BY NANCY N. RABALAIS

Troubled Waters of the Gulf of Mexico

The Roger Revelle Commemorative Lecture Series was created by the Ocean Studies Board of the National Academies in honor of Dr. Roger Revelle to highlight the important links between ocean sciences and public policy. Nancy Rabalais, the twelfth annual lecturer, spoke on March 29, 2011, at the Baird Auditorium, Smithsonian Institution, National Museum of Natural History.

INTRODUCTION

The gusher has ended, but before it did, an estimated 206 million gallons of crude oil and methane gas escaped from the Macondo well in lease block Mississippi Canyon 252. We know it better as the BP Deepwater Horizon oil spill that resulted from a series of mechanical and safety failures leading to an explosion, the deaths of 11 workers, and the largest accidental oil spill in history. The well was in the northern Gulf of Mexico in 1,500 m of water, not the deepest in this petroleum production frontier, but in an otherwise blue-water, pristine ocean home to deepwater corals and pods of sperm whales, and one of two spawning areas for Atlantic bluefin tuna. Satellite images of black oil at the surface marred this picture as the oil continued to spew from the ocean bottom and spread into the northern Gulf of Mexico. Innumerable lives were affected—from microbes to humans—and the world was transfixed by the continuous images of oil and gas blowing from the Gulf bottom while technology raced to catch up with Mother Nature.

In addition to being the center for oil and gas production in the United States, the northern Gulf of Mexico provides essential resources and services to the region and the nation: transportation, marine fisheries, tourism, recreation, and shipping and navigation. But the focused resource use by so many sectors has not come without cost. Although the region has been altered many times by natural forces, in modern times, human activities have reshaped the delta and degraded water quality, causing major losses of wetlands and creating the largest hypoxic zone in the United States. When the spill began in spring 2010, water-quality problems from excess nutrients already existed, triggering a world-class "dead zone" that expanded in size and severity throughout the summer. The immediate and dramatic insult inflicted by the spill's intensity garnered global attention, highlighting not only the spill but the many existing stressors that already threatened this valuable ecosystem.

OILMAGGEDON

On April 20, 2010, something went terribly wrong with the drilling of the BP Macondo well by the drilling platform Deepwater Horizon 80 km southeast of the Mississippi River delta in 1,500 m of water. The exact details are still under investigation, but there were several unexpected events, technological and mechanical failures, failed safety precautions, and human error in diagnosis and action. There was an explosion, the drilling rig caught fire, burned for two days, and then sank into the depths of the Gulf of Mexico, leaving an uncontrolled gushing of oil from a broken casing and several leaks in associated underwater pipes.

By the time the broken well was successfully capped on July 15 (about three months later), it was estimated that 206 x 10^6 gallons (780 x 10^6 liters)

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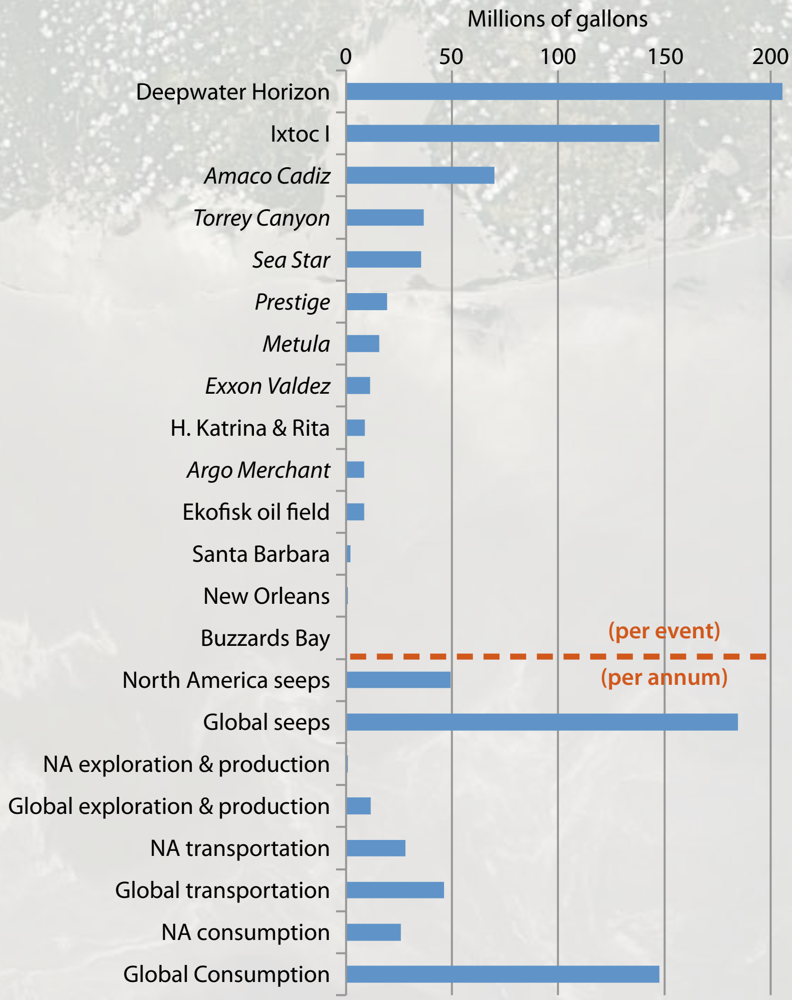

