A Guide to the Fertile Fisheries Crescent with an Emphasis on Louisiana

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By

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PREFACE

I joined the faculty of Department of Zoology and Physiology at Louisiana State University in August 1972 with three assignments: develop marine biology courses, run an environmental toxicology lab titled Petroleum Refiners Environmental Council of Louisiana (PRECOL, funded by the States petroleum refiners), and teach the Human Physiology course. I knew that Louisiana was known as “Sportsman’s Paradise”. I was blessed to be the major professor of 15 M.S. students and 11 Ph.D. students over the next 43 years. I learned a lot from them.

Research in marine environmental physiology, development and teaching upper division courses titled Environmental Physiology, Marine Communities, Estuarine Ecology and Marine Ecology gave me the experience that prompted me to write the Fertile Fisheries Crescent. My 96 research publications covered a wide geographical area, including the northern Gulf of Mexico, Washington, Alaska, and England. Several papers dealt with the biological response of marine invertebrates to their environment over a larger geographical range in the Gulf of Mexico or the west coast of North America. These studies provide the global perspective for my study of the “Fertile Fisheries Crescent”.

After conducting research intermittently from 1974 through to 2007 with Dr. Stanley Rice at the National Marine Fisheries Service Lab near Juneau, Alaska, I started teaching an Academic Programs Abroad course there, titled LSU Marine Biology in Alaska. Alaska is “The Last Frontier”, as the state’s slogan proclaims. We have completed 12 program summers with 298 alumni. One component of that Marine Communities course compares the marine biology of the Alaskan ecosystem with the Fertile Fisheries Crescent in Louisiana - the concept that birthed this book.

ACKNOWLEDGEMENTS

Several people provided valuable input about material in this book. James Van Remsen and Larry Reynolds, LDWF Biologist Director, provided information about the bird and migratory waterfowl. Gene Turner, Jeff Short and Ben Dubansky provided valuable comments about the Dead Zone and petroleum hydrocarbons section. Shiao Wang provided information about barrier Islands. David Norris from the Louisiana Department of Wildlife and Fisheries provided constructive comments on the Fish and Shellfish section of the book.

Chris Austin, Director of the LSU Museum of Natural History and Tom Shirley provided suggestions on wetland reptiles and mammals. Boyd Professor Harry Roberts provided invaluable insight about coastal land loss, LSU's contribution to understanding the present Mississippi River and previous deltas, and the deltaic salt marsh plain and hydrocarbon seeps off the Louisiana coast. John Day wrote several summary papers on the effects of climate change on coastal wetlands in the Fertile Fisheries Crescent.

I am grateful to several people who improved the first draft of the book. Boyd Professor Gene Turner, from the LSU Coast and the Environment, provided constructive comments. Tom Shirley, formerly a chaired Professor of Biodiversity at the Harte Institute at Texas A&M at Galveston provided insightful comments with respect to natural history.

Ken Brown, Professor Emeritus in the Department of Biological Sciences at LSU, made several organizational suggestions and made constructive editorial comments. Shiao Wang, Professor Emeritus at the University of Southern Mississippi, provided valuable advice about the organization of the book. Bill Kelso, F. O. Bateman Distinguished Professor of Renewable Natural Resources at LSU also provided valuable editorial advice. My wife Versa Stickle corrected my writing style and supported my writing.

Chapter 1: Introduction

Dr. Gordon Gunter, of the Gulf Coast Research Laboratory in Ocean Springs Mississippi (1963), named the Fertile Fisheries Crescent as the coastal area of the northern Gulf of Mexico between Mobile Bay Alabama and Sabine Pass on the Louisiana-Texas border and extending to the edge of the continental shelf. He applied the name because of the abundance of finfish in this water mass. The Mississippi River supplies freshwater and nutrients that fuel high algal, zooplankton shellfish and finfish biomass within their food webs. Consequently, Gulf menhaden, white and brown shrimp, blue crab and oysters supply the United States with seafood, fish meal and fish oil. Unfortunately, freshwater and nutrient outflow from the Mississippi River is also responsible for the dead-water zone, an area of extremely low oxygen levels that develops off the Louisiana coast every summer. Natural oil seeps and oil leaks also stress the Fertile Fisheries Crescent. Remediation of Coastal loss is at the forefront of public debate today.

My experience at LSU prepared me to write “A Guide to Fertile Fisheries Crescent with an emphasis on Louisiana.” LSU Museum of Natural Science focuses on the Natural History of vertebrates, and the Department of Oceanography and Coastal Science is world class in studying the geology of the coastal plain and delta formation. Harry Roberts was most helpful in discussing their research. Three ecologists in the School of Oceanography and Coastal Science are experts in Landscape Ecology of the coastal zone: John Day, Nancy Rabalais, and Gene Turner. Fellow ecologists in the department of Biological Science, Ken Brown and John Fleeger, provided stimulating dialogue. My research in the Gulf of Mexico, the West Coast of North America and England provided worldwide perspective. Teaching courses in Environmental Physiology, Marine Communities, development of the LSU Marine Biology in Alaska Program, and the 11 PhD students and 15 MS graduates broadened my perspective of the importance of the Fertile Fisheries Crescent.

This book synthesizes multiple areas of study and includes the following topics: (1) Introduction (2) The role of the Mississippi River drainage system in producing the “Fertile Fisheries Crescent” (3) Geology of the Coastal plain (4) Bays, barrier islands estuaries and salt marshes (5) The economic value of the “Fertile Fisheries Crescent (6) Other Biota of the Fertile Fisheries Crescent (7) Remediating Louisiana’s current coastline (8) Summary and Future Perspectives.

For those interested in further information, the Gulf of Mexico has been the subject of several recent books which address different aspects of this magnificent sea. The role of the Mississippi River in the making of the United States is documented in The Source; How Rivers Made America and America Remade its Rivers (Doyle 2018). The geographical and historical aspects of the Gulf of Mexico are presented in The Gulf; The Making of an American Sea (Davis 2017). The Louisiana Coast: A Guide to an American Wetland (Gomez 2008) discusses our coastal wetlands. Understanding human culture in Louisiana is elucidated in The Louisiana Field Guide: Understanding Life in the Pelican State (Orgera and Parent eds. 2014).

Tropical storms and hurricanes that impacted the Gulf of Mexico over the last 100-150 years are documented and highlighted in Hurricanes of the Gulf of Mexico (Keim and Muller 2009). Texas A& M University has published a five-volume series on the "Gulf of Mexico: Origin, Waters, and Biota: Volume 1, Biodiversity ed. by Felder and Camp (2009); Volume 2, Ocean and Coastal Economy ed. by Cato (2008); Volume 3, Geology ed. by Buster and Holmes (2011); Volume 4, Ecosystem-Based Management ed. by Day and Yanez-Arancibia (2013), and Volume 5 Chemical Oceanography ed. by Bianchi (2019). Finally, A Louisiana Coastal Atlas; Resources, Economies, and Demographics displays many features graphically (Hemmerling 2017).

