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A review of ecological impacts of oil and gas development on coastal ecosystems in the Mississippi Delta

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Abstract

We review the multiple ecological impacts of oil and gas development on coastal ecosystems in the Mississippi Delta. This area has one of the greatest developments of oil and gas production in the world. This activity has generated significant impacts on coastal ecosystems due to the toxicity of spilled oil and the secondary and indirect effects of petroleum-related activities, such as alteration of hydrology. Effects on plant communities include disruption of plant–water relationships, direct impacts to plant metabolism, toxicity to living cells, and reduced oxygen exchange between the atmosphere and the soil. Effects on consumers include growth inhibition, reduced production, altered metabolic systems, and biomagnification of hydrocarbon compounds. Petroleum-related activities have contributed significantly to wetland loss in the Delta. Subsidence was increased by 2–3 times due to fault activation. Canals altered natural hydrology by altering water flow pathways, increasing saltwater intrusion, and reducing overland flow and sediment inputs. The combination of these factors increased plant stress and plant death.

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1. Introduction

The Mississippi Delta encompasses the largest area of coastal wetlands in the US 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) [1]. 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 coastal zone and coastal Louisiana contains about 60% of the estuaries and marshes in the Gulf of Mexico [1]. Coastal wetlands are vital for protecting developed areas from storm surges, providing wildlife and fish habitat, and improving water quality [2]. 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. In this paper, we discussed two generalized impacts of petroleum-related activities: (1) impacts of oil pollution and (2) hydrologic and water quality impacts of produced water and dredging and spoil placement.

Historically, Louisiana has been the second most important oil and gas producing state, only after Alaska. Crude petroleum is a complex mixture of mainly hydrocarbons, and organic compounds of sulfur, nitrogen, and oxygen. Geologically, organic matter, which accumulated in sandstones, siltstones, and shales during Cenozoic time, was transformed into petroleum by heat and pressure [1]. 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, onshore oil and gas are produced mainly from Miocene formations, while offshore oil and gas production is from Miocene, Pliocene, and Pleistocene formations [1]. 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 1950s, and reached a peak in 1970 with 72 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. Louisiana's coastal zone had more than 500 oil and gas fields in 1990. By 1987, more than 13,000 state leases for oil and gas development had been issued and more than half of the leases are located in the coastal zone [1]. Approximately 20% of crude oil and 33% of natural gas of the nation flow through Louisiana's coastal marshes [3]. In year 2000, the revenue was $354 million for mineral royalty only and approximately 1.8 million jobs in Louisiana were related to the energy-related industries [4]. More than $12 billion in revenues from leases and production in the coastal zone were collected from 1926 to 1983. Forty percent of the US refining capacity is located within the coastal zone in the Gulf of Mexico region

[1]. Therefore, risks of oil spills have been high. In 1994, for example, a total of 3471 oil spills, due mainly to human errors or mechanical problems, were reported in state waters and lands [3].

These oil and gas development-related impacts have caused multiple ecological consequences to wetlands and coastal ecosystems, through the various stages of oil and gas development including oil exploration, site access, site preparation, drilling, production, pipeline installation, spill control and cleanup, and site closure [5]. The ecology of the coast is susceptible to oil and gas-related activities for a number of reasons: (1) the high productivity of wetland vegetation is dependent on natural hydrologic flows that provide nutrients and sediments to the Mississippi Delta; (2) artificial levees, canals, and impoundments disrupt the natural hydrologic regime in the Mississippi Delta and in turn affect plant health and sediment dynamics; (3) settling due to depressurization from oil and gas production enhances subsidence; (4) pipeline building for transporting oil and gas produced inside the coastal zone and from the Outer Continental Shelf (OCS) disrupts the natural hydrologic regime and provides additional stresses; (5) spilled oils deteriorate vegetation habitats; (6) spilled oil and produced water stress estuarine consumers by increasing turbidity, introducing toxins, etc., and (7) loss of wetland area decreases the value of the estuarine zone as a nursery ground for estuarine consumers (e.g., shrimps and fishes) and its economic value to human economy (Fig. 1).

In this paper, we review the multiple ecological impacts of oil and gas-related impacts and synthesize existing information to help researchers and managers understand how oil and gas developments affect coastal and wetland ecosystems in Louisiana, focusing on (1) plant physiology, (2) remediation efforts (in situ burning, chemical methods, bioremediation), (3) estuarine consumers including the benthic community, and (4) water quality, hydrological disturbances, and wetland loss.

2. Impacts on plant physiology

2.1. Impacts of oil spills

Wetland plants are subject to stresses related to oil and gas development, including oil spills during production and transportation (using tankers, pipelines, and tank trucks). Oil spills can have significant short-term and long-term impacts on coastal ecosystems, due to oil's physical effects and chemical toxicity, leading to decreased primary production, plant die-back, and marsh erosion. The mechanisms of these impacts are through (1) disruption of plant–water relationships, (2) direct impacts to plant metabolism, (3) toxicity to living cells, and (4) reduced oxygen exchange between the atmosphere and the soil [6,7]. If leaves are coated with spilled oils, leaf stomata are blocked, oxygen diffusion to the roots decreases, and root oxygen stress increases leading to reduction in plant growth. Further, an oil covered soil surface decreases oxygen movement resulting in more anaerobic soil conditions and increasing oxygen stress on plant roots [8]. Aerobic microorganisms in the oxidized

