrub–scrub (U.S. Geological Survey, National Wetlands Research Center data base, 1990).

The net result of a series of overlapping delta lobes is a row of estuaries from east to west along the coast, each bounded on the east and west by the natural levees of old distributaries and on the seaward edge by a barrier headland or island system. The interdistributary basin is

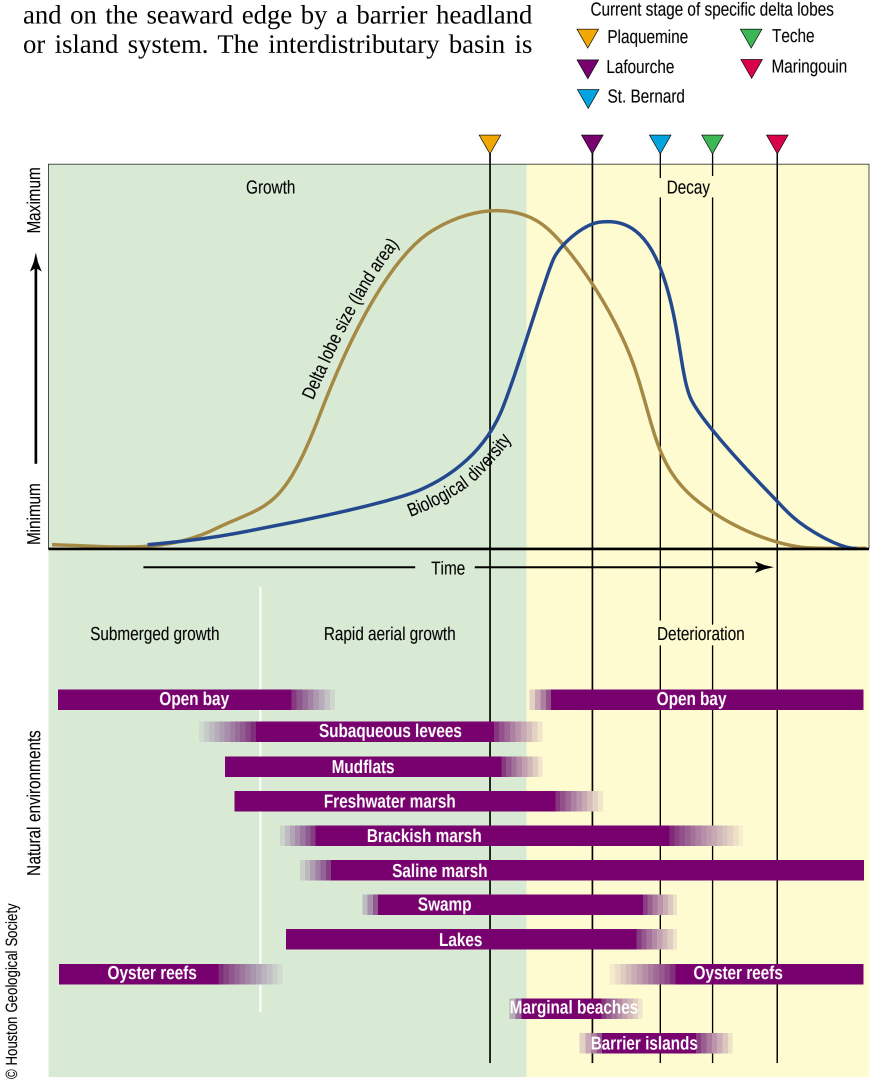

Fig. 18. Graphical depiction of the growth and decay of a delta lobe (adapted from Gagliano and Van Beek 1975; Neill and Deegan 1986). Habitat and biological diversity peak in the early to middle stage of the decay phase.

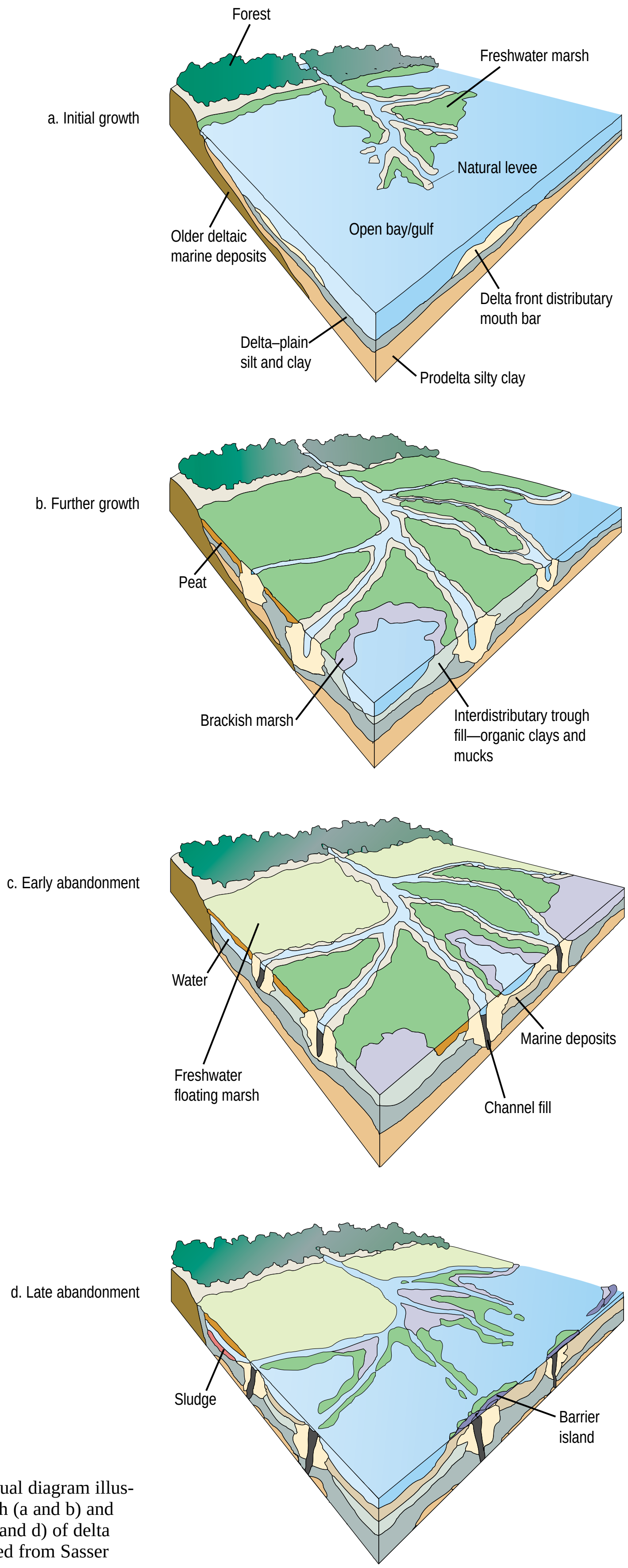

Fig. 19. Conceptual diagram illustrating the growth (a and b) and abandonment (c and d) of delta marshes (modified from Sasser 1994).

flanked by the degrading lobes of earlier deltas, and the interior is a series of bays and freshwater lakes.

The water regime of each estuary is fairly isolated. The natural levees of the old major distributaries confine the small flows they now receive, so that the estuary has little direct freshwater input except from local runoff and rain. The elevated remnants of the natural levees of the minor distributary network fork out across the degrading delta lobe like the branching system of an old tree. When the remnants are young, they support oak forests, which are replaced by shrubs and finally, as they subside, by vascular marsh plants. The stark silhouettes of dead trees across a flat marsh is a common signal of the remnants of an old natural distributary.

Marshes lie between the branches of the distributary system, and as subsidence progresses they grow over and obliterate the lower ends of the distributaries with a thick skin of organic peat. The broad natural levees at the landward edge of the estuary are nearly all developed for human occupation. They were once terrestrial forests dominated by live oaks, but few patches of forest remain, as most are replaced by villages, sugarcane fields, shipyards, and seafood processing plants.

As natural levees slope downward away from the stream that formed them, the terrestrial vegetation is replaced by flood-tolerant vegetation, first by bottomland forests, then by deep swamps dominated by baldcypress and tupelo gum. Seaward, the forests give way to freshwater marshes, many of them on a floating organic mat thick enough to support a mature man with ease (Sasser 1994). Runoff from adjacent uplands and rain falling on the estuary tend to freshen the system, while marine tides bring saline water in through the barrier island passes. These processes maintain a strong salinity gradient that fluctuates seasonally and spatially under the influence of evapotranspiration, storms, and frontal systems. Freshwater marshes give way to brackish and then to saline marshes seaward.

The barrier islands fronting the Gulf of Mexico are typically low and sandy, with poor dune development. They are dominated by salt-tolerant xeric grasses and succulent herbs on the dune face and crest, grading into brackish and salt marshes on the bay side (Visser and Peterson 1995). Barrier headlands form with the reworking of river-mouth sediments. The coastal ridges of the Chenier Plain often have higher relief than the barrier islands, and historically they supported maritime forests dominated by live oaks. Only remnants of these forests remain, the rest lost to subsidence and human development.

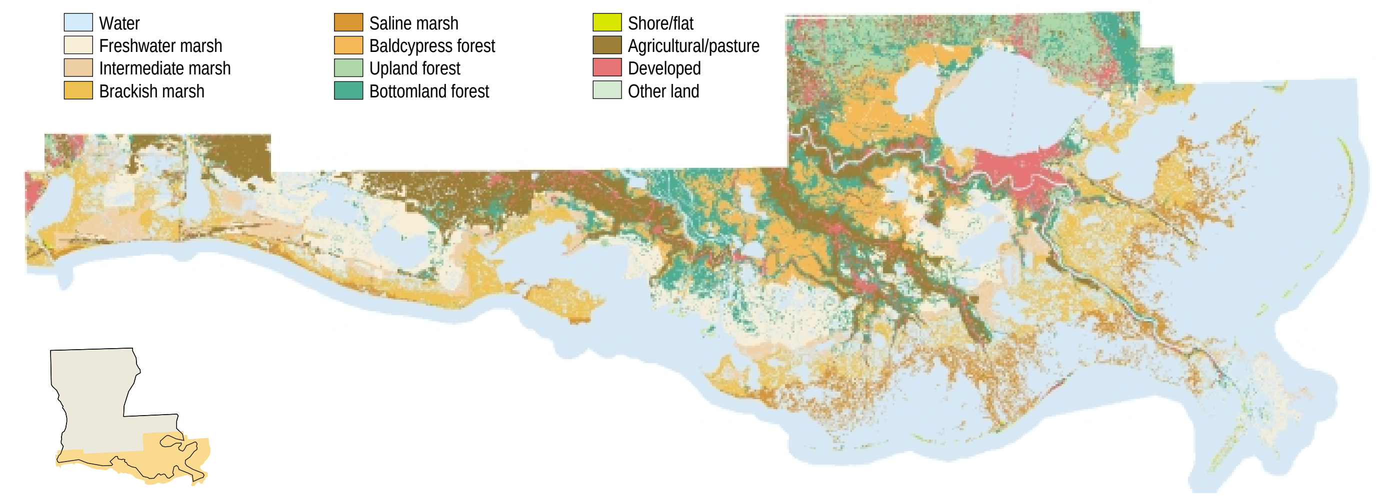

Fig. 20. Map of major coastal habitats of Louisiana, 1988–1990 (data from U.S. Geological Survey, National Wetlands Research Center data base).

The two major rivers of the coast, the Mississippi and the Atchafalaya, flow between the estuaries as if through large closed pipes. The Mississippi River's area of active deposition is now so far out to sea that most of its sediments are deposited in deep water on the Continental Shelf, and its surface expression is small. Where exposed wetlands do occur, however, both sediment deposition and subsidence are rapid, and the cycle of growth and decay of crevasse splays (mini-deltas formed as water goes through a break; see Fig. 6) is short. Because of the enormous volume of river water, the environment is almost entirely fresh water. The large nutrient load of the river results in rapid growth of willows on the levees of the channels and a wide spectrum of marsh vegetation on the mudflats (White 1993), including extensive stands of common reed. Farther west along the coast, the Atchafalaya River flows into the shallow Atchafalaya bay. This new delta lobe is similar to the Balize delta but differs in its slower sedimentation rate and generally lower river energy. Nevertheless, plant invasion of the new mudflats and subsequent community development and change are extremely rapid, reflecting a complex mix of physical and biological factors (Shaffer et al. 1992).

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Fig. 21. Fingers of swamp forest on slightly elevated land fan out into a freshwater marsh.

Marshes

Intertidal marshes (Fig. 21) are the most abundant landform on the Louisiana Coastal Plain. They stretch in a broad band across the entire state, covering 10,192 square kilometers (Table 2), about 40% of all U.S. coastal marshes (Field et al. 1991). The first thorough description of major coastal wetland plant communities in Louisiana was made by Penfound and Hathaway (1938). They described baldcypress–tupelo gum swamps; freshwater marsh dominated by cattails, giant bulrush, sawgrass, and maidencane; a cane zone adjacent to levee areas dominated by common reed in the freshwater areas and by big cordgrass in the more saline areas; saltwater marshes dominated by saltgrass and smooth cordgrass; and brackish marshes dominated by wire-grass, saltgrass, and needlegrass rush. O'Neil (1949) published the first vegetation map of the Louisiana coast, but since his book was primarily about muskrats, his vegetation zones reflect the vegetation most important as muskrat food. The map delimits marsh zones by species and salinity tolerance and is the first (and until recently, the only) map to identify freshwater and brackish floating marshes.

The most comprehensive vegetation surveys of the coastal marshes were carried out in 1968 by Chabreck and other scientists from the Louisiana Department of Wildlife and Fisheries (Chabreck et al. 1968). The maps were updated in 1978 and 1988 (Chabreck and Linscombe 1978, 1988), although the detailed vegetation transects of previous surveys were not repeated

Table 2. Areas of major ecosystem types in the Louisiana coastal zone in 1988–1990 (data from U.S. Geological Survey, National Wetlands Research Center).

Ecosystem	Area (square kilometers)
Marsh	10,192
Fresh	3,829
Intermediate	1,495
Brackish	3,209
Saline	1,659
Forested wetland	5,935
Baldcypress forest	2,541
Bottomland/scrub–shrub	3,393
Upland	7,656
Forest/scrub–shrub	2,022
Developed	1,649
Pasture/agriculture	3,943
Barren	41
Water bodies	10,491
Submerged aquatics	306
Shore–flat	87
Other	2
Total	34,668

for the whole coast. These maps show adjacent bands of salt, low-salinity (Chabreck divided this zone into brackish and intermediate), and freshwater vegetation lying parallel to the coast in a landward direction. The maps were updated in 1990, based on high-altitude color-infrared photography and remotely sensed imagery (Landsat Thematic mapper; U.S. Geological Survey, National Wetlands Research Center and Louisiana Department of Natural Resources; Fig. 20).

As Penfound and Hathaway (1938) showed, three primary environmental factors control plant species distribution throughout the marsh: salinity, flood frequency, and flood duration. The broad vegetation bands in Figure 20 reflect such salinity differences. Flooding is an important species selector in areas where drainage is artifically controlled, and in areas adjacent to coastal streams, where slightly elevated natural levees allow less flood-tolerant species to grow.

Table 3 shows the percent cover of dominant plant species in the different salinity zones from Chabreck's 1968 survey (Chabreck 1972). Species richness predictably increases from saltwater to freshwater environments. Although many vascular plants apparently can tolerate a periodically flooded substrate, not many can tolerate the combined stresses of flooding and high salinity. Chabreck's salinity zones and plant associations were based on his broad experience in the field and on the precedents of Penfound and Hathaway (1938) and O'Neil (1949). Recently Visser (*in* Reed 1995) carried out a cluster analysis of Chabreck's 1968 data. Chabreck's freshwater, brackish, and saltwater marsh associations are identified in Visser's cluster analysis, but the low-salinity *intermediate* marsh is not as clearly seen. Generally, Visser's analysis refines Chabreck's classification, identifying a number of distinct plant clusters within each salinity zone.

What is particularly interesting about Visser's analysis is the rapid change in species dominance over the period of about 25 years since Chabreck's first survey in 1968 (Fig. 22). The constant percentage of open water showed that marsh loss was negligible in a freshwater to brackish area of the coastal wetland on the eastern flank of the Atchafalaya River that receives considerable sediment from the river during floods. However, there has been a steady replacement of about half of the maidencane during this period, primarily by spikerushes. The maidencane was growing on thick, apparently stable, floating substrates, many of which have become thin, insubstantial floating mats dominated by spikerush.

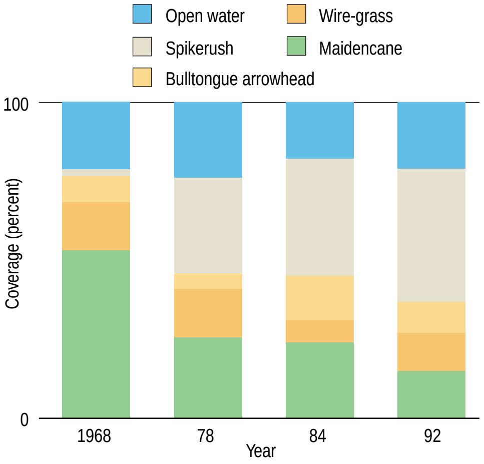

Fig. 22. Changes in dominant plant species in a freshwater to brackish marsh adjacent to the Atchafalaya River, coastal Louisiana, from 1968 to 1992. Data collected by Chabreck and Linscombe: Chabreck et al. 1968; Chabreck and Linscombe 1978, 1988. Data analyzed by J. V. Visser, Louisiana State University, Baton Rouge.

Table 3. Percent cover of dominant plant species in major marsh zones of the Louisiana coast (Chabreck 1972). Numbers may not sum because of rounding.

Species	Marsh zone (percent cover)			
	Salt	Brackish	Intermediate	Fresh
Alligatorweed	0	0	2.5	5.3
American bulrush	0	5	3.3	0.5
Bulltongue arrowhead	0	0	6.5	15.2
Coastal waterhyssop	0	0.9	4.8	1.4
Common reed	0	0.3	6.6	2.5
Dwarf spikerush	0	2.5	0.5	0.5
Leafy threesquare	0.7	1.8	0.7	0
Maidencane	0	0	0.8	25.6
Manyflower marshpennywort	0	0	0	1.9
Needlegrass rush	10.1	3.9	0.7	0.6
Saltgrass	14.3	13.3	0.3	0.1
Saltwort	4.4	0	0	0
Seashore paspalum	0	1.4	4.5	0.4
Smooth cordgrass	62.1	4.8	0.9	0
Spikerushes	0	0.8	3.3	10.7
Variable flatsedge	0	0.8	2.2	1.6
Walter's millet	0	0.4	2.7	0.7
Widgeongrass	0	3.8	0.6	0
Wire-grass	6	55.2	34	3.7
Other plants	2.4	5.1	25.1	29.1
Total	100	100	100	98.8
Number of species	17	40	54	93

Freshwater Marshes

Freshwater marshes cover 3,829 square kilometers of the Louisiana coastal zone (Table 2) and are the most abundant habitat type. These marshes look and function quite differently in the active delta than in the inactive delta. In the former, they occur in an actively accreting, sediment-rich, high-energy riverine environment. Sediment introduction and water level are strongly seasonal, with spring floods and late summer low-water periods. Freshwater marshes are sites of primary succession, as new land is produced in an expanding delta lobe. Though spring floods are the rule, expansion of the delta is episodic. In the Atchafalaya basin, for example, expansion occurs only in years when river discharge exceeds about 7,000 cubic meters per second (Roberts and van Heerden 1992; Fig. 23).

