Wetlands: Impacts of Energy Development in the Mississippi Delta

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Glossary

accretion The upward growth of a sedimentary deposit due to settling of suspended sediments or *in situ* organic soil formation (due to root growth).

benthos Aquatic bottom-dwelling organisms; benthic is the adjective form (e.g., benthic animals).

bioremediation The addition of materials to a contaminated environment to cause an acceleration of the natural biodegradation processes.

estuary Any semi-enclosed coastal body of water that has a connection with the open sea and within which fresh water and salt water mix.

impoundment An enclosed wetland that is hydrologically isolated, either completely or partially, from the surrounding ecosystem; impoundment can be due to a combination of natural (e.g., beach ridge, natural levee ridge) and anthropogenic (e.g., road embankment, spoil bank) features.

levee A linear dike or embankment built along the bank of a channel, often to prevent inundation of lowlands by flooding.

primary production Total amount of organic matter newly formed during photosynthesis.

produced water By-product of the oil production process that is brought to the surface along with petroleum; produced water often contains high levels of salt, heavy metals, and hydrocarbons.

relative sea level rise A rise in sea level relative to that of the land due to a combination of eustatic sea level rise (i.e., worldwide sea level rise due to global warming) and sinking of the land as a result of subsidence.

subsidence Sinking or settling of the land surface due to natural (compaction and consolidation of sediments) or artificial causes.

The Mississippi Delta encompasses the largest area of coastal wetlands in the United States and supports one of the most extensive developments of petroleum extraction of any coastal area in the world. This area has experienced ecological impacts from energy development related human activities since the early 1900s. The Louisiana coastal zone encompasses approximately 3.8 million ha (9.5 million acres). The zone includes water bodies, marsh (fresh, intermediate, brackish, and salt), forested wetlands, submerged aquatic vegetation, mudflats, beaches, and upland habitats on natural levees with forests, agriculture, and urban development. Marshes make up approximately 63% of the land area in the coastal zone, and coastal Louisiana contains approximately 60% of the estuaries and marshes in the Gulf of Mexico. Coastal wetlands are vital for protecting developed areas from storm surges, providing wildlife and fish habitat, and improving water quality. The coastal zone has experienced multiple ecological impacts due to human activities, including leveeing of the Mississippi River, large-scale wetland reclamation, water quality deterioration, pollution, and widespread disruption of hydrology. Oil and gas development has contributed significantly to these impacts.

1. INTRODUCTION

Historically, Louisiana has been the second most important oil- and gas-producing state behind only Alaska. Crude petroleum is a complex mixture of mainly hydrocarbons and organic compounds of sulfur, nitrogen, and oxygen. Geologically, organic matter that accumulated in sandstones, siltstones, and shales during the Cenozoic era was transformed into petroleum by heat and pressure. The northern coast of the Gulf of Mexico had a thermal regime favorable to optimal maturation of organic matter into hydrocarbons and formed stratigraphic traps through faulting and salt movements. In Louisiana, oil and gas are produced from formations of the Paleocene through Pleistocene eras in the subsurface coastal and offshore areas. Oil production in Louisiana began in 1902, and the first oil production in the coastal zone occurred in 1926. The coastal zone produced more than 50% of oil production in the state during the 1950s and reached a peak in 1970 with 513 million barrels. From the 1920s to the 1980s, 58% of the state's total oil production and 47% of the state's natural gas production were in the Louisiana coastal zone. Gas production in the coastal zone peaked in 1969 at 7.8 trillion cubic feet. By 1990, there were more than 500 oil and gas fields in the Louisiana coastal zone. By 1987, more than 13,000 state leases for oil and gas development had been issued, and more than half of the leases were located in the coastal zone. Approximately 25% of domestic crude oil and 33% of domestic natural gas of the nation flow through Louisiana's coastal marshes. More than $12 billion in revenues from leases and production in the coastal zone was collected from 1926 to 1983. In 2000, the revenue was $354 million for mineral royalties only, and approximately 1.8 million jobs in Louisiana were related to the oil industry. Fully 40% of the U.S. refining capacity is located within the coastal zone in the Gulf of Mexico region. Therefore, the risk of ecological damages in the Mississippi Delta from energy development has been high (Fig. 1).

Oil and gas development activities have had multiple ecological impacts on wetlands and coastal ecosystems through the various stages of oil and gas development, including oil exploration, drilling site access, site preparation, drilling, production, pipeline installation, spills and cleanup, and site closure (Table I). Wetland ecosystems are susceptible to oil- and gas-related activities for a number of reasons. First, the high productivity of wetland vegetation is dependent on natural hydrological flows and inputs of nutrients and sediments to the Mississippi Delta. Second, levees, canals, and impoundment disrupt the natural hydrological regime in the Mississippi Delta and, in turn, affect plant health and sediment dynamics. Third, subsidence due to depressurization from oil and gas production enhances subsidence. Fourth, pipelines for transporting oil and gas