Figure 1. Volume estimates for oil spills in millions of gallons per event (above the dashed orange line; compiled from multiple sources) and oil reaching the sea in millions of gallons per annum (below the dashed orange line; compiled from National Research Council, 2003). The National Research Council (2003) estimates are for: North American seeps, of which two-thirds are in the Gulf of Mexico, followed by global seeps; Global exploration and production, which would include well blowouts such as Deepwater Horizon, Ixtoc I, Santa Barbara, and Ekofisk; NA transportation, which includes cargo losses through accidents in North America, e.g., *Exxon Valdez*; similar losses in Global transportation, e.g., *Prestige*; and consumption losses in North America and Global, which include atmospheric deposition of fossil fuel burning, automobile exhaust onto roadways, and oil and grease runoff into gutters. *Based on data from National Research Council, 2003; N.N. Rabalais, LUMCON*

of oil and gas had escaped from the ocean floor. This accidental oil spill is the largest in history (Figure 1), exceeded only by the amount of oil released during the 1972 Gulf War, estimated at 242–462 x 10^6 gallons (916–1,749 x 10^6 liters). By comparison to *Exxon Valdez*, the BP Deepwater Horizon spill is almost 20 times larger.

The volumes of oil released are headline makers, but caution should be taken in inferring impacts based on the spill size alone (National Research Council, 2003). Spills in enclosed spaces or within biologically complex or fragile ecosystems may increase exposure to the toxic hydrocarbons in oil compared to spills in areas where dispersion and weathering effects may reduce the amount of oil and lower toxicity levels. There is no doubt, however, that the massive volume of oil released by the BP Deepwater Horizon well increased the potential for large-scale impacts.

The northern Gulf of Mexico is not only a center of industrial extraction of oil and gas but also the site of natural hydrocarbon seeps, which occur along the slope edge and escarpment and account for two-thirds of the North American seeps in Figure 1. Gulf seeps amount to about 40 × 10^6 million gallons (151 x 10^6 liters) per year (National Research Council, 2003), which is a substantial amount of oil released into the environment. However, seeps occur over a large area, are not continuous, and the oil that reaches the surface or the beaches is highly weathered. Seeps also support a community of microorganisms that live off the hydrocarbons, and these microbes can help biodegrade oil from accidental spills such as the Deepwater Horizon. In contrast, a spill, or gusher, is a finite input (volume) over a shorter period (single event to months) of a range of hydrocarbon components (not weathered and inclusive of the more toxic forms). The BP Deepwater Horizon spill entered the open Gulf of Mexico and began to move primarily northward, threatening the eastern edge of the Mississippi River Delta, Breton Sound, and Chandeleur Sound by early May 2010. By early July, oil had spread across the northern Gulf of Mexico coastline from Galveston, TX, to Panama City, FL, and across over 10,000 km^2 in the open

Figure 2. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite captured this image of sunlight illuminating the lingering Deepwater Horizon oil slick off the Mississippi Delta on May 24, 2010. *Source: http://www.flickr.com/photos/gsfc/4638932803/sizes/l/in/photostream; NASA Goddard Center*

Figure 3. Intersection of sediment-laden Mississippi River plume with blue water of the Gulf of Mexico. Petroleum production platform seen in the distance (left). *N.N. Rabalais, LUMCON*

northern Gulf of Mexico (Figure 2). In 2010, the Loop Current did not move as far northward as possible, which resulted in good news for the Gulf, as the oil was not entrained and sent along the west Florida shelf onto reef tracks or into the Atlantic Ocean.

During the spill, people became aware of the many oil and gas platforms in the northern Gulf of Mexico; in fact, there is a web of oilfield drilling and production platforms that includes many deepwater wells and pipelines connected to shore. The infrastructure extends inshore as a maze of pipeline canals, access canals, and navigation channels that dice up the fragile delta landscape.

The short-term and long-term impacts of the oil gusher (not a leak, not a spill, not an incident) are still unknown. Immediate attention was focused on how the oil spill was affecting oceanic ecosystems, plankton communities, deep-sea benthos, deepwater corals, mesopelagic fishes, marine mammals and turtles, and fishery resources. As the oil moved onto the fragile, coastal wetlands (seagrass and mangrove habitats), concern grew for these biogenically structured systems that provide so many ecosystem services, such as nursery grounds for commercially important fishes and crustaceans, sediment stabilization, filtering of contaminants and nutrients, and habitat for recreational activities, such as fishing and hunting. The more visible coastal oiling in the form of black oil on sandy beaches threatened the nearshore pelagic and intertidal communities as well as curtailed tourism. The environmental and human impacts are being documented, and these assessments will likely continue for a decade or more.