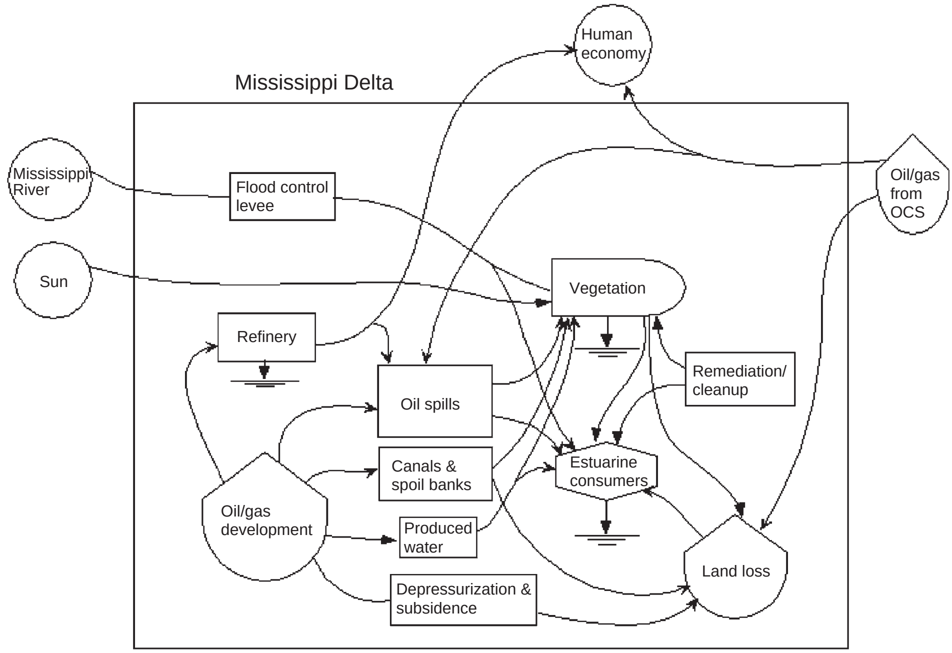

Fig. 1. A conceptual diagram of ecological impacts of oil and gas development in Louisiana wetlands. The two main types of impacts are toxicity of hydrocarbons and hydrologic changes. From [114].

sediment are more cable of degrading hydrocarbons than anaerobic microorganisms in reduced sediment of the same pH [9].

In the short term, spilled oil can form a coating on plant foliage and the soil surface, which increases temperature stress and reduces photosynthesis. These impacts are controlled by the amount of oil spilled, hydrologic conditions (tides, winds), types of dispersed oil, and sensitivity of plants (Table 1). When surface soils were contaminated with spilled oil, plants' photosynthesis was reduced for the first month and slowly recovered after that and different degrees of response among plants were monitored [7,10-11]. Plants with blocked leaves showed higher mortality rates than plants in contaminated soils, when exposed to similar levels of oil contamination [12–14]. The growth of *Spartina alterniflora*, the dominant species in Louisiana salt marshes, was affected by increasing concentrations of oil. With an oil density of up to 8 l/m^2, there was no short-term decrease in aboveground biomass, and no new shoots were detected during the second year of monitoring when the density reached 16–32 l/m^2 [12]. However, when leaves were coated with oil, a low-level oil density of 0.28 l/m^2 resulted in a significant reduction of the biomass of *Spartina alterniflora* [13].

Toxicity varies among different oil types, for example, diesel and no. 2 oil are more toxic to marsh plants than crude oil [15]. Higher organic soils of fresh marshes are more sensitive to oil spills than salt marsh through more rapid penetration and sorption of oil onto the soil. Further, *Sagittaria lancifolia* is more tolerant than

Spartina alterniflora, which is more tolerant than *Spartina patens* [7]. Lin et al. [10] studied the response over a growing season of *Phragmites australis* to an oil spill and found that the spill reduced plant stem density, plant shoot height, and aboveground biomass.

There are long-term consequences of oil spills due to the persistence of oil or petroleum fractions in marshes. Hester and Mendelssohn [16] monitored plant photosynthetic response for 5 years after an oil spill, and found no significant residual effect of oiled sediment on plant photosynthesis in high marshes in the final year, but there were recovery failures in low marshes, primarily due to increased flooding stress. They suggested that successful restoration of die-back areas in oil-impacted marshes may require sediment addition to reduce the intensity of flooding stress before vegetation transplantation. In another study, Mendelssohn et al. [17] suggested that 3 years may be needed for full recovery from accidental oil spills.

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 its biological nature and composition [18]. On the long-term effect of plants exposed to constant hydrological oil spills, Latimer et al. [19] found a correlation between the Pb level in tree rings within 2 km of an oil refinery and the history of refinery opening and dredging, implying a translocation of Pb along the xylem rays in cypress trees. Further, Marcantonio et al. [20] found that Pb uptake by cypress trees is controlled by hydrological factors, in addition to availability of Pb from oil-related pollutants.

2.2. *In situ burning*

Traditional cleansing methods to remove spilled oil (e.g., water flushing, sand blasting, sediment removal, and vegetation removal) 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 damages to both the vegetation and the underlying substrate, accelerating marsh degradation [21–23]. Specifically, intensive cleanup by flushing and oil recovery by airboats reduced the residual oil in the marsh, but also increased oil incorporation into the sediment, and increased risks of physical damages to marsh plants in Louisiana [10]. The negative impacts of physical removal of contaminated marsh plants lasted more than a year [24].

As a way to control oil spill impacts, while minimizing physical damages on impacted wetlands, in situ burning has been considered. Burning is easily controlled and causes minimal environmental problems with low cost under certain conditions [25]. In Louisiana, 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 in damaged wetlands, in situ burning has proven an efficient option, because water on the surface will allow a successful burn of the aboveground vegetative component while absorbing heat produced by the fire and preventing root burning [26]. Lin et al. [15] reported that 10 cm of water overlying the soil surface was sufficient to protect the marsh soil from burning impacts (Table 2).