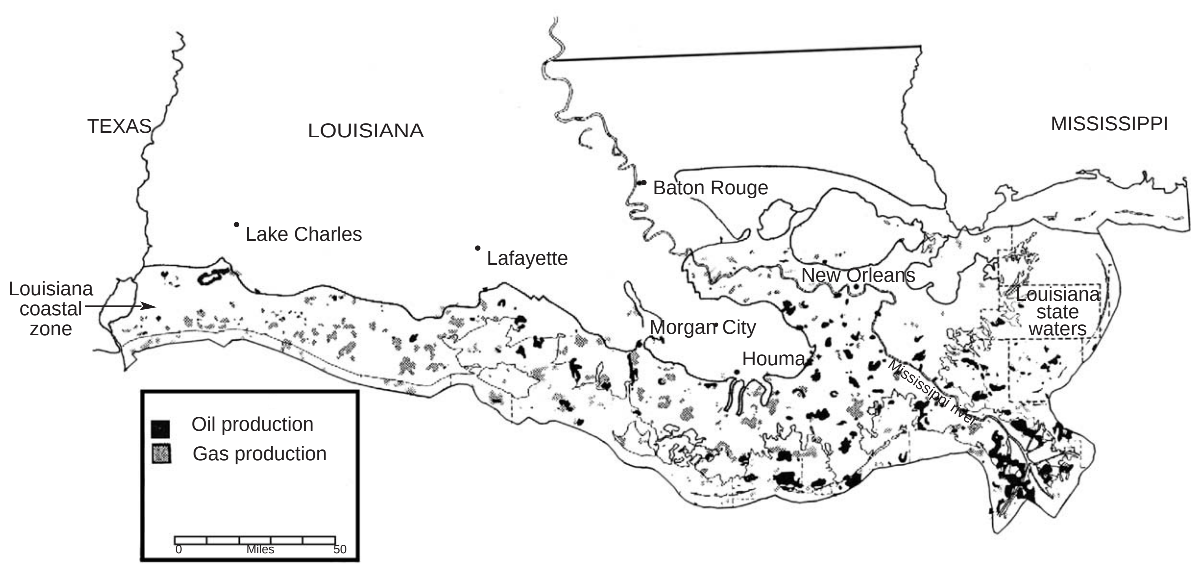

FIGURE 1 The distribution of oil and gas fields in the Louisiana coastal zone as of 1981. Reprinted from Lindstedt *et al.* (1991).

TABLE I

Multiple Impacts of Energy Development inside Wetlands

Stage	Short-term impacts	Long-term impacts
Exploration	Changes in marsh surface elevation	Changes in surface hydrology and drainage
	Breaks in natural hydrological barriers	Saltwater intrusion
	Noise and commotion during exploration	Changes in plant growth, organic matter accumulation, and sediment distribution
	Immediate loss of marsh vegetation	
	Destruction of biota	
	Changed habitat	
	New migration pattern of aquatic organisms inside marsh	
Access to site	Direct conversion to open water	Increased wave action
	Direct conversion to spoil bank habitat	Changed water circulation and turnover; stagnant water
	Return of nutrients and toxins to marsh	Dredged canal deeper than natural channel
	Noise and commotion during construction	Intercepted freshwater flow
	Immediate loss of marsh/shallow water habitat	Saltwater intrusion
	Changes in soil/water chemistry	Increased drainage of marsh
	Destruction of biota	Changes in surface hydrology and drainage
	Potential for interrupting fish spawning and feeding	Changes in sediment distribution
	Potential negative impact on plant growth	Changes in interaction of surface/subsurface hydrology and sediment distribution
	Potential for disturbing avifauna nesting by noise	
Drilling	Reduction in water quality	Alteration of surface hydrology and drainage
	Return of nutrients and toxins to surroundings	Changes in subsurface hydrology and drainage
	Inhibition of rainfall penetration	Changes in sediment distribution
	Noise and commotion during construction	Saltwater intrusion
	Increase in suspended solids	
	Changes in soil/water chemistry	Increased sediment release from discharges
	Changes in plant growth	Anoxia
	Destruction of biota	Loss of marsh habitat
	Potential for interrupting fish spawning and feeding	Altered soil/water chemistry
	Potential for disturbing avifauna nesting by noise	Possible negative influence on aquatic/benthic organisms
		Changes in mineral accretion and soil nutrition
Production	Noise and commotion during construction	Noise of processing facilities
	Flowlines in the marsh	Changes in surface hydrology and drainage
	Pit construction; toxins to surroundings	Changes in subsurface hydrology and drainage
	Changes in marsh elevation	Saltwater intrusion
	Reduction in water quality	More saltwater species
	Saltwater disposal	Anoxia
	Oil spills	Increased localized subsidence
	Destruction of biota	Loss of marsh habitat
	Potential for interrupting fish spawning and feeding	Altered soil/water chemistry
	Potential for disturbing avifauna nesting by noise	Possible negative influence on aquatic/benthic organisms
Pipeline building	Direct conversion to open water	Changes in surface hydrology
	Increased turbidity	Bank erosion
	Loss of forested wetlands	Compacted marsh surface
	Noise and commotion during construction	Direct habitat conversion
	Increased susceptibility to storm damage	Indirect wetland loss