THE BIG MUDDY

The Mississippi River system has long dominated the geological and biological landscape of the northern Gulf of Mexico. The watershed encompasses 41% of the lower 48 United States (~ 3.2×10^6 km^2), surpassed in size only by the Amazon and Zaire Rivers (Milliman and Meade, 1983; Meade, 1996). The river's length and its freshwater and sediment discharge rank among the world's top 10 rivers. The annual average freshwater discharge of 580 km^3 enters the northern Gulf of Mexico through two main distributaries: the birdfoot delta southeast of the city of New Orleans, Louisiana (Figure 3), and the Atchafalaya River delta ~ 200 km to the west on the central Louisiana coast (Meade, 1995).

Sediment deposition and accumulation are essential for maintaining the delta to offset natural subsidence and prevent drowning of wetlands. Over tens of thousands of years, the flow of sediment-laden freshwater created a series of delta lobes that prograded, subsided, and switched across the northern Gulf coastal landscape, establishing a deltaic plain that eventually formed the current birdfoot delta about 1,000 years ago

(Penland et al., 1988). Substantial inputs of river sediments sustained the wetlands across the coast. Over two centuries, transformation to a primarily agricultural landscape, with water systems engineered for drainage of agricultural lands, navigation, and flood control, has altered the river basin landscape, changed flow regimes, and reduced the suspended sediment load. The changes have lessened the buffering capacity of the watershed against pollutants and contributed to the loss of landforms in the watershed and at the coast (Boesch et al., 1994; Turner and Rabalais, 2003). Watershed manipulations along with natural deltaic processes and intense human development of the coastal zone have resulted in over 5,000 km^2 of coastal lands lost since the 1930s (updated from Barras, 2006).

The "Big Muddy" is not as sediment-laden as it was ca. 1700, according to estimates of Meade (1995); presently, the sediment load is roughly half its former size. During the twentieth century, the hydrology of the vast Mississippi River system was greatly altered by locks, dams, reservoirs, earthwork levees, channel straightening, and spillways for purposes of flood protection, navigation, and water supply. The largest decrease in suspended sediments occurred after 1950, when the natural sources of sediments in the drainage basin were cut off from the Mississippi River mainstem by the construction of large reservoirs on the Missouri and Arkansas Rivers (Meade and Parker, 1985; National Research Council, 2007).

In addition, landscape changes across the middle of the country since the 1800s have altered the ability of the Mississippi River Basin to assimilate excess nutrients (Turner and Rabalais, 2003). Vast areas

Roger Revelle

For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College and the University of California, Berkeley. In 1936, he received his PhD in oceanography from the Scripps Institution of Oceanography. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950–1961, 1963–1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He organized the first continual measurement of atmospheric carbon dioxide, an effort led by Charles Keeling, resulting in a long-term record that has been essential to current research on global climate change. With Hans Suess, he published the seminal paper demonstrating the connection between increasing atmospheric carbon dioxide and burning of fossil fuels. Revelle kept the issue of increasing carbon-dioxide levels before the public and spearheaded efforts to investigate the mechanisms and consequences of climate change.

Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961–1963) and as the first Director of the Center for Population Studies at Harvard (1964–1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmental effects of radiation to understanding sea level change.

Photo credit: SIO Archives, UCSD

of the Mississippi River basin prairies and forests were converted to cropland and other agricultural uses as European settlement expanded westward. By 1920, large areas of virgin forests were reduced to remnant forests (Greeley, 1925). The river basin has also accommodated the drainage and conversion of millions of acres of wetlands, as over one half of the original wetland ecosystems has been converted to other land uses (Prince, 1997; Figure 4).

DEAD ZONES

Since the middle of the twentieth century, the Mississippi River has transported anthropogenic nitrogen and phosphorus in such quantities that it now induces a zone of hypoxia (low-oxygen water conditions) that is the second largest human-caused coastal hypoxic area in the world (Rabalais et al., 2007). This "poster child" for deteriorating coastal water quality is popularly referred to as the "dead zone," a term that originated with trawler fishermen who would drag the bottom with their nets and not capture any shrimp when the oxygen was below 2 mg l^{-1} (Renaud, 1986). "Normal" oxygen levels are two to three times greater.

Low-oxygen values are of concern because of detrimental effects to marine life, biodiversity, commercial and recreational fisheries, trophic dynamics, energy flow, and ecosystem functioning (Rabalais and Turner, 2001; Díaz and Rosenberg, 2008; Levin et al., 2009; Ekau et al., 2010; Rabalais et al., 2010). Sharks and rays will swim away from water with dissolved oxygen less than 3 mg l^{-1}; demersal fishes, crabs, and shrimp will attempt to move away from oxygen concentrations less than 2 mg l^{-1}; and few marine animals survive in prolonged exposure to oxygen concentrations below those levels.