Chapter 2: The role of the Mississippi River drainage system in producing the Fertile Fisheries Crescent

The "Fertile Fisheries Crescent" in the northern Gulf of Mexico between Mobile Bay, Alabama and the Sabine River on the Louisiana/Texas border describes the abundant fishery in the water influenced by the Mississippi River. The term Fertile Fisheries Crescent was originally applied to the Mississippi Sound and adjacent waters by Dr. Gordon Gunter, Director of the Gulf Coast Research Laboratory in Ocean Springs Mississippi from 1955 to 1971, in three papers (Gunter 1938,1963, and 1967). The waters of the Gulf of Mexico are profoundly affected by the massive discharge of fresh water, nutrients and sediment from the Mississippi and Atchafalaya rivers. Over 55% of the United States commercial fish and shellfish catch is dependent upon estuaries for spawning and nursery functions, but estuaries (see Appendix 1 for a more detailed description of the types of estuaries) cannot function ecologically without an adequate supply, seasonal inflow, and quality of freshwater and nutrients from inland rivers. There is strong circumstantial evidence worldwide that nutrient enriched riverine discharge enhances fishery production on adjacent continental shelves; this appears to be the case with the Mississippi River, where 70-80% of Gulf of Mexico fishery landings come from waters surrounding the Mississippi River delta.

The delta of the Mississippi river is one of North America's most impressive alluvial plains, and one of the Gulf of Mexico's most outstanding geographical features. The Mississippi River is North America's largest riverine system (Davis 2017). Its outflow is responsible for both the Northern Gulf of Mexico's tremendous productivity and the dead water zone that develops west of the Mississippi River every summer. The location of Louisiana's coastline has varied from north Louisiana to 250 miles offshore. The coastline is receding today due to natural and anthropogenic factors. Shellfish and fish utilize the Fertile Fisheries Crescent for sustenance and protection from predators while young. The alluvial plain holds North America's largest Deltaic salt marsh system and an extensive Chenier Plain marsh system. Waterfowl and songbirds utilize the coastal system in their seasonal movements.

The Mississippi River drainage basin is North America's second largest drainage system, (surpassed only by the Hudson Bay basin) encompassing 1.83 million square miles and including tributaries from 32 US States and two Canadian Provinces (Fig. 1). The Mississippi River drainage basin is the fifth largest discharge river worldwide. The Mississippi River flows 2,333 miles from Lake Itasca, Minnesota to its Delta in southern Louisiana (Water Encyclopedia). Its length is second to that of the Missouri river in North America. Because of the construction of dams on the Missouri River, the average annual suspended sediment input to the Gulf of Mexico has decreased from 400 to 210 million tons per year (Milliman and Syvitski 1992). Sediment built the deltaic and chenier plains in Louisiana. By comparison, because of water withdrawal by western states (Doyle 2018), There have been five deltas, plus the Atchafalaya delta, formed over the past 7,000-8000 years (Coleman 1988; Bloom and Roberts 2009: Fig. 2). Most of the major river deltas in the world have been formed in the last 8109 years (Turner et al 2018). The floodplain forms the largest continuous system of wetlands in North America and is used by 40% of North America's waterfowl and wading birds.

Figure 1:

The Drainage Basin of the Mississippi River includes all 10 states and two Canadian Provinces which the river runs through and the other four connected rivers. The Drainage Basin is 3,263,400km squared. Source: A Geography Oral Assignment.

The Mississippi River has undergone tremendous natural and anthropogenic change over this timespan. It has carried meltwater from continental ice sheets in the geological past, and has carved out and filled valleys in response to floods and droughts. The river has also been engineered for commercial navigation and flood control. Levee construction has cut off the freshwater and sediment supply to the deltaic plain. The river has delivered nutrients and sediments to the northern Gulf of Mexico in coastal waters adjacent to the river mouth. Nutrient contribution by the Mississippi River undoubtedly accounts for the high production of fisheries in this region of the Gulf of Mexico, as well as the development of hypoxic water masses (dead water) during the summer months. Prior to leveeing and damming sections of the river basin, river sediment built the Deltaic Plain marshes west of Vermillion Bay.

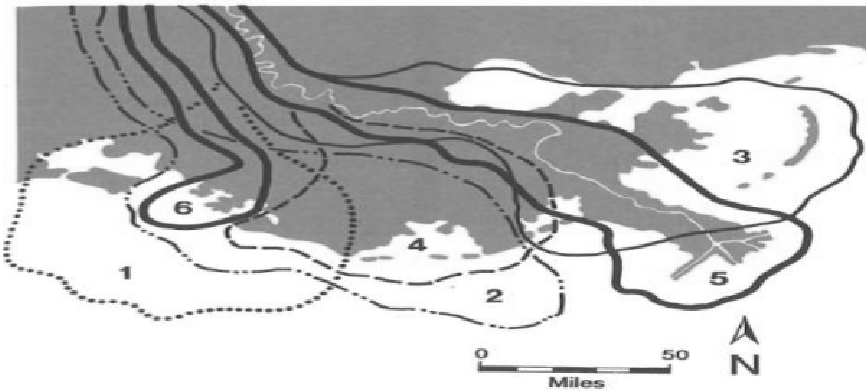

Figure 2:

Geologic map of the Mississippi River delta plain illustrates the extent of the present Holocene delta plain, as well as the mapped extent of individual deltas (numbered 1 to 6) that developed at various times in the past 7,000–8,000 years (Blum and Roberts 2009). 1-Maringouin-Sale-Cypremort about 7.5-5 kyr; 2-Teche about 5.5-3 kyr; 3-St. Bernard about 4-2 kyrs ; 4- Lafourche about 2.5-0.5 kyr; 5- Plaquemine-Balize about 1.3-0 kyrs; Atchafalaya-Wax Lake about 0.5-0 kyr.

When the main Mississippi River channel occupied the central and western parts of the alluvial valley, fine-grained sediments were transported westward to form the Chenier plain and its marshes west of Vermillion Bay (Fig. 3). The Chenier plain was built by sediment emanating from these deltas and is now suffering marsh loss due to sea level rise, lack of sediment supply, and the barrier island effect on Cameron parish. This marsh loss puts Lake Charles in danger of being lost. Sediment has been pumped into the marsh around Cameron which has built marsh (Smith 2021).

Sediment supply to the lower Mississippi River has been severely reduced by damming the Missouri River. Other engineering activities such as meander cutoffs, river-training structures, and bank revetments as well as soil erosion controls have trapped sediment, eliminated sediment sources, or protected sediment that was once available for transport episodically throughout the year. Removing major engineering structures such as dams would probably not restore sediment discharge to a pre-1900 state, because of the numerous smaller engineering structures and soil-retention works throughout the Missouri-Mississippi system (Meade and Moody 2009).

Coastal eutrophic (elevated nutrients and phytoplankton primary production) and hypoxic or dead zones (lower than normal oxygen levels), which stress and kill marine animals; <2ppm O_2), are occurring with greater frequency in the world's coastal areas. Two conditions must be met to cause the development of dead zones; (1) elevated nutrient levels to fuel algal blooms, and (2) salinity stratification. The development of dead zones around the world is well documented by Kirchman (2021).