Table 1
Effects of oil exposure on plants in Louisiana coastal marshes

Species	Oil type	Exposure	Duration	Research type	Effects	Reference
Distichlis spicata	Crude oil	$0.28\,l/m^2$	3 months	Field	64% decrease in live cover in mixed species assemblage	[13]
Distichlis spicata	Crude oil	$0.28\,l/m^2$	5 years	Field	Overall recovery of vegetation completed in 5 years	[16]
Juncus roemerianus	Crude oil	$2\,l/m^2$	5 weeks	Laboratory	6–30% decrease in photosynthesis for first 4 weeks and partially improved after that	[14]
Phragmites australis	Crude oil		1 year	Field	Significant reduction in stem density, plant shoot height, and aboveground biomass	[10]
Sagittaria lancifolia	Crude oil	$24\,l/m^2$	3 months	Greenhouse	No significant changes in photosynthesis; increased aboveground biomass	[7]
Spartina alterniflora	Crude oil	Up to $8\,l/m^2$	4 months	Greenhouse	No significant difference in aboveground biomass	[12]
Spartina alterniflora	Crude oil	$2\,l/m^2$	5 weeks	Laboratory	6–30% decrease in photosynthesis for first 4 weeks and partially improved after that	[14]
Spartina alterniflora	Crude oil	$0.28\,l/m^2$	3 months	Field	64% decrease in live cover in mixed species assemblage	[13]
Spartina alterniflora	Crude oil	$24\,l/m^2$	3 months	Greenhouse	50% reduction in photosynthesis	[7]
Spartina alterniflora	Crude oil	$16–32\,l/m^2$	16 months	Greenhouse	No new shoots after first harvest	[12]
Spartina alterniflora	Crude oil	$0.28\,l/m^2$	5 years	Field	Overall recovery of vegetation completed in 5 years	[16]
Spartina alterniflora	No. 2	29 mg/g dry soil	3 months	Greenhouse	Significant decrease in belowground biomass	[11]
Spartina alterniflora	No. 2	228 mg/g dry soil	3 months	Greenhouse	Constrained plant growth and microbial activities	[11]
Spartina patens	Crude oil	$0.28\,l/m^2$	3 months	Field	64% decrease in live cover in mixed species assemblage	[13]
Spartina patens	Crude oil	$24\,l/m^2$	3 months	Greenhouse	75% decrease in photosynthesis; 80% reduction in aboveground biomass	[7]
Spartina patens	Crude oil	$0.28\,l/m^2$	5 years	Field	Overall recovery of vegetation completed in 5 years	[16]
Taxodium distichum	Crude and refined oils	Chronic exposure	70 years	Field	Higher Pb uptake by tree than ambient environment	[20]

Most marsh plants showed similar reactions to in situ burning. *Spartina alterniflora* sensitivity to in situ burning of applied crude oil did not show significant differences between natural remediation and in situ burning-induced recovery over a year [27]. Similar results were reported for *Sagittaria lancifolia* [28]. Full recovery of marsh vegetation from in situ burning reportedly takes one to three growing seasons [27,29]. In situ burning may be a viable remediation method if a rapid response is needed for oil removal, and control of oil migration [27,28]. In situ burning generates atmospheric pollutants, whose chemical components are a variety of gaseous sulfur (e.g., carbonyl sulfide and carbon disulfide) and carbon compounds (methane, and carbon dioxide), and reduced alkylated naphthalene compounds from post-burn oil [30]. Similar results of air pollutants from an in situ burning of oil contaminated *Spartina alterniflora* were reported [29].

2.3. Chemical methods

The approach to cleaning up an oil spill is a decision involving trade-offs balancing physical damage to the marsh and oil toxicity [31,32]. While in situ burning is one removal method, chemical approaches using dispersants, cleansers, and solidifiers are also available. Dispersants can be added to floating oil in deep waters, but they are not practicable for use in coastal wetlands. Dispersants wash oil from surfaces, such as rocks and vegetation, and nutrients can be added to floating oil or oiled marshes to accelerate degradation of the oil (Table 2). DeLaune et al. [24] studied the impacts of dispersants on salt marshes and found that a high dose (0.3 l/m^2) reduced total and aboveground biomass significantly over a month, while a low dose (0.01 l/m^2) did not cause reduction or stimulation of plant growth. Light cleanup, by installing containment booms and applying sorbents, did not adversely affect the marsh vegetation, but stimulated plant growth when sediment was contaminated with a moderate level of hydrocarbon residue (18–50 mg/g) [10].

Application of a cleanser (e.g., COREXIT 9580) improved the survival, regeneration, and aboveground biomass growth, because application leads to a recovery of stomatal conductance, photosynthesis and respiration. The effectiveness of a cleanser in cleaning up the oil depends on oil type, delivery mode, timing, and amount of oil [31,33]. A study of the impact of oil on three species of fresh marsh plants (*Sagittaria lancifolia*, *Scirpus olneyi, Thpha latifolia*) found that *Sagittaria lancifolia* (bulltongue) was the least sensitive species to cleanser use [32]. Further, cleanser application to brackish (*Spartina patens*) and fresh (*Sagittaria lancifolia*) marshes removed oil from marsh grasses and reduced the short-term impact of oil spills on gas exchange of the vegetation, but still resulted in reduced aboveground biomass for the first growing season [34].

Another chemical method for oil spill cleanup is to apply solidifiers, which are dry, granular, hydrophobic polymers, which react with oil to form a floating, cohesive, solidified mass. Once solidified, the oil-contaminated material can be easily removed, leaving very little residue. DeLaune et al. [35] investigated the success of using a solidifier to remove spilled oil, and reported a removal rate greater than 70% in open water following a spill in coastal wetlands.

Table 2
Effects of in situ burning and chemical methods on plants in Louisiana coastal marshes

Tool	Species	Oil type	Exposure	Research type	Monitoring	Effects	Reference
Cleanser (Corexit 9850)	*Spartina alterniflora*	Crude oil	$2\,l/m^2$	Field	2 years	Increased photosynthesis and aboveground biomass, restored stomatal function	[33]
Cleanser (Corexit 9850)	*Spartina alterniflora*	Crude oil	Oil coating of plant leaves	Greenhouse	8 weeks	Increased photosynthesis and aboveground biomass, restored stomatal function	[31]
Cleanser (Corexit 9850)	*Spartina patens*	Crude oil	Oil coating of plant leaves	Greenhouse	8 weeks	Increased photosynthesis and aboveground biomass, restored stomatal function	[31]
Cleanser (Corexit 9850)	*Panicum hemitomon*	Crude oil	Oil coating of plant leaves	Greenhouse	8 weeks	Increased photosynthesis and aboveground biomass, restored stomatal function	[31]
Cleanser (Corexit 9850)	*Sagittaria lancifolia*	Crude oil	Oil coating of plant leaves	Greenhouse	62 days	Improved gas exchange	[32]
Cleanser (Corexit 9850)	*Scirpus olneyi*	Crude oil	Oil coating of plant leaves	Greenhouse	62 days	Improved gas exchange	[32]
Cleanser (Corexit 9850)	*Typha latifolia*	Crude oil	Oil coating of plant leaves	Greenhouse	62 days	Improved gas exchange	[32]
Cleanser (Corexit 9850)	*Sagittaria lancifolia*	Crude oil	Oil coating of plant leaves	Field	10 weeks	Carbon fixation recovered within 12 weeks, no significant impacts on live shoots	[34]
Cleanser (Corexit 9850)	*Spartina patens*	Crude oil	Oil coating of plant leaves	Field	10 weeks	Carbon fixation recovered within 12 weeks, reduced aboveground biomass during the first growing season	[34]
Containment booms and sorbents, leading to 18–50 mg/g^1 dry soil	*Phragmites australis*	Crude oil		Field	1 year	Higher total biomass in treatment site than no-cleanup site, faster recovery than mechanical cleanup	[10]