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Table I continued

Stage	Short-term impacts	Long-term impacts
	Formation of open water ponds	Changes in forest succession
	Disruption of natural surface drainage	Changes in plant species, composition, diversity, and percentage cover
	Release of nutrients and toxins	Shoreline bank stability
	Soil oxidation	
	Changes in plant species, composition, diversity, and percentage cover	
	Nesting disturbance	
	Changed habitat	
	Disturbance of fish spawning and feeding	
	Impacts on plant growth	
	Destruction/Disturbance of benthos	
Spill control	Interruption of tidal cycle	Loss of marsh habitat
	Direct conversion of marsh to open water	Injury to birds and wildlife
	Trampling of vegetation	
	Immediate loss of marsh habitat	
	Temporary interruption of aquatic organism migration and flux of matter	
	Injury to birds and wildlife	
	Disruption of avifauna nesting	
Cleanup	Potential disruption of substrate	Loss of marsh habitat
	Removal of vegetation	Injury to birds and wildlife
	Immediate loss of marsh habitat	
	Decrease in biological production	
	Destruction of vegetation and benthic organisms	
	Potential negative impact on plant growth	
	Potential injury to wildlife	

produced inside the coastal zone and from the Outer Continental Shelf (OCS) disrupt natural hydrology. Fifth, spilled oils have an impact on wetland habitats. Sixth, spilled oil and produced water stress estuarine consumers by increasing turbidity, increasing salinity stress, introducing toxins, and so on. Finally, wetland loss decreases the value of the coastal zone as a nursery ground for estuarine consumers and the economic value to the human economy (Fig. 2).

This article reviews the multiple ecological impacts of oil- and gas-related impacts and synthesizes existing information to help researchers and managers understand how oil and gas development affects coastal wetland ecosystems in Louisiana, focusing on (1) plant physiology, (2) estuarine consumers (including the benthic community), and (3) hydrological disturbance and wetland loss.

2. IMPACTS ON PLANT PHYSIOLOGY

2.1 Impacts of Oil Spills

Wetland plants are subject to stresses from oil spilled during production and transportation (using tankers, pipelines, and tank trucks). Oil spills can have significant short- and long-term impacts on coastal ecosystems due to oil's physical effects and chemical toxicity, leading to decreased primary production, plant dieback, wildlife mortality, and marsh erosion. The mechanisms of these impacts are through (1) disruption of plant–water relationships, (2) direct impacts on plant metabolism, (3) toxicity to living cells, and (4) reduced oxygen exchange between the atmosphere and the soil. If leaves are coated with spilled oil, leaf stomata are blocked, oxygen diffusion to the roots decreases, and root oxygen stress

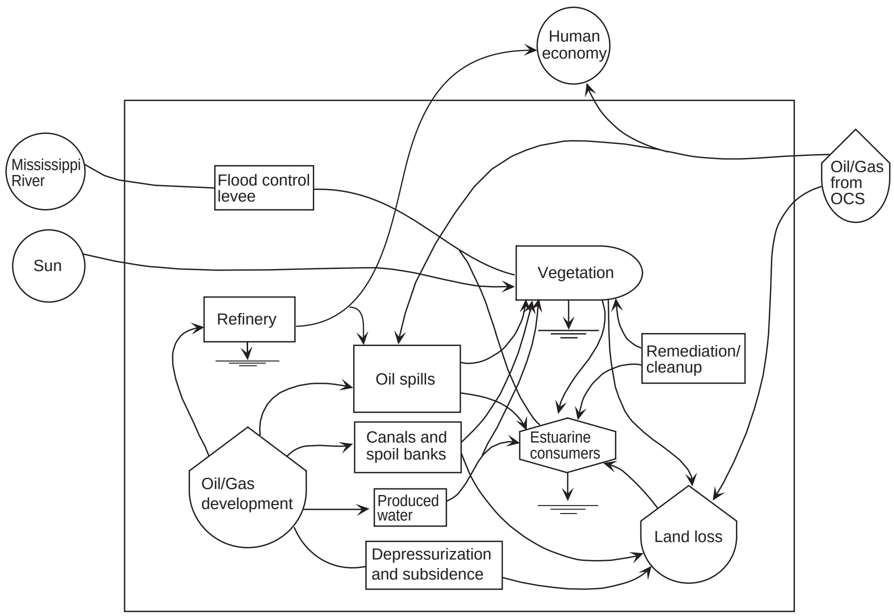

FIGURE 2 A conceptual diagram of ecological impacts of oil and gas development in Louisiana wetlands. The two main types of impacts are toxicity of hydrocarbons and hydrological changes.

increases, leading to reduction in plant growth. An oil-covered soil surface decreases oxygen movement, resulting in more anaerobic soil conditions and increasing low-oxygen stress on plant roots. Aerobic microorganisms in the oxidized sediment are more cable of degrading hydrocarbons than are anaerobic microorganisms in reduced sediment of the same pH. Oil coating on leaves results in higher mortality rates of marsh plants than does soil surface contamination.