Tremendous quantities of nitrate and phosphate are added to the Fertile Fisheries Crescent via the Mississippi and Atchafalaya rivers. Five Corn Belt states (Ohio, Indiana, Illinois, Iowa, and Minnesota) grow about half of the corn and soybeans in the United States. Corn yields have increased from 20-30 bushels per acre in 1800 to 160 bushels per acre in 2018 (Fig. 5.2; Kirchman 2021). Changes in agriculture have contributed to the higher yields including: 1. Use of hybrid corn; 2. Use of herbicides and pesticides: 3. An increase in planting density of corn; and 4. An increase in fertilization of corn that also increased nitrate and phosphate concentrations in river water. Added nutrient levels from the Mississippi and Atchafalaya have fueled increased algal primary production in the coastal waters of one of the most productive fishing grounds in the world. This is the primary cause of the dead zone in Louisiana.

Figure 3:

Environments where sediment is deposited and patterns of sediment dispersal in Gulf waters. Predominant winds from the southeast move sediment northwestward from the Birds-foot delta (Scott 1969; Figure from Spearing 2015).

Drs. Nancy Rabalais and Gene Turner have been studying the Louisiana dead water zone since 1975. The Dead Zone in Louisiana occurs west of the Mississippi River between March and October each summer, in continental shelf water between 10 and 60m depth.

The dead water area is larger than New Jersey and has been increasing since the 1980's (Rabalais et al. 2002). The Dead Zone affects up to the lower 80% of the water column this is the largest bottom-water hypoxic area in the western Atlantic, and rivals the Dead Water Zones in the Baltic and Black seas. Increased input of nitrogen and phosphorous stimulates increased primary production by phytoplankton blooms, and salinity stratification allows dead phytoplankton, zooplankton and their fecal pellets to sink to the ocean floor where bacterial (archaea) oxidation depletes the oxygen level to stressful levels for animals. Tropical storms and hurricanes disrupt the stratified water column and may render the entire water column oxygenated until the water column becomes stratified again.

The cumulative effects of global climate change, increased population, and more intense industrialization and agribusiness, will likely continue and intensify the course of eutrophication in estuarine and coastal waters. As a result, noxious and harmful algal blooms, reduced water quality, loss of habitat and natural resources, severity of hypoxia and the extent of hypoxia in estuaries and coastal waters will intensify. Global climate change will likely result in higher water temperatures, stronger stratification, and increased inflows of freshwater and nutrients to coastal waters in many areas of the globe. History and model forecasts suggest that these changes will result in enhanced primary production, higher phytoplankton and macroalgal standing stocks, and more frequent or severe hypoxia. The negative consequences of increased nutrient loading and stratification may be partly, but only temporarily, compensated for by stronger or more frequent tropical storm activity in low and mid-latitudes. In anticipation of the negative effects of global change, nutrient loadings to coastal waters need to be reduced, so that further water quality degradation is prevented (Rabalais et al 2014).

Swimming invertebrates and fish avoid the dead water zone, while bottom dwelling animals die. Their populations are replenished by larval recruitment over winter. Tolerance of hypoxia/anoxia varies by taxonomic group (Rabalais et al 2001). Demersal fish and brown shrimp aggregate at the edge of the Dead Zone where they are harvested (Craig 2012). An Ecospace model predicts that, except for red snapper, there is an increase in fish biomass and fisheries landings because of an increase in primary production, which outweighs the decrease in survival under hypoxic conditions (DeMutsert et al 2016). Juvenile lesser blue crabs (Callinectes similis) are coastal and avoid hypoxia whereas juvenile blue crabs (C. sapidus), which are estuarine and exposed to diurnal variation in oxygen levels, move more but do not avoid hypoxia (Das and Stickle 1994). White and brown shrimp also detect and avoid hypoxia in laboratory experiments (Renaud 1986).

We know the cause of the development of the Dead Zone west of the Mississippi River every summer with certainty. We do not know the effects of the development of the Dead Zone on the area outside of it in the Fertile Fisheries Crescent so well.

The Fertile Fisheries Crescent and the entire northern Gulf of Mexico are not pristine because of natural hydrocarbon input from oil seeps, which accounted for 95% of hydrocarbon input prior to the Deepwater Horizon Oil leak. Oil and gas seeps are numerous in the Gulf of Mexico, and are biogenic, thermogenic, or mixed in origin. These cold seeps have been well studied at the west Florida escarpment and the Louisiana slope (Willmer et al 2005). Seeps occur as gases, liquids, asphalts, and tars. Biogenic gas seeps have a microbial metabolic origin. Thermogenic hydrocarbons rise to the surface from more deeply buried source rock horizons or accumulations, and these hydrocarbons will persist as long as oil and gas continue to migrate to the seafloor. Seepage of oil and gas into marine sediments initiates a complex biogeochemical cycle.

A unique ecology has evolved in association with oil and gas seeps based on chemosynthesis and symbioses. Consortia of microbial species mediate the geological and biogeochemical processes essential for supporting what are commonly referred to as cold-seep communities (Fisher et al. 2007). Carbon dioxide fixation into organic carbon and ATP generation allow a symbiotic relationship to exist between extremophile bacteria (Archea) and animal hosts (Duttagupta et al 2008). At these locations, bacteria oxidize hydrocarbons to carbon dioxide or bicarbonate ions, which favor the formation of hard ground substrate in otherwise mostly muddy environments (Roberts and Feng 2010). Thermogenic oil and gas seeps and biogenic gas seeps are pervasive and intrinsic features of the Gulf of Mexico **(Fig. 4)**. Thermogenic seeps will persist when oil and gas migrate from more deeply buried rock formations to the seafloor. The seep sites, in water depths from 180 to 900m, span an area from the Mississippi River delta to the upper Texas continental slope (Kennicutt et al 1988).

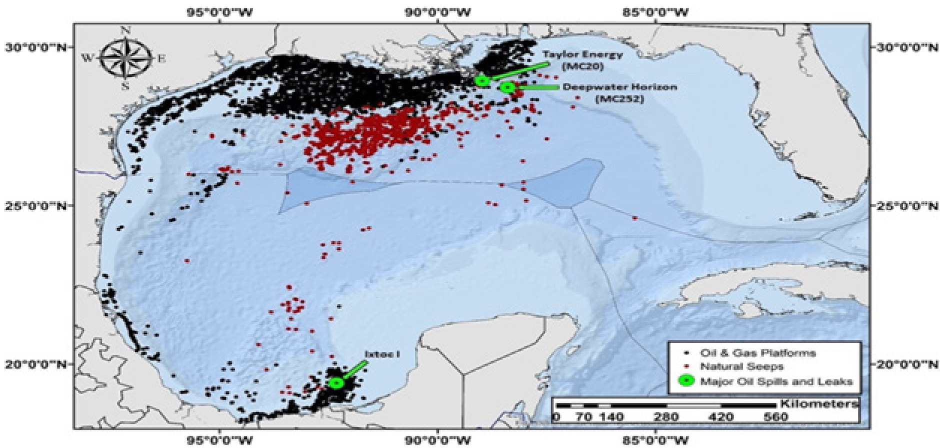

Figure 4:

A Comprehensive Baseline of Hydrocarbon Pollution in Gulf of Mexico (Nature).