Dispersant application (0.3–0.01 l/m^2)	*Spartina alterniflora*	Crude oil	2 l/m^2	Laboratory	2 years	Significant reduction of biomass after a month of high dose, no significant reduction or stimulation at low dose	[24]
Fertilizer and vegetative transplantation	*Spartina alterniflora*	Crude oil	250 mg/gdry soil	Greenhouse	15 months	Significant aboveground biomass growth	[38]
Fertizer	*Spartina alterniflora*	Crude oil	2 l/m^2	Greenhouse	4 months	Increased soil microbial respiration rate, reduced hydrocarbons	[41]
Fertilizer	*Sagittaria lancifolia*	Crude oil	5–10 l/m^2	Mesocosm	18 months	Reduced oil residue, higher biomass growth	[37]
Fertilizer and vegetative transplantation	*Spartina patens*	Crude oil	100 mg/g dry soil	Greenhouse	15 months	Significant aboveground biomass growth	[38]
Fertilizer	*Alternanthera philoxeroides*	Crude oil	5–10 l/m^2	Mesocosm	18 months	Reduced oil residue, higher biomass growth	[37]
Fertilizer	*Panicum hemitomon*	Crude oil	5–10 l/m^2	Mesocosm	18 months	Reduced oil residue, higher biomass growth	[37]
Fertilizer	*Panicum hemitomon*	Crude oil		Microcosm	3 months	Maximum degradation with 22–44 mg NH^4-N/g oil	[39]
Fertilizer	*Phragmites australis*	Crude oil	5–10 l/m^2	Mesocosm	18 months	Reduced oil residue, higher biomass growth	[37]
In situ burning	*Distichilis spicata*	Gas condensate product		Field	7 months	Lower biomass than unburned site, recolonization	[26]
In situ burning	*Spartina alterniflora*	Crude oil	2 l/m^2	Field	1 year	Short-term detrimental effects, no differences between burning and natural recovery in a year	[27]
In situ burning	*Spartina alterniflora*	Crude oil	2 l/m^2	Field	1 year	Full recovery	[29]
In situ burning	*Spartina alterniflora*	Diesel	1.5 l/m^2	Mesocosm	7 months	10 cm of water over the soil surface sufficient to protect the marsh sods, not combusted or evaporated oil detected	[15]

Table 2 (*continued*)

Tool	Species	Oil type	Exposure	Research type	Monitoring	Effects	Reference
In situ burning	*Sagittaria lancifolia*	Crude oil	2 l/m^2	Field	53 weeks	Seasonal differences in recovery	[28]
In situ burning	*Spartina patens*	Gas condensate product		Field	7 months	Lower biomass than unburned site, recolonization	[26]
Addition of microbes	*Spartina alterniflora*	Crude oil	2 l/m^2	Greenhouse	4 months	No significant positive effects of the treatment	[41]
Removal of contaminated vegetation	*Spartina alterniflora*	Crude oil	2 l/m^2	Laboratory	2 years	Reduced aboveground biomass production, more susceptible to erosion, 3 years required for recovery	[24]
Soil oxidant	*Spartina alterniflora*	Crude oil	2 l/m^2	Greenhouse	4 months	No positive effects of the treatment	[41]
Solidifier		Crude oil		Field		70% oil recovered in open water	[35]
Water flushing w/ and w/out dispersant	*Spartina alterniflora*	Crude oil	2 l/m^2	Laboratory	1month, 2 years	Significant reduction in aboveground biomass after 1 month and recovered over 2 years	[24]
Water flushing and oil recovery, leading to 7–17 mg/g dry soil	*Phragmites australis*	Crude oil		Field	1 year	No significant differences, potential of physical damages	[10]

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, where soil microbes can use it for more efficient (aerobic) respiration [36]. For example, if an oil spill is relatively small scale and the floating oil is not continuous, light or no cleanup action for *Phragmites australis*-dominated marshes is recommended, because *Phragmites australis* tolerates up to 30–50 mg/g of weathered oil in the surface soil [10].

Dowty et al. [37] tested oil phytoremediation potential of different species of coastal marsh plants with fertilizer application, and concluded that *Sagittaria lancifolia* (bulltongue) and *Panicum hemitomon* (maidencane) are more suitable than *Alternanthera philoxeroides* (alligatorweed) or *Phragmites australis* (roseaucane) for use in revegetation projects of bioremediation in fresh marsh when the original vegetation fails to recover. Another study suggested that *Spartina patens* is suitable for phytoremediation in contaminated marsh with residual oil as high as 100 mg/g and *S. alterniflora* as high as 250 mg/g [38]. Another indictor of bioremediation potential is the intrinsic rate of biodegradation. Jackson and Pardue [39] conducted kinetic microcosm studies to determine the intrinsic rates of biodegradation of Louisiana crude oil in fresh marsh and found that the fresh marsh soils have high rates of degradation, 2.0%/day for the alkane fraction (C11–C66) and 6.8%/day for the polycyclic aromatic hydrocarbon (PAH) fraction.