In the short term, spilled oil can form a coating on plant foliage and the soil surface, increasing temperature stress, reducing oxygen diffusion, and reducing photosynthesis. The severity of these impacts is controlled by the amount of oil spilled, hydrological conditions (e.g., tides, winds), types of dispersed oil, and sensitivity of plants. Toxicity varies among various oil types. For example, diesel and number 2 oil are more toxic to marsh plants than is crude oil. Higher organic soils of fresh marshes are more sensitive to oil spills than is salt marsh through more rapid penetration and sorption of oil into the soil. For example, *Sagittaria lancifolia* is more tolerant than *Spartina alterniflora*, which in turn is more tolerant than *Spartina patens*.

There are longer term consequences of oil spills due to the persistence of oil or petroleum fractions in marshes. A period of 3 to 5 years may be required for natural recovery from accidental oil spills. Over time, oil concentrations are reduced in wetlands through oil evaporation, natural degradation of oil, and recovery of marsh plants.

However, plants subject to chronic exposure to oil spills accumulate oil-related pollutants through increased uptake of pollutants such as lead in contaminated sediments. The severity of biological effects of chronic spills is controlled by the volume and chemical nature of the pollutants, the physical nature of the receiving environment, and the biological character and composition of the ecosystem.

Traditional cleanup methods to remove spilled oil (e.g., water flushing, sand blasting, sediment removal, vegetation removal, sorbent application) often show limited removal efficiency. These methods can also cause potentially deleterious effects on long-term recovery of the impacted marsh system because they can result in further physical damage to both the vegetation and the underlying substrate, accelerating marsh degradation. Specifically, initial intensive cleanup by flushing and oil recovery by airboats reduces the residual oil in the marsh but also increases oil incorporation into the sediment and increases risks of physical damage to marsh plants. The negative impacts of physical removal of contaminated marsh plants can last for several years.

2.2 *In Situ* Burning

As a way in which to control oil spill impacts while minimizing physical damage to impacted wetlands, controlled *in situ* burning has been tested and used as an option to remove oil and gas condensate in contaminated wetlands. When water depth is sufficient (e.g., 10 cm) in damaged wetlands, *in situ* burning can be an efficient option because water on the surface will allow a successful burn of the above-ground vegetative component while absorbing heat produced by the fire and preventing root burning. However, flooding following *in situ* burning adversely affects plant growth in many species because the immediate reduction of plant cover decreases oxygen transportation to below-ground tissues. Full recovery of marsh vegetation from *in situ* burning reportedly takes 1 to 3 growing seasons. *In situ* burning generates atmospheric pollutants whose chemical components are a variety of gaseous sulfur (e.g., carbonyl sulfide, carbon disulfide) and carbon compounds (e.g., methane, carbon dioxide) and reduced alkylated naphthalene compounds from postburn oil.

2.3 Chemical Methods

Dispersants wash oil from surfaces such as rocks and vegetation. However, high doses (e.g., 0.3 L/m^2) reduce total and above-ground biomass significantly, at least for a short time. Another problem in dispersant application is that it is not practicable for use in coastal wetlands because there is little water to dilute the dispersed oil inside wetlands. Application of cleansers (e.g., COREXIT 9580), another chemical method, does not disperse oil but rather allows oil to be washed from surfaces, such as soils and plants, and to be collected in adjacent open water areas by boats. Plants improve their survival, regeneration, and above-ground biomass growth because the application leads to a recovery of stomatal conductance, photosynthesis, and respiration. The effectiveness of the cleanser in cleaning up oil depends on oil type, delivery mode, timing, and amount of oil. Marsh plants (e.g., *S. lancifolia*, *Scirpus olneyi*, *Thpha latifolia*) show different sensitivities to cleanser use. Cleanser application to brackish (*S. patens*) and fresh (*S. lancifolia*) marshes removes oil from marsh grasses and reduces the short-term impact of oil spills on gas exchange of the vegetation, but it still reportedly results in reduced above-ground biomass for the first growing season. Another problem in cleanser application is the potential impact of cleanser toxicity on various organisms in wetlands. Finally, solidifiers, which are dry, granular, hydrophobic polymers, can be used for spilled oil removal. Solidifiers react with spilled oil to form a floating cohesive and solidified mass that is easily removable, leaving very little residue.

2.4 Bioremediation

Wetland plants have the potential to enhance the bioremediation process through diffusion of oxygen from the shoots to the roots and soil, and its effectiveness can be increased through applications of fertilizer, microbial products, or soil oxidants. Fertilizer may be applied to spilled oil in water bodies before it reaches the marsh or may be applied directly to marshes already contaminated with oil. Additions of soluble inorganic fertilizers stimulate microbial activity and prolong the period of active oil degradation. The microbial activities lead to degradation of toxic petroleum products into carbon dioxide and water. However, the effectiveness of bioremediation may be limited by marsh plant tolerance to oil-related stress, risk of eutrophication, and soil type. Nutrients added to marshes may be transported to adjacent water bodies, leading to algal growth. Fertilizer application is more effective in sandy soils than in mineral soils. In some cases, the best action may be to allow the marsh to recover on its own, using no cleanup techniques.