An explosion on the Deepwater Horizon drilling rig on April 27, 2010 led to a catastrophic oil and gas blowout at the BP operated Macondo Prospect (MC252) at 1522 m depth, in the east Mississippi Canyon area of the northern Gulf of Mexico. The platform was located 66 km off the coast of Louisiana. When the well was capped 87 days later, a vast area of the northern Gulf of Mexico was polluted with oil. An estimated 3.19 million barrels of oil were released into the ocean during the leak, in addition to several hundred thousand tons of hydrocarbon gases. Approximately 7000m3 of oil-dispersing agents were added to the oil, with 40% of it added to the gusher at the seabed and 60% to surface oil slicks offshore.

The deep-sea application of dispersant contributed to formation of large plumes of hydrocarbon rich water that spread laterally in deep-water (>1000 m depth) and led to contamination of deep-water habitats. Much of the oil surfaced and formed oil slicks that reached a size of >40,000 km2 at their maximum on June 19, and that cumulatively covered >112,000 km2 of the ocean surface (DWH-NRDA, 2015). The weathering process produced oily aggregated materials which partly sank to the seabed as "marine snow". Oil slicks were pushed toward the coast by ocean currents, and wind and waves washed onto the shoreline in Louisiana, Mississippi, Alabama, and Florida. More than 2100km of shoreline was affected, including beaches, marshes, wetlands and estuaries that are important habitats and nursery areas for a wide range of species. Fisheries in parts of the northern Gulf of Mexico were temporarily closed due to public concern that seafood might have been contaminated with hydrocarbons.

Evidence of the oil leak coming ashore in June of 2010 was documented through shoreline contamination assessments, by visually surveying the coast and by the deployment of passive sampling devices constructed from additive-free, low-density linear polyethylene membranes (Allan et al 2012: Stickle et al unpublished data).

A comprehensive database of shoreline oiling exposure was constructed, as determined by field and remotely-sensed data to support oil exposure and injury quantification. The data presented from this database simplified oil exposure classes for both beaches and coastal wetland habitats: the classes were derived by integrating intensity and persistence of oiling on the shoreline over time. As a result, oiling was documented along 2113 km of 9545 km of surveyed shoreline - an increase of 19% from previously published estimates, representing the largest marine oil spill in history by length of shoreline oiled (Nixon et al 2016).

These data were used to generate maps and calculate summary statistics to assist in quantifying and understanding the scope, extent, and spatial distribution of shoreline oil exposure. Louisiana shores and wetlands received the bulk of oiling from the Deep-Water Horizon Oil Leak, accounting for 82% of the beaches oiled and 99% of oiled wetlands **(Fig. 5).**

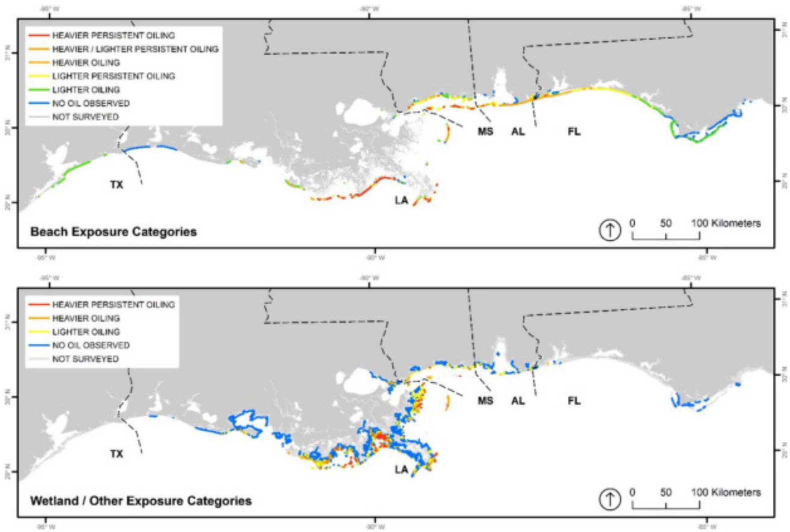

Figure 5:

Kilometers of shoreline oiled by Deepwater Horizon oil exposure by categories for beaches, and coastal wetland habitats. (Nixon et al. 2016).

The objective of the Allan et al (2016) study was to assess bioavailable polycyclic aromatic hydrocarbons (PAHs) in the coastal waters of four Gulf Coast states that were impacted by the spill. For over a year, beginning in May 2010, passive sampling devices were used to monitor the bioavailable concentration of PAHs. Prior to shoreline oiling, baseline data were obtained at all the study sites, allowing for direct before-and-after comparisons of PAH contamination. Significant increases in bioavailable PAHs were seen following the oil spill at Grand Isle, Louisiana (Fig. 6), however, pre-oiling levels were observed at all sites by March 2011. A return to elevated PAH concentrations, accompanied by a chemical fingerprint like that observed while the site was being impacted by the spill, was observed in Alabama in summer, 2011. Chemical forensic modeling demonstrated that elevated PAH concentrations are associated with distinctive chemical profiles.

The 2010-2011 Stickle et al study (reported here) of four bay systems along the Louisiana coast documented low level PAH contamination in Lake Calcasieu (315-425ng per strip), Timbalier Bay (320-700 ng per strip) and East of the Mississippi River (180-730 ng per strip). Deepwater Horizon's PAH heavily contaminated eastern Barataria Bay during the summer and fall of 2010 (1000-9100 ng per strip: Fig. 7). Quantitative values per strip are not comparable between the two studies.

Coastal Louisiana is chronically affected by low level PAH exposure from oil seeps and oil spills. Several studies in the Fertile Fisheries Crescent found no level of concern among vulnerable children through consumption of seafood in water potentially impacted by the Deepwater Horizon oil leak (Sathiakumar et al 2017).