Details of colonization and early succession are given by Shaffer et al. (1992) and Johnson et al. (1985) for the Atchafalaya delta and by White (1993) for inner deltaic splays caused by natural or intentional crevassing in the Balize delta. Johnson et al. (1985) described the vegetation of the Atchafalaya delta 7 years after the first occurrence of subaerial land in 1973. A typical river-mouth bar island (Fig. 24) is formed from a submerged bar that divides the flow of the river. During floods, this incipient island is submerged, and because the water slows as it passes over the island, it drops coarse sediments. This process creates an arrowhead-shaped island, with the highest elevations and coarsest sediments at its upstream apex and along its flanks and finer sediments at the interior and distal ends of the island. When the head of the island is high enough, black willow invades, stabilizing the substrate and protecting the downstream island, which is colonized by broadleaved cattails and a mixture of flatsedge, broad-leaved arrowhead, dwarf spikerush, and purple ammania. The low island mudflats are colonized by broad-leaved arrowhead and delta duckpotato, often in expansive stands of plants of the same genus.

White (1993) sampled vegetation during the first 7 years after a crevasse initiated a cycle of mudflat accretion in the Balize delta. He observed colonization in the first summer by a mixed group of "primary colonizers," including several species of sedges, and many of the same species observed by Johnson et al. (1985) in his mixed association. These are mostly annual plant species that propagate rapidly with widely dispersed seeds. Willows did not invade until the island elevations were about 11 centimeters above the mudflat. White (1993) found the same pattern of plant distribution in the Balize delta as Johnson et al. (1985) had found in the Atchafalaya delta, but an elephant's ear association replaced the Atchafalaya delta cattail association, and American bulrush dominated the flats at the lower ends of the islands. Elephant's ear is an introduced species that is now becoming common in the Atchafalaya delta.

Apparently, physical processes determine vegetation zonation patterns; elevation is the dominant factor, and sediment coarseness is secondary. Sediment grain size, however, is related to elevation, and both are determined by hydrology. White (1993) noted that on one island, the American bulrush-dominated association was replaced by broad-leaved arrowhead (vegetation similar to that of the Atchafalaya back-island flats) when the pass feeding water to the site was blocked by formation of a shoal, so that sediments no longer reached the island. Subsidence apparently lowered elevation where the American bulrush grew, leading to its replacement by broad-leaved arrowhead.

In the years following the study by Johnson et al. (1985), vegetation changes in the Atchafalaya delta continued at a rapid rate. Most of the large expanses of broad-leaved arrowhead died, leaving bare mudflats (Shaffer

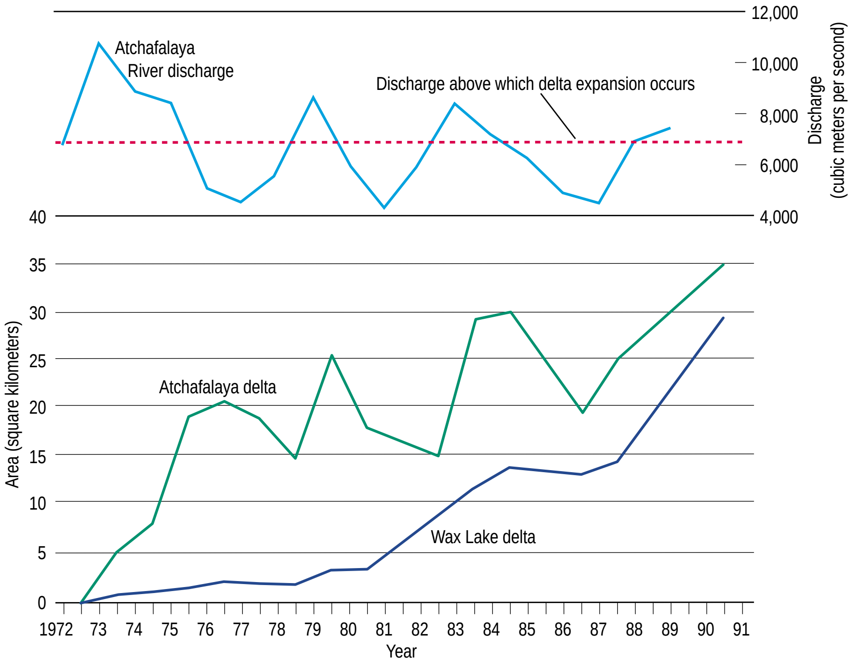

Fig. 23. The relationship of growth of the Atchafalaya and Wax Lake deltas to river discharge.

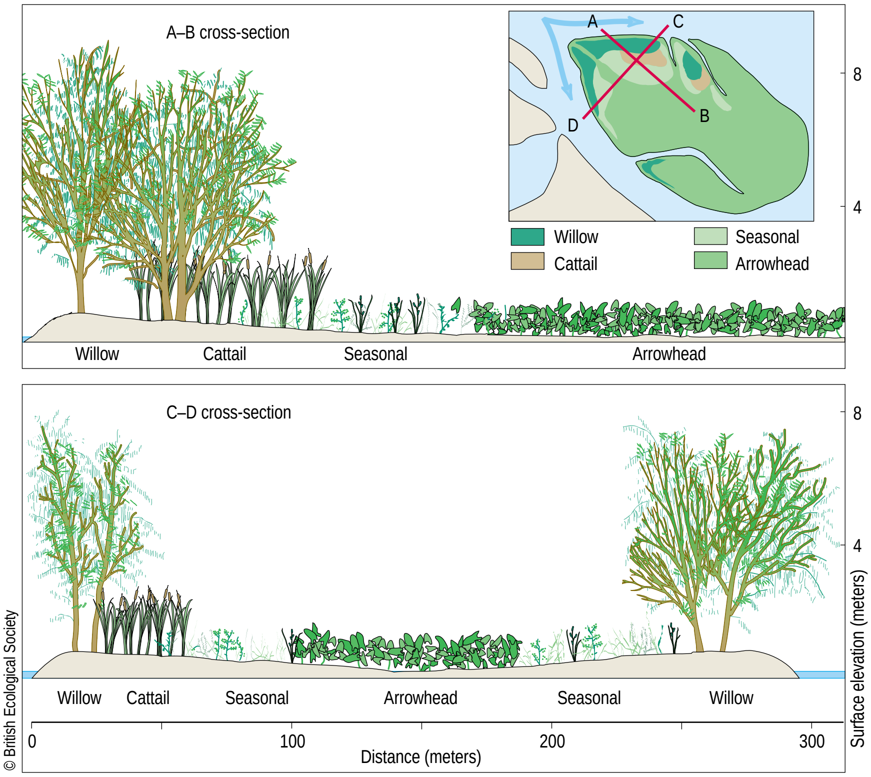

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Fig. 24. Illustration of a typical mouth-bar island in the Atchafalaya River delta, Louisiana, showing both aerial and cross-sectional views. Arrows represent direction of predominant water flows (Johnson et al. 1985).

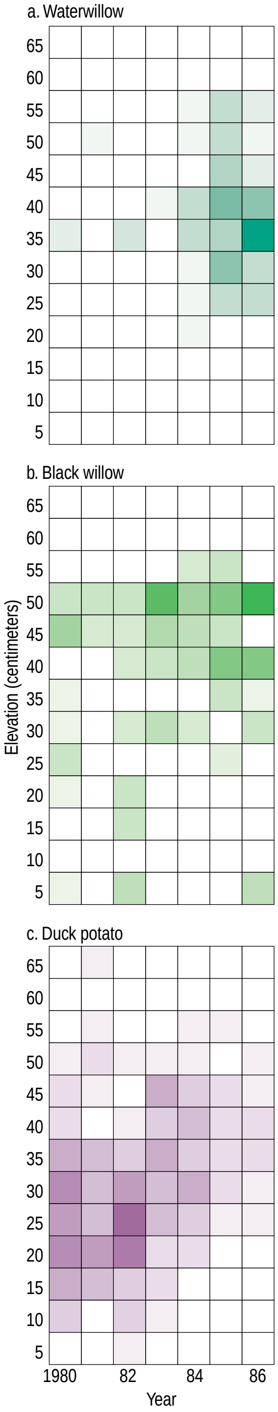

Fig. 25. Relative cover (proportional to color intensity; the deeper the intensity, the higher the coverage) of selected plant species with respect to time (*x*-axis) and elevation (*y*-axis) in the Atchafalaya delta, Louisiana. Examples illustrate species that a) increase in cover through time and stabilize on certain elevational zones, b) are relatively stable over time, and c) occur over a wide range initially but eventually disappear at low elevations (modified from Shaffer et al. 1992).

et al. 1992). From 1980 to 1986, vegetation was structured into more distinct groupings, and species richness increased. The mean cover per species peaked in 1981, falling off in later years, but total cover in the vegetated areas increased because there were more species. Species richness was directly related to elevation. Shaffer et al. (1992) identified three patterns of change:

- Species increased in cover through time (Fig. 25a). For example, the area occupied by looseflower waterwillow increased as the species became established in circular patches in the mudflats, apparently through dispersal of stem and root segments. The plant formed dense, monospecific stands that appeared to trap sediments efficiently.
- Species were relatively stable over time (Fig. 25b). Once established, willow seedlings grew into trees, regardless of changes in elevation, but spread little to other sites.
- Species are present over a wide range initially but eventually disappear at low elevations (Fig. 25c). Broad-leaved arrowhead was the dominant species on the delta islands in 1980, forming large, nearly monotypic stands at low to medium elevations on the islands. In 1983, this species began to decline in abundance and by 1986 had decreased by 90%. In places where broad-leaved arrowhead had occurred at elevations with more than 4,000 hours of flooding per year, no vascular plant species replaced it, but at higher elevations, most of the plots were revegetated by other species. Broad-leaved arrowhead is probably susceptible to grazing by nutria and waterfowl, and its disappearance can be linked to the high density of nutria, a nonindigenous species, on the delta islands (Fuller et al. 1985; Evers et al. 1988; Llewellyn and Shaffer 1993).

In the upper reaches of abandoned delta lobes, freshwater marshes have developed under quiet conditions of slow flows and low suspended sediment, beyond the reach of marine processes. Water levels vary, but lunar tides are replaced by wind tides that raise water levels when the wind is from the south and lower them when the north winds of winter fronts come through. As a result, periods of flooding and drainage are longer in freshwater marshes than in tidal marshes, and the frequency of flooding is lower. When the river abandons a delta lobe and the sediment supply is lost, further marsh development occurs primarily through peat formation. Such marshes have organic substrates.

J. Visser (Louisiana State University, Baton Rouge) described six freshwater marsh plant associations from Chabreck et al.'s 1968 survey (Reed 1995). This is a simplification of freshwater marsh diversity, as Chabreck (1972) described 93 plant species in freshwater marshes, Conner et al. (1986) listed 154 species, and Johnson et al. (1985) identified 46 marsh species in the Atchafalaya delta alone. The most frequently encountered plant association is dominated by common spikerush and smooth beggartick. Several species of spikerush are common in freshwater marshes. Although Chabreck did not identify the specific species in his 1968 study, in an unpublished description of a similar plant association he recently identified it as common spikerush. Smooth beggartick is common in marshes and forested wetlands, and its distribution has increased over the past 20 years. Its fruit is often disseminated by attaching to a host animal. Nutria, for example, are abundant in freshwater marshes and frequently come in contact with smooth beggartick, thus disseminating the seeds. The achenes, with their barbed awns, however, may pierce the nutria's skin, causing a chronic dermatitis that destroys the commercial value of the fur (Chabreck et al. 1977).

Maidencane is probably the species most closely associated with freshwater coastal marshes in Louisiana. It dominates so many stands that other species are not noticed at a casual glance, but in such a marsh Sasser and Gosselink (1984) listed 67 other species. Maidencane is also found in associations as a codominant with arrowhead species, though it is not as common in the Chenier Plain, where bulltongue arrowhead-dominated stands and alligatorweed replace it.

Except in the active deltas, much of the freshwater marsh appears to be floating. According to O'Neil (1949), a floating marsh develops from an anchored marsh that builds up an organic substrate over many years. As the original marsh surface subsides and the organic layer becomes thicker, the buoyancy of the mat increases until during some high-water period the mat tears loose from the substrate and floats. Sasser et al. (1996) observed that some floating marshes can become anchored during periods of low water and may take months to break loose again. They estimated that as much as 70% of coastal freshwater marsh may be floating. Three plant associations are maidencane dominated, one is dominated by bulltongue arrowhead, wire-grass, and spikerush, and one is dominated by dwarf spikerush and Baldwin's spikerush. Some wiregrass dominated marshes also appear to be floating (Sasser et al. 1996). Species characteristic of a floating maidencane mat include royal fern, southern marsh fern, snowy orchid, and tuberous grasspink. Wax myrtle bushes may develop on maidencane marshes anchored in the floating mat and may grow to 4–8 meters tall. When the floating mat begins to sink under the mass of the wax myrtles, the trees die and the cycle begins again (Williamson et al. 1984; Sasser et al. 1994).

Maidencane is well adapted for life in a floating marsh because it has an extensive, strong, fibrous, and intertwined root mass that makes up about three-fourths of total plant biomass (Sasser et al. 1994). Floating mats are about 50–60 centimeters thick, with the top 25 centimeters composed of a thick mat of intertwined live and dead roots; the bottom half is peat in progressive stages of decomposition with depth (Fig. 26). Under the mat, there is typically a layer of clear water, its thickness dependent on the water level in the adjacent lake or stream. Below the water column, a layer of highly decomposed sludge often forms, apparently derived from decomposing peat that falls from the overlying mat. A clay layer typically lies under the sludge; researchers believe this layer is the original surface upon which the marsh was formed.

A plant association dominated by dwarf spikerush and Baldwin's spikerush in the spring and by anglestem primrose willow, common fogfruit, and smooth beggartick in the summer is apparently expanding. This association forms a thin floating mat and has replaced some thick maidencane mats over the past 20 years. Despite observations of the disappearance of maidencane-dominated marshes, on the whole they appear to be stable through time. Sasser et al. (1995a,b), for example, found no change in vegetative composition in one such marsh over an 11-year period. Biomass, however, has varied from year to year, which could be accounted for by a combination of climatic variables and water level.

In a developmental sense, floating marshes are at the opposite extreme from the freshwater marshes of the active delta. Whereas the active delta marshes are almost completely structured by abiotic forces, the highly organic substrates of floating marshes enable them to maintain a constant water level in the marsh substrate, regardless of how high water rises around them. Thus they are unaffected by flooding, the major variable that appears to control species distribution in other freshwater marshes. The surface of a well-developed mat floats about 5 centimeters above the water level, and the root system develops in this damp but unflooded upper 5 centimeters of substrate, creating an ideal plant environment—full sunlight without water limitations.

Saltwater Marshes

At the coastal edge of the estuary, 1,650 square kilometers of saltwater marshes (Fig. 27) provide a contrast to interior freshwater marshes. These saltwater marshes are characterized by daily tidal flushing rather than wind-driven, periodic water-level changes and by saline marine water rather than fresh river or rainwater. Table 4 compares flooding frequency and duration in different marsh zones in the Barataria basin. Although the total annual hours of inundation does not vary much across marshes (except for streamside saltwater marshes that are flooded for a relatively short time), the number of inundations decreases sharply as tidal influence wanes. Hence the average length of a single flooding event decreases from about 100 hours in the freshwater marsh to about 20 hours in a saltwater marsh. These differences in flooding duration and salinity result in dramatic geomorphic and biological differences between saltwater marshes and freshwater marshes. Daily inflow and outflow of tidal water carve bidirectional streams out of the marsh, and the higher water energy supports a heavier load of suspended sediment, which is deposited along the marsh edge as tides overflow the surface. Compared with broad expanses of unbroken freshwater marsh, saltwater marshes present a surface highly dissected with streams, whose

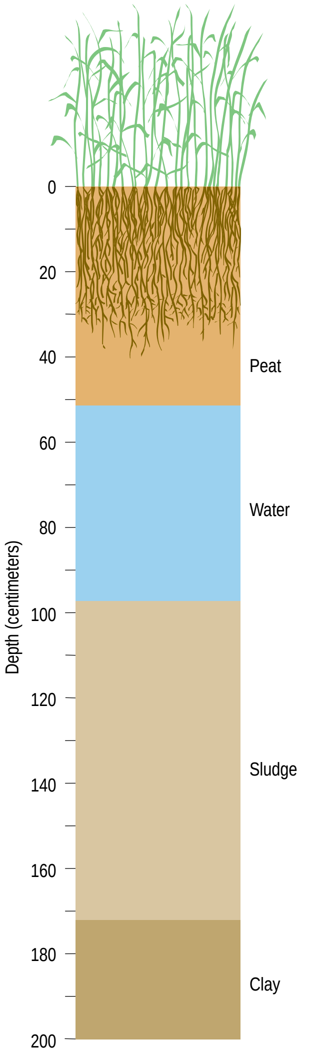

Fig. 26. Vertical depth profile of substrate in a maidencane-dominated floating marsh (modified from Sasser et al. 1995a).

Table 4. The annual duration and frequency of inundation of marshes in the Barataria basin, Louisiana (Gosselink 1984).

Marsh zone	Reference	Duration[a] (hours per year)	Frequency (number per year)	Duration of event (hours)
Salt				
Inland	Baumann 1980	4,396 (50)	263	16
	Byrne et al. 1976	4,400 (50)	200	22
	Sasser 1977	4,100 (47)	150	27
Streamside	Byrne et al. 1976	1,050 (12)	160	7
Brackish	Byrne et al. 1976	3,700 (42)	75	50
	Sasser 1977	3,500 (40)	125	28
Intermediate[b]	Sasser 1977	2,300 (26)	32	29
Fresh	Byrne et al. 1976	3,700 (42)	32	115

[a] Figures in parentheses indicate the percentage of the year a marsh is inundated.

[b] Wire-grass and bulltongue association.

Courtesy T. Michot, USGS, National Wetlands Research Center

Fig. 27. A Louisiana saltwater marsh.

banks have a slightly elevated streamside surface that supports more vigorous plant growth than can be found farther into the marsh. This is the *tidal subsidy* effect described by Odum and Fanning (1973).