3. IMPACTS ON ESTUARINE CONSUMERS

Benthic and nekton species are key organisms, both ecologically and economically, in coastal and wetland systems. The benthic community is an important link in transferring contaminants from the sediment to higher trophic levels, and the benthic community structure is sensitive to petroleum hydrocarbon exposure. The ecological and biological impacts of energy development on coastal marshes and estuarine environments are broad and sometimes persistent, including mortality, growth inhibition, reduced production, altered metabolic systems, and tainted flesh in fish and shellfish. Oil and gas production and transportation in coastal wetlands in Louisiana have resulted in the accumulation of polycyclic aromatic hydrocarbons (PAHs) and heavy metals in impacted areas. These compounds cause ecological impacts, including alteration of aquatic community structure and food chains. Biodiversity and population density of the benthic community are significantly lower in oil-contaminated areas. Recruitment and feeding patterns can also be altered by oil pollution.

4. HYDROLOGICAL DISTURBANCE AND LAND LOSS

Petroleum-related activities in coastal Louisiana have several secondary and indirect impacts. These include the production of produced water, drilling-induced subsidence, and hydrological modifications due to dredging activities. Dredging results in two interrelated impacts: creation of new water pathways and spoil placement.

4.1 Produced Water

Produced water is a by-product of the oil production process. There are often substantial amounts of water contained in subsurface formations where oil and gas occur. When oil and gas are produced, this water is brought to the surface and must be disposed of in some way. Produced water contains high concentrations of volatile (e.g., benzene, toluene), and semivolatile hydrocarbon contaminants (e.g., aliphatic hydrocarbons, alkylated polycyclic aromatic hydrocarbons) as well as high concentrations of aromatic acids and aliphatic fatty acids. Some produced water also contains metals such as vanadium, arsenic, and copper. These toxic metals and organics often accumulate in wetlands due to poor freshwater flow or tidal exchange. Produced water also often contains high levels of brine. The degree of ecological impacts on wetlands is influenced by (1) discharge rate, (2) quantity and quality of the hydrocarbons and trace metals present in a particular discharge, (3) local hydrology, (4) sediment disturbances (e.g., dredging, boat traffic), and (5) sediment types (organic carbon content and texture). Volatile and semivolatile organic compounds of produced water are accumulated in organisms (e.g., oysters, freshwater mussels). However, when exposed to a contaminant-free environment, oysters release accumulated hydrocarbons. Heavy metals are reported not to influence hydrocarbon degradation in sediments at the produced water discharge site. The degradation rate of petroleum hydrocarbon in sediments exposed to produced water is controlled by oxidation, redox potential, and pH and can be increased by the addition of fertilizer.

4.2 The Delta Cycle and Wetland Loss in the Mississippi Delta

Coastal wetland loss is a major environmental problem in coastal Louisiana. The remainder of this article discusses evidence on the causes of this land loss and the role of petroleum-related activities in contributing to wetland loss.

4.2.1 The Delta Cycle

To understand the factors related to wetland loss, it is necessary to understand how the Mississippi Delta was formed. The sea level stabilized near its current level at the end of the last glaciation 5000 to 7000 years ago. Since that time, delta switching of the Mississippi River has created a series of overlapping deltaic lobes that currently form the Mississippi deltaic plain in coastal Louisiana. Delta switching occurs every 1000 years or so, resulting in new loci for sedimentation and marsh development. Rapid land building occurs in active delta lobes, whereas submergence and wetland loss occur in abandoned lobes. The Atchafalaya River is the most recent diversion in the delta switching process. Subaerial expression of the new Atchafalaya Delta began in 1973, and this area has a net gain of wetlands. Thus, the delta building process is a balance between forces that lead to growth of the delta and those that cause deterioration. The Mississippi River is the major force leading to land gain. Overbank flooding and reworking of sands have formed a skeletal framework of natural levee ridges and barrier islands within which the delta plain has formed. Deposition of both coarse and fine-grained sediments formed wetlands and maintains existing wetlands. Sediments resuspended during storms are an important source of sediments to maintain marshes. Once a wetland forms, organic soil formation by wetland plants is an important mechanism for maintaining coastal marshes.

Naturally, wetland deterioration is caused by two primary forces: subsidence and wave erosion along shorelines. Geological subsidence is caused by compaction, dewatering, and consolidation of sediments. Subsidence in deltas leads to a rate of relative sea level rise (RSLR) that is often much greater than eustatic rise. For example, whereas the current rate of eustatic rise is 1 to 2 mm/year, the RSLR in the Mississippi Delta is greater than 10 mm/year; thus, eustatic sea level rise accounts for only 10 to 15% of total RSLR. If wetlands in deltas do not accrete vertically at a rate equal to the rate of RSLR, they will become stressed due to factors such as waterlogging, sulfide toxicity, and salt stress and will ultimately disappear. Because vertical accretion is stimulated by both outside sediment input and *in situ* organic soil formation, a reduction of sediment input or an increase in plant stress can lead to lowered accretion rates and wetland loss. Subsidence generally leads to wetland loss in interior wetlands. Wave erosion leads to wetland loss along exposed shorelines. As a deltaic lobe progressively deteriorates, wave erosion becomes relatively more important.