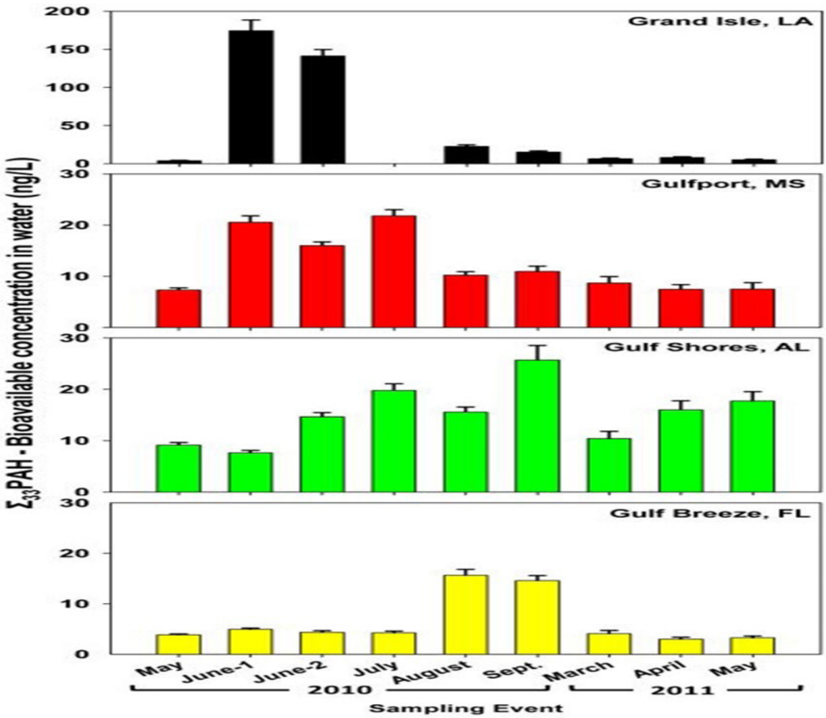

Figure 6:

Bioavailable concentration of PAHs in coastal waters of the Gulf of Mexico (Allan et al. 2012).

By January 2016, more than 500 research papers addressing a wide range of environmental aspects of the oil leak had been published in peer reviewed journals.

The environmental research literature on the Deepwater Horizon oil leak can be summarized under four themes: (1) the environmental fate of spilled oil and gas; (2) biological/ecotoxicological effects in off-shore ecosystems; (3) effects on nearshore and coastal sites; and (4) effects on long-lived marine organisms. The term offshore is beyond the northern Gulf of Mexico shelf edge (>200 m depth), while the term near-shore represents the areas stretching from estuarine waters to the continental shelf

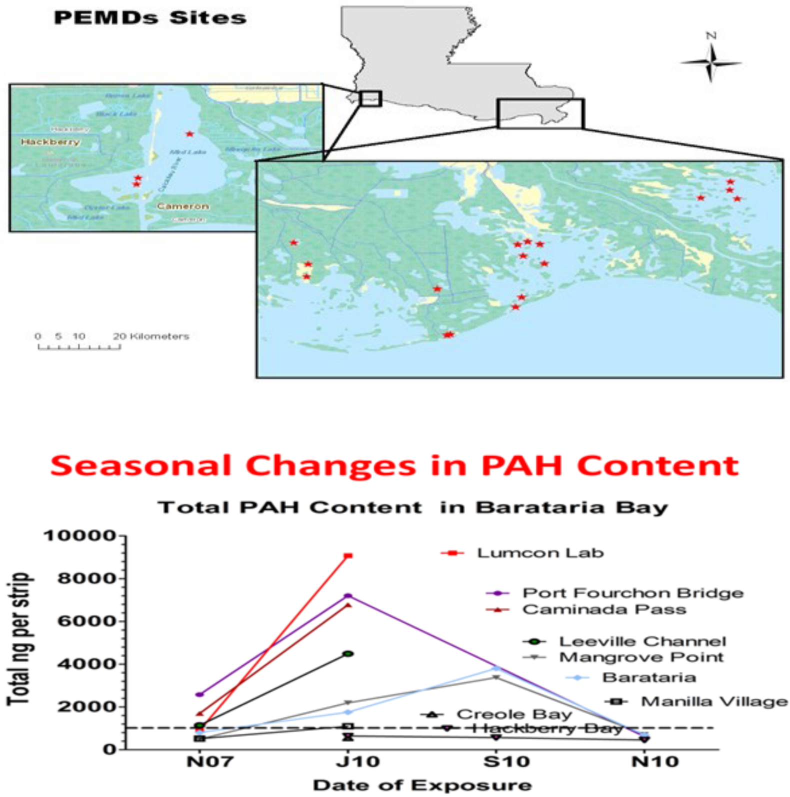

Figure 7:

Sampling sites (A) and Bioavailable concentrations of PAHs in Barataria Bay, Louisiana (B) before and after Deepwater Horizon oil came ashore in the summer of 2010 (Stickle et al. unpublished).

edge (0 m–200 m). Oil dispersants were not used near shore, or in connection with coastal cleanup operations during the Deepwater Horizon response. Nonetheless, experimental studies have addressed issues related to dispersant application in oiled coastal systems because a combination of oil and dispersants came ashore. The effects of oil on organisms may be at the individual, organ and tissue, clinical indicator, or mechanism of action level via adsorption, ingestion, inhalation, feeding or aspiration exposure routes (Beyer et al 2016). This discussion will focus on trophic level and individual responses to the Deep-Water Horizon oil leak.

Parsons et al. (2015) observed that, overall, the phytoplankton abundance was only 15% as high in 2010 compared to the baseline data from 1994,1996,1998, 2001, 2003, and 2008, and that the species composition of the phytoplankton community moved towards diatoms and cyanobacteria and away from ciliates and phytoflagellates. The trophic impacts of the purported lower abundance of phytoplankton in 2010, coupled with the observed assemblage shift, are unknown.

Following the 2010 Deepwater Horizon blowout, most surface oil remained more than 40 km offshore, precluding a reliable estimation of offshore avian mortality based on shoreline counts. Using an exposure probability model as an alternative approach, (Haney et al 2014a) it is estimated that between 36,000 and 670,000 birds died in the offshore Gulf of Mexico due to exposure to oil from the Deepwater Horizon, with the most likely number near 200,000. Two separate approaches, a carcass sampling model and an exposure probability model, provided estimates of bird mortalities of 600,000 and 800,000 respectively.

Most mortality affected four species: laughing gull Leucophaeus atricilla (32% of the northern Gulf of Mexico population killed), royal tern Thalasseus maximus (15%), northern gannet Morus bassanus (8%), and brown pelican Pelecanus occidentalis (12%). Declines in laughing gulls were confirmed as ~60% reductions in National Audubon Society Christmas Bird Count data for 2010-2013 along the Gulf coast. Effects on population level in apex predators of this magnitude likely had effects on prey populations which warranted careful assessment (Haney et al. 2014b).

The Deepwater Horizon Oil leak resulted in many predator species being killed by oiling, which led to a large increase in the Gulf Menhaden population. This, in turn, increased competition among the Gulf Menhaden for food, thereby resulting in their poor physiological condition and low lipid content during 2011 and 2012 (Short et al 2017). This finding provided strong evidence for an ecosystem effect, because of seabird, bottlenose dolphin, wading bird and fish-eating marsh bird mortalities leading to predator release. Low lipid content in Gulf Menhaden likely caused them to become “junk food” of little nutritional value to their predators, as has been previously documented for seabird breeding in the North Sea, Gannets feeding on fishery waste, and Stellar sea Lions feeding on Pollock (Short et al 2021).