The northern Gulf of Mexico hypoxic area is large, at times extending from the Mississippi River birdfoot delta onto the upper Texas coast and into the Mississippi Bight east of the delta (Figure 5). The size has averaged 13,825 km^2 in mid summer between 1985 and 2010 and has been as large as 22,000 km^2 (updated from Rabalais et al., 2007). Seasonal hypoxia arises from the high productivity of surface waters fueled by nutrients from the Mississippi watershed, coupled with stratification, in which the warm, less-saline surface waters overlay the colder, saltier deep waters with little mixing (Committee on Environment and Natural Resources, 2000; Science Advisory Board, 2007; Rabalais et al., 2007; Turner et al., 2007; Kemp et al., 2010). Nutrients stimulate the growth of phytoplankton, creating large blooms in surface waters. The excess organic matter from these blooms rains down into deeper waters where it is consumed (oxidized) by organisms, thereby depleting the deep waters of dissolved oxygen. These conditions are found in many coastal areas where hypoxia is getting worse or where hypoxia has only recently been observed (Díaz and Rosenberg, 1995, 2008).

The severity and extent of hypoxic events are primarily influenced by stream flows, nutrient runoff from agriculture and urban centers, and precipitation. Because the amount of freshwater delivered to the northern Gulf of Mexico affects both the nutrient loads and the strength of stratification, variability or long-term trends in river discharge influence the extent and severity of

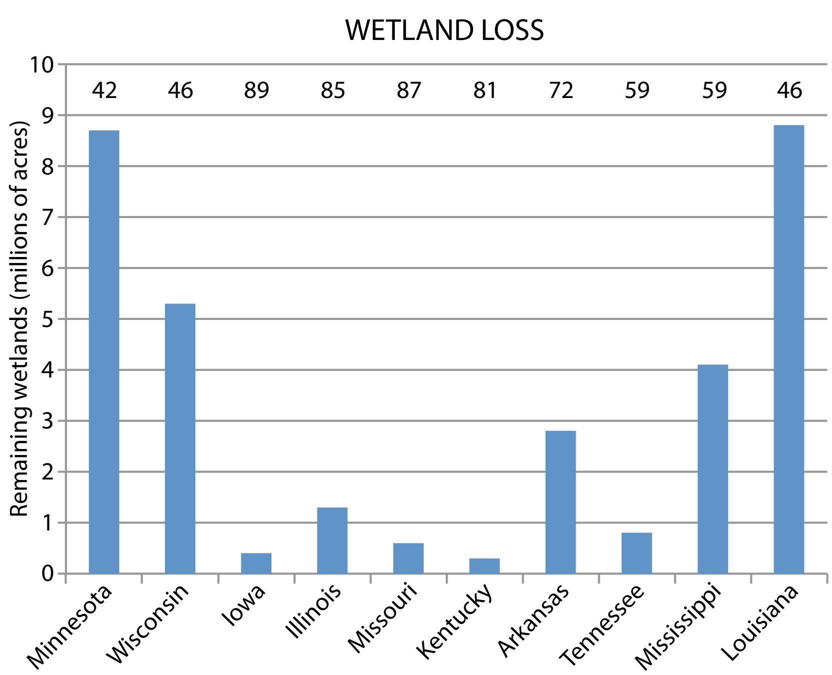

Figure 4. Wetland loss in the Mississippi River mainstem states. Percent loss is shown across the top of the histogram. Values are millions of acres of wetlands remaining, ca. 1980s. *Based on data from Dahl (1990)*