Plant species richness is markedly lower in saltwater marshes than in freshwater marshes because few vascular plants can survive the combined stress of salt and flooding. Chabreck (1972) reported only 17 plant species in Louisiana saltwater marshes, and Conner et al. (1986) identified 25 species. Visser (*in* Reed 1995) listed only two plant associations, both dominated by smooth cordgrass, one with saltgrass and the other with needlegrass rush. In much of the saltwater marsh, smooth cordgrass is virtually the only species present, except along the slightly elevated stream edges where the codominants (wire-grass, leafy American bulrush, and sometimes big cordgrass) and the salt-tolerant shrubs bigleaf sumpweed and sea-oxeye are found. Sea-oxeye is often covered with the orange-tinted vines of the epiphyte called dodder. In pockets of high salinity the succulents saltwort and pickleweeds are found. Black-mangrove, at the northern limit of its natural range in Louisiana saltwater marshes, usually grows as a large bush that is periodically killed by winter frosts. This species provides excellent nesting habitat for some coastal birds, including the eastern brown pelican.

Because coastal Louisiana winters are mild, smooth cordgrass grows year-round (Kirby and Gosselink 1976). Shoot senescence also occurs throughout the year but peaks in late fall after the maximum production of live biomass. Dead shoots do not accumulate on the marsh. Instead, as shoots decompose and fragment, they are swept into adjacent streams by flood tides, where large aggregations of decaying organic material (locally called “coffee grounds”) accumulate along the edges of streams and tidal lakes.

Not much is known about nonvascular plants in salt marshes. The regularly flooded bases of smooth cordgrass shoots support a vigorous epiphytic population of algae, including the filamentous forms *Enteromorpha* and *Ectocarpus* in the winter and *Bostrichia* and *Polysiphonia* in the summer, as well as a diverse population of diatoms (Stowe 1982). These epiphytes are net producers only along the stream edge where adequate light is available. The microflora of the marsh surface has not been studied in Louisiana, but cyanobacteria *Lyngbya* and *Rivularia* and the green algae *Ulothrix, Rhizoclonium, Chaetomorpha, Ulva, Enteromorpha,* and *Monostroma* are distributed in saltwater marshes around the world (Chapman 1960; Ursin 1972). In Georgia, saltwater marshes support hundreds of species of diatoms, dominated by *Cylindrotheca*, *Gyrosigma*, *Navicula*, and *Nitzschia*, which make up 75%–93% of the benthic algal biomass (Williams 1962).

Marshes are detritus-based ecosystems. In Louisiana, the trophic structure and energy flow of saltwater marshes are much better understood than for other marsh types. Energy flow in saltwater marshes was described by Montague and Wiegert (1990) and Gosselink (1984). Probably 90% of the net energy from plant photosynthesis reaches animals higher in the food web through decomposition by bacteria and fungi on the surface of the marsh and through ingestion by micro- and meiofauna in the sediments (Fig. 28). Flooding of the marsh surface provides access by aquatic animals, and tidal flushing of decaying material and microorganisms delivers food to the adjacent streams. In both cases the detritus and microfauna are available to benthic feeders: crabs, shrimp, snails, and filter feeders, which in turn are fed upon by bottom-feeding fish, wading birds, and small mammals. It is estimated that about 10% of primary production is grazed by insects (Smalley 1960).

In Louisiana, saltwater marshes are not grazed much by mammals and herbivorous waterfowl, but in freshwater and brackish marshes, muskrats, nutria, and a number of duck species can do serious damage to marshes as they feed on underground roots and rhizomes (R. G. Linscombe and N. Kinler, Louisiana Department of Wildlife and Fisheries, Baton Rouge, unpublished manuscript). It is unlikely that the direct ingestion of plant material is the major cause of the damage; rather, the destruction of plants by the animal’s movements while grazing is extensive. This dead material enters the detrital food chain.

Primary production and plant biomass are also highest along the edge of the marsh (Kirby and Gosselink 1976; Mitsch and Gosselink 1993). *Edge effects*, the concentration of physical energy and biological activity at the interface of habitat types—in this instance the marsh and adjacent water—are most clearly evident in saltwater marshes. Tidal energy is focused at the marsh edge; as rising water spills over the marsh, the edge receives the coarsest sediments and the most nutrients, with finer sediments deposited farther into the marsh. Also, because of the many tidal streams, the length of edge per unit of marsh is highest in the saltwater marsh (Fig. 29). As the dead plant matter decomposes, it accumulates both on the marsh edge and in the adjacent water as fine particles of decaying organic matter. Macroinvertebrates, nematodes, and benthic infauna concentrate in this detritus, and the larger invertebrates—shrimp and crabs—feed there, both in the edge of the

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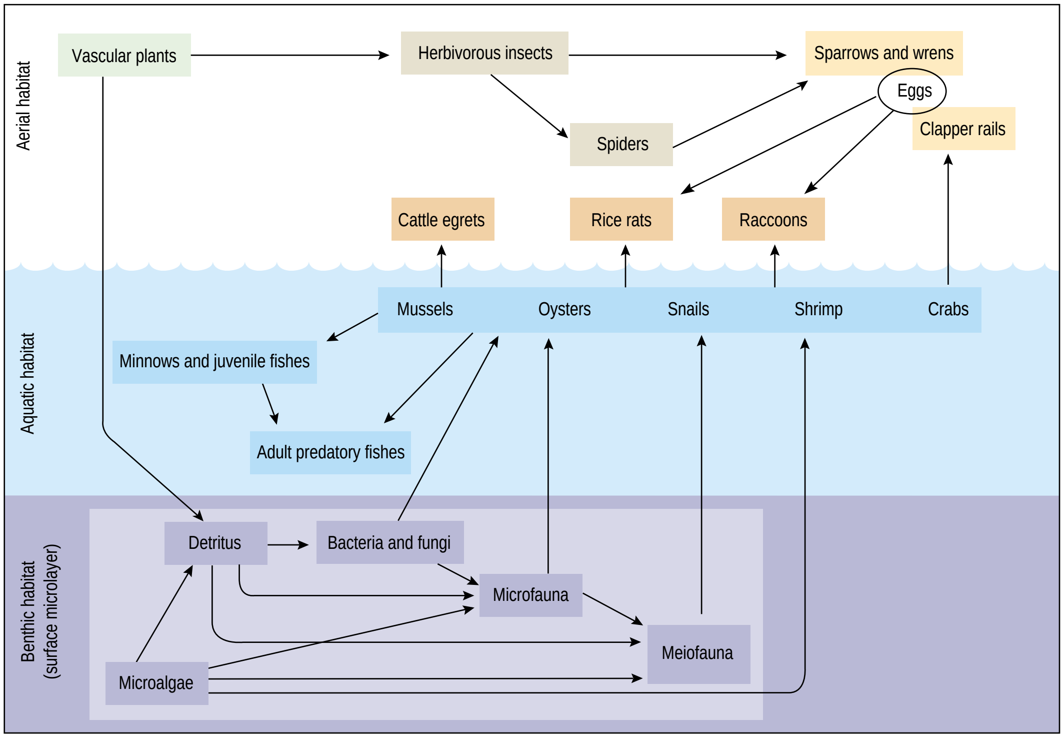

Fig. 28. Saltwater marsh food web, showing the major consumer groups of aerial, benthic, and aquatic habitats (modified from Mitsch and Gosselink 1993).

stream and on the marsh when it is flooded (Zimmerman et al. 1990). It is no wonder that the top carnivores—such as wading birds, seatrout, and redfish—also congregate there. Concentrated activity at marsh edges is also seen in other marshes (Odum et al. 1984) but is not as strongly expressed as it is in saltwater marshes.

Low-Salinity Marshes

Low-salinity marshes are those classified by Chabreck et al. (1968) and Chabreck and Linscombe (1978, 1988) as brackish and intermediate. Such marshes cover 4,704 square kilometers (Table 2), ranging in salinity from as low as 1 part salt per thousand to as high as 10 parts salt per thousand. Because salinity is a continuous gradient in nature, this group of marshes overlaps with both freshwater and saltwater marshes, and the boundaries are not sharp, especially at the freshwater edge.

Visser's analysis of Chabreck's data (see Reed 1995) identifies four brackish plant associations; only three have broad distribution. These three are dominated by wire-grass, with saltgrass, American bulrush, and yellow cowpea as codominants. At the saltwater marsh end of the gradient, other common species are smooth cordgrass and needlegrass rush, whereas at the freshwater end, dwarf spikerush, coastal water-hyssop, Walter's millet, and seashore paspalum are common. Species that seem most characteristic of low-salinity marshes are wire-grass and American bulrush. Yellow cowpea, an annual vine, is common but is also widely distributed in freshwater environments. Chabreck (1972) identified 40 plant species in brackish marshes, whereas Conner et al. (1986) found 23 species.

Chabreck's intermediate salinity marshes are at the freshwater end of the salinity gradient, apparently supporting freshwater species that can tolerate occasional salt spikes of up to about 8 parts per thousand. Penfound and Hathaway (1938) classified these marshes as slightly brackish, and they are probably the same kinds of marshes that Odum et al. (1984) described on the south Atlantic coast as tidal freshwater marshes (R. H. Chabreck, Louisiana State University, Baton Rouge, personal communication). In Visser's analysis, this group probably coincides with the wire-grass–cowpea and the freshwater arrowhead associations.

Functionally, low-salinity marshes are probably the least understood marsh group. They have an organic substrate ranging from nearly pure organic matter (some sites are floating) to mineral soils similar to those of saltwater marshes. Low-salinity marshes are generally low-energy systems, and because they are located some distance from both a strong tide and local upland drainage, they probably receive few sediment and nutrient inputs. Despite this, aboveground production and standing biomass can be extremely high in these marshes (Hopkinson et al. 1978). The root systems of intermediate marshes are fine and shallow, and underground live root mass is small; only about a third of production is allocated to the roots, compared with about half for maidencane (Sasser et al. 1994). Beneath the root mat, the substrate is often an unconsolidated, semi-fluid muck.

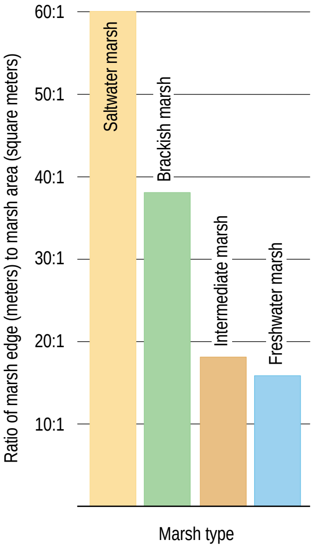

Fig. 29. The relative length of marsh edge to area in saltwater, brackish, intermediate, and freshwater marshes along the Louisiana coast (data from Gosselink et al. 1979a,b,c).

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In much of the low-salinity marsh, accretion does not balance subsidence, and consequently the marshes are the most rapidly degrading type in the coastal zone. From the air, low-salinity marshes have a clumpy appearance caused by large, apparently vigorous individual plants separated from each other by bare mud (Nyman et al. 1993a). The plant clumps are elevated above the rest of the marsh; the root system is very shallow, and often the clump with its intact roots can be lifted with little apparent disturbance of the substrate.

Physiological and growth characteristics of wire-grass may make it particularly susceptible to subsidence. This species grows vigorously at upper elevations in the tidal zone and is a good competitor under these circumstances, as is demonstrated by its wide distribution. Most wetland plants respond to increased flooding by producing root aerenchyma (a gas-filled tissue produced in some plants in response to flooding and which sometimes aids in oxygen flow), which enable the roots to maintain their oxygen supply directly from the aerial portions of the plant (Webb and Jackson 1986; Burdick 1989). In wire-grass, however, aerenchyma production does not compensate for oxygen deprivation associated with flooding as shown by a simultaneous increase in anaerobic fermentation (Pezeshki et al. 1991; Naidoo et al. 1992). Although species like smooth cordgrass produce many roots that grow downward into the soil (like most plants) in response to flooding, wire-grass produces few roots and these protrude up out of the substrate (Naidoo et al. 1992).

Wire-grass is apparently physiologically unable to cope with increased flooding associated with net subsidence. As a result, its growth is curtailed and fewer roots are produced to counter subsidence. The net subsidence rate increases, setting up a positive feedback loop that accelerates marsh degradation (Nyman et al. 1993b). Though root production apparently provides the structural framework that controls the accretion rate, mineral sediments strongly influence accretion. Nyman and DeLaune (1991) found that wire-grass marshes require about 1,000 grams per square meter per year of mineral sediment to accrete 1 centimeter per year. Many are accreting at only about half to two-thirds of this rate.

Forested Wetlands

Forested wetlands on the Louisiana coast are located at the landward edges of the estuaries that flank the Mississippi River and its major distributaries. They fall into two broad vegetation zones, baldcypress–tupelo swamps and bottomland hardwood forests. Because dry terrain is at a premium in the coastal zone, much of the land firm enough to develop was long ago cleared for agriculture, industry, and urban use. Most of the remaining forest, therefore, is wetland, most of it swamp and low bottomland sites. A diagrammatic elevation profile of the Mississippi River Deltaic Plain region illustrates the relationship of wetland forests to adjacent marshes on one side and the developed levees on the other (Fig. 30).

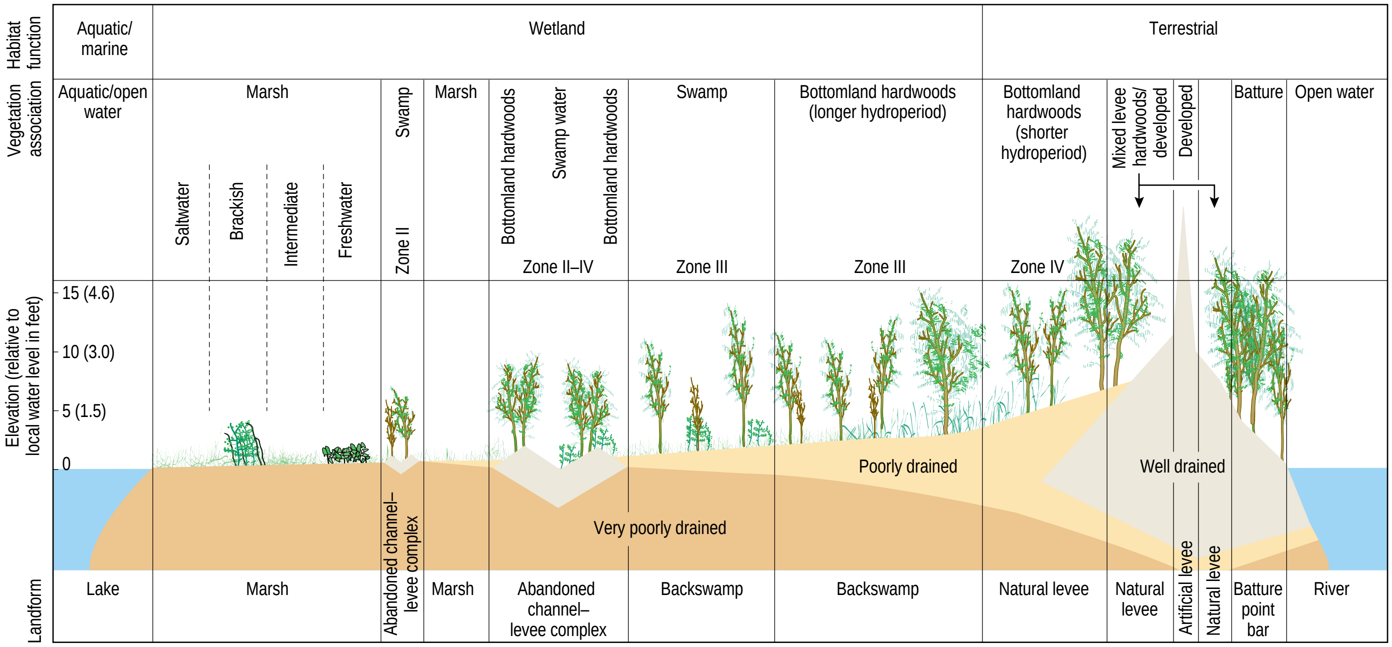

Fig. 30. Relation of habitat and vegetation associations to landforms in the Mississippi River Deltaic Plain region (Wicker 1980). Elevation relative to local water level is given in feet (meters in parentheses).

Larson et al. (1981) classified bottomlands into five forest zones based on elevation and flooding frequency. Nearly all the forested wetlands in the Louisiana coastal zone fit into Zones II, III, and IV; Zone I is permanently flooded and supports no woody vegetation. Zone II is the wettest area of flooded forest habitat, including wet flats, sloughs, swales, and backswamps (shown as backswamp only in Fig. 30). Flooding and soil saturation are constant year-round except for periods of extreme drought. Soils are highly reduced, high in organic matter, and nutrient-rich, although nutrient availability is limited by the anaerobic conditions. This is the classic deep swamp environment, dominated in Louisiana by baldcypress and water tupelo (Table 5), which are often found either in nearly pure stands or in mixed stands of the two species. Other overstory trees include green ash, pumpkin ash, and red maple. Buttonbush, Virginia-willow, and American and red maple are common understory species. The presence of standing water nearly year-round allows for the growth of numerous floating aquatic and emergent plants. Duckweeds, water hyacinth, Carolina mosquitofern, and American frog's-bit are common floating plants. Lizard's tail and water smartweed are the most common emergent herbaceous plants, which, along with woody seedlings, can be found growing on logs, stumps, baldcypress knees, and even on the buttresses of the baldcypress trees.

Zones III and IV, the natural levee environment (Fig. 30; Table 5), are slightly more elevated than Zone II (swamp in Fig. 30). Flooding occurs for extensive periods during the growing season, and saturated soils that are prevalent most of the year are mottled gray, indicating periodic reduced conditions. However, soils surrounding the root are commonly dry in summer. In early stages of succession, these zones support black willow, red maple, and sometimes eastern cottonwood (Table 5). American elm, sweet gum, sugarberry, and red maple become dominant. The woody understory is composed of red maple and boxelder saplings. In places where light can penetrate, a thick tangle of vines and herbs grows, including poison ivy, greenbriers, peppervine, and Virginia creeper.

These are extremely diverse environments, in terms of both microhabitats and plant species. The meandering of the river across the floodplain creates old oxbows, sloughs, ridges, ponds, mudflats, and other areas of slightly differing elevation and soil characteristics (Mitsch and Gosselink 1993). It is no surprise then that Conner et al. (1986) listed 146 species associated with bottomlands and 140 species with swamps.

The extent of the area occupied by forested wetlands in the Louisiana coastal zone is unknown. Recent detailed studies of coastal wetland change (for example, Britsch and Kemp 1991; Johnston et al. 1995) have focused on marsh loss, and forested wetlands were not included in the Waterways Experiment Station study of wetland loss discussed previously (Dunbar et al. 1992); other inventories used different coastal zone boundaries. One of the largest areas of bottomland forest in the United States occurs in the Atchafalaya basin, which is usually considered an inland basin and is not a part of the jurisdictional coastal zone. Without including this basin, Wicker et al. (1992) reported 3,820 square kilometers of swamp in the Louisiana coastal zone in 1955 and 3,530 square kilometers in 1978. The National Wetlands Research Center estimated 5,930 square kilometers of forested wetland from 1990 aerial imagery (L. R. Handley, U.S. Geological Survey, National Wetlands Research Center, Lafayette, Louisiana, personal communication). Regardless of the absolute area of forested wetland, the direction of change is clear. A period of intensive logging occurred from the mid-1800's until about 1920, overlapping a period of forest clearing for crop production, which continued into the 1980's. In recent years, sea-level rise and coastal subsidence seem to have threatened the future of coastal forested wetlands.