4.2.2 Wetland Loss in the Mississippi Delta during the 20th Century

During the 20th century, there was a dramatic reversal of the net growth of the Mississippi Delta that had taken place over the past several thousand years. High rates of land loss occurred (with estimates up to 100 square kilometers/year), and a total area of 4000 square kilometers of coastal wetlands has been lost. A number of factors have been linked to land loss, including elimination of riverine input to most of the coastal zone due to construction of flood control levees along the Mississippi River, altered wetland hydrology due to factors such as canal construction and impoundments, saltwater intrusion, wave erosion along exposed shorelines, a decline in suspended sediments in the Mississippi River, the effects of geological faulting, and high RSLR.

4.2.3 Effects of Oil and Gas Production on Subsidence

As stated previously, the regional rate of geological subsidence in the Mississippi Delta is approximately 10 mm/year. This is due to compaction, dewatering, and consolidation of sediments. Recently, Morton and colleagues showed that the rate of subsidence in producing oil and gas fields was considerably higher than this regional average (as much as 23 mm/year). They concluded that the increasing and then decreasing pattern of land loss in south central Louisiana was attributable partly to increased and then decreased oil and gas production. Decreases in subsurface pore pressures associated with production were so large that stressed faults were reactivated, leading to rapid subsidence on the down-thrust side of the fault. This enhanced subsidence led to wetland plant stress and death, as discussed previously. Thus, enhanced subsidence on top of regional geological subsidence led to much greater waterlogging stress on plants. Spoil banks associated with oil and gas fields led to reduced sediment input and lower organic soil formation, exacerbating sediment accretion deficits.

4.3 Canal and Spoil Banks

Canals have been constructed in the coastal wetlands of Louisiana since Europeans first settled in the region during the early 1700s. For nearly two centuries, these canals were dredged mainly for navigation, flood protection, and drainage. However, after the 1930s, the discovery of oil and gas fields in the coastal zone led to an explosion of canal construction related to oil and gas production. By the mid-1980s, there were more than 15,000 km of canals, the surface area of canals was equivalent to 2.3% of wetland area, and the total area of spoil bank levees plus canal surface was approximately 9.5% of wetland area.

When a canal is dredged, the dredged material is deposited along the sides of the canal, creating a more or less continuous elevated bank called a spoil bank. Spoil banks generally consist of highly organic marsh soil. As the spoil banks settle and dewater and as organic matter oxidizes, they create a levee that runs parallel to the canal (Fig. 3). Canals and associated spoil banks alter natural hydrology in two main ways. First, the canals are deep and straight, in striking contrast to the mostly shallow and sinuous tidal channels. Because of this, dredged canals tend to preferentially capture flow from natural channels. It has been shown that as the density of canals in an area increases, the density of natural channels decreases. If canals are long and deep enough (e.g., navigation channels that stretch from the Gulf of Mexico inland to freshwater areas), they can cause significant saltwater intrusion and death of freshwater wetlands. Two notable examples of this are the Mississippi River Gulf Outlet, which caused the death of extensive cypress forests southeast of New Orleans, and the Calcasieu Ship Channel, which led to loss of extensive sawgrass marshes in southwest Louisiana.

In contrast to deep canals that enhance water flow, spoil banks reduce water exchange. Spoil banks reduce or even eliminate overland flow. Because of the presence of spoil banks, partially impounded areas have fewer but longer periods of flooding and reduced water exchange in comparison with unimpounded marshes. Ponds usually develop behind canals and spoil banks, and high wetland loss is associated with areas of high hydrological changes.