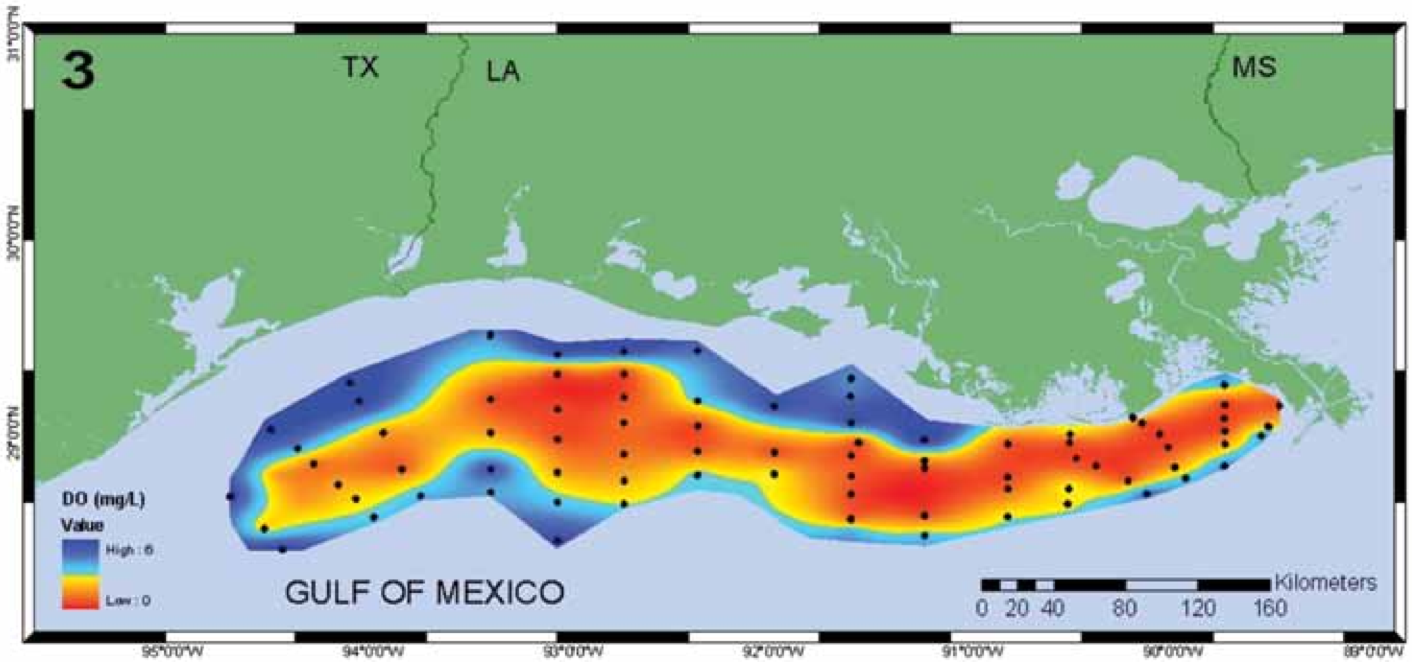

Figure 5. Distribution of bottom-water dissolved oxygen content on the Louisiana-Texas continental shelf in July 2006. This distribution is typical of years without disruption of hypoxia by hurricanes or tropical storms or anomalous winds and currents. Hypoxia also occurs intermittently east of the Mississippi River but in small areas (Rabalais et al., 2007). *N.N. Rabalais, LUMCON; Funding: NOAA, CSCOR*

hypoxia. On a multicentury time scale, discharge has been relatively stable from 1820–1992 (Turner and Rabalais, 2003; Turner et al., 2007). In contrast, Mississippi River nutrients, especially nitrate-nitrogen have changed dramatically during the last century, with an acceleration of these changes since the 1950s (Turner and Rabalais, 1991), due primarily to an increase in concentration coincident with the increase in application of artificial fertilizers. Smaller fractions arise from human sewage, non-agricultural fertilizer use, and precipitation (Goolsby et al., 1999; Alexander et al., 2008). Changes in both nitrogen and phosphorus lead to stimulation of phytoplankton growth in the offshore waters. While the overall change in the development and extent of hypoxia is due primarily to the nitrogen load of the river, the Science Advisory Board (2007) of the US Environmental Protection Agency concluded that both nitrogen and phosphorus reductions (about 45%) were necessary to mitigate the occurrence of hypoxia on the northern Gulf shelf. The Science Advisory Board (2007) further recommended that nutrient reductions be targeted at those areas in the watershed where the yields of nitrogen and phosphorus were the highest, corresponding to the Corn Belt (Alexander et al., 2008).

All lines of evidence point to increased nutrients, primarily in the last half of the twentieth century, as the initiating factor for hypoxia on the shelf and its worsening since then. Alternative causal hypotheses for the dead zone include broad-scale landscape changes in the watershed and hydrological changes along the river. For the most part, these alterations (Turner and Rabalais, 2003) occurred well before the advent of increased nutrient loads, and are not coincident in time with the development and worsening of hypoxia. The watershed is less capable of removing nutrients, but the consensus for mitigating excess nutrients is to reduce them as close to their sources as possible (Science Advisory Board, 2007). However, actions taken to manage the distribution of river flow through the Mississippi-Atchafalaya deltaic plain in the future, especially as a mechanism for coastal restoration, could be of major consequence to the development and distribution of hypoxia on the continental shelf and eutrophication of ambient receiving waters (Ren et al., 2009). Further, the inputs of terrestrial carbon from the watershed or loss of carbon from deteriorating wetlands along the coast have been ruled out as contributors to the carbon loading that leads to hypoxia (Eadie et al., 1994; Turner and Rabalais, 1994; Turner et al., 2007; Das et al., 2010). Nutrient stimulation via upwelled waters, atmospheric deposition onto the Gulf, and groundwater inputs is unlikely or limited (Rabalais et al., 2007).