The early history of baldcypress logging is recounted by Conner and Toliver (1990). To early settlers, swamps were dangerous and forbidding, and the best use for them was drainage and agricultural production. In the meantime, the vast baldcypress forests were the main cash crop of the colonists, especially in southern Louisiana. Baldcypress logs were first harvested by girdling, allowing them to dry in place, then felling and floating them out of the forest. Low levees were often piled around a forest patch to maintain water levels deep enough to float the logs. Some of these levees remain today. During the 1890's, the pullboat, and later the overhead-cableway skidder and railway system, increased the range of the loggers and consequently the amount of timber that could be brought out of the forest. Logging continued to accelerate until the peak year of 1913, when more than 1.7 million cubic meters of lumber were processed in 94 mills (Mattoon 1915; Fig. 31). As the last of the old-growth timber was harvested during the 1920's, production crashed, and by the early 1930's production had decreased by 95% from its peak. The last major baldcypress logging operation closed in 1956 (Conner and Toliver 1990).

Table 5. Selected tree and shrub species of bottomland forests in the southeastern United States (Larson et al. 1981). Zone II, also known as swamp, is the wettest area, generally saturated almost permanently throughout the growing season (see Fig. 30); Zone III is slightly more elevated and is inundated or saturated more than 25% of the growing season; Zone IV is the least frequently flooded swamp area, typically inundated between 12.5% and 25% of the growing season.

Species	Ecological zone		
	II	III	IV
American elm		X	X
American snowbell		X	
Baldcypress	X	X	
Black willow	X	X	
Boxelder		X	X
Buttonbush	X	X	
Carolina ash		X	X
Cedar elm		X	
Common persimmon		X	X
Dwarf palmetto			X
Eastern baccharis		X	X
Eastern cottonwood		X	X
Green ash		X	X
Green hawthorn			X
Hazel alder			X
Honeylocust		X	X
Laurel oak		X	X
Leadplant		X	X
Live oak			X
Nuttall oak			X
Overcup oak		X	X
Possumhaw		X	X
Red maple		X	X
River birch		X	X
Sugarberry		X	X
Swamp dogwood		X	X
Swamp-privet	X	X	
Sweet gum		X	X
Sycamore			X
Virginia-willow		X	
Water-elm	X	X	
Water hickory		X	X
Water locust	X	X	
Water tupelo		X	X
Water viburnum		X	
Willow oak			X
Winged elm			X

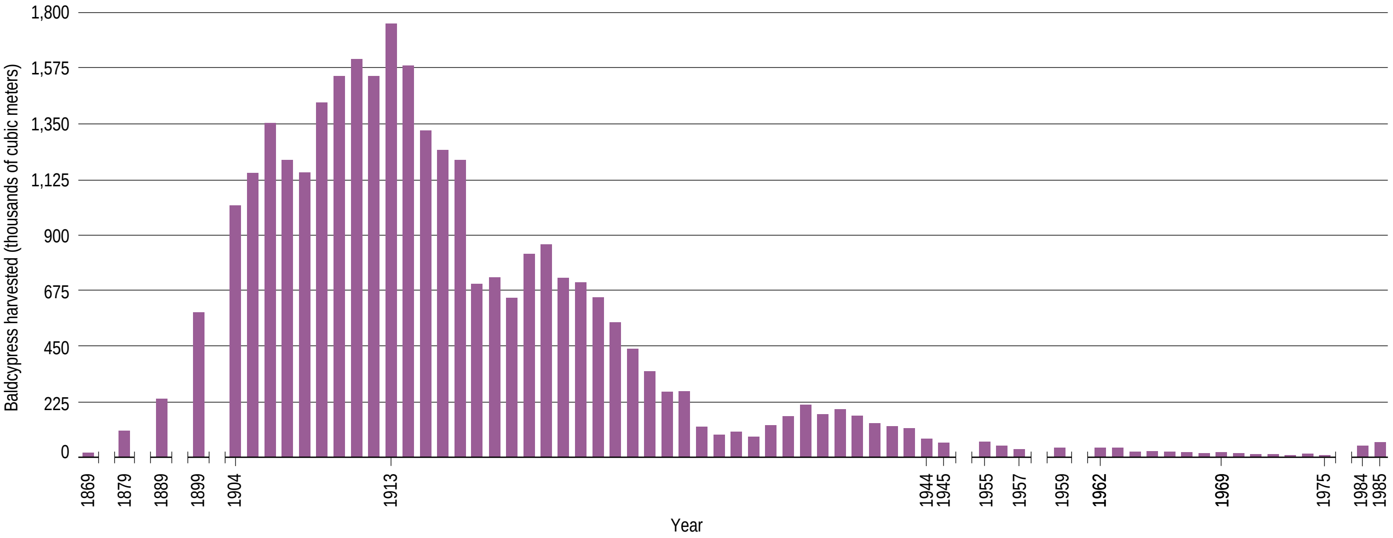

Fig. 31. The volume of baldcypress logged in Louisiana (Conner and Toliver 1990; data from Anonymous 1943, 1956–1976, 1957; Steer 1948; Mistretta and Bylin 1987). Solid wood, converted as 423.8 board feet = 1 cubic meter.

Second-growth forests have regenerated after the logging, and many stands are now about 80 years old. Estimates from various sources of growing stock (Conner and Toliver 1990) suggest a volume of about 15 million cubic meters in 1954, increasing to about 40 million cubic meters in 1984. In recent years, because of the large reserves and new techniques of logging, baldcypress logging has once again become attractive (Marois and Ewel 1983).

The second period of human activity that affected wetland forests was the clearing of bottomlands for agriculture. In the colonial period, agriculture was confined to the natural levees that were dry during the growing season. These rich soils were replenished with mineral nutrients when the adjacent river overflowed its banks during spring floods, and no fertilization was needed to grow vigorous crops. With the development of powerful tractors and equipment and of crops (especially soybean varieties) that would mature even if planted as late as early July, there was a strong economic incentive to clear bottomlands for agriculture. In the Mississippi River alluvial floodplain, clearing was linked to flood-control projects funded with tax dollars. The result was a rapid clearing of the floodplain from about 1930 through about 1980. The Nature Conservancy (1992) estimated that before European settlement, the Mississippi River alluvial floodplain contained about 80,000 square kilometers of riparian forests; fewer than 20,000 square kilometers remained in 1991.

Surveys that depend on aerial imagery to determine habitat changes are not particularly effective in discerning the slow, subtle change threatening the remaining coastal wetlands. Conner and coworkers (Conner and Day 1988a,b, 1989, 1991; Conner and Toliver 1990) and Pezeshki et al. (1990, 1993) have described the effects of rising sea level and substrate subsidence on wetland forests. In impounded forests with elevated water levels, regeneration stops because seed germination almost always requires exposed soil. The less flood-tolerant species, such as green ash, slowly die. Baldcypress and water tupelo survive, and basal area is not greatly affected at first because as some trees die, the flood-tolerant ones continue to grow (Conner et al. 1981). These changes are not evident on aerial photographs, but the forest is in decline—it is not reproducing itself. Coastal forested wetlands are subsiding at a rate of about 0.85 to 1.4 centimeters per year (DeLaune and Patrick 1987; Conner and Day 1988b), whereas accretion is only about 0.3 to 0.6 centimeters per year. The forests are thus slowly sinking. As flooding frequency and depth increase, the trees will respond as they do in impoundments. Regeneration is nearly absent in many coastal swamps.

The density of nutria in many coastal forests and their consumption of baldcypress seedlings complicate regeneration. Seedling survival seems to depend on the density of nutria near the plantings; sleeves over the seedlings have been ineffective in preventing nutria damage (Conner and Toliver 1987; Conner 1988).

Natural Levees, Ridges, Cheniers, and Barrier Islands

Several maritime communities occur along the Louisiana coast. All are linear and elevated above the coastal wetlands. To describe them as upland communities would be to stretch the definition of uplands; most are only a meter or two above the ambient water level and are flooded during any moderate storm surge. These communities fall into two groups. The first includes natural levees of major and minor distributaries (Fig. 32) that diverge from larger distributaries as they trend toward the coast, and it also includes the cheniers that run parallel to the coast, are part of the mainland coast, and are separated from the beach by intervening marshes. Deposits of mostly linear dredged material that crisscross the coast also mimic natural levees in some respects (Monte 1978). The second group of communities includes the barrier islands and headlands fronting the Gulf of Mexico.

These communities do not encompass a large area compared with the coastal marshes, but in coastal basins they play an important ecological role through their function as barriers between the ocean and the estuary and as water regime barriers within an estuary and because they present the only elevated, sometimes forested land within a plain of wetland and water. They provide periodic or continuous habitat for nearly all mammals and birds in the coastal zone.

Trends

All the maritime communities are decreasing in area, primarily as a result of the geomorphic processes described earlier. The larger levee communities have the potential to be forested, but most have been cleared. The remaining forests occur mainly along the inland edge of the coastal zone, and some forests remain on the high coastal cheniers, particularly in the Chenier Plain. Many are used for cattle grazing and others are modified by human occupation, but they still provide habitat for many birds.

Older residents of Leeville, a community near the seaward end of the subsiding Bayou Lafourche natural levee, can remember when rice was raised nearby on the back slopes of the levee. The land is now too low and too saline for rice cultivation. Flood-control dikes and pumps along the backswamp edge of the natural levees have been constructed to keep the towns and pastures dry, but recently the bayou itself has begun to flood over the highest part of the natural levee with the occurrence of almost every minor tropical disturbance. On unprotected natural levees out in the marsh, the trees have been replaced, first by woody shrubs such as bigleaf sumpweed and wax myrtle, then by marsh grasses and other herbs, and finally by shallow ponds.

The cheniers are settling, but many are still as much as 3 meters above sea level, and they are still major elements of the landscape. The barrier islands are also rapidly degrading, as are barrier islands around the rest of the United States (Williams and Johnston 1995). The U.S. Department of the Interior identified 2,055 kilometers of undeveloped shoreline in its Coastal Barrier Resources System. Louisiana has 287 kilometers of undeveloped shoreline, or about 14% of the U.S. total, but the total length of the barrier system in Louisiana is about 600 kilometers of undisturbed shoreline (Penland et al. 1990). Still, Louisiana's coastal barrier retreat rate is the highest in the nation, averaging 4.2 meters per year over the past 50 years. The rate is not constant through time nor across the coast—at different locations, barrier retreat rates range from +3.4 meters per year to -15.3 meters per year. Most of the retreat occurs during major storms and hurricanes and can be as great as a loss of 20–30 meters over a 3- to 4-day storm (Penland et al. 1990).

In addition to beach retreat, the total area of Louisiana's barrier shoreline is decreasing. In 1880 the total barrier island area was 98.6 square kilometers. By 1980 the total area had decreased by 41%, to 57.8 square kilometers (Penland and Boyd 1982). The barrier island system is now a series of arcs of isolated islands formed by fragmentation of earlier large islands. The relief on these islands is low; dunes are seldom more than 2–3 meters high, and overwash occurs during even moderate storms. Except for Grand Isle and Grand Terre, the largest island remnants of the Lafourche delta lobe, the islands are treeless.

Vegetation

The larger cheniers and natural levees still support some groves of live oaks, formerly the dominant tree species. Other common species include sugarberry, American elm, red maple, waterlocust, prickly-ash, common persimmon, and water oak. Baldcypress is found in low areas. Palmetto is a common understory species, as are haws, buttonbush, possumhaw,

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Fig. 32. Natural levees along an abandoned distributary of Bayou Lafourche. Most of the surrounding marsh has degraded, leaving the old distributary streambed with remnants of the natural levee on each side.

and eastern baccharis. On heavily grazed cheniers, chickasaw plum, saltcedar, and prickly pear dominate. Vines, especially grape, are ubiquitous (Gosselink et al. 1979a,b,c).

Vegetation on the Louisiana coastal islands is generally similar to that found on barrier islands of the south Atlantic coast and the rest of the Gulf of Mexico coast (Stalter and Odum 1993), except that sea oats, which dominate those areas, are replaced by wire-grass in Louisiana (Barbour et al. 1987). Surveys of the *beach face* (from the beach edge of the vegetation line to the point where beach vegetation is mixed with stabilized dune, forest, marsh, or inland species) identified a Louisiana beach association distinct from those to the east and the west (Barbour et al. 1987). Gulf beaches everywhere have a number of species in common: saltgrass, beach morning glory, and gulf croton. In addition, two species of heliotropes are found only on Louisiana beaches, and coast sandbur is found only on Louisiana, Texas, and south Florida beaches.

On transects extending across an entire barrier island, Visser and Peterson (1995) identified 12 plant species dominated by smooth cordgrass, saltwort, black-mangrove, coastal dropseed, perennial pickleweeds, and seaoxeye. The species were distributed according to elevation and degree of exposure to the ocean, with the succulent species and vines on the lower beach face, wire-grass at highest elevations, and smooth cordgrass and black-mangrove on the protected bayside flats.

The Isle Dernieres system, the remnant of the headlands of the Teche delta lobe, is an example of a typical barrier island system. In 1853 this system consisted of a single large island and one small island, separated from the coast by a narrow bay (Fig. 33). In the 1850's the large island was a popular beach resort for the residents of New Orleans and other Louisiana cities, who fled the summer heat and humidity (and the mosquitoes that transmit yellow-fever) for the hotel and beach cottages of Last Island (Sothern 1980). The island supported a thriving community, especially during the summer. On 9 August 1856, at the height of the resort season, a severe hurricane ravaged the island, killing about 200 of the approximately 500 people on the island. One account (*in* Sothern 1980:p. 69) by a member of a rescue party that reached the island several days later said, "There were about one hundred houses on the island, not one was left, nay not a sill nor sleeper, not any part of their foundations to indicate that buildings had once been there."

The islands have never recovered from the storm. For a while, the curious came to view the ruins, but with time the waves and shifting sands erased all traces of human habitation. In 1890 the island system had an area of 3,360

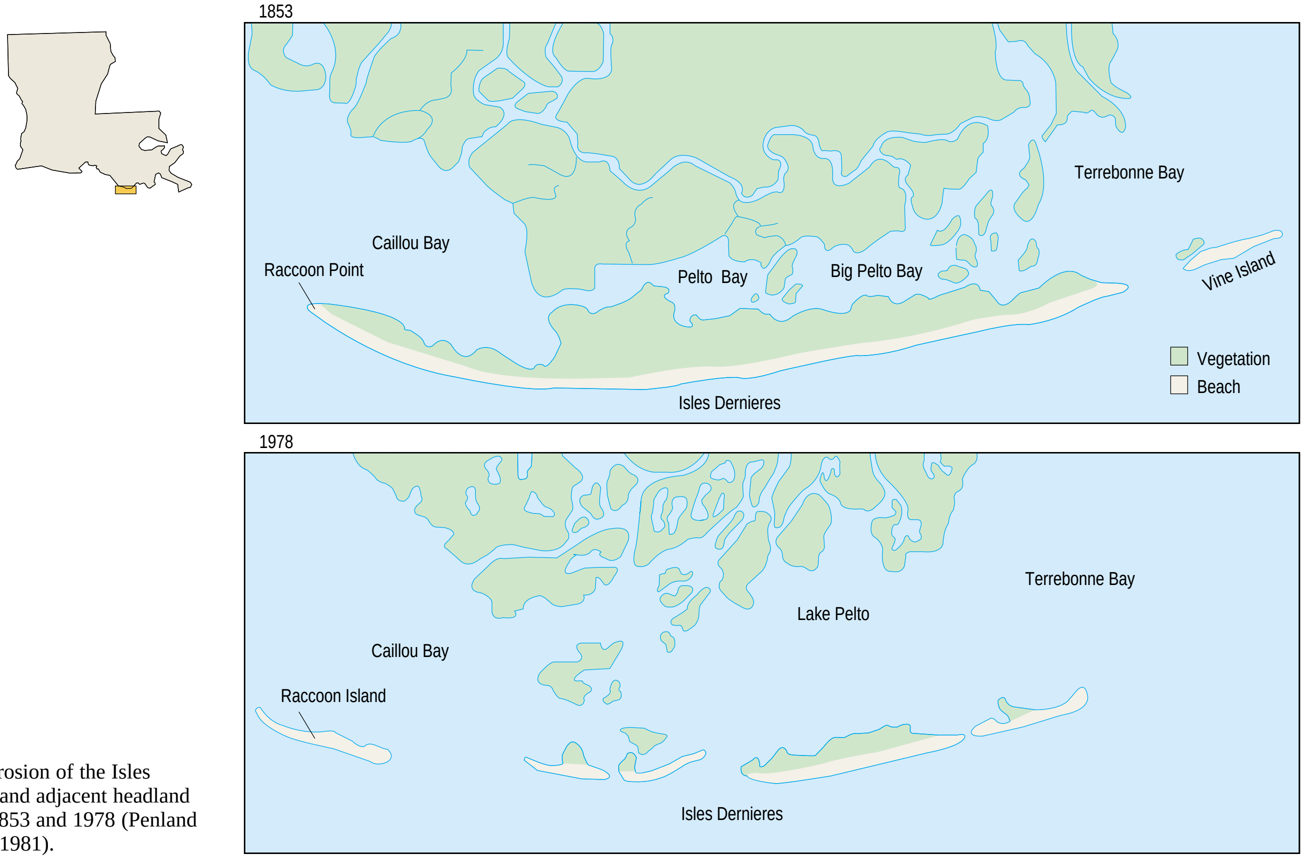


Fig. 33. Erosion of the Isles Dernieres and adjacent headland between 1853 and 1978 (Penland and Boyd 1981).

hectares. By 1978 the Isles Dernieres had eroded to a series of small island fragments well separated from the mainland, with an area of less than 8 square kilometers. In the intervening years, the center of the barrier arc retreated at a rate of 19.1 meters per year (Penland et al. 1990). Before the 1856 hurricane, most of the buildings were clustered at the western end of the island. That site is now known as Raccoon Island, and the vegetation map (Fig. 34) indicates how the forces of storms and waves have changed the island.

Aquatic Ecosystems

Aquatic ecosystems of the Louisiana coast include those described by Moore (1992) as low-salinity lagoons, as well as the brackish to saline estuarine systems described by Dardeau et al. (1992). Chabreck (1971) inventoried the bays, lakes, and ponds of the Louisiana coastal zone. In 1968 the estuarine system was dominated by marsh ponds of less than 0.5 hectares (Table 6). A more recent comprehensive inventory showing the effects of 25 years of marsh degradation does not exist, but because most marsh loss starts with small ponds that later coalesce, the probability is that the small ponds still dominate, although there must have been an increase in the total area of larger ponds. Small ponds are concentrated in the low-salinity marshes, probably because these marshes are breaking up most rapidly. As marsh degradation occurs, the area of open water in the coastal zone increases, mostly in ponds within the marsh, but as these grow in size and coalesce, they open into adjacent bays and lakes. In addition, the edges of water bodies large enough to have significant wave fetch are eroding slowly. Virtually all the wetland loss documented in Table 1 appears as open water gain.