Chemical fertilizer addition has proven successful in increasing bioremediation efficiencies and in reducing treatment periods, because nutrients increase microbial activity and thus oil degradation [11,37-38,40]. Inorganic nitrogen fertilizer is more suitable than applications of microbial products and soil oxidants in achieving oil spill cleanup in coastal wetlands [41]. Shin et al. [40] reported that the most efficient biodegradation of crude oil was achieved at a loading rate of 28.3–56.6 g N/m^2. However, the effectiveness of bioremediation is limited by marsh plant tolerance to oil-related stress. For example, *S. alterniflora* is relatively tolerant to no. 2 oil and thus is efficient for phytoremediation, but it has limited remediation usefulness at fuel oil levels of 228 mg/g dry soil, because both plant growth and microbial activity may be constrained at that level [11].

3. Estuarine consumers: benthic and nekton communities

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 benthic community structure is sensitive to petroleum hydrocarbon exposure [42,43]. The ecological and biological impacts of oil and gas development in coastal marshes and estuarine environments are broad and sometimes persistent, including growth inhibition, reduced production, altered metabolic systems, and biomagnification of hydrocarbon compounds [43]. For example, oil and gas production and transportation in coastal wetlands in Louisiana have resulted in the accumulations of PAHs and heavy metals (e.g., Pb and Zn) in impacted areas. These contaminants cause ecological impacts, including alteration of aquatic community structure and food chains (Table 3).

It has been reported that the biodiversity and population density of benthic communities are significantly lower in oil-contaminated areas [24,44-45]. Specifically, the population density of *Capitella capitata* was lower in an area contaminated by oil, and lowest in an area with a mixture of oil and dispersant [24]. There were also reduced population densities for most meiofauna species, except *Nitrocra lacustris* and *Cletocamptus deitersi* [24]. Lindstedt [44] reported that benthic organisms (e.g., mussels, oysters, grass shrimp, and crabs) accumulated higher concentrations of petroleum hydrocarbons in their tissues than did nektonic species in the same area, presumably due to the fact that the detritus-based food web is readily contaminated. Carmen et al. [46] reported that decreased population density reduced grazing pressure on microalgae by copepods in a high diesel treatment, attributable to high copepod mortality, while nematode grazing rates increased, implying possible competition between copepods and nematodes. However, total meiofaunal grazing on microalgae was reduced in high diesel treatment [46]. This affect is likely attributable to temporarily stimulated metabolic activities of surviving microbes in oil-contaminated soil community [47], and that PAH contamination enhanced microphytobenthic abundance due to either loss of benthic grazers or direct uptake of PAHs as a source from the sediment [48]. Diesel contamination of benthic microalgae in salt marsh communities also resulted in microalgal blooms in contaminated sediments, which are a response to both reduced grazing pressure and enhanced nitrogen availability, triggered by decay of organisms killed by diesel fuel toxicity [49].

Recruitment and feeding patterns can be altered by oil pollution. McCoy and Brown [50] examined barnacle recruitment to oil-treated clay tiles and found that hydrocarbons initially depressed recruitment, but this impact was reduced later by leaching or by hydrocarbon-degrading microbes. Deposit feeders (*Streblospio benedicti*, bivalves, and gastropods) were found more sensitive to metal contamination (e.g., Cu, Cr, Cd, Pb, and Hg) than particle feeders (nematodes, ostracods, copepods), suggesting feeding strategy, habitat preference, and pore-water metal availability and activity are factors affecting metal enrichment and impact on benthic meiofauna [51]. Hinkle-Conn et al. [52] found that spot did not alter feeding behaviors at moderate to high PAH concentrations, which puts them at risk for both sublethal and lethal effects of oil pollution (e.g., immune-system suppression, reduced growth, endocrine disorders, fin erosion, skin lesions, cataracts, and ultimately death). Another factor controlling metabolism of the benthic community is stress related to low dissolved oxygen and increased concentrations of several metal contaminants [53]. Mitra et al. [54] studied biota-sediment accumulation factors (BSAFs) in two PAH-contaminated coastal marshes, and concluded that different BSAFs were attributable to compositional differences in particulate organic matter (POM) and dissolved organic matter (DOM), which are rarely in equilibrium in coastal marshes.

Table 3
Effects of oil spill and cleanup activities on the benthic community in Louisiana wetlands

Species	Oil type	Exposure	Effects	Reference
Macrofauna	Crude oil	Constant exposure	Significant reduction in macrofaunal populations	[44]
Macrofauna	Crude oil	$2\,\mathrm{l/m^2}$	No immediate initial die-back, generally low densities in oiled area	[24]
Macrofauna	Crude oil	$2\,\mathrm{l/m^2}$	Significant population decrease	[24]
Macrofauna	Crude oil	$2\,\mathrm{l/m^2}$	Highly significant population decrease	[24]
Meiofauna	Crude oil	$2\,\mathrm{l/m^2}$	Stimulated population increase after 5–60 days	[24]
Meiofauna	Crude oil	$2\,\mathrm{l/m^2}$	Population increase after 30 days	[24]
Microphytobenthos	PAH	Chronic contamination	Reduced benthic grazers and increased microphytobenthos	[48]
Darter Gobies	PAH	Chronic contamination	No acclimation, no adaptation	[56]
Microbial, meiofaunal	PAH	Chronic contamination	Possible adaptation of microbial/meiofaunal community to PAH	[42]
Microalgae, mieofauna	Diesel	Chronic contamination	Competition between copepod and nematode over microalgae, increased copepod mortality	[46]
Meiofauna		Chronic contamination	Reductions in abundance and grazing activity of crustaceans, enhanced algal biomass	[55]
Meiofauna	Diesel	Chronic contamination	Initial nitrogen limitation by reduced grazer pressure and increased microalgae growth, enhanced NH_4^+ in a longer term	[49]
Barnacle	Crude oil	Chronic contamination	Higher recruitment in open-coast sites	[50]
Grass shrimp	PAH	Chronic contamination	No catches in contaminated area during summer	[45]
Macrofauna	PAH	Chronic contamination	Low diversity and low abundance	[45]
Meiofauna	PAH	Chronic contamination	Nematodes, oligochaetes, rotifers found dominant	[45]
Meifouna	PAH	Chronic contamination	No feeding habit changes, higher mortality risk	[52]
Epibenthic species	PAH	Chronic contamination	Bioaccumulation of PAHs depending on characteristics of site and PAHs, and exposure time	[54]
Macrofauna	Crude oil	Chronic contamination	Sparse population, lower biodiversity	[53]
Meiofauna	Crude oil	Chronic contamination	Deposit feeders were more sensitive to metal contamination than particle feeders.	[51]
Macrobenthic	Crude oil	Chronic contamination	Lower populations, contaminated detritus-based food web	[44]