OILMAGGEDON AND DEAD ZONES

The northern Gulf of Mexico dead zone received much media attention in 2010 for several reasons:

1. It was above average in size, severity, and persistence (http://www.gulfhypoxia.net), consistent with higher-than-normal Mississippi River flows in spring and summer (→ stronger stratification → greater nutrient loads → higher carbon fixation and carbon flux)
2. There were areas of lower oxygen associated with the BP Deepwater Horizon oil spill at 1,100–1,200-m depth where the subsurface oil plume was observed (Joint Analysis Group, 2010, but see Camilli et al., 2010), but never near approaching hypoxia or even the natural low-oxygen area at 500–800-m depth (Rabalais et al., 2002)
3. Oil mitigation measures (release of Mississippi River water through diversions) likely increased the noxious and harmful algal blooms, hypoxia, and fish kill problems to the east of the Mississippi River delta where there was also visible oil
4. Typical shelf hypoxia overlapped with the distribution of emulsified oil on the water surface during the three months of oil gushing (recent work of the author and colleagues)
5. The media really wanted to link the oil spill to the formation of hypoxia on the continental shelf

By many analyses too detailed to outline here, there is little indication that the BP Deepwater Horizon oil spill contributed to shelf hypoxia in 2010. Rather, the usual suites of conditions that lead to hypoxia were in force. In addition, the discharge of the Mississippi River in 2010 was well above average, with three peaks in spring and above-average flow from July to October, extending the conditions of hypoxia formation and maintenance much later into the "hypoxia year" (recent work of the author and colleagues). Still, the media rightly focused attention on the northern Gulf of Mexico dead zone as an environmental problem caused by humans over a half century of willfully ignoring the downstream fate of pollutants, especially nutrients from excess fertilizer. The Oil Spill Commission (2011) also recognized the dead zone as an issue that needed to be addressed by the Gulf Coast Ecosystem Restoration Task Force (Presidential Executive Order, 2010).

VANISHING LANDS

Slow-moving, still waters meandering in bayous through quiet swamps and expansive wetlands teeming with fish and wildlife is the often-conjured landscape of coastal waters across the northern Gulf of Mexico. The earliest aerial photographs of coastal Louisiana would support that vision and showed vast expanses of wetlands (equal to 85% of the total land area; Baumann and Turner, 1990) and an interwoven network of natural channels. Eighteen percent of the coastal land present in the 1930s (3,954 km^2) was lost by 1990 (Britsch and Dunbar, 1993), and 70% of this land loss occurred in the deltaic plain. The coast-wide land-loss rate peaked in the 1960s and 1970s (104 $km^2\ yr^{-1}$), slowed (62 $km^2\ yr^{-1}$) between 1990 and 2000 (Barras, 2006), and was on a trajectory to be only 10 $km^2\ yr^{-1}$ at the turn of the century (Turner, 2009) until Hurricanes Katrina and Rita in 2005 converted 513 km^2 of land to open water (Barras, 2006).

Manipulation of the coastal landscape began as soon as European settlers arrived, with construction of levees and draining of swamps to create land for cities and agriculture, ditching of wetlands for mosquito control, cutting of cypress trees, dredging of navigation routes, and dynamiting of channels for fur trapping. By 1915, agricultural impoundments across the Louisiana coast captured 452 km^2 of former wetlands (Turner and Streever, 2002). Several large impoundments (Delta Farms, The Pen, and Big Mar) in the deltaic plain are now open water following soil compaction and levee failures. Since the late 1930s, the water levels of 3,400 km^2 of coastal wetlands and open waters have been managed by water-control structures and man-made levees to control salinity, enhance vegetation, mitigate land loss, or improve wildlife habitat (Boyer, 1997). Rather emergent plant cover was sometimes reduced behind the weirs (Turner et al., 1989), and the management practices were causally related to increased land loss or were of no benefit (Boyer, 1997).

Most wetland losses in Louisiana have resulted from submergence, as accretion of new soil and organic plant material is unable to keep pace with the relative sea level rise because of altered hydrology, lack of mineral sediments, and deteriorated landscapes that do not support continued growth of marshes. Dredging of canals for oil and gas recovery efforts began in the 1930s and peaked in the 1960s. Direct removal of sediments over that period is equivalent to 1,017 km^2 (Britsch and Dunbar, 1993) and an equal area of spoil banks on the adjacent wetlands (Figure 6; Baumann and Turner, 1990). A much larger indirect impact from canals and dredged spoil deposits, demonstrable at several temporal and spatial scales, is inferred from close correspondence between land-loss rates in the deltaic plain and dredging (Turner, 2009). There are plausible cause-and-effect explanations for these relationships that are related to the loss of accumulated organic matter and plant stress that accompanies altered hydrology (Swenson and Turner, 1987; Turner, 1997, 2004).