Several characteristics of Louisiana coastal aquatic ecosystems determine the composition and distribution of species and the trends in species' populations through time:

- Most populations that have been studied (chiefly commercially important species) are stable at present (Condrey et al. 1995), but marsh loss and marsh–water interface changes are expected to be major factors in the future. The size of the offshore harvest of commercial fishes and shellfishes that use the estuary as a nursery is directly related to the area of marsh in the estuary (Turner 1977, 1982) because the young of these species concentrate at the marsh–water interface (Zimmerman et al. 1990, 1991; Minello and Zimmerman 1992). As a marsh fragments, the marsh–water interface increases until about half of the marsh is gone, after which the loss of wetlands then decreases the length of this interface (Browder et al. 1989). The total edge length is still climbing, but Browder et al. (1989) estimated that it will reach its maximum around the turn of the century, after which the interface length should decline rapidly. Shellfish and fish populations are expected to follow the interface trend (Condrey et al. 1995).
- Fishing pressure is the cause of population declines of commercial species all over the world. However, in Louisiana most of the commercial species have short life cycles and are harvested during their first or second year of life. The interannual variation in population size is high, related to environmental conditions, but because of the short life cycle, fishing pressure has had little apparent effect on the stocks of all but one or two species (Perret et al. 1993).
- Eutrophication of the estuaries may result in hypoxic and anoxic conditions and shifts in populations of primary producers that are food for fishes and shellfishes (Rabalais et al. 1995). In particular, the closing of shellfish beds because of high coliform bacteria counts is a constant threat to the oyster industry (Kilgen et al. 1985).
- Marsh management or water-level management by construction of levees and water-control structures is practiced in the Louisiana coastal zone as a means of protecting marshes from saltwater intrusion and excessive water currents. However, the control structures limit access to marshes by the larval and juvenile stages of commercial species; thus, yields of these species are seriously reduced (Herke et al. 1987; Herke and Rogers 1989). Because marsh management projects now cover a significant area in the coastal zone and permit requests for many more have been filed (Day et al. 1990), there is concern that such management may be deleterious to commercial fish yields.

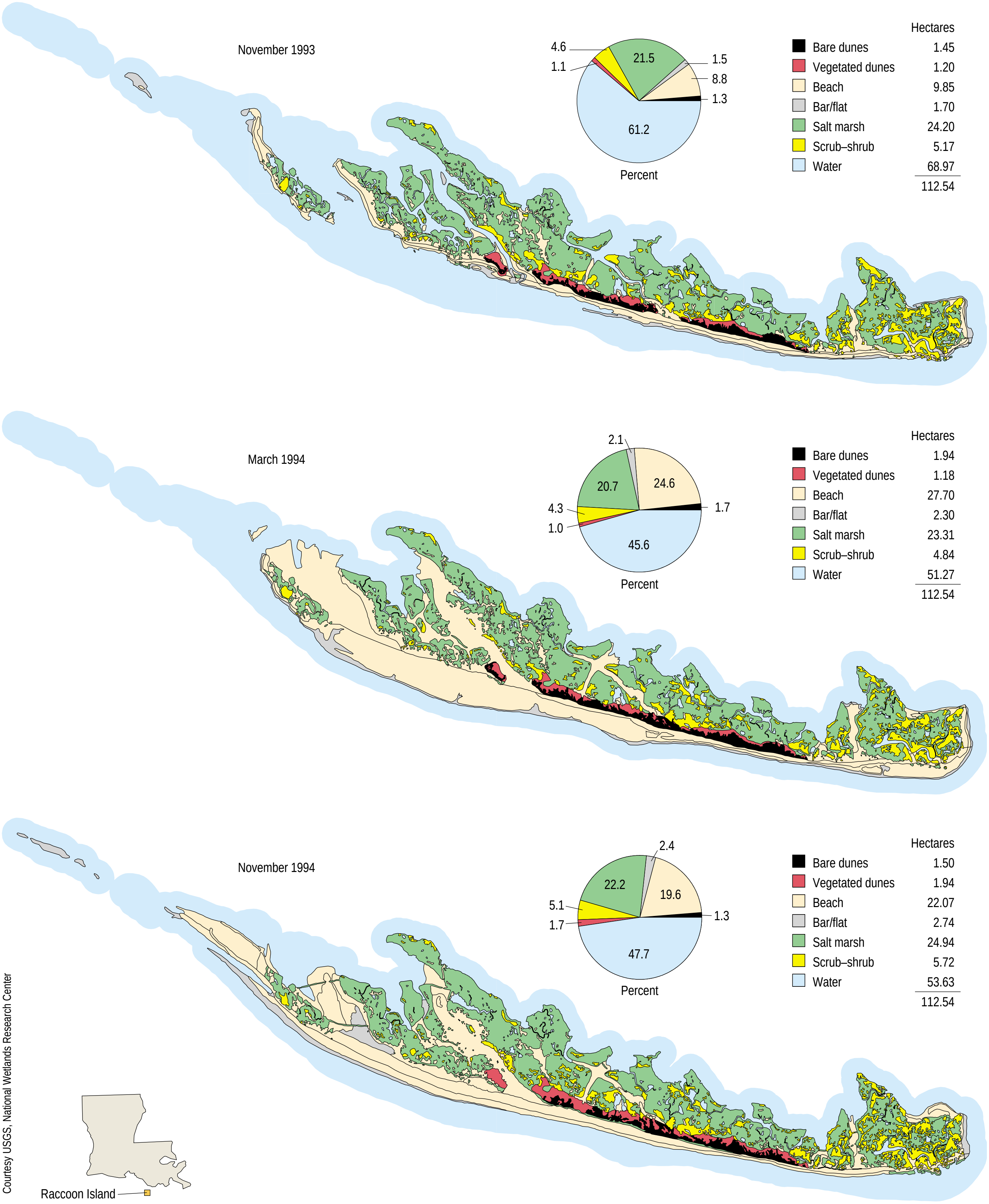
Table 6. Number and area of ponds and lakes along the Louisiana coast by size classes (Chabreck 1972).

Size class (hectares)	Number of ponds and lakes	Total area included (hectares)
<0.004	2,950,000	11,478
0.004–0.04	1,889,000	30,468
0.04–0.40	425,800	53,571
0.40–4.05	43,460	49,960
4.05–32.4	5,472	59,997
32.4–259.2	722	61,009
259.2–1,296	149	90,032
1,296–6,480	15	46,494
6,480–25,920	7	145,476
>25,920	1	173,503
Total	5,314,626	721,988

Two additional factors that determine the composition and distribution of nektonic species are discussed in subsequent sections. First, salinity is probably the most important determinant of species distribution and composition, especially when freshwater areas are compared to salt-influenced ones. Second, migration between the Gulf of Mexico and estuaries is characteristic of almost all of the commercially important fishes and shellfishes. *Temporal niche* or *habitat sharing* is often associated with these migration patterns.

Primary Producers

Waters in the coastal zone are shallow: only 1–2 meters deep in the largest bays, except for the major tidal channels. The muddy, shallow bottom sediments are easily suspended by winds, and the water is typically turbid except in small ponds. As a result, bottom-dwelling filamentous algae and submerged vascular aquatic plants are found only in small, shallow ponds. Most of the aquatic producers are small filamentous or single-celled algae. The algal flora



Courtesy USGS, National Wetlands Research Center

Fig. 34. These vegetation maps of Raccoon Island show how vegetation recovers from storms over time. The state of Louisiana began a beach restoration and nourishment program to reestablish the portions of the island that had been swept away by Hurricane Andrew in 1992. The long-term stability of these newly restored areas may be significantly improved by the establishment of vegetative cover.

of Louisiana estuaries has not been much studied, except to measure the magnitude of primary production (Day et al. 1973, 1977; Stowe 1982; Moncrieff 1983; Shaffer 1986). Day et al. (1973, 1977) found that although gross production in bays and lakes is high, the systems are generally heterotrophic—that is, respiration exceeds production—probably because of the inflow of organic matter from the adjacent marshes and swamps. Production depends strongly on water clarity. In one shallow saline lake studied, benthic production was greater than water column production, but only when light penetrated to the bottom. Salinity and degree of eutrophication determined which species were dominant (Table 7). Freshwater lakes were dominated by blue-green algae, filamentous forms in the spring and unicellular and small colonial species in the summer. Diatoms dominated the winter flora. In low-salinity areas, green algae, dinoflagellates, and diatoms were more important under eutrophic conditions than in less eutrophic conditions where colonial and single-cell coccoid cyanobacteria (blue-green algae) were dominant. The algal flora of a small saline lake was dominated by diatoms during the winter and by dinoflagellates during the summer (Day et al. 1973).

Table 7. Some dominant microorganisms in Louisiana estuaries (Sp = spring; Su = summer; F = fall; W = winter; Y = year-round; x = present). Data from Conner and Day (1987).

Species group	Salinity zone		
	Fresh	Low salinity	Saline
Blue-green algae			
Anabaena species	Su		
Anabaenopsis elenkinii	Su		
Chroococcus species	Sp	Y	
Gloeocapsa species	Sp	Su,F	
Gomphospheria species		Su,F	
Lyngbya contorta	Su		
Merismopedia species	Sp	Su,F	
Microcystis aeruginosa		Su,F	
Green algae			
Chlamydomonas species		F	
Chlorella vulgaris		F	
Pediastrum biradiatum	Su		
Scenedsemus quadricauda	Su		
Staurastrum americanum	Su		
Diatoms			
Actinoptychus undulatus			W
Biddulphia aurita			W
Chaetoceros breve			W
Coscinodiscus species			W
Cyclotella species	W	W	
Diploneis elliptica		W	
Nitzschia species	W	W	
Surirella robusta		W	
Dinoflagellates			
Ceratium hircus			Su
Gymnodinium species		x	Su
Peridinium cinctum		x	Su
Prorocentrum species			Su
Cryptophytes			
Cryptomonas species		Y	
Chrysophyte			
Ochromonas species		Y	
Euglenoids			
Trachelomonas hispida		Y	

Submerged vascular plants are concentrated in shallow marsh ponds of less than 4 hectares (Chabreck 1971). None occur in the saline zone, and widgeongrass is nearly the only species found in brackish areas. Species richness increases from brackish to freshwater areas, with coontail, Eurasian watermilfoil, and southern waternymph appearing in low-salinity areas, and with many additional species present in freshwater ponds (Table 8). A green algal species, *Chara vulgaris*, forms large submerged mats in low-salinity areas during the spring. Floating duckweed solidly carpets forested waterways and flooded swamps, and water hyacinth mats are common obstructions in freshwater lakes and waterways. Water hyacinth, alligatorweed, hydrilla, and Eurasian watermilfoil are all introduced species that have spread widely in Louisiana and are nuisance plants that cause economic damage and are expensive to eradicate.

Table 8. Submerged aquatic plant species in ponds and lakes by marsh zone along the Louisiana coast, August 1968 (Chabreck 1971).[a]

Plant species	Marsh zone (percent cover)			
	Entire coast	Brackish	Intermediate	Fresh
Alligatorweed	0.9	0	0	1.3
American frog's bit	0.8	0	0	1.1
American lotus	1.3	0	0	1.9
American white waterlily	3.4	0	0	5
Blue waterhyssop	0.2	0	0	0.4
Bulltongue arrowhead	0.9	0	0	1.2
Carolina fanwort	2.5	0	0	3.6
Carolina mosquitofern	0.4	0	0	0.6
Carolina spiderlily	0.3	0	0	0.5
Chara vulgaris	8.8	0	32.5	8.1
Coastal waterhyssop	2.5	5	11.7	0.4
Coontail	7.7	0	0	11.2
Creeping primrosewillow	0.2	0	0	0.2
Dwarf spikerush	7	23	10.1	1.6
Eurasian watermilfoil	9.1	3.1	8.9	11
Giant bulrush	0.1	0	0.8	0
Greater duckweed	0.7	0	0	0.9
Horned bladderwort	4.1	0	0	6
Largeleaf pennywort	0.1	0	0	0.1
Lesser duckweed	10.8	0	2.4	15.3
Long-leaf pondweed	0.2	0	0	0.2
Manyflower marshpennywort	1.2	0	0	1.7
Pennywort	0.4	0	0	0.6
Small pondweed	2.3	0	4.9	2.7
Southern waternymph	4.9	0	8.9	5.8
Spikerushes	9.3	4	6.8	11.3
Twoleaf watermilfoil	0.3	0	0	0.5
Water hyacinth	3.1	0	0	4.5
Watershield	1.5	0	0	2.2
Widgeongrass	14.7	62.3	13	0.2

[a] No vegetation in salt marsh zone.

Zooplankton

Zooplankton are an important link in the marine food chain. In the coastal estuaries, for example, the most abundant fish, the bay anchovy, depends largely on zooplankton throughout its life cycle (Darnell 1961). There are relatively few detailed studies of zooplankton from estuarine Louisiana (Stern and Stern 1969; Bouchard and Turner 1976; DeNoux 1976; Gillespie 1978; Stone et al. 1980). The zooplankton community is dominated by the copepod genus *Acartia*, especially *Acartia tonsa*, which accounts for about 50% of the total zooplankton count from low-salinity lakes near the offshore zone. Other copepod species are also common, and Gillespie (1971) reported that ctenophores are often the most conspicuous zooplankters in high-salinity waters. Fish larvae and fish eggs are also abundant (Raynie and Shaw 1994).

Rotifers, copepods, and cladocerans dominate freshwater environments. Rotifer populations peak once or twice a year, when they may constitute almost the entire zooplankton community. Copepods are represented by *Diaptomus dorsalis*, *D. reighardi*, *D. siciloides*, and *Osphrantieum labronectum*. Cladocerans are the most diverse group, with 17 species, all but 2 of them inhabiting fresh water.

Total numbers of zooplankton species are greatest in nearshore and offshore waters (Table 9). Saline areas have large zooplankton populations but low species richness. Fresh water supports many species, but for reasons not understood, population size and species richness are much lower in brackish zones (Bouchard and Turner 1976; Gillespie 1978; Conner and Day 1987).

Table 9. Zooplankton concentrations and species richness counts within Barataria Bay (cited *in* Conner and Day 1987).

Zone	Bouchard and Turner (1976)		Gillespie (1978)	
	Individuals per cubic meter (mean)	Species richness	Individuals per cubic meter (mean)	Species richness
Coastal water (offshore/nearshore)	83,960	16	9,227	37
Inshore saltwater	19,158	28	5,246	31
Brackish water	1,427	21		
Freshwater	12,682	68		
Backswamp	29,078	59		

At least four factors regulate zooplankton densities: predation by nekton and ctenophores; duration of the larval stages of meroplankton, such as crab zoeae, shrimp, and fish larvae; changes in the aquatic environment brought about by the populations themselves; and externally determined environmental fluctuations (Darnell 1962; Bouchard and Turner 1976). For example, *Acartia tonsa* thrives in a wide range of salinities, and the low salinities in the estuary probably limit competition from other copepods, but ctenophores probably control copepod populations because ctenophores feed voraciously on copepods. When nutrient levels are low, rates of reproduction and densities of organisms decline.

The migration of planktonic phases of fishes and shellfishes is a subject of particular concern because of its importance to the commercial fisheries of the Louisiana coast. Fish larvae seem to move with flood tides from offshore into estuaries, especially deep in the water column. On the ebb tides, larger larval bay anchovies are transported along the pass edges. These observations suggest that the fish and shellfish larvae modify their behavior to enable their transport into the estuary or to stay within it (Raynie and Shaw 1994).

Benthic Organisms

Vittor and Associates, Inc. (1995) reported on a 14-year survey of the benthic infauna in both a low-salinity and a high-salinity area of the Barataria estuary, Louisiana. The number of taxa and density of organisms varied greatly, both seasonally and annually, obscuring any fine differences. Both locations were dominated by annelid worms (oligochaetes and polychaetes), mollusks (bivalves), and arthropods (luciculous amphipods and chironomids). Dominant taxa in the low-salinity zone were the oligochaete worms; *Mediomastus*, *Streblospio*, and *Hobsonia* (polychaete worms); the family Chironomidae (a group of midges); and *Corophium* and *Gradidierella* (amphipods). In the high-salinity zone, some of the same organisms were common—oligochaetes, *Mediomastus*, *Streblospio*, and *Corophium*, as well as the bivalve mollusks surfclams and tellins, and the amphipod *Ampelisca*. Besides the effects of salinity on population composition, the populations appeared structured by sediment grain size. This is particularly apparent in the low-salinity zone, where a long-term trend toward coarser sediments was correlated with an increase in the proportion of arthropods to annelid worms and mollusks.

In a more spatially comprehensive study (32 stations from freshwater to saline environments, each sampled once), Philomena (1983) found that crustaceans, polychaetes, oligochaetes, nematodes, and insects represented nearly 90% of all organisms collected. Abundance of organisms was highest in stations near the marsh edge and in shallow bayous, and it increased from saline sites to freshwater ones. Crustaceans and mollusks were found basinwide; insects, nematode worms, and oligochaete worms were reported mostly in freshwater and low-salinity environments; and polychaete worms and nemerteans were prevalent in brackish and marine environments. Overall, crustaceans were the most abundant group, with 44 genera represented. They appeared at 94% of the stations and contributed 3% of the total biomass. The most important orders were amphipods, cladocerans, ostracods, and isopods. Polychaete worms (13 genera) were found in 46% of all stations and made up about 1.5% of the total biomass. One species, *Hobsonia florida*, accounted for almost 40% of the total number of worms. Mollusks, with 18 genera, were found in 78% of the stations and made up 93% of the biomass, mostly because of the large size of the Atlantic rangia clam. The narrowmouth hydrobe was the species represented by the largest number of individuals. Oligochaete worms were found at 60% of the stations but constituted only 0.5% of the total biomass. Chironomids were the most abundant insects but only made up about 0.5% of the biomass and 5% of the total number of organisms collected.

The best-known mollusk in Louisiana estuaries is the eastern oyster, which has been extensively studied because of its commercial importance (Fig. 35). At the seaward end of the estuary, oysters are being pushed inland by encroaching saltwater, which favors oyster predators and parasites. Conner and Day (1987) cited evidence that most of the observed summer oyster deaths in the lower (more saline) estuary are related to the protozoan *Perkinsus marinus* rather than to predators such as conchs, stone crabs, boring sponges, and oyster piddocks. At the landward end of the estuary, oysters are being pushed seaward by pollution from developed areas (Van Sickle et al. 1976; Kilgen et al. 1985). Despite this squeeze, the area of substrate potentially suitable for eastern oyster production is increasing as wetlands degrade, and the area leased for oyster production is also increasing (Condrey et al. 1995).

Oysters build extensive reefs or beds. The fauna associated with these structures is diverse, and its biological organization is complex. Bahr and Lanier (1981) reported a total of 42 species of macrofauna representing seven phyla associated with oyster reefs in Georgia, but this is only a fraction of the 303 species listed by Wells (1961) in a monograph on subtidal and intertidal oyster beds.