Benthic communities can adapt to oil-related pollution. Carman et al. [42] found an adaptation potential of the sedimentary microbial/meiofaunal community to PAH stress. Later, Carmen et al. [55] reported different sensitivities of benthic communities to continued oil contamination through a comparative study of contaminated Louisiana wetlands and relatively non-contaminated wetlands in the State of Mississippi. Carman et al. [55] suggested that different tolerances to hydrocarbon contaminants led to a higher proportion of more tolerant species or increased tolerance among individual species in the Louisiana marsh. There were also reductions in abundance and grazing activity of crustaceans that led to enhanced algal biomass, reduced copepod diversity, and altered competitive interactions among meiofauna. However, Klerks et al. [56] did not find an adaptation in their examination of allozyme variation in darter gobies (*Gobionellus boleosoma*) living in coastal marshes contaminated by the discharge of produced water for the years 1950–1994.

Oil cleanup activities also generate significant stresses on benthic communities. Total meifauna densities including copepods increased after water flushing, probably due to higher grazing rates on the microflora community following microbial stimulation, and reduced predation by macroepifauna (e.g., fish, shrimp) or macroinfauna (e.g., fiddler crabs, annelids) after oil spills [24]. Vegetation removal by clipping had significant impacts on copepod community structure by decreasing *Enhydrosoma woodini* (Thistle) densities, and increasing *Cletocamptus deitersi* densities [24]. DeLaune et al. [24] also found that macroinfaunal populations did not significantly change in response to oiling (up to $2 l/m^2$), but decreased after dispersant application, and argued that dispersant with oil is more harmful to benthic fauna than oil alone. Additionally, DeLaune et al. [24] found no meiofauna mortality due to dispersant application, and that oil stimulated higher meiofauna densities after 5–60 days of oiling, and concluded that Louisiana salt marsh fauna must have a high tolerance to hydrocarbon stress and low oxygen conditions.

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 hydrologic modifications due to dredging activities. Dredging results in two interrelated impacts, creation of new water pathways and spoil placement. We will treat each of these below.

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. Produced water contains various radionuclides and volatile and semi-volatile hydrocarbon contaminants, as well as high concentrations of brine, which can contaminate surface waters and sediments [57]. All of these can cause negative biological effects [44]. The degree of ecological impacts on wetlands are 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 and boat traffic), and (5) sediment types (organic carbon content and texture) [57].

Produced water affects estuarine organisms in different ways. DeLaune et al. [58] conducted laboratory studies on the effects of the heavy metals, chromium (Cr) and lead (Pb), on biodegradation of oil in sediments collected from an area impacted by a produced water discharge. They concluded that heavy metals would not influence hydrocarbon degradation in sediment at the produced water discharge site. DeLaune et al. [9,59] studied rates of petroleum hydrocarbon degradation in sediments exposed to produced water and found that degradation rates were controlled by oxidation, redox potential, and pH. Most hydrocarbons showed rapid decay under high redox (aerobic) conditions. When fertilizer was added, degradation of *n*-alkanes increased [59]. Oysters exposed to produced water accumulated volatile and semi-volatile organic compounds [57].

4.2. The delta cycle and wetland loss in the Mississippi Delta

Coastal wetland loss is a major environmental problem in coastal Louisiana. In the rest of the paper, we discuss evidence of the causes of this land loss and the role of petroleum-related activities in contributing to wetland loss.

4.2.1. The delta cycle

In order to understand the factors related to wetland loss, it is necessary to understand the Mississippi Delta cycle. Sea-level rise stabilized near its present level after the last glaciation between 5000 and 7000 years ago [60]. Since that time, delta switching of the Mississippi River has created a series of overlapping deltaic lobes that presently form the Mississippi deltaic plain in coastal Louisiana [61,62]. Delta switching occurs about every 1000 years, resulting in new loci for sedimentation and marsh development [62,63]. Rapid land building occurs in active delta lobes, while submergence and wetland loss occurs in abandoned lobes. The Atchafalaya River is the most recent channel in the delta switching process, with subaerial expression of the new Atchafalaya Delta beginning in 1973 and this area presently has a net gain of wetlands [64,65].

Thus, the delta building process is a balance between forces that lead to growth of the deltaic land mass and those that cause deterioration. The Mississippi River is the major force leading to land gain. Overbank flooding, crevasse splays, and reworking of sands have formed a skeletal framework of natural levee ridges and barrier islands within which the delta plain has formed [62,66–69]. Crevasse splays occur where overbank flow becomes concentrated in a well-defined channel with enough scour capacity to erode permanent or semi-permanent breaks in the levee. Deposition of both coarse and fine-grained sediments initially formed wetlands (as in the emerging Atchafalaya Delta) and maintained existing wetlands. Sediments resuspended during storms are an important source of sediments to maintain marshes. Much of the sediments deposited on the surface of coastal marshes in the Mississippi Delta are resuspended during hurricanes and frontal passages from bay bottoms or transported from the nearshore area [70–72]. Once a wetland forms, organic soil formation by wetland plants is an important mechanism maintaining coastal marshes [73].

Naturally, wetland deterioration is caused by two primary forces: subsidence and wave erosion along shorelines. Geologic subsidence is caused by compaction, dewatering, and consolidation of sediments. Subsidence in deltas leads to a rate of relative sea level rise (RSLR) which is often much greater than eustatic rise. For example, while the current rate of eustatic rise is between 1–2 mm/year [74], the RSLR in the Mississippi Delta is in excess of 10 mm/year, thus eustatic sea level rise accounts for only 10–15% 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 such factors as waterlogging, anoxia, sulfide toxicity, and salt stress, and ultimately disappear [75–77]. For example, Mendelssohn and McKee [75] found that sulfide toxicity and extended periods of anaerobic metabolism in root systems are major factors leading to standing crop reduction and die-back in areas with waterlogged soil and increased salinity. This leads to a significant decrease in live aboveground biomass and stem density on freshwater marsh plants (e.g., *Panicum hemitomon*, *Sagittaria lancifolia*, and *Leersia oryzoides*) [76]. Since vertical accretion is stimulated by both outside sediment input and in situ organic soil formation, a reduction of sediment input or increasing plant stress can both lead to lowered accretion rates and wetland loss.