The oil spill resulting from the explosion of the Deepwater Horizon drilling platform also initiated immediate concern for common bottlenose dolphins in sensitive coastal habitats. To evaluate potential sublethal effects on dolphins, health assessments were conducted in Barataria Bay, Louisiana - an area that received heavy and prolonged oiling - and in a reference site, Sarasota Bay, Florida, where oil was not observed. Dolphins were temporarily captured, received a veterinary examination, and were then released.

Dolphins sampled in Barataria Bay showed evidence of hypoadrenocorticism, consistent with adrenal toxicity as previously reported for laboratory mammals exposed to oil. Barataria Bay dolphins were 5 times more likely to have moderate to severe lung disease, generally characterized by significant alveolar interstitial syndrome, lung masses, and pulmonary consolidation. Of 29 dolphins evaluated from Barataria Bay, 48% were given a guarded or worse prognosis, and 17% were considered poor or grave, indicating that they were not expected to survive. Disease conditions in Barataria Bay dolphins were significantly greater in prevalence and severity than those in Sarasota Bay dolphins, or in other previously reported wild dolphin populations. Many disease conditions observed in Barataria Bay dolphins are uncommon, but consistent with petroleum hydrocarbon exposure and toxicity (Schwacke et al 2014).

The polycyclic aromatic hydrocarbons in oil cause teratological (developmental) abnormalities of all fish embryos (Incardona and Scholz 2018). Prior studies on pink salmon and Pacific herring showed such abnormalities in laboratory studies after the Exxon Valdez oil spill. Heart abnormalities have also been found in fish from the northern Gulf of Mexico. Toxicity from exposure to crude oil can affect populations of fish that live or breed in oiled habitats, as was also seen following the Exxon Valdez oil spill. Dubansky et al (2013) studied the effects of Deepwater Horizon oiled sediment from Grand Terre, Louisiana on embryos of resident Gulf Killifish Fundulus grandis: Gulf killifish were collected from an oiled site (Grande Terre, LA) and two reference locations (coastal Mississippi and Alabama), and monitored for evidence of exposure to crude oil. Killifish collected from Grande Terre had divergent gene expression in the liver and gill tissue coincident with the arrival of contaminating oil, and up-regulation of cytochrome P4501A (CYP1A) protein in gill, liver, intestine and head kidney for over one year following peak landfall of oil (August, 2010) compared to fish collected from reference sites. Furthermore, laboratory exposures of Gulf killifish embryos to field-collected sediments from Grande Terre and Barataria Bay, LA also resulted in increased CYP1A and developmental abnormalities compared to exposure to sediments collected from a reference site.

These data are predictive of impacts upon population level in fish exposed to sediments from oiled locations along the northern Gulf of Mexico's coast.

The Deepwater Horizon disaster oiled the upper surface water spawning habitats of many commercially and ecologically important pelagic fish species. Consequently, the developing embryos and larvae of tuna, swordfish, and other large predators were potentially exposed to crude oil derived polycyclic aromatic hydrocarbons (PAHs). Fish embryos are generally very sensitive to PAH-induced cardiotoxicity, and adverse changes in heart physiology and morphology can cause both acute and delayed mortality. Cardiac function is particularly important for fast-swimming pelagic predators with high aerobic demand.

Offspring for these species develop rapidly at relatively high seawater temperatures. Incardona et al (2014) studied the impacts of field-collected Deepwater Horizon (MC252) oil samples on embryos of three pelagic fish: bluefin tuna, yellowfin tuna, and amberjack. They documented that environmentally realistic exposures (1–15 μg/L total PAH) cause specific dose dependent defects in cardiac function in all three species, with circulatory disruption culminating in pericardial edema and other secondary malformations. Each species displayed an irregular atrial arrhythmia following oil exposure, indicating a highly conserved response to oil toxicity. A considerable portion of Gulf water samples collected during the oil leak had PAH concentrations exceeding toxicity thresholds observed in their study, indicating the potential for losses of pelagic fish larvae.

Subtidal oyster reef populations were monitored by state resource agencies prior to and after the DWH incident (Grabowski et al 2017). Fishery-independent surveys were conducted in each of the following Gulf States, using either diver-collected quadrat samples (Louisiana, Mississippi, Florida) or dredge surveys (Texas) at fixed sites. They assessed trends in oyster density of recently settled (spat), juvenile to young adult (seed), and adult (market) oysters.

Compared to baseline values (average 2006-2009), the densities of spat, seed, and market oysters were extremely low in 2010, with little recovery in 2011 and 2012 in areas in eastern Louisiana-Mississippi. In contrast, densities of all oyster size classes in western Louisiana and Texas, outside the footprint of oil or freshwater release from the Davis Pond and Carnarvon structures, and juvenile oysters in Apalachicola Bay, Florida, revealed no consistent pattern of change in 2010 compared to baseline levels. Thus, major declines in oyster populations occurred within the northern Gulf of Mexico in summer 2010, and populations remained low through 2012. The spatial footprint of this decline is largely coincident with the oiling and freshwater diversion response activities associated with the Deepwater Horizon oil leak. Fisheries-independent datasets offer much needed baseline data that can be used to assess potential impacts from disturbances.

A basic overview of the chemistry and biology of oil spills in coastal wetlands includes an assessment of the potential and realized effects on the ecological condition of the Mississippi River Delta and its associated flora and fauna (Mendelsshon et al. 2012, Fig. 8; Figure 1). This assessment should serve as a framework within which to examine long term effects of salt marsh oiling.

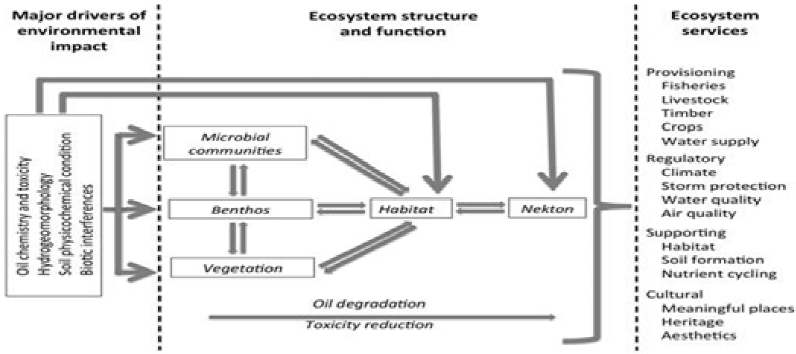

Figure 8:

The drivers of environmental impacts during an oil spill include the oil, which changes in composition and toxicity over time, and other stressors and disturbances acting on the ecosystem. The environmental drivers may influence coastal wetlands directly by affecting the habitat or indirectly by way of various interacting ecosystem components. The final outcome may be expressed at higher trophic levels, such as fisheries, and in the numerous wetland-derived ecosystem services on which society it relies. We provide an overview of the impacts of the Deepwater Horizon oil spill from this theoretical context (Fig. 1 Mendelsshon et al. 2012).