Nekton

This group of organisms includes those that can actively swim independently of current movements. In coastal Louisiana, it comprises numerous fishes; invertebrates such as squids, portunid crabs, and penaeid shrimps; and marine mammals such as bottle-nosed dolphins. Most of these species are a part of the planktonic community for the early stages of their life cycles (Thompson and Forman 1987). Numerous studies (Sabins and Truesdale 1974; Guillory 1982; Herke et al. 1987; Thompson and Forman 1987; Perret et al. 1993; Rogers et al. 1993), as well as a number of excellent theses and dissertations, have documented the composition of nektonic species in Louisiana's coastal estuaries and the major factors controlling their distribution.


Courtesy USGS, National Wetlands Research Center

Fig. 35. Eastern oysters are a commercially important species and are being adversely affected by encroaching saltwater and pollution.

A total of 237 species of fish and nektonic invertebrates has been recorded from the Louisiana deltaic plain alone. The estuaries in the inactive delta tend to support similar fish communities. The active deltas of the Mississippi and Atchafalaya rivers are usually fresh water and support a diverse nektonic fauna dominated by freshwater species. During periods of low river flows, however, these deltas have a strong estuarine–marine component. Thompson and Forman (1987) divided coastal nekton into four groups: freshwater, estuarine, estuarine–marine, and marine. Although marine species dominate the inshore fish community, migratory estuarine–marine species (Deegan and Thompson 1985) are by far the most numerically abundant group in the system.

The ten most abundant fish species caught in trawls are bay anchovy, Atlantic croaker, Atlantic bumper, Gulf menhaden, spot, hardhead catfish, sand seatrout, Atlantic threadfin, striped anchovy, and gafftopsail catfish. All but three of these species (Atlantic bumper, striped anchovy, and Atlantic threadfin) have estuarine–marine life histories and a strong affinity for high-salinity estuarine areas. Table 10 compares the relative abundance and biomass contributions of the dominant fish species of the upper, low-salinity (less than 8 parts per thousand) estuary with the lower reaches of the high-salinity (10–27 parts per thousand) estuary. Bay anchovy is the dominant species in terms of both numbers and biomass almost across the entire estuary. In low-salinity zones, catfishes and alligator gar, which are seldom found in high-salinity zones, can make up much of the biomass (Conner and Day 1987).

Among the most common trawl-caught species are a number of estuarine–marine invertebrates, including brown shrimp and white shrimp (Figs. 36 and 37), which seasonally rank in abundance and biomass with the top ten nektonic fish species. Lesser amounts of pink shrimp and seabob shrimp are also harvested commercially. The latter species is apparently not estuarine-dependent, although it is frequently caught in the lower estuary. Brown shrimp and white shrimp exhibit the marsh–estuarine life cycle typical of most commercial invertebrates and fishes on the Gulf of Mexico coast. Brown shrimp spawn in the Gulf of Mexico, and their larvae move into the lower estuaries in February and March, where the postlarval and juvenile stages develop in shallow ponds and streams deep in the marsh. The young adults emigrate to deeper estuarine waters and the nearshore Gulf of Mexico in early to midsummer (Fig. 38); their emigration is keyed to lunar tides (Blackmon 1974). White shrimp have a similar migration pattern, but inshore recruitment occurs in June through August, and mass emigration is keyed to the passage of cold fronts in late fall and early winter.

Blue crab, the most important commercial crab species in the Gulf of Mexico (Fig. 39), is found from the offshore marine waters to the most inland Louisiana freshwater marshes. In late summer, egg-bearing females emigrate offshore to spawn. The larvae follow the inshore migration pattern of the estuarine–marine fish. The mature males generally stay in fresh water or near freshwater areas for the remainder of their life cycle, unlike the males of a related (noncommercial) species, the lesser blue crab, which emigrate offshore with the females where both complete their adult life cycles on the Continental Shelf. The brief squid is the only nektonic mollusk that occurs in any numbers within the estuaries. It is a true estuarine species, and there is evidence of egg deposition by squids within the estuary (Roper et al. 1984).

The freshwater fish assemblage in estuarine Louisiana is poorly studied (Condrey et al. 1995). A modest commercial fishery harvests blue and channel catfishes. Bluegill, black crappie, white crappie, and largemouth bass are caught by sport-fishers in freshwater lakes. In the freshwater areas of the active deltas, freshwater and saltwater fishes are often found together.

Resident estuarine fishes include minnows, killifishes, silversides, and gobies that spend their entire lives in the estuary. Information on these species is relatively poor; since they

Table 10. Abundance and biomass of fish assemblages[a] of the upper and lower Barataria basin (Conner and Day 1987).

Species	Upper bay[b]		Lower bay[c]	
	Number	Weight (kilograms)[d]	Number	Weight (kilograms)[d]
Alligator gar	25	255.8	3	20.6
Atlantic croaker	12,686	64.1	5,300	22.9
Bay anchovy	557,994	303.8	52,633	34.2
Blue catfish	3,498	80.3	0	0
Channel catfish	27,871	404.5	0	0
Gulf menhaden	8,862	40	14,782	23
Hardhead catfish	414	Trace	2,169	52.5
Inland silverside	2,290	Trace	836	Trace
Rough silverside	1,563	Trace	4,514	20.8
Silver perch	10	Trace	899	31.2
Spot	245	Trace	5,786	20.4
Striped mullet	277	Trace	181	18.4

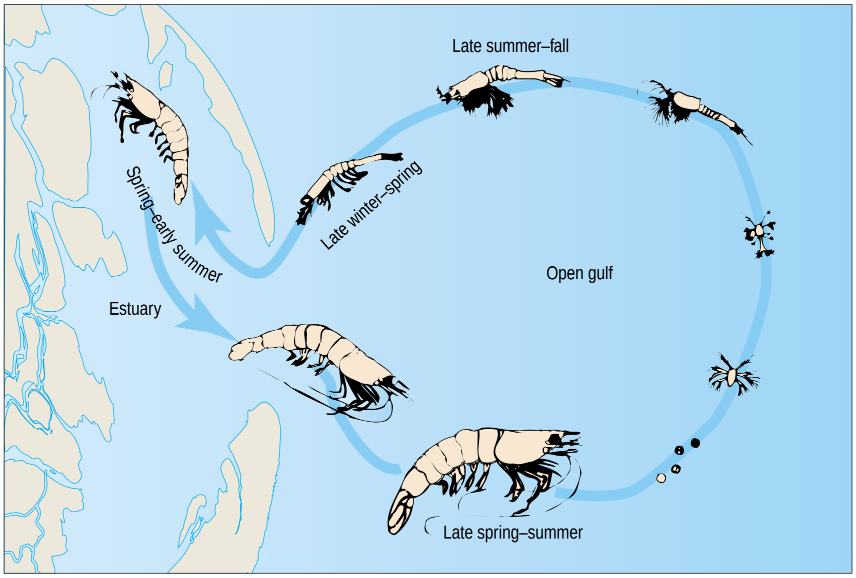
[a] All sampling gears combined.
[b] Chambers 1980 (study done in 1978).
[c] Wagner 1973 (study done in 1971–1972).
[d] Weight is relative but comparable among samples.


Courtesy I. K. Workman, National Marine Fisheries Service

Fig. 36. In coastal Louisiana and in the southeastern U.S., the by-catch of the shrimp fishery as pictured here includes young and adults of various species, as well as invertebrates and other crustaceans such as blue crab.


Courtesy USGS, National Wetlands Research Center

Fig. 37. Commercial shrimp catch.



Courtesy USGS, National Wetlands Research Center

Fig. 38. The life cycle of brown shrimp illustrates the typical cycle of an estuarine-dependent fish or shellfish species.

Courtesy USGS, National Wetlands Research Center

Fig. 39. Commercial catch of blue crabs.

concentrate in shallow marsh ponds and along marsh edges, they are caught relatively infrequently in trawls. Studies using seines have documented that gulf killifish and longnose killifish are among the most abundant estuarine fish species, whereas bayou killifish and the marsh killifish are much less abundant (Thompson 1988). In small saltwater marsh ponds, sheepshead minnow, tidewater silversides, and sailfin molly are common, as well as the killifishes (Ruebsamen 1972).

The most abundant group of coastal Louisiana finfish, which includes most of the commercially and recreationally important finfish on the northern gulf coast, have estuarine–marine life histories similar to the brown and white shrimps (Condrey et al. 1995; Figs. 38, 40, and 41). They are typically euryhaline, and small juveniles often migrate many kilometers up the estuaries. The timing and routes of migration lead to a complex pattern of habitat use in both time and space (Figs. 40 and 41). Most of the commercial catch occurs in the nearshore waters of the Gulf of Mexico, which are the inshore marsh areas that serve as nurseries for the juveniles. The unintended catch of fishes from shrimp trawling is substantial. Studies show a 75% reduction in demersal biomass (that is, the total weight of all species living near the bottom of the water column) occurring within the estuary shortly after the opening of the shrimp-trawling season. Most of these by-catch fish (Fig. 36) are discarded and die, and most are young individuals of the migratory estuarine–marine fishes, including Atlantic croaker, spot, sand seatrout, gulf menhaden, catfishes, and bay anchovy. Many rarer species are taken in smaller numbers. Without the incorporation of turtle excluding devices, trawls also catch endangered sea turtles often enough to threaten their survival (Condrey et al. 1995).

The estuarine-dependent Louisiana fishery is an $875 million (dockside) industry. Shrimp generate the largest share of this income, followed by oysters, menhaden, blue crabs, and striped mullet (Louisiana Coastal Wetlands Conservation and Restoration Task Force 1993; Table 11). The menhaden purse-seine fishery handles the largest volume of catch, but the low price per unit is reflected in the total annual value of about $87 million. In addition, there are important fisheries for estuarine–marine spotted seatrout, black drum, red drum, and southern flounder. Commercial freshwater species include blue catfish, channel catfish, flathead catfish, yellow bullhead, bowfin, carps, gars, and buffaloes. For sport-fishers, primary game species include largemouth bass, yellow bass, black crappie, bluegill, spotted sunfish, redear sunfish, warmouth, and several catfish species in freshwater areas; and seatrouts, red drum, southern flounder, sheepshead, gafftopsail catfish, and Atlantic croaker in estuarine areas.

Most of the commercial and game species are fairly short-lived and are harvested in the first or second year of life. Because of the high recruitment rate, population data do not show any trends that suggest overfishing, and these species are assumed to be stable. Red drum and black drum are long-lived, a characteristic that has led to management strategies to ensure spawning by multiple year-classes (Condrey et al. 1995).

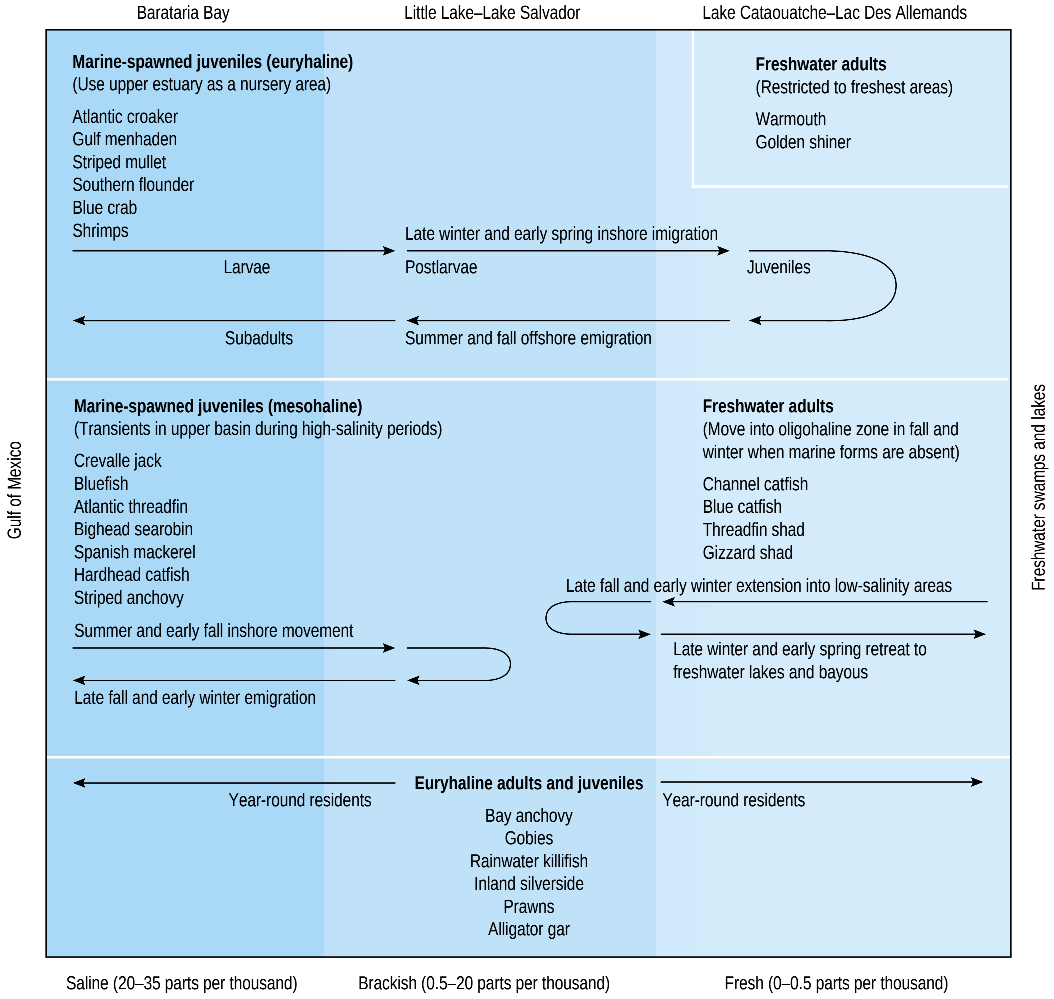


Fig. 40. Patterns of estuarine use by nektonic organisms in the Barataria estuary, Louisiana (modified from Chambers 1980).

Table 11. Harvest and value of the estuarine-dependent commercial fisheries of the Gulf of Mexico and Louisiana coastal area (Louisiana Coastal Wetlands Conservation and Restoration Task Force 1993).

Species	1983–1990 Average corrected landing[a,b] (metric tons)	1992 Gross dockside value[c] (dollars)
Blue crab	56,060	71,618,978
Shrimps	224,779	1,074,386,530
Oysters	18,685	107,187,451
Menhaden	789,708	86,972,225
Atlantic croaker	140	178,282
Black drum	3,193	3,094,473
Red drum	1,589	4,026,099
Catfishes	2,613	3,452,935
Flounders	669	1,532,494
Northern kingfish	304	247,558
Striped mullet	11,355	10,254,730
Sea catfish	62	28,452
Spotted seatrout	1,228	3,137,112
White seatrout	235	278,888
Sheepshead	1,596	808,300
Spot	124	79,143
Finfish	3,075	1,557,835
Total Gulf of Mexico	1,115,415	1,368,841,485
Louisiana coastal area[d]	713,839	876,058,551

[a] Source: U.S. Department of Commerce, National Marine Fisheries Service, published and unpublished data for 1983–1990.

[b] Correction factors based on information provided by the Louisiana Department of Wildlife and Fisheries, Baton Rouge.

[c] Based on 1992 normalized prices and the 1983–1990 average corrected landings.

[d] Gulf of Mexico landings allocated to the Louisiana coastal area are based on the relative abundance of estuarine marsh habitat.

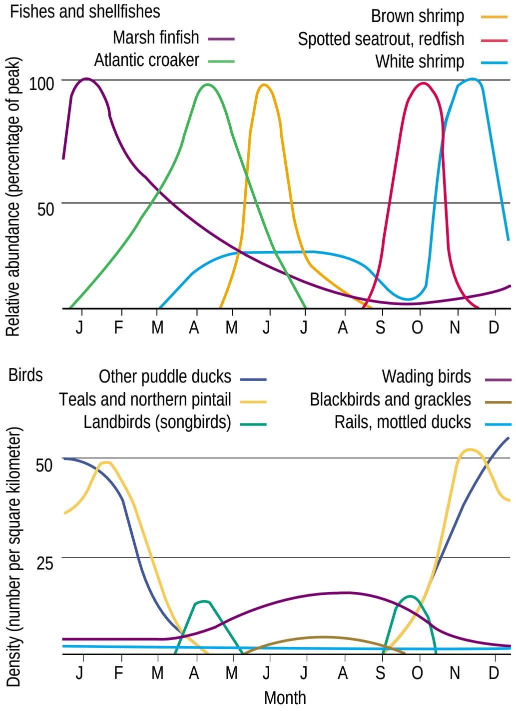


Fig. 41. Seasonal use of wetlands by migratory birds, shellfishes, and fishes (Gosselink 1984).

Status and Trends of Sensitive and Introduced Populations and Groups

Birds

More than 400 species of birds are known to occur in Louisiana, most of them in the coastal region. Coastal Louisiana provides habitat for numerous species of waterfowl, colonial-nesting birds, and other resident and migratory birds. Important nonwaterfowl game species include American coot, clapper rail, king rail, sora, common moorhen, purple gallinule, American woodcock, and common snipe (Michot 1984). Hundreds of nongame species inhabit the coastal marshes, including the wood stork, American white pelican, pied-billed grebe, magnificent frigatebird, black-necked stilt, American avocet, killdeer, black-bellied plover, willet, and various sandpipers, gulls, and terns (Lowery 1974a). The coastal marshes are also of primary importance to large numbers of waterfowl, especially in winter.

Birds and Barrier Islands

Barrier islands and cheniers provide nesting and resting sites for many animals and birds that forage in the marsh. These habitats are particularly important for seabirds, wading birds, and Neotropical migrants. Egg and feather collectors nearly eradicated the abundant bird populations found by early French explorers. Fortunately, these birds responded to conservation measures enacted in the early 1900's. Between 1940 and 1960, however, many seabird populations were reduced by toxic chemicals in coastal waters. The local extinction of the eastern brown pelican is the most dramatic example of the deleterious effects of the pesticide DDT in the food chain. Eastern brown pelicans were reintroduced from Florida and have reestablished a number of colonies (see Endangered Species section in this chapter).

The Louisiana coast has a comparative abundance of seabirds that nest on sandbars, barrier beaches, and marsh islands at the edge of large bays. Most are colonial nesters (for example, pelicans, gulls, terns, and skimmers) which feed on small fishes, primarily within the shallow bays and the near coastal waters. Twenty-eight species of seabirds and wading birds have established nesting colonies in the Louisiana coastal zone (Portnoy 1977; Keller et al. 1984). Louisiana provides the most important breeding area for many species, including Sandwich terns (77% of the United States breeding population), black skimmers (44%), and Forster's tern (52%). Keller et al. (1984) found 188 active bird colonies in coastal Louisiana. In a time-series comparison of colonial bird sites, almost half of the colonies moved between years from one location to another. Because of the rapid loss of barrier islands, nesting habitat is at a premium, and habitat availability is probably the major long-term threat to these populations. Human disturbance of nesting sites is also a serious problem on the accessible islands and headlands (Condrey et al. 1995).

Pelicans nest on the barrier islands, but wading birds—egrets (Fig. 42), herons, and ibises—more often nest inland of the barrier beaches in mangroves, wax myrtle thickets, and other forested areas. These birds are mostly carnivorous, catching frogs, small fishes, snakes, crayfishes, and a wide assortment of worms and insects. Wading birds prefer freshwater and brackish marshes to saline marshes but are common across the entire coast.