Wave erosion along exposed shorelines is also a cause of wetland loss [78]. This is not a major process in interior marshes but has caused large losses along shores of large lakes and bays and along barrier islands. The rate of shoreline erosion is high during hurricanes [79]. Hurricanes can also cause high loss rates in floating marshes. This is thought to be partially responsible for the high rates of land loss in the modern birdfoot delta [80]. Over the last decade (1990–2002), wave erosion has caused an increasing proportion of land loss [65].

4.2.2. Wetland loss in the Mississippi Delta in 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 [81]. High rates of land loss occurred with estimates up to 100 km^2/year [82,83], and a total area of about 3900 km^2 of coastal wetlands has been lost [84]. Land loss rates were highest in the 1960s and 1970s and have declined since, although rates remain high [85,86]. Over the past decade (1990–2002), coastwide land loss rates were about 65 km^2/year [65].

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 such factors as canal construction and impoundments, saltwater intrusion, wave erosion along exposed shorelines, a decline of suspended sediments in the Mississippi River, the effects of geologic faulting, and high relative sea-level rise (see [81,84,87-88] for a review of these issues). Most have concluded that land loss is a complex interaction of these factors acting at different spatial and temporal scales (e.g., [66-67,81,84,89–92]).

In summary, wetland loss has been caused both by a reduction of the forces leading to land gain and an enhancement of forces leading to land loss. The leveeing of the river has led to isolation of most of the delta from flooding by the river. The dense network of canals has led to both a high degree of hydrologic alteration and isolation that has reduced resuspended sediment input to wetlands and to increased saltwater intrusion. Both of these forces have increased plant stress and wetland loss. We will now consider how oil and gas activities of drilling and dredging have contributed to the problem of land loss.

4.2.3. *Effects of oil and gas production on subsidence*

As stated above, the regional rate of geologic subsidence in the Mississippi Delta is about 10 mm/year. This is due to compaction, dewatering, and consolidation of sediments. Recently, Morton et al. [88] 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 above. Thus enhanced subsidence on top of regional geologic 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.

4.2.4. *Canals and spoil banks*

Canals have been constructed in the coastal wetlands of Louisiana since Europeans first settled in the region in the early 1700s (e.g., [93]). For nearly two centuries, these canals were dredged mainly for navigation, flood protection, and drainage. After the 1930s, however, the discovery of oil and gas fields in the coastal zone led to an explosion of canal construction related to hydrocarbon production (e.g., pipeline routes and access to drilling sites). For example, in 1984, 70–80% of the permits for canal construction were issued for oil and gas development-related activities [94]. By the mid-1980s, 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 about 9.5% of wetland area [87].

When canals are dredged, the excavated material is deposited along the sides of the canal, creating an elevated bank (called a "spoil bank"). Spoil banks generally consist of highly organic marsh soil. As the spoil banks settle and dewater and organic matter oxidizes, they create a levee that runs parallel to the canal (Fig. 2). Canals and associated spoil banks alter natural hydrology in two main ways. First, most 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 [87]. If canals are long and deep enough (e.g., navigation channels that stretch from the Gulf inland to freshwater areas), they can cause significant saltwater intrusion and death of fresh water wetlands. Two notable examples of this are the Mississippi River Gulf Outlet that caused death of extensive cypress forests southeast of New Orleans and the Calcasieu Ship Channel that led to loss of extensive sawgrass marshes in southwest Louisiana [81].

In contrast to the deep canals that enhance water flow, spoil banks reduce water exchange. Much water flow in wetlands occurs as a thin sheet flowing over the surface of the marsh (e.g., sheet flow or overland flow). Sheet flow hydrology in wetlands is extremely important in controlling most biogeochemical and ecological processes in wetlands including chemical transformations, sediment transport, vegetation health, and migration of organisms [95,96]. 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 when compared to unimpounded marshes [97]. And, as discussed in the previous section, if canals are associated with oil and gas fields, subsidence is enhanced through depressurization. Ponds usually develop within 2–3 km of canals and spoil banks, and high wetland loss is associated with areas of high hydrologic changes [98].

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 ranges between 2 and 14% per year for a doubling time of 5–60 years [83]. Canals are generally dredged to a depth of 2.5 m, ranging from 20 to 40 m in width and from 100 m to 1000 m or more in length [99].

Canals also contribute to water quality problems. Normally, most nutrient and sediment-laden point and non-point source upland runoff in the Mississippi Delta would naturally flow slowly through wetlands where nutrients and sediments would be assimilated [100]. Canals short circuit this flow leading to eutrophication in open water bodies [83,101].

One way to restore wetlands from negative impacts of canal building and spoils bank is to backfill the canals. After canals are abandoned, then bulldozing spoil banks back into the canals, and revegetation follows. Turner et al. [99] examined recoveries of backfilled canals over 10 years, and found that longer canals have higher re-vegetation rates and wetland organic content is inversely related to canal depth, arguing for the usefulness of backfilling canals. However, Gosselink [102] argued that backfilling is not effective, because bare substrate in degraded marshes is too deeply flooded to sustain emergent species.