Salt marshes in northern Barataria Bay, Louisiana were studied for 3.5 years after the marshes were impacted by the Deepwater Horizon oil leak (Lin et al 2016). Marshes were exposed to varying degrees of Deepwater Horizon oiling, to determine the effects of oiling on shoreline-stabilizing vegetation and soil processes. In moderately oiled marshes, surface soil total petroleum hydrocarbon concentrations were ~ 70 mg g- 1 nine months after the spill. Though initial impacts of moderate oiling were evident, Spartina alterniflora and Juncus roemerianus above ground biomass and total live belowground biomass were equivalent to reference marshes within 24–30 months post spill. In contrast, heavily oiled marsh plants did not fully recover from oiling, with surface soil total petroleum hydrocarbon concentrations exceeding 500 mg g- 1 nine months after oiling. Initially, heavy oiling resulted in near complete plant mortality, and subsequent recovery of live aboveground biomass was only 50% of reference marshes 42 months after the spill. Heavy oiling also changed the vegetation structure of shoreline marshes from a mixed Spartina–Juncus community to predominantly Spartina; live Spartina aboveground biomass recovered within 2–3 years, whereas Juncus showed no recovery. In addition, live belowground biomass (0–12 cm) in heavily oiled marshes was reduced by 76% three and a half years after the spill. Detrimental effects of heavy oiling on marsh plants also corresponded with significantly lower soil shear strength, lower sedimentation rates, and higher vertical soil-surface erosion rates, potentially affecting shoreline salt marsh stability. These effects will exacerbate increased salt marsh loss post Deepwater Horizon oil leak.

Deepwater Horizon oil spill also impacted salt marsh fiddler crabs (Uca spp.). Fiddler crabs influence marsh ecosystem structure and function through their burrowing and feeding activities, and are key prey for marsh and estuarine predators. Oiling had a negative effect on fiddler crab burrow densities, burrow diameter and species composition. Given the spatial and temporal extent of data analyzed, this synthesis provides compelling evidence that the Deepwater Horizon spill suppressed populations of fiddler crabs in oiled marshes, likely affecting other ecosystem attributes, including marsh productivity, marsh soil characteristics, and associated predators (Zengel et al, 2016).

Although recovery from many of the direct effects of exposure to the Deepwater Horizon oil leak has occurred at the macro level, sublethal effects will likely last much longer. Key results of published research on the effects of oiling on coastal habitats, from microbes to vertebrates, have been summarized. There were immediate negative impacts in the moderately to heavily oiled marshes, and on the resident fish and invertebrates. Recovery occurred in many areas within two years following the oiling and continued into 2016, but permanent damage from heavily oiled marshes has resulted in eroded shorelines.

Organisms, including microbial communities, invertebrates, and vertebrates, were harmed by acute and chronic hydrocarbon exposure. However, the inherent variability in populations and levels of exposure, compounded with multiple stressors, often masked what were expected, predictable impacts. The effects are expected to continue to some degree or the marsh ecosystem will reach a new baseline condition in heavily damaged areas (Rabalais and Turner 2016).

Chapter 3: Geology of the Coastal Plain

The shoreline has varied dramatically with ice ages and interglacial periods. 60-66 million years ago, the coastal plain of Louisiana extended 250 miles into the Gulf of Mexico in deposits 50,000 to 60,000 feet thick. Shoreline positions passed through North Louisiana during the great ice ages of the Lower Tertiary (66-58 million years ago) through the Pleistocene (0.1-2 million years ago). Louisiana's vast coastal plain has developed in just the last 7,500 years (Spearing 2015; Fig. 11). Three data sets of high-resolution sea level curves through time have been developed and compared for the 20,000 years since the time of the Wisconsin Ice sheet to document these sea level changes (Balsillie and Donoghue, 2011).

The key ethical question is whether we should we try to maintain our coastal plain at its present location, or allow the coastal plain to vary in location as it has in the past.

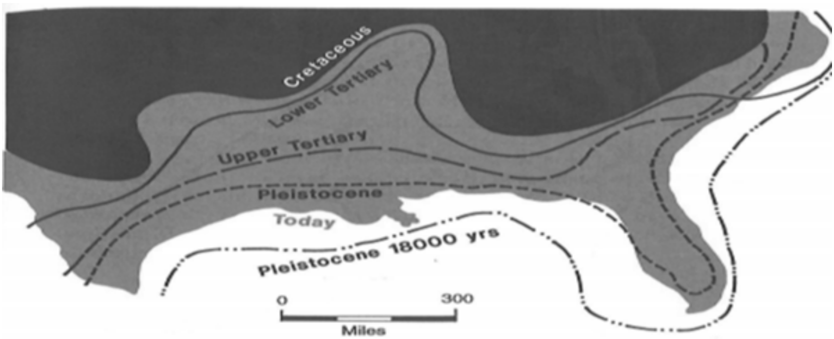

Figure 9:

Shoreline position along the Gulf of Mexico during the past 60 million years (Walker and Coleman 1987; Spearing 2012).

Dr. R. J. Russell, founder of LSU's Coastal Studies Institute, was one of the first researchers to recognize that Louisiana was losing wetlands, and that coastal plain marshes were changing composition. The disappearance of Louisiana's coastal wetlands has long been of concern, given the ecological services and societal values they provide as described by Dr. Jim Gosselink, an early chairman of the Department of Marine Sciences at LSU, and his colleagues. Reasons for the loss of Louisiana's coastal wetlands are numerous and have complex interactions. There was comparatively little scientific focus on this problem until Gagliano and Van Beek wrote about wetland loss (1970). By the early 1980s, Gagliano and others determined that there was a wetland loss rate of 130 sq km/yr, which further encouraged coastal researchers to investigate the various processes contributing to this significant problem for coastal Louisiana. They offered suggestions on how to slow or reverse wetland loss (Gagliano et al 1981).

Causes of Louisiana's wetland loss belong in five general process categories: (1) oceanographic (sea level rise, wave erosion, and saltwater intrusion), (2) geologic (subsidence from sediment loading and dewatering – compaction, faulting, and sediment deprivation), (3) biologic (nutria and muskrat marsh destruction) (4) catastrophic events (tropical storms and droughts), and (5) human activities (levee and dam construction, canal dredging, agricultural impoundments, and fluid withdrawal).

Levees were built along the Mississippi River, extending throughout the alluvial valley, to the modern Belize or "birdfoot" delta. They stopped overbank flow and crevassing during annual floods. These flood-related processes had supplied the coastal plain with sediment that helped to counterbalance subsidence, build substrate, and supply nutrients for wetland plant communities. Early researchers recognized that the coastal plain went through cycles of "construction" and "destruction" depending on the location of the mouth of the Mississippi River (Fisk et al 1954; Kolb and Van Lopik 1958). Delta-building and progradation of the coast occurred when the Mississippi River occupied a given location, while the rest of the delta plain was starved of sediment and slowly deteriorated. Switching river courses was found to occur on a frequency of ~1000-1500 years. Explained as the "delta cycle" by Roberts (1997), switching positions of the main Mississippi River channel built the Louisiana coastal plain over the last ~7000 yrs, a period when the rate of sea level rise dramatically slowed following a rapid rise from the latest glacial maximum ~18-20 km/yr before today.