Barrier islands and chenier ridges are important to Neotropical migrant songbirds (Fig. 43) for slightly different reasons. Many species use the barrier and ridge habitats irregularly or accidentally during their migrations. Some breed on the Louisiana coast but migrate to Central and South America during the winter. A few breed in the northeastern United States and winter on the Louisiana coast, but most breed in the Northeast and winter in Central and South America. Thus, they must either cross or circumvent a broad ecological barrier, the Gulf of Mexico, during the spring and fall of each year. The majority of migrants fly nonstop for more than 1,000 kilometers to cross the Gulf of

Courtesy USGS, National Wetlands Research Center

Fig. 42. The snowy egret is one species of wading bird that nests in coastal Louisiana in mangroves, wax myrtle thickets, and other forested areas. These birds were almost extirpated from Louisiana in the early 1900's when they were killed for the use of their feathers in the millinery trade, but snowy egrets have recovered and are now common in the state's coastal wetlands.

Courtesy USGS, National Wetlands Research Center

Fig. 43. Prothonotary warbler, a Neotropical migrant that nests in the baldcypress swamps of coastal Louisiana, is one of at least 63 migratory bird species that regularly use woodlands along the Louisiana coast to replenish their energy reserves either before or immediately after crossing the Gulf of Mexico to the Yucatan Peninsula or South America.

Mexico each spring. During the fall, most migrants fly along the coast through Texas and around the gulf. Birds often concentrate in habitats adjacent to ecological barriers during migration, and the geographic position of the Chenier Plain makes cheniers and barrier islands important stopover habitats for enroute migrants. At least 63 species of migratory birds regularly use these wooded habitats to replenish energy reserves necessary to successfully complete their migration before, or immediately after, crossing the Gulf of Mexico. During spring migration, birds usually leave Central and South America at night, making landfall along the northern gulf coast the next midday.

In spite of the difficulty in crossing the Gulf of Mexico, many spring trans-gulf migrants continue flying inland until they reach the more contiguous tracts of forest north of the Chenier Plain. Gauthreaux (1971) found that during fair weather, such as southerly winds and clear skies, approximately 10% of in-transit spring migrants land in coastal woodlands. Under poor conditions of northerly winds or precipitation, however, as many as 80% of the individuals on a trans-gulf flight make landfall in the cheniers and other coastal woodlands, which temporarily support tremendous densities of land birds (Gosselink et al. 1979a,b,c; Condrey et al. 1995; Barrow et al. 1997).

When autumn migrants fly southwesterly around the Gulf of Mexico, the coastal cheniers are important habitat corridors and staging areas for a variety of passerine birds, both those that nest in coastal Louisiana and those that breed farther north, including 180 species of passerines and a few species of cuckoos, swifts, hummingbirds, and goatsuckers. The belted kingfisher and several species of woodpeckers are also residents of the coastal area (Lowery 1974a; Michot 1984).

The Nearctic–Neotropical migratory bird system is complex. Neotropical migrants require a variety of habitats across continents, presenting multiple biological and political challenges. Although increasing international attention is focused on the deforestation of tropical forests and fragmentation of temperate forests, little attention has been given to enroute habitats. Stopover habitats, such as coastal forests near ecological barriers, are undergoing dramatic changes that may threaten Neotropical migrants (Barrow et al. 1997). At present, about one-half of the human population in North America resides in coastal counties (U.S. Department of Commerce 1990); from 1960 to 2010, the coastal population will have grown from 80 million to more than 127 million people, an increase of almost 60% (U.S. Bureau of the Census 1995). As a result, human development will place considerable pressure on remaining coastal habitats. The enroute habitats where migrants tend to concentrate need further quantification, and appropriate conservation and management measures are required.

Waterfowl

Waterfowl are an important commercial resource for the recreational hunting industry: the value of waterfowl hunting to the state of Louisiana is estimated to exceed $10 million annually (Louisiana Coastal Wetlands Conservation and Restoration Task Force 1993). From an ecological point of view, though, waterfowl dramatically illustrate the coupling of ecosystems in the Louisiana coastal region. Although many organisms already discussed move from one ecosystem to another within the coastal zone—or in the case of nektonic fishes, from coastal estuaries to the Gulf of Mexico—waterfowl and other migratory birds link the Louisiana coast with the northern U.S. and Canadian wetlands and with Central American wetlands to the south.

Besides the intrinsic interest in the evolution of waterfowl's complex migratory patterns from an ecological standpoint, the conservation of waterfowl populations also presents major management challenges. The migratory patterns of waterfowl are well studied and understood (see, for example, Bellrose 1980). Generally, waterfowl species nest in northern U.S. or Canadian prairie pothole wetlands in spring and early summer (see chapter on Grasslands). These pothole wetlands are particularly important breeding grounds for ducks. Wetlands as far north as the arctic tundra are used by geese. With the approach of winter, waterfowl migrate along well-established flyways through the heart of the continent to coastal wetlands in the southern United States, where most spend the winter. A few species, such as northern pintail and teals, continue south to Central America. With the return of spring, the flocks begin the return trip to their nesting grounds (Fig. 44). Although waterfowl winter in coastal wetlands from the south Atlantic coast (Smith and Odum 1981) to Texas and California, Louisiana is at the southern extreme of the major duck and goose migration corridors.

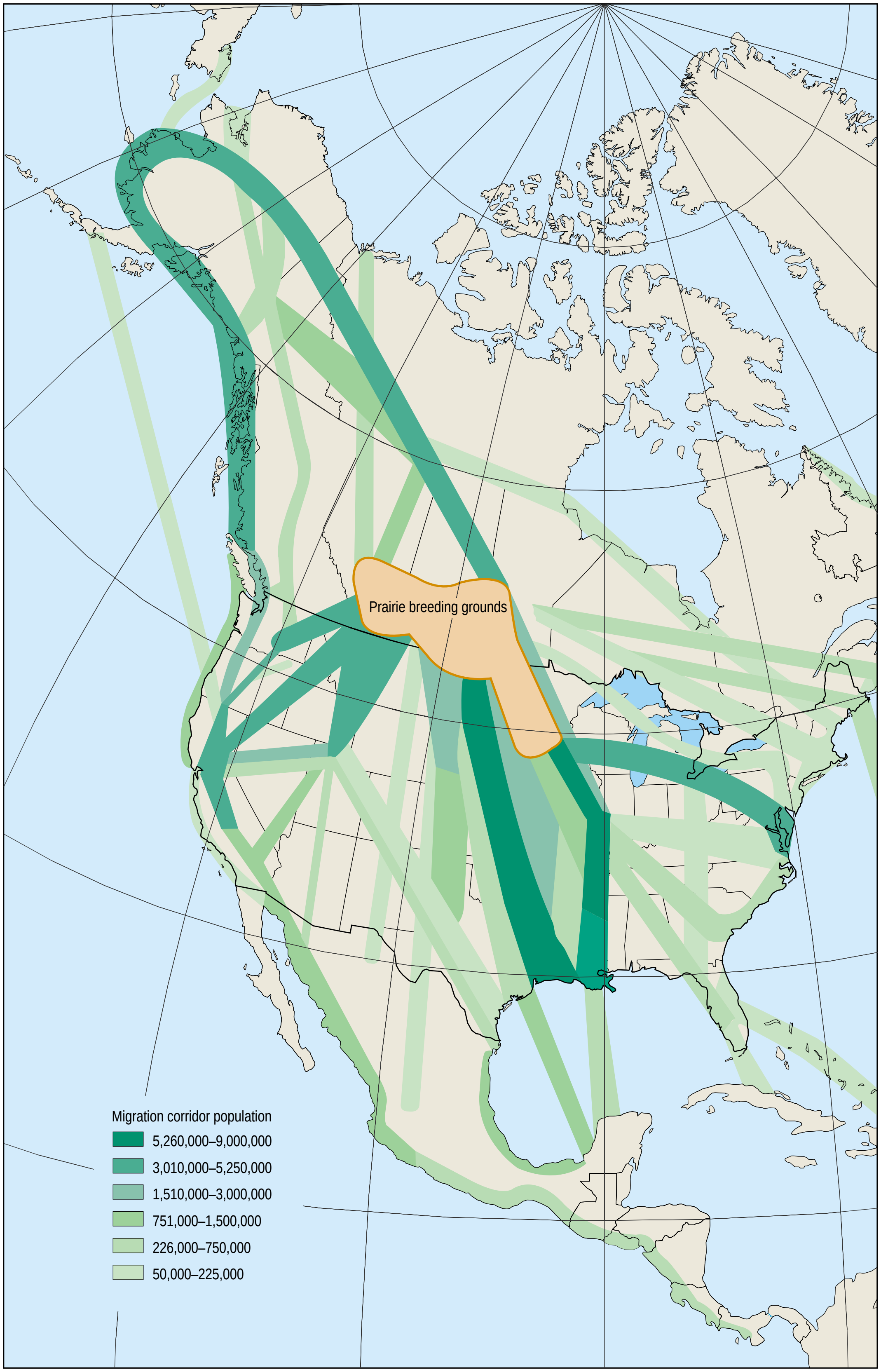


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Fig. 44. Major duck migration corridors to Gulf of Mexico coastal marshes (Bellrose 1980).

Population data gathered from nesting surveys by the U.S. Fish and Wildlife Service and the Canadian Wildlife Service (1994) provide the most reliable estimates of population trends, whereas Louisiana data reflect local population distributions. Ducks and geese are highly opportunistic and will seek superior winter feeding grounds.

Continental populations are influenced by nesting success and recruitment and by mortality, including hunting mortality, throughout the ranges of waterfowl. Population densities of various waterfowl species in Louisiana are influenced by habitat conditions both within and outside the state, winter mortality, local rainfall and weather patterns, and outbreaks of contagious and infectious diseases (Condrey et al. 1995; see box on Duck Plague in Grasslands chapter). In addition, the *short-stopping* of ducks and geese also affects the population densities of some species. Short-stopping occurs when migratory birds "stop short" of their normal wintering grounds because of increased winter food supplies or habitat along their migratory routes.

During the late 1970's through the early 1990's, many waterfowl populations declined precipitously (Michot 1996) because of a severe drought on their breeding grounds. Populations of most species have rebounded in the last few years, primarily in response to wet years and to favorable wetland and upland habitat conditions on the prairies to the far north.

Table 12 and Figure 45 give population estimates for the state's most abundant duck and geese species. Dabbling ducks and geese feed in shallow ponds and flooded freshwater and brackish marshes, although they also frequent adjacent rice fields and other agricultural areas. The birds eat seeds, leaves, shoots, rhizomes, and tubers of emergent marsh plants and submerged aquatic plants; they supplement this diet with insects, mollusks, and other invertebrates. The most abundant dabbling ducks in the Louisiana coastal marshes are gadwall, green-winged teal, mallard, and northern pintail (Fig. 45). The mottled duck, also an important winter species, is one of the three duck species that nest in Louisiana. Mottled duck numbers have increased slightly over the last 25 years in southeast Louisiana (Condrey et al. 1995), but they showed no significant trend over the entire Louisiana coast from 1969 to 1994 (Michot 1996). No other duck population changed significantly during that period, either for all of coastal Louisiana (Michot 1996) or for southeastern Louisiana (Condrey et al. 1995).

Diving ducks feed in large, shallow freshwater lakes and brackish bays, and some species rest offshore in the Gulf of Mexico. Their diverse diet includes emergent and submerged plants, and animals such as fishes, clams, snails,

Table 12. Estimated numbers (mean and standard deviation, in thousands) of ducks and geese in January, 1969–1994, for the Louisiana coastal area, for the U.S. midwinter population, and the percentage of the U.S. midwinter population represented by the Louisiana coastal area population (Michot 1996).

Species or species group	Louisiana coastal area[a]			U.S. total[b]			Percent Louisiana coastal area[c]		
	Number of years	Mean	Standard deviation	Number of years	Mean	Standard deviation	Number of years	Mean	Standard deviation
Dabbling ducks									
Mallard	25	387	230	26	5,911	1,456	25	7	4
Mottled duck	25	67	32	26	104	37	25	63	16
Gadwall	25	734	261	26	1,017	302	25	70	10
American wigeon	25	201	125	26	1,095	306	25	18	8
Green-winged teal	25	617	268	26	1,450	399	25	42	14
Blue-winged teal	25	96	86	26	121	95	25	72	16
Shoveler	25	156	77	26	712	182	25	22	11
Northern pintail	25	372	168	26	3,528	1,538	25	12	7
Total dabblers[d]	25	2,631	754	26	13,928	3,542	25	19	5
Diving ducks									
Redhead	22	15	6	26	389	128	22	4	2
Canvasback	25	21	21	26	269	52	25	7	7
Scaups	25	413	348	26	1,187	337	25	32	25
Ring-necked ducks	24	61	53	26	240	120	24	23	10
Total divers[d]	25	506	355	26	2,085	331	25	23	15
Total ducks[d]	25	3,137	919	26	16,023	3,646	25	19	5
Geese									
Lesser snow	25	345	55	26	1,747	524	25	22	9
Greater white-fronted	25	56	10	26	271	109	25	22	7
Total geese[d]	25	401	48	26	2,018	591	25	21	7
Total waterfowl[c]	24	3,490	913	26	18,041	3,290	24	19	4

[a] Includes all areas south of U.S. Highway 90. Estimates provided by the Louisiana Department of Wildlife and Fisheries, Baton Rouge (all ducks except redhead), and the U.S. Fish and Wildlife Service (redheads and all geese).

[b] U.S. Midwinter Survey data from the 48 conterminous states, all four flyways combined, from the U.S. Fish and Wildlife Service.

[c] For each year (1969–1994), the estimated number of birds for each species for coastal Louisiana was divided by the midwinter estimate (number of birds) for the United States to obtain an estimate of the percentage of the U.S. wintering population that winters in coastal Louisiana. These percentages were then summed over all years and divided by the number of years to obtain a mean percentage for each species over the period of analysis; that mean with its standard deviation is reported in this table. The value for each mean, therefore, differs from a value obtained by dividing the two means presented to the left of it in this table.

[d] Total dabblers, total divers, total ducks, total geese, and total waterfowl include only the species listed in this table; each total presented is a mean of the values for the period of analysis (1969–1994), and thus does not represent a sum of the values presented above it in this table.

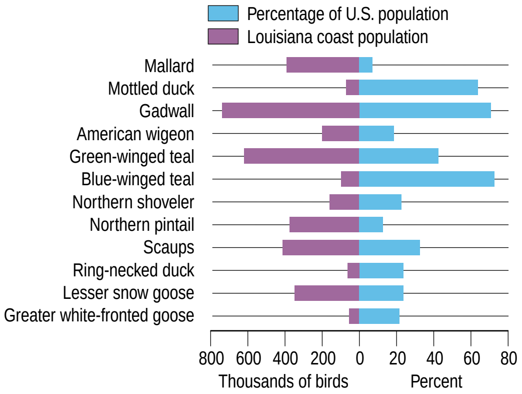

Fig. 45. Number of individuals (1969–1994 mean) of predominant waterfowl species in coastal Louisiana, and for each, the mean percentage of the U.S. wintering population represented by the Louisiana coastal population (Michot 1996).

Courtesy USGS, National Wetlands Research Center

Fig. 46. Lesser scaups. About 25% of the U.S. winter population of scaups are found in coastal Louisiana, where numbers average about a half-million and in some years may approach a million. Scaups feed primarily on the estuarine invertebrates produced in coastal wetlands.

and crabs. Scaups (Fig. 46) are the most numerous diving ducks, followed by ring-necked ducks, canvasbacks, and redheads (Table 12). The wood duck, like the mottled duck, nests in coastal Louisiana and is also present during the winter. About 40% of the wood ducks shot in Louisiana are residents, and the rest are migrants (Bellrose and Holm 1994). Wood ducks nest in tree cavities in coastal forested wetlands (wooded swamp and bottomland hardwoods) and feed primarily on seeds and nuts, although young wood ducks require some animal food, mostly insects.

Enormous numbers of geese occur in coastal Louisiana, primarily in the Chenier Plain, and to a lesser extent in the active delta of the Mississippi River. The abundance of geese in the Chenier Plain region is probably related to the proximity of the coastal wetlands to extensive rice fields and possibly to aggressive management of wetlands for waterfowl in state and national wildlife refuges there. The lesser snow goose is the most abundant goose wintering in Louisiana (Table 12), and white-fronted geese occur in relatively large numbers as well. The Canada goose was formerly abundant in coastal Louisiana, but now only a few thousand winter there while the rest of the population winters farther north. Both snow geese and white-fronted geese increased in the U.S. midwinter population from 1969 to 1994; however, snow geese in coastal Louisiana decreased over that period, whereas white-fronted geese numbers paralleled the national trend (Michot 1996).

Mammals

Fifty-eight species of land mammals are residents of Louisiana (Lowery 1974b), many of them in the coastal marshes. Important game mammals include white-tailed deer, eastern cottontail, swamp rabbit, gray squirrel, fox squirrel, and raccoon; furbearers include muskrat, nutria, raccoon, mink, Virginia opossum, striped skunk, bobcat, beaver, and coyote. Many other land mammals are also found there, including insectivores, bats, rodents, and the nine-banded armadillo. Whales and dolphins inhabit the gulf waters adjacent to the coast, and some, particularly dolphins, enter the estuaries (Michot 1984).

Amphibians and Reptiles

Amphibians are generally found in the freshwater wetlands of the coastal zone. The bullfrog and pig frog are important for commercial and recreational hunting. Other amphibians include lesser siren, three-toed amphiuma, Gulf Coast toad, Fowler’s toad, green treefrog, spring peeper, cricket frog, eastern narrow-mouthed toad, and bronze frog.

The commercially important reptiles are found in many freshwater and estuarine habitats; they include the American alligator, common snapping turtle, alligator snapping turtle, smooth softshell, spiny softshell, and diamondback terrapin. Other noncommercial reptiles common in freshwater habitats include the red-eared turtle, painted turtle, common musk turtle, Mississippi mud turtle, green anole, broad-headed skink, diamondback water snake, broad-banded water snake, green water snake, gulf salt marsh snake, western ribbon snake, speckled kingsnake, and western cottonmouth. The gulf salt marsh snake and diamondback terrapin are also common in brackish to saline marshes (Michot 1984).

Introduced Species

Alligatorweed

Alligatorweed is an introduced nonindigenous plant that has become a major pest. It grows in shallow marsh ponds and on the edges of bayous and sheltered lakes, as well as on the wetland surface. Chabreck (1972) recorded it as having 5% cover in freshwater marshes and 2.5% in intermediate-salinity marshes. In some freshwater marshes, it is codominant with sensitive jointweed. The alligatorweed flea beetle was introduced as a means of biologically controlling the plant and has apparently succeeded in checking its expansion (Gosselink et al. 1979a,b,c).