4.2.5. Impoundment

Coastal marshes exchange water, organic materials (e.g., detritus), nutrients (e.g., nitrogen and phosphorus), and organisms with surrounding estuarine waters [103], supporting estuarine fish and shellfish [104]. One impact that has affected these processes in coastal marshes is impoundment. Impoundments have been constructed

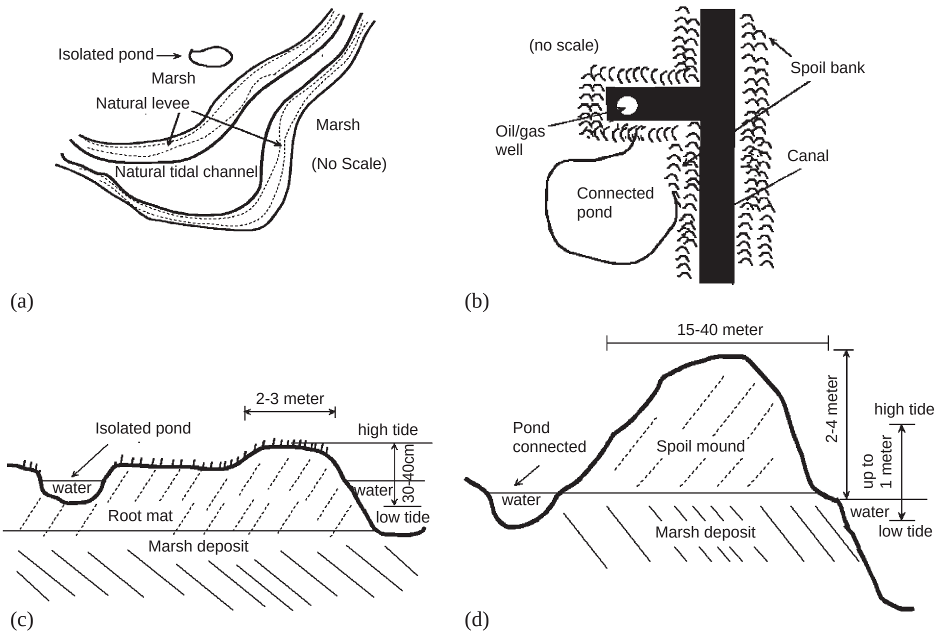

Fig. 2. Schematic diagrams of canal dredging on coastal marshes: (a) top view showing a natural tidal channel and natural levee; (b) top view of canal dredging showing straight canal and spoil bank; (c) cross-sectional view of natural marsh. Note the streamside natural levee, the shallow tidal channel, 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 that the spoil bank is higher than normal high tide preventing flooding of the marsh. From [114].

for a number of reasons. Beginning in the 19th century, impoundments were constructed for the purpose of land reclamation for urban and agricultural activities (e.g., [69,105]). Many of these reclaimed areas failed due to excessive subsidence and flooding during hurricanes. Some remain, however, mainly in the metropolitan area of New Orleans. In the 20th century, many wetland impoundments were constructed in the coastal zone to enhance conditions for waterfowl and for marsh management [106,107]. These areas were semi-impounded, that is, they were surrounded by low levees with a number of water control structures. These were called structural marsh management where management was done primarily by manipulation of water levels. Water control structures are either passive (e.g., with fixed-crest weirs) or active (variable crest weirs and flap gates to allow one-way flow of water). In addition to these purposefully constructed impoundments, large areas of the coastal zone have been inadvertently completely or partially impounded by the cumulative impacts of canal and spoil bank construction. About 30% of the total wetland area in coastal Louisiana has been impounded, either purposefully or by accident [107,108].

Impoundments have been shown to reduce tidal exchange and the influx of suspended sediments, lower accretion rates, lower productivity, and reduce the movement of migratory organisms [89,106,109,110–113]. In a study of impoundment marsh management in two Louisiana marshes, Cahoon [112] and Boumans and Day [113] reported higher deposition in unmanaged wetlands. Water control structures greatly reduced water exchange and sediment input to the managed areas.

4.2.6. *Petroleum-related activities and wetland loss*

From the above 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 increases leading to plant stress and death, rates of organic soil formation, herbivore grazing). Prior to extensive alteration by human activity, there were large gains and losses of wetlands in different parts of the deltaic plain as the river changed course. But over the past 5000–6000 years, the net result of the above processes was a large net gain of wetlands in the Mississippi Delta.

In the 20th century, the long-term net gain of wetlands was reversed and wetland area in the delta decreased by about 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 hydrologic change and dramatically increased subsidence. Morton et al. [88] have shown clearly that in the vicinity of oil and gas fields, the subsidence rate was increased by 2–3 times due to faulting associated with depressurization.

From a hydrological point of view, there have been two pervasive changes. First, the Delta has been almost 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 plain, there have been massive hydrological changes. A dense network of canals, most associated with petroleum activity, has dramatically changed the Delta. These canals allow saltwater intrusion, and reduce water and sediment movement and contribute to low accretion rates. Impoundments isolate large areas of the coastal zone from adjacent estuarine areas.

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 in situ organic soil formation. Some have attributed practically all wetland loss in the coastal zone to canals [87]. 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. But 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 because of 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 the paper. Both the supply side (inputs to the Delta) and the receiving system (the delta plain) have been affected and oil and gas activity have affected both of these. Both riverine input and resuspended inputs have been reduced. The alteration of the internal hydrology of the Delta has strongly affected sediment input to wetlands. However, the combination of elimination of riverine input and internal hydrological disruption led to dramatic wetland loss. The Atchafalaya region is an example of how riverine input can offset the impacts of canals. At the mouth of the Atchafalya River, oil and gas fields are generally not associated with wetland loss [81]. Thus, we can conclude that oil and gas activity have had a very significant impact on wetland loss. But it is one of a number of factors acting together that have caused the overall land loss problem.

5. Summary and conclusions

Petroleum exploration, production, and transportation in the Louisiana coastal zone increased dramatically from the early 20th century until the 1970s. Oil and gas production in inshore bays and wetlands of the coastal zone then decreased beginning in the 1970s but there is still a high level of transportation of oil and gas through the coastal zone from the outer continental shelf (OCS) and Louisiana Superport. These activities have generated significant impacts to 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 hydrologic 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. no.2), time of spill (e.g., after or before the growing season), density of spilled oil, and sensitivity of 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 et al. [10] 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, etc. should be considered as options. However, they did not recommend the use of heavy equipments 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 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 die-back, subsequent erosion of the marsh substrate, and the formation of small ponds, which 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 resulting from 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 up to 2–3, because of 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.

More holistic studies are needed to investigate interacting impacts of energy development. These studies should involve both scientists and stakeholders.

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