Figure 6. Canals dredged for drilling platforms and access to well heads from a natural channel. More dredged access canals can be seen in the background. *N.N. Rabalais, LUMCON*

Until completion of the levee system along the lower Mississippi River, seasonal overbank flooding provided river sediment input to the coastal landscape, but extensive river control was completed before the dramatic land losses began. The drop in suspended sediment supply is consistent with the completion of a series of dams and reservoirs on the Missouri River in 1950 (Turner and Rabalais, 2003; Blum and Roberts, 2010). As described below, high rates of localized subsidence in the deltaic plain can be attributed to oil and gas extraction (Morton et al., 2005). Except for the current birdfoot and Atchafalaya-Wax Lake deltas, the deltaic plain as a whole is in retreat (Penland et al., 1988; Blum and Roberts, 2009). Although some of the causes are natural factors, most of the deterioration has been due to human activities, which disrupted river flows and altered hydrology. As with mitigation of nutrients, the causes of ecosystem change and the processes underlying it are essential knowledge in restoring or mitigating coastal land loss (National Research Council, 2008).

PETROLEUM INDUSTRY DEVELOPMENT

The 1930s marked the birth of the petroleum industry in the bays and wetlands of Louisiana when drilling in the wetlands began from submergible barges (Priest, 2007). A free-standing structure that produced oil in the open Gulf was installed in 1938 a mile and a half offshore of Cameron, LA. The first recognized offshore platform was installed in 1947 in Kerr-McGee's Ship Shoal Block 32 in 6 m of water. Afterward, there was a wave of open-water developments, with technological advances moving wells beyond 20-m depth in the 1960s (Priest, 2007). By 2007, there were nearly 4,000 active platforms servicing 35,000 wells and 29,000 miles (46,671 km) of pipeline on the continental shelf waters of Louisiana and Texas (Priest, 2007), providing close to one-third of the US oil and gas production. Although reserves are becoming depleted and redrilling wells is not always profitable, work continues in the nearshore and continental shelf waters of the northern Gulf.

The flat coastal landscape, with its many bayous and natural waterways, coupled with advancing technology to access reservoirs of oil and natural gas along with onshore facilities that could be built close to the sources helped the initial expansion of the industry. As oil was discovered and produced, access canals were cut through marshes, navigation channels were dredged, thousands of miles of pipeline were laid to consolidate and transport the oil and natural gas inland, and seismic vehicles crisscrossed the landscape looking for more oil. Supportive and protective governments facilitated oil and gas expansion in coastal Louisiana. Facilities were built to separate the petroleum or natural gas from highly saline and contaminated waters that were brought to the surface along with the oil and gas from the deep geologic formations. These waters were held in pits awaiting evaporation of the water, which would be followed by scooping out the remaining contaminants for transfer elsewhere inland, or the contaminated waters were discharged into local waters. Discharge of the contaminated waters is no longer legal within the coastal zone (since 1999), but offshore production platforms routinely separate waters from the petroleum products and discharge them at sea within regulatory limits.

Since the mid-1980s, exploration for oil and gas has extended into ever-deeper waters of the Gulf of Mexico, defined as 200 m or more by the Deepwater Oil and Gas Royalty Relief Act. Extraordinary technological developments allowed the industry to drill for oil at great depths, efforts that were rewarded by yields that exceeded shelf wells by an order of magnitude. There are approximately 7,310 active leases in the US Gulf of Mexico Exclusive Economic Zone, and 58% of them are in deep water (Nomack, 2010). The BP Deepwater Horizon drilling platform in 1,500 m of water was not the first exploration and production venture into the deep water of the Gulf of Mexico and not the deepest. In 2007, the Minerals Management Service (now Bureau of Ocean Energy Management, Regulation and Enforcement) reported 15 rigs drilling for oil and gas in water depths of 1,500 m or more (Nomack, 2010).

Petroleum exploration and production infrastructure (shipyards, tank farms, fabrication yards, ports, transportation centers, and related businesses) dot the coast. Major industrial installations were built to support the discovery, extraction, production, transport, and refining of petroleum products. Economic benefits, employment opportunities, and improved social support systems were also generated in its wake. The petroleum enterprise reshaped the coastal landscape and altered the social substance as well.

The maze of canals, channels, and pipeline crossings have scarred the coastal landscape and contributed, among other factors, to massive erosion and drowning of marshes (Figure 7). The fractured coast is less able to protect people and infrastructure, including that of the petroleum industry, in the face of severe hurricanes such as Ivan in 2004, Katrina and Rita in 2005, and Ike in 2008. Shrimp production across the northern Gulf of Mexico is intimately linked with the acreage of coastal wetlands (Turner, 1977), and it is clear that the bountiful fisheries of the northern Gulf of Mexico depend on coastal wetlands for survival. A fine friction between the petroleum industry and the fishing industry holds together the economy and culture of the region. Oil and gas coexist with crabbing and recreational fishing, but the essence of the landscape has changed, dramatically endangering both.