Water Hyacinth

Water hyacinth is a perennial, aquatic vascular plant that forms floating mats and has a wide distribution in the tropics. It is probably native to Brazil but has spread throughout South America and is now a serious pest in the southern United States. The first authentic account of its introduction is from the Cotton Centennial Exposition at New Orleans in 1884. The plant was apparently introduced as a nonindigenous species "which readily made friends on account of its beautiful bloom and the little difficulty . . . in growing it" (Klorer 1909). The plants were cultivated in ponds at homes around New Orleans and eventually escaped from cultivation. It is an important pest in Florida and has been reported from all the southeastern coastal states as far north as Virginia.

In Louisiana, water hyacinth invades freshwater areas of the coast, including the lower reaches of rivers and freshwater marshes (Penfound and Earle 1948). Its mats become so thick that they obstruct navigation and impede drainage. In the late 1940's damage was as high as $15 million a year (Penfound and Earle 1948). The federal government still spends millions of dollars each year to keep canals and rivers navigable. Fortunately, this tropical plant has little resistance to cold temperatures, and its population is periodically reduced by winter frosts. Mats of water hyacinth may choke out native submerged aquatic plants and can shade and kill marsh plants when high water carries mats into the marsh. The species has been blamed for the death of large areas of floating marshes during the extreme floods of the early 1970's, although this effect has not been verified.

Nutria

O'Neil (1949) discussed the damage done by muskrats in coastal marshes. A related rodent, nutria, was introduced into Louisiana from South America several times during the 1930's. Whether it escaped or was released for fur production is not clear, but the early escaped populations apparently did not become established. However, in 1939, 12 pairs owned by the McIlhenny family on Avery Island (a salt dome surrounded by marsh) escaped, another 150 animals were released during a 1940 hurricane, and landowners began releasing breeding stock into their marshes for fur production and weed control (Lowery 1974b). Two hundred and fifty nutria were transplanted to the Mississippi River delta in 1951, and the population increased so rapidly that the marsh in the delta was completely torn apart by 1957. By 1959 the nutria population in Louisiana was more than 20 million animals (Lowery 1974b). During the 1970's and early 1980's, the population was controlled by trapping, but the demise of the wild fur industry in the United States in the past decade has led to a resurgence of nutrias.

O'Neil (1949) described muskrat *eat-outs* in the marsh that took years to recover. Very little documentation of nutria damage has been available until recently, when a large part of the inactive delta was surveyed. Scientists found widespread damage over an estimated 200 square kilometers of marsh in the Terrebonne and Barataria estuaries alone (Linscombe and Kinler, unpublished report). Effects of nutria on coastal wetlands have been dramatic. Before the introduction of nutria, muskrats were the dominant mammal in freshwater marshes. They are now found primarily in brackish marshes, displaced by the larger and more aggressive nutria (Lowery 1974b). Evers et al. (1988) showed that nutria grazing was a major factor leading to denuding of intertidal flats in the Atchafalaya delta. Linscombe and Kinler (unpublished report) stated that nutria grazing is most destructive in freshwater floating marshes, and there is some evidence that the localized rapid degradation and disappearance of these marshes result primarily from grazing. Nutria are also responsible for the failure of baldcypress regrowth in many coastal baldcypress swamps. Conner and Toliver (1990) reported that nearly all naturally germinating or planted baldcypress seedlings, even if protected with plastic sleeves, were destroyed by nutria in places where their populations were dense.

Endangered and Threatened Species

Many endangered, threatened, and rare taxa in the United States depend on wetlands. Of the 188 animals federally designated in these

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categories in 1988, 94 (50%) were associated with wetlands. Of these, 17 were bird species or subspecies. Twenty eight percent of the plants listed were wetland-dependent. Of the estimated 2,500 plants still in need of protection, about 700 may be associated with wetlands (Niering 1988). A publication of the Louisiana Natural Heritage Program (Lester 1988) lists 103 plants and 64 animals of special concern in the Louisiana coastal zone. Although most of these species occur in other states and may have healthy populations elsewhere, in Louisiana they are now rare. Some species, though, have low numbers throughout their range, or even lower populations at the edge of their natural range, but for many species there are local factors that limit their distribution. The highest-profile species are those that are federally listed (Table 13). The following brief descriptions of endangered and threatened animals were compiled from information in Gosselink and Hebrard (1979), Lester (1988), Condrey et al. (1995), Louisiana Department of Wildlife and Fisheries (1995), and U.S. Fish and Wildlife Service (1997), unless otherwise indicated.

Mammals

Although the Louisiana black bear was widely distributed before European settlement, probably only 200–300 remain in Louisiana, and fewer than half of these occur in the coastal zone. Black bears in east Texas, Louisiana, and the southern half of Mississippi are recognized as a distinct subspecies and are listed as threatened under the Endangered Species Act (U.S. Fish and Wildlife Service 1997). Heavy hunting pressure before 1930 and habitat changes—especially the widespread conversion of forests in the Lower Mississippi River valley to row crop agriculture—were the main causes of the bear's decline. Coastal bears extensively use mixed wetland forests and upland habitats on salt domes and canal spoil areas, but bears also occur in wet scrublands, baldcypress swamps, and sugarcane fields. Fragmentation and isolation of wetland forest tracts by development and agriculture make maintenance of a viable population of black bears within the coastal zone of Louisiana difficult.

The red wolf was once found in the Mississippi River valley from Illinois to the Gulf of Mexico coast and from Texas to Florida. Its natural range has shrunk to the marshes and coastal prairies of parts of southwestern Louisiana and southeastern Texas; whether true red wolves remain is uncertain because of their hybridization with coyotes, which have moved into the wolf's range as forests have been cleared. Red wolf populations have declined because of heavy hunting and trapping pressure combined with encroaching agricultural and industrial use of wolf habitat. The species is federally listed as endangered (U.S. Fish and Wildlife Service 1997). By 1980, after a large trapping effort that recovered only 14 pure red wolves, the U.S. Fish and Wildlife Service declared the species extinct in the wild. A coyote-like canid has become established in many of the coastal wetlands once occupied by red wolves and may serve the same ecological function.

Several species of whales frequent Louisiana's coastal waters and are sometimes stranded in its bays or on its barrier beaches. Sightings of West Indian manatee in Louisiana have increased in recent years with about 30 reported sightings from 1975 to 1995; during warmer months individuals disperse from Florida as far west as Louisiana (Louisiana Department of Wildlife and Fisheries 1995).

There are sporadic unconfirmed sightings of the Florida panther, which once ranged across the entire Southeast, but the few animals that remain are probably all in Florida.

Birds

The eastern brown pelican, a large, dark gray-brown waterbird with distinctive white about the head and neck of adults, nests in colonies mostly on small coastal islands (Fig. 47). This species was extirpated from the Louisiana coast during the 1960's, primarily because of thin-shelled eggs and other reproductive failures linked to ingestion of pesticide (chlorinated hydrocarbon) residues in food fishes. A restoration project that was sponsored jointly between the Louisiana Department of Wildlife and Fisheries and the Florida Game and Freshwater Fish Commission introduced 1,276 pelicans at three release sites between 1968 and 1980. In 1995 the Louisiana Department of Wildlife and Fisheries (1996) conservatively estimated that there were 10,000 eastern brown pelican nests and that an estimated 16,000 young were fledged.

The piping plover is endangered throughout its northern U.S. breeding range and threatened along its gulf coast wintering range. Piping plovers are an uncommon to rare winter resident, seen most often on the Louisiana barrier islands. The Chandeleur Islands supported from 3 to 17 birds per kilometer in an early 1991 survey, and the Isles Dernieres and Timbalier Islands supported 9 to 12 birds per kilometer, whereas mainland beaches supported only 2 to 4 birds per kilometer (R. Martin, Louisiana Department of Wildlife and Fisheries, Baton Rouge, personal communication). Wintering habitats have been lost to natural changes in barrier systems due to sea-level rise and lack of a renewable riverine supply of sand to replenish eroding islands. Coastal projects to stabilize

Table 13. Federally listed threatened and endangered vertebrates in Louisiana. T = threatened, E = endangered (Louisiana Department of Wildlife and Fisheries 1995; U.S. Fish and Wildlife Service 1997).

Species	Status
Mammals	
Blue whale	E
Fin whale	E
Humpback whale	E
Right whale	E
Sei whale	E
Sperm whale	E
Florida panther	E
Louisiana black bear	T
Red wolf	E
West Indian manatee	E
Birds	
Brown pelican	E
Peregrine falcon	E[a]
Bald eagle	T
Eskimo curlew	E
Least tern	E
Piping plover	T
Ivory-billed woodpecker	E
Red-cockaded woodpecker	E
Bachman's warbler	E
Attwater's greater prairie chicken	E
Whooping crane	E
Reptiles	
American alligator	T[b]
Gopher tortoise	T
Ringed sawback turtle	T
Green turtle	T
Kemp's ridley	E
Leatherback	E
Loggerhead	T
Hawksbill	E
Fishes	
Gulf sturgeon	T
Pallid sturgeon	E

[a] Endangered due to similarity of appearance.
[b] Threatened due to similarity of appearance.

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Courtesy USGS, National Wetlands Research Center

Fig. 47. Eastern brown pelicans. The eastern brown pelican, whose nesting was completely eliminated from Louisiana in the 1960's, was reintroduced and now has several colonies with a total of more than 10,000 nests (Louisiana Department of Wildlife and Fisheries 1996).

inlets, beaches, and shorelines; to reduce overwash; and to allow human development have probably contributed to shifts in wintering ground use and a general reduction in habitat availability.

The least tern nests on barrier beaches and is extremely vulnerable to human disturbance and to severe storms (Visser and Peterson 1994; see box on Western Snowy Plovers and California Least Terns in California chapter). Their populations vary widely from year to year, but they are a fairly common sight on the coast. Two least tern populations occur in Louisiana, and only the northern interior population is actually endangered. Most of the least terns on the coast are part of the southern population.

Populations of both the bald eagle and the peregrine falcon had declined precipitously until recent efforts to restore them. Both are birds of coastal marshes and swamps. The eagle builds nests in large trees in forested wetlands and forages in adjacent marshes. About 100 nests are known in Louisiana (Hess 1996). The peregrine falcon is a winter (nonbreeding) resident, although one nest was reported in 1942 (Lowery 1974a). Populations of both species were probably severely harmed by chlorinated hydrocarbons in the same way as the eastern brown pelican (Lowery 1974a). The arctic peregrine falcon was officially removed from the federal list of endangered species in 1994 and is no longer considered threatened. However, it remains classified as "endangered due to similarity of appearance" to the nearly identical American peregrine falcon, to protect that subspecies (U.S. Fish and Wildlife Service 1997).

The red-cockaded woodpecker and Bachman's warbler inhabit the interior of upland forests and are only peripherally associated with coastal Louisiana. Bachman's warbler was thought to be locally extinct until a recent (1988) sighting in bottomland forests upriver from the coast (R. Hamilton, Louisiana State University, personal communication). The red-cockaded woodpecker was formerly found throughout the state in mature pine forests, but fewer than 400 active colonies remain in Louisiana, most of them in the center of the state. The ivory-billed woodpecker has not been seen in Louisiana for many years, but the Cuban subspecies has recently been identified in the Caribbean.

Attwater's greater prairie chicken and the whooping crane formerly inhabited the Chenier Plain, but current populations are restricted to coastal Texas and no Louisiana sightings have occurred since the 1940's (Lowery 1974a). The eskimo curlew was last recorded in Louisiana in the late 1800's, but there were several sightings near Galveston, Texas, in the 1960's (Lowery 1974a).

Reptiles

The Kemp's ridley, a marine turtle, is federally listed as endangered. It nests primarily near Rancho Nuevo on the northeast coast of Mexico and may have the most restricted distribution of any sea turtle. Juveniles and subadults occur along the Eastern Seaboard of the United States as well as in the Gulf of Mexico, but adults are usually confined to the gulf. Along the Louisiana coast, there are occasional sightings and incidental catches of sea turtles in shrimp trawls, even within the estuaries, and sightings of Kemp's ridley are more frequent along the western coast of Louisiana. With the exception of loggerheads, which have been observed to nest on the Chandeleur Islands (Lester 1988); no other sea turtle species is currently known to nest in Louisiana.

Human-induced mortality appears to be the primary reason for the decline in numbers of Kemp's ridley. From the 1940's through the 1960's, before the nesting area was protected, large numbers of turtle eggs were removed and packed out of the area in mule trains and trucks and by horseback from the Rancho Nuevo nesting beach. The most important factor now affecting the reproductive ability of this species is the growth of the shrimp-trawling industry. The increased entrainment of turtles in trawls associated with the intense growth of the shrimp fishery from the 1940's to the present is the major cause for the population decline of the Kemp's ridley (U.S. Fish and Wildlife Service 1992). During 1994, 457 Kemp's ridleys were found stranded and dead on U.S. shores, and of these, 26% were found on the Louisiana coast (Steiner 1994). The good news is that the number of turtles nesting at Rancho Nuevo is increasing (Eckert and Eckert 1996), perhaps because of the mandatory use of turtle excluder devices on shrimp trawls.

The ringed sawback turtle, a small animal, is endemic to the Pearl River and its tributary, the Bogue Chitto. It is found in sandy or gravelly riverine beach and bar environments with a moderate current and numerous basking logs. The coastal portion of the Pearl River enters the Gulf of Mexico along the Louisiana–Mississippi boundary, but the turtle is seldom encountered that far south. Surveys using mark–recapture techniques (Jones 1991) indicated that the population ranged between 85 and 341 turtles per kilometer. The population decline of this species is attributed to habitat alteration caused by channel modification for flood control, navigation, and impoundment and to water quality degradation from siltation and pollution (U.S. Fish and Wildlife Service 1992). The species is federally listed as threatened (U.S. Fish and Wildlife Service 1997). The gopher tortoise occurs in sandy, well-drained soils of upland longleaf pine and mixed pine-hardwood forests in the Coastal Plain from South Carolina through Florida to southeastern Louisiana (Louisiana Department of Wildlife and Fisheries 1995).

American alligators are the largest nonmarine reptiles in North America with the exception of the American crocodile. They prefer freshwater marshes, swamps, and associated water bodies and occur across the South from Florida to Texas and as far north as North Carolina. Alligators are prized for their skins, and hunting pressure had reduced the population so dramatically by 1960 that the state of Louisiana declared a moratorium on hunting. In 1967 alligators were declared federally protected over nearly all of their range. With a moratorium on hunting, the Louisiana population rebounded so rapidly that alligators are a frequent sight in the coastal wetlands and are now legally hunted under strict state regulations. For law enforcement purposes, however, the alligators in Louisiana are now classified as “threatened due to similarity of appearance” to American crocodiles. Biologically, alligators are now considered neither endangered nor threatened (U.S. Fish and Wildlife Service 1997).

Fishes

The gulf subspecies of sturgeon is the only anadromous species to spawn in Louisiana. Its range is predominantly east of the state, but it is known to move up the Pearl River to spawn. Both immature and mature individuals participate in freshwater migration. Young fish less than two years of age apparently do not migrate out of rivers and estuaries. Seagrass beds with mud and sand substrates, such as those found behind the Chandeleur Islands, are important marine habitats for the species (Mason and Clugston 1993). The gulf subspecies is federally listed as threatened (U.S. Fish and Wildlife Service 1997). Primary reasons for its decline are habitat destruction and degradation—exacerbated by the potential for overexploitation—including dam construction, dredging, and navigation maintenance, all of which lower river elevations and eliminate deep holes and river substrate; and a decrease in groundwater flow that is thought to offer warmwater refugia. Agricultural, industrial, and urban contaminants may also be a factor in the gulf sturgeon’s population decline.

Information Gaps

The Louisiana coastal zone is an immense area of wetlands. For the past two decades, scientists have sounded the alarm about the serious rate of degradation of this resource. In recent years their concern has galvanized citizens of the state and federal agencies in Washington to rise to the challenge of coastal restoration. What is our knowledge of the resource, and how is that related to our ability to retard and possibly reverse the loss of wetlands? Our understanding of geomorphic processes is strong, and spatially based data on rates of wetland change are probably better known for coastal Louisiana than for almost any other area of comparable size. Much of the research in the coastal zone has been process-oriented, as scientists have struggled to understand how wetland loss occurs and how it can be stopped. We know that the biological resources—the fisheries and waterfowl, for example—depend on healthy wetland habitat, and conservation of the habitat has been the major research focus. In the 1970’s and 1980’s, several reviews of ecosystem function were prepared with federal agency funding (for example, Gosselink et al. 1979a,b,c; Costanza et al. 1983; Gosselink 1984; Conner and Day 1987). More recent studies have generally focused on problems related directly to wetland loss (for example, Turner and Cahoon 1987a,b,c; Cahoon and Groat 1990a,b,c,d; Boesch et al. 1994; Reed 1995).

Although these are excellent summaries of available data, they also reveal serious gaps:

- In the immense area of the Louisiana coast, available field studies are thinly distributed. The coast is notoriously heterogeneous, and this variability has hardly been probed. With the advent of computer capacity to interpret high- and low-resolution aerial photography and satellite-based spatial data, this problem is beginning to be addressed, although many processes cannot be deciphered with information gained from these techniques.

- The data base documenting the diversity of species in different coastal environments is quite weak, and biodiversity is receiving little attention.
- Water-regime information is vital to understanding coastal ecosystems. However, although a good deal of information has been published about the variation in time and space of gauge data—water levels, flooding duration, and so on—the velocity and pattern of flows are extremely expensive to measure and yet are vital to our management of the estuaries. The development of fine-structured spatial models of hydrology would seem to be the next generation of necessary research in this area.
- Subsidence is a dominant, though geographically variable, feature of these vast coastal marshes, yet accurate benchmarks for elevation and subsidence rates are few.
- Our understanding of biological variability of wetland vegetation and its response to physical and biotic forces is still in its infancy.
- The interaction of vertebrates and invertebrates with these dynamic coastal systems is understood only at the gross level, and detailed relationships required to fully restore these vast marshes are not well understood.
- Landscape-level synthesis of information, including interactive models that can simulate the consequences of proposed projects, is desperately needed. Management is occurring in small projects all over the coast. Both the state and federal governments, through the Coastal Wetlands Planning, Protection, and Restoration Act, are committed to massive coastal restoration. Proposed projects range from small beach and barrier plantings to retard erosion to massive freshwater river diversions to initiate new delta lobe cycles. The cumulative effect of these projects has not been addressed and probably cannot be addressed with our present knowledge limitations. Fortunately, Coastal Wetlands Planning, Protection, and Restoration Act projects are required to include monitoring to ensure their efficacy. Monitoring is overseen by five federal agencies and the Louisiana Department of Natural Resources and is carried out by the Department of Natural Resources and the Biological Resources Division of the U.S. Geological Survey of the U.S. Department of the Interior. The Department of Natural Resources and the U.S. Geological Survey's National Wetlands Research Center, along with Louisiana State University personnel, have begun to develop a coastwide monitoring program to ensure that cumulative restoration can be evaluated. This monitoring program will include periodic mapping of habitats from satellite imagery and ground-based measurements of all important physical and biological processes; it has the potential to be not only a comprehensive source of long-term information but also a model for monitoring programs elsewhere (Steyer and Stewart 1993).

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