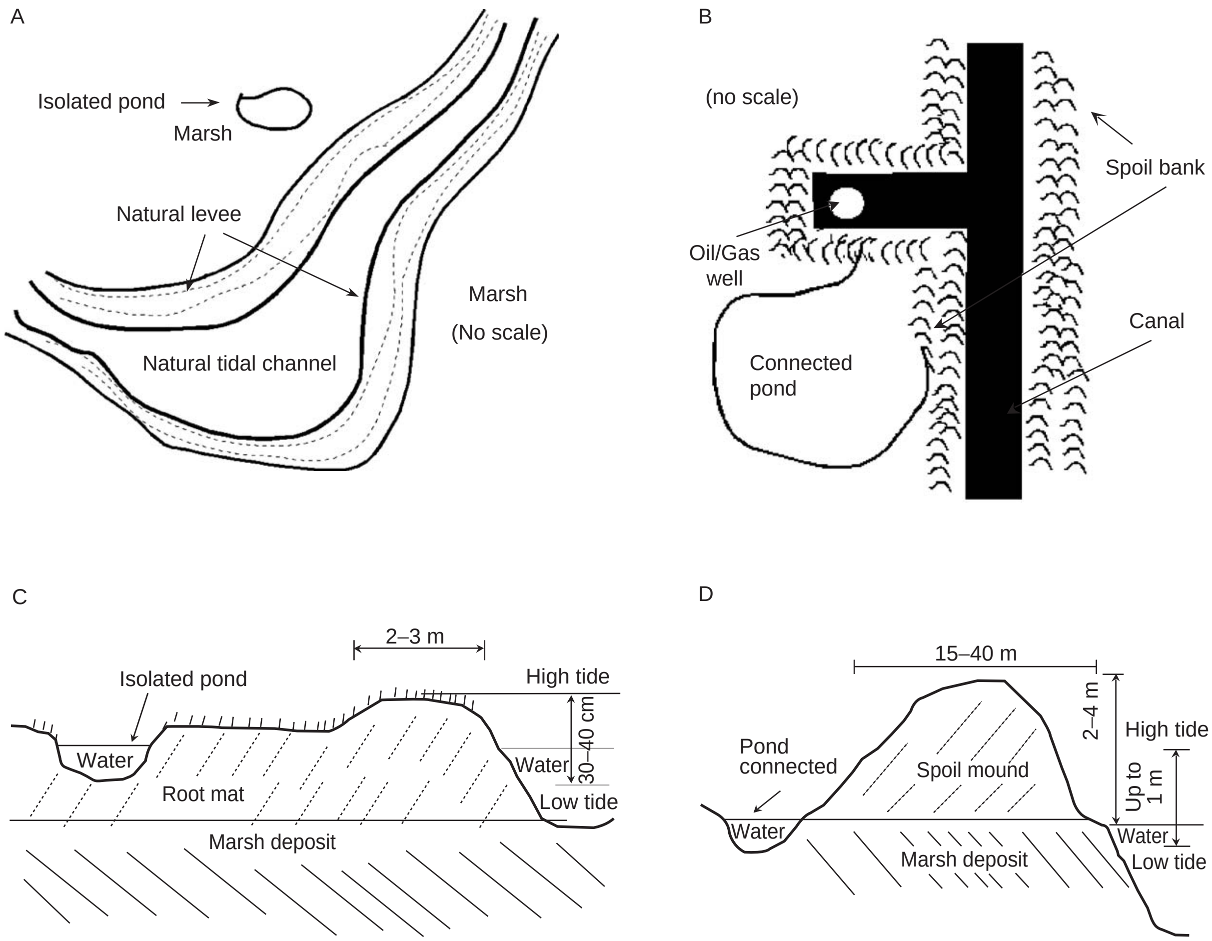

FIGURE 3 Schematic diagrams of canal dredging on coastal marshes. (A) Top view of a natural tidal channel and natural levee. (B) Top view of canal dredging showing straight canal and spoil bank. (C) Cross-sectional view of natural marsh. Note the streamside natural levee and shallow tidal channel and that high tide is higher than the natural levee. (D) Cross-sectional view of a dredged canal. Note that the dredged canal is deep, water level variation is higher than in natural channels, and the spoil bank is higher than normal high tide, preventing flooding of the marsh.

As discussed previously, if canals are associated with oil and gas fields, subsidence is enhanced through depressurization during and after oil and gas production.

Tidal currents are stronger through dredged canals than through natural channels. This, coupled with erosion from boat wakes, results in erosion of the banks. Annual increases in canal widening range between 2 and 14% per year, for a doubling time of 5 to 60 years. Canals also worsen water quality problems. Normally, nutrient- and sediment-laden point and nonpoint source runoff from uplands would naturally flow slowly through wetlands where nutrients and sediments would be assimilated. Canals short-circuit this flow, leading to direct introduction of nutrients and suspended sediments and to eutrophication in open water bodies.

4.4 Impoundment

Coastal marshes exchange water, organic materials (e.g., detritus), nutrients (e.g., nitrogen, phosphorus), and organisms with surrounding estuarine waters, supporting estuarine fish and shellfish. One impact that has affected these processes in coastal marshes is impoundment. Impoundments have been constructed for a number of reasons. Beginning in the 19th century, impoundments were constructed for the purpose of land reclamation for urban and agricultural activities. Many of these reclaimed areas failed due to excessive subsidence and flooding during hurricanes. But some remain, mainly in the metropolitan area of New Orleans. During the 20th century, many impoundments were constructed in the coastal zone to enhance conditions for waterfowl and for marsh management. In addition to these purposefully constructed impoundments, large areas of the coastal zone have been completely or partially impounded by the cumulative impacts of canal and spoil bank construction. Approximately 30% of the total wetland area in coastal Louisiana has been impounded, either purposefully or by accident. Impoundments have been shown to have a number of detrimental impacts in that they reduce water exchange and accretion inside impoundments, lower vegetation productivity, and reduce movement of migratory fishes, leading to deteriorating marshes.

4.4.1 Petroleum-Related Activities and Wetland Loss

From the preceding discussion, a number of conclusions emerge. Naturally, wetland establishment and deterioration in the Mississippi Delta is a very complicated process involving numerous factors, including geological and geophysical (e.g., channel switching, sediment introduction and deposition, subsidence, vertical accretion, wave erosion, saltwater intrusion, sea level rise), biogeochemical (e.g., anaerobic soil formation, sulfate reduction, peat decomposition), and ecological (e.g., waterlogging and salinity increase leading to plant stress and death, rates of organic soil formation, herbivore grazing) factors. Prior to extensive alteration by human activity, there were large gains and losses of wetlands in various parts of the deltaic plain as the river changed course. But over the past 5000 to 6000 years, the net result of these processes was a large net gain of wetlands.