Coastal researchers agree that the leveeing of the Mississippi River in the early 20th century, which cut off a sediment supply to the coastal plain, is a main cause which led to increasing rates of Louisiana's coastal plain land loss. Dredging of access canals to oil and gas drilling and production sites is an additional cause of land loss by removing marsh, causing saltwater intrusion, and altering sedimentation and marsh hydrology (Turner and McClenachan 2018). Stone recognized that the combined effects of sea level rise and subsidence was enlarging our coastal bays (Georgiou et al 2005). Because of increasing fetch (distance that winds blow over water), erosive wave energy along the marsh perimeter around the bays was also increasing. In addition to quantifying this wave energy that causes the marsh perimeter to retreat, they promoted rebuilding Louisiana's barrier islands as buffers to incoming normal marine wave energy as well as storm swells.

Construction of dams in the Mississippi River drainage basin has caused the sediment load of the river to decrease by > 50%. A study by Blum and Roberts (2005), using a sediment budget for the Mississippi River and growing accommodation space in the subsiding coastal plain, projected loss of most of the present coastal wetlands by 2100 unless large-scale restoration measures are initiated. An increasing rate of sea level rise and decreasing sediment load carried by the Mississippi River results in a bleak outlook for the coastal plain.

The survival and productivity of Louisiana's coastal plain marshes depends on the influx and accumulation of sediment, which stimulates plant growth and builds substrate to offset the negative effects of subsidence. Sediment accumulation and subsidence rates are difficult to measure. 137Cs dating was used to measure sedimentation rates in accreting Louisiana marshes, documented higher sedimentation rates in streamside marshes compared to immediately adjacent inland marsh zones. This allows the streamside marshes to better keep pace with relative sea level rise (Delaune et al 1978). They pointed out that accurate measurements of subsidence and sedimentation are needed to predict long term trends in marsh stability. This research led to the documentation that interior marsh dieback and pond formation was a result of prolonged flooding and resulting soil waterlogging, inducing anaerobic soils, the accumulation of toxic hydrogen sulfide, and plant anaerobic stress. Using 14C dating of long borings across the coastal plain, Roberts et al (1994) documented that subsidence rates increased with the increased thickness of Holocene sediments above the Pleistocene-Holocene boundary. Later, they found that most of the subsidence was taking place in the young deposits of the upper 15 m of the sediment column.

Because of subsidence and sea level rise, marshes are undergoing waterlogging and increasing salinity stress. Mendelssohn, McKee and their students conducted critical experiments that identified the negative effects of rising water levels and increasing salinity on the viability of coastal marsh plants. They documented that wetland plants were growth-limited by hydrogen sulfide (Mendelsshon and McGee 1988; Koch and Mendelsshon 1989; Webb et al 1995; Mendelsshon 2000). On a larger scale, Baumann et al (1984) showed that deteriorating marshes receive most of their sediment input during floods. Recent studies of the Wax Lake Delta and surrounding marshlands by Roberts et al (2015) emphasized the importance of the introduction of riverine sediments during floods to marshlands. This sediment was found to be an important source of nutrients for enhancing marsh plant productivity and substrate building, in order to offset the negative effects of subsidence. They found that cold front related processes drove sediment-rich waters from Atchafalaya Bay into the marshlands, making the marshes surrounding the bay some of the most productive in the entire Louisiana coastal plain. This body of research, in conjunction with the ecological and biogeochemical research of Mendelssohn, Delaune, White, Gosselink, Sasser and others, as well as the flood-pulse research by Day (Twilley et al 2019), validated the use of sediment diversions and hydraulically dredged sediment-slurries for wetland restoration. These were the two primary restoration approaches employed by state and federal agencies as part of Louisiana's Comprehensive Master Plan for a Sustainable Coast.

Research conducted by the faculty of the Department of Oceanography and Coastal Sciences at LSU has identified the many critical components of wetland loss, their relative importance, physical, geological, and biological mechanisms determining wetland loss, and restoration approaches to help mitigate impacts to one of the world's great wetland systems. Future basic and applied research will continue to tackle these challenges to our understanding of the suite of interacting coastal processes that control wetland loss and successful restoration.

The basic geological features of Louisiana are clearly laid out in Darwin Spearing's book titled Roadside Geology of Louisiana (Spearing 2015; **Fig. 12).** Louisiana's geological beginning is revealed thousands of feet below the surface through oil well drilling. Though these early rocks are found below the surface in Louisiana, they are found at the surface in Arkansas, Texas, and Oklahoma. The geological puzzle can be unraveled on a regional scale. The geological history of Louisiana is revealed by sedimentary rocks, where sand becomes sandstone, mud becomes shale, silt becomes siltstone, gravel becomes conglomerate, shells become limestone and salt remains salt.

An important feature of the Coastal region of Louisiana is the presence of salt domes. The Louann salt, a thick layer of bedded salt, lies deep beneath Louisiana under 10 miles of bedded rock. Salt is less dense than sandy and muddy sediments, so it rises to the top under the pressure of thousands of feet of rock.

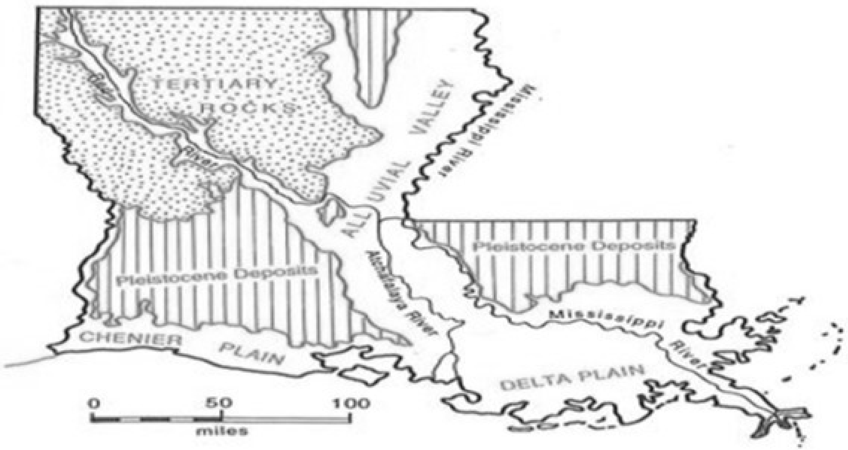

Figure 10:

Basic geological features of Louisiana (Spearing 2015).

Oil and gas exploration in Louisiana revealed hundreds of salt domes (Fig.14). Geologists have studied the mechanics of salt dome deformation. Several prominent features of a salt dome include a Diapir, a rising plug of salt driven upward by the weight of the overlying rocks, and downbuilding where sediments above the salt collapse along curving faults, displacing the Louann salt downwards. Small basins form, and the undisturbed salt remains as high ridges and domes between the basins. The displaced salt below the basins moves down the continental slope.