Figure 7. Eroded wetlands surrounding pipeline canals and dredged access canals in the Lafitte Oil Field in the Barataria estuary, southeastern Louisiana. *N.N. Rabalais, LUMCON*

RESTORATION OF A DAMAGED ECOSYSTEM

The oil from the BP Deepwater Horizon spill stopped flowing on July 16, 2010, after almost three months. By the end of the year, some impacts had been noted such as the 1,500 km of oiled shoreline habitats; the numbers of oiled or dead birds, sea turtles, and marine mammals; days of lost income due to fishing closures; loss of rental income for beachside property; or other visible and tangible signs. But considerable effort continues on the assessment of damages, and relevant research programs are underway. It will be years before the agreed-upon estimate of how much oil and gas spewed from the well is established, a comprehensive picture of the fate of the oil is drawn, broader environmental and social impacts are documented, and economic damages summed. It may be years—decades or longer—before effects on fisheries resources or sensitive populations are fully determined. And, we must consider that we may never know the levels of exposure to oil or whether suspected impacts are at all related to the spill.

The federal and state trustees charged with assessing and restoring oil-damaged natural resources issued a Notice of Intent on September 29, 2010, to conduct restoration planning. This action means the government found evidence of oil damage to natural resources that warrants a formal Natural Resource Damage Assessment in which the oil spill's impact will be quantified. This work, in turn, will form the basis for a financial claim against the responsible parties—BP and other companies—for the cost of restoring natural resources and lost uses to their pre-spill conditions. In addition, President Obama issued an Executive Order (Presidential Executive Order, 2010) for a Gulf Coast Ecosystem Restoration Task Force to develop a restoration strategy that addresses environmental degradation in the Gulf of Mexico before the oil disaster. Thus, the ills suffered by the coastal landscape and coastal waters through decades of human mismanagement become a broader focus and an opportunity for restoration of a deteriorating landscape. The Oil Spill Commission (2011) recommended that long-term restoration efforts have the ability to set binding goals and priorities, allocate funding in a way that addresses the relative restoration needs of individual states, balance the roles and interests of state and federal governments, ensure that decisions are made efficiently and quickly, incorporate good science without unduly slowing valuable projects, and incorporate meaningful public input. The Commission recommended that Congress establish a joint state-federal council similar to the *Exxon Valdez* Oil Spill Trustee Council to ensure an effective restoration effort.

GRAND CHALLENGE AND OPPORTUNITIES

With the creation of the Gulf Coast Restoration Task Force, President Obama committed to a vision of restoration that reaches far beyond our usual understanding. The vision encompasses remediating the short- and long-term impacts of the BP Deepwater Horizon oil spill on ecological and social systems and strives to "right the wrongs" of multidecadal mismanagement and abuse by humans unwittingly, but also willingly, destroying the environment that provided them with their ecological and economic support. Among the "wrongs" to be addressed are the long-term failures in water quality that lead to and support the "dead zone" in the Mississippi River-influenced Gulf of Mexico (National Research Council, 2007) and the deteriorating wetlands and altered landscapes of the coastal zone.

The challenge is daunting but accompanies a rare opportunity to address the long-standing and critical needs of the Gulf of Mexico ecosystem in an integrated manner. The idea is to form partnerships among the federal government agencies, states, communities, academia, industry, and stakeholders across the diverse, culturally rich region. The plan should not only correct obvious impacts (impaired habitat, fishery resources, and community infrastructure) but also support the restoration of "resilient, healthy Gulf of Mexico ecosystems that support diverse economies, communities, and cultures of the region" (Mabus, 2010).

> "THE TRAGEDY OF UNINTENDED CONSEQUENCES HAS DONE MUCH TO DEGRADE THE GULF ECOSYSTEM OVER THE LAST CENTURY, AND THE CHALLENGE OF THE FUTURE IS TO ANTICIPATE AND AVOID ACTIONS THAT MAY DO MORE HARM THAN GOOD."

Habitat, resource, and social goals include:

- Healthy and resilient coastal wetland and barrier shoreline habitats
- Healthy, diverse, and sustainable fisheries
- Adaptive and resilient coastal communities, with more sustainable storm buffers
- Healthy and well-managed inland habitats, watersheds, and offshore waters

These goals are "Grand Challenges" to say the least. As we move forward, a few guiding principles should be employed:

- Restoration should be ecosystem-based. The Gulf coast ecosystem does not have state boundaries and is an interconnected system.
- Maintain conceptual vision. What is a healthy and resilient Gulf ecosystem that supports living resources and sustained human uses?
- Consider climate change. Recognition that coastal lands and resources are subject to the effects of changing climate, particularly sea level rise.
- Take a tactical approach. With large, but fixed, funding, address areas and issues of systemic environmental degradation.
- Practice adaptive management. Be prepared to adapt restoration plans in response to monitored results of clearly stated project endpoints.
- Expect nonlinearity. Be prepared for elusive, slow, or unexpected results.

And one last principle: Exercise caution. The tragedy of unintended consequences has done much to degrade the Gulf ecosystem over the last century, and the challenge of the future is to anticipate and avoid actions that may do more harm than good.

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