During the 20th century, the long-term net gain of wetlands was reversed and wetland area in the delta decreased by approximately 25%. Clearly, some of this loss was natural and would have occurred without human impacts. But it seems clear that the dramatic reversal from net gain to net loss can be attributed to human activities. Two general and interrelated processes are responsible for the losses: pervasive hydrological change and dramatically increased subsidence.

From a hydrological point of view, there have been two pervasive changes. First, the delta has been nearly completely isolated from the river that built it. Levees extend to the mouth of the main channel of the river, and 70% of sediments and water flow into the Gulf of Mexico. Only in the Atchafalaya Delta region does river water enter a shallow inshore area, and this is an area of land gain. Internally in the delta, there have been massive hydrological changes. A dense network of canals, most associated with petroleum activity, has changed the delta dramatically. These canals allow saltwater intrusion, reduce water and sediment movement, and contribute to low accretion rates. Impoundments isolate large areas of the coastal zone from adjacent estuarine areas.

4.4.2 Role of Petroleum Activity

In the vicinity of oil and gas fields, subsidence increased due to depressurization and surface hydrology was altered due to canals and spoil banks. Thus, RSLR was increased and the rate of accretion was reduced. This is due both to a reduction in allochthonous sediment input and to *in situ* organic soil formation. Some have attributed practically all wetland loss in the coastal zone to canals. There is no doubt that oil and gas activity have had a major impact on wetland loss. In areas of intense oil and gas extraction, it is likely that most wetland loss can be related to the combined impacts of increased subsidence and surface alterations. But high rates of wetland loss are also related to wave erosion, saltwater intrusion, and changes in the engineering of the mouth of the Mississippi River. Nonetheless, there is no doubt that petroleum-related activities are directly responsible for a significant proportion of the land loss in the coastal zone. It is probably not possible to put a specific value on this land loss due to the complexity of the land loss problem.

From a broader perspective, it is better to consider the functioning of the whole coastal system and the conceptual model developed earlier in this article. Both the supply side (inputs to the delta) and the receiving system (the delta plain) have been affected. Both riverine input and resuspended inputs have been reduced. At the mouth of the Atchafalaya River, oil and gas fields are not associated with wetland loss. Thus, it is the combination of all these forces, but oil and gas have had a dramatic impact.

5. CONCLUSION

Petroleum exploration, production, and transportation in the Louisiana coastal zone increased dramatically from the early 20th century to the 1970s. Oil and gas production in inshore bays and wetlands of the coastal zone then decreased beginning in the late 1970s, but there is still a high level of transportation of oil and gas through the coastal zone from the OCS and Louisiana Superport. These activities have had significant impacts on floral and faunal communities, resulting in significant deterioration of coastal and wetland ecosystems. These impacts are related to the toxicity of spilled oil and the secondary and indirect effects of petroleum-related activities such as alteration of hydrology. The impacts of OCS development are related to construction of pipelines and navigation channels. Thus, the risks of oil spills and hydrological disruption continue, even though inshore oil and gas production has decreased.

Responses of plant metabolism to oil impacts are complex, depending on exposure type (e.g., oil-coated leaves vs soil contamination), oil type (e.g., crude oil vs number 2 oil), time of spill (e.g., after the growing season vs before the growing season), density of spilled oil, and sensitivity of various marsh plant species to oil. Another complex matter is the impact of oil cleanup on wetlands. Removal of oil has been reported to cause significant damage to wetland communities, including reduced growth of marsh plants and reduced population of benthic organisms.

Lin and colleagues suggested that methods and intensity of oil spill cleanup depend on the type and amount of spilled oil and environmental conditions at the time of the spill. If the spill is a relatively small volume and the floating oil is not continuous, light or no cleanup action is recommended. In the case of large-volume oil spills, cleanup activities consisting of sorbent application, low-pressure flushing, vacuuming, rope mops, and the like should be considered as options. However, Lin and colleagues did not recommend the use of heavy equipment and intrusive mechanical cleanup due to the concerns of physical damage to fragile marshes.

Louisiana experienced a high rate of coastal marsh loss during the 20th century. This high loss rate has been attributed to a number of factors. The immediate cause of much loss is due to plant stress resulting from both natural and anthropogenic causes, followed by plant dieback, subsequent erosion of the marsh substrate, and the formation of small ponds that then coalesce into larger open water bodies. Causes of plant stress in Louisiana marshes have been attributed to waterlogging stress (due to insufficient elevation of the marsh surface resulting from high subsidence rates in the deltaic plain and low accretion rates) and salinity stress (due to saltwater intrusion, often from storm surge events, into the more interior marshes).

Petroleum-related activities have contributed significantly to wetland loss in the Mississippi Delta. Oil and gas extraction increased the subsidence rate, sometimes by a factor of as high as 2 to 3, due to reduction of pressure that led to faulting-related subsidence. On the surface, canals significantly altered natural hydrology. Deep dredged canals altered water flow pathways and sometimes resulted in saltwater intrusion. Spoil banks reduced overland flow exchange and sediment input to the wetland surface. The combination of these two factors increased plant stress and plant death.

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