

Deepwater Horizon Oil Spill Impacts on Organisms and Habitats

BY SARA BERESFORD, JESSIE KASTLER, RACHEL MCDONALD, DAN DINICOLA, AND KATIE FILLINGHAM

- Conclusive statements about how organisms and biological communities fared after the Deepwater Horizon accident are still difficult to make nearly a decade after the spill. Much of the work on organisms and their habitats will continue for years to come, and some of the impacts will only be apparent with long-term study.
- Scientists have learned, and will continue to learn, important lessons by studying the impacts of the largest accidental oil spill in history on marine habitats and life in the Gulf of Mexico, such as impacts on large vertebrates (fish, cetaceans, birds), deep-sea organisms, phytoplankton and other marine microbes, coastal and pelagic fishes, and marsh plants and animals. Gulf of Mexico Research Initiative (GoMRI) researchers are finding that sublethal impacts (those that do not immediately kill the animal, but affect its feeding habits, navigation, gene expression, and/or reproduction) are important, and understanding them provides critical insight about longer-term, population-level impacts of the spill on marine life.
- One of the most valuable lessons from this accident has been that it is critically important to collect baseline data for ecosystems, in particular those which are most at risk of impact by industrial activities, and GoMRI researchers are helping to contribute to this body of knowledge.
- Researchers developed innovative ways to investigate the impacts of oil on many different organisms and habitats. An associated activity provides students the opportunity to conduct their own virtual experiment on two species of fish, assessing changes in swim behavior and vision after oil exposure with "fish treadmills."

INTRODUCTION

What happened to marine organisms in the months and years following the Deepwater Horizon (DWH) oil spill in the Gulf of Mexico? Almost a decade after the spill, the answer to that question is still not completely clear. There is no single condition report for all of the animals affected by the spill. Some species, like gulls and wading birds, were gravely injured. Others did not appear to be greatly affected, like

some species of estuarine fish (Haney et al. 2014b; Able et al. 2015; McCann et al. 2017). Many individual organisms, including dolphins, were killed immediately, while some, such as mahi-mahi fish, suffered sublethal impacts that affected the way they feed, navigate, or reproduce (NOAA(c); Incardona et al. 2014). In many cases we don't know and may never know. Scientists participating in the Gulf of Mexico Research Initiative (GoMRI) have been working to understand and determine impacts of the oil and dispersant (see box on page 28) on organisms, and here we highlight some of their research efforts. Moving from deep sea to coastal habitats, we focus on a few groups of organisms.

SPECIALIZED DEEP-SEA COMMUNITIES

How Did Oil Enter the Deep-sea Food Web?

Cold seeps play an important role in the deep Gulf of Mexico ecosystem (Fisher 2007). Cold seeps are areas where hydrogen sulfide, brine, methane, and other hydrocarbon-rich fluids naturally 'seep' out of the ocean floor. Mussels and tubeworms dominate the cold seep communities and provide structure and habitat for diverse associations of benthic or bottom-dwelling animals such as shrimp, crabs, polychaete worms, and eventually deep-sea coral. The hydrocarbon seepage at cold seeps requires that microorganisms living in the vicinity be able to degrade, or at least tolerate, hydrocarbon exposure (Joye et al. 2014; 2016).

While sunlight fuels the food web in the shallower, sunlit waters of the Gulf, microbes near cold seeps are capable of converting oil and methane into energy, which is then carried into higher trophic levels by microplankton-like protists. The microbial response to the DWH spill likely transferred significant amounts of oil- and gas-derived carbon into the planktonic-microbial food web (Fernandez-Carrera et al. 2016). Researchers detected oil in the food web as early as late summer 2010 using isotopes to trace DWH carbon to zooplankton (Graham et al. 2010; Chanton et al. 2012). This hydrocarbon was still being recycled through the food web for two years after the end of the spill (Fernandez-Carrera et al. 2016).

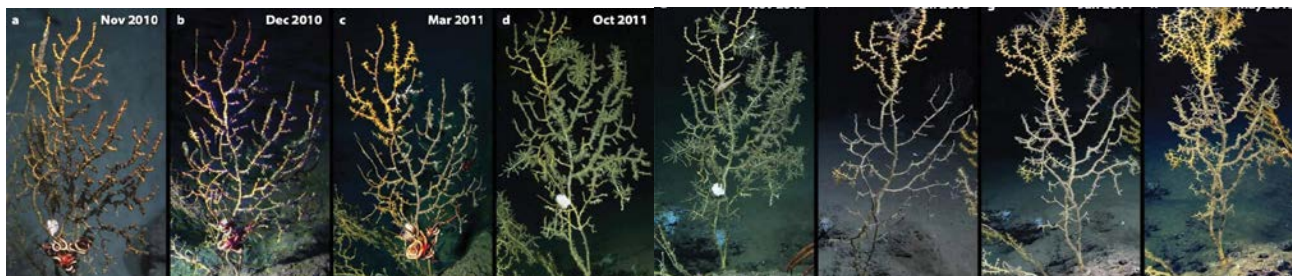


FIGURE 1. Photo time series demonstrating oil spill impact on a deep-sea coral community over time. Coral is partially covered by oily flocculent material in 2010, and by 2011 many branches of the coral have died and become covered by hydroids. The brittle star and anemone living on the coral were gone by 2013. Courtesy of F. Girard; Figure 3 from Fisher et al. 2016

Microbes also played an important role in transporting oil to the deep sea. Marine snow is formed when a sticky mucus excreted by zooplankton, phytoplankton, and bacteria combines with organic and inorganic particles already in the water. Settling of these particles is an important mechanism for transporting nutrients to the deep sea. Scientists were surprised to learn after the DWH spill that this process also transported a significant amount of oil and dispersant to the bottom and ultimately into the marine food web (Joye et al. 2014).

Documenting Damage to Deep-sea Corals

Deep-sea colonial corals are slow-growing and known to live for hundreds to thousands of years (Fisher et al. 2014a; Fisher et al. 2016). In the deep Gulf, they colonize the hardground substrate resulting from microbial activity at cold seeps and serve as an important foundation species within deep-sea benthic communities. Their complex structures provide habitat, energy, and organic matter for a variety of organisms, including fishes, sponges, clams, oysters, crabs, brittle stars, barnacles, and krill. They are diverse, sessile (fixed in place), sensitive to damage, and slow to recover.

Damage to deep-sea corals from the DWH accident was documented in an area 13 kilometers (km) to the southwest of the accident site in November 2010 (White et al. 2012; Fisher et al. 2016; Fisher et al. 2014b; Hsing et al. 2013). This site was known to be in the path of a well-documented, mid-depth plume of neutrally buoyant water enriched with petroleum hydrocarbons from the spill. Scientists observed numerous coral colonies at this location showing widespread signs of stress, including tissue loss, deformation of calcite hard parts, excess mucus, death of associated animals, and covered by a layer of aggregated oil, dispersant, mineral, and organic material known as “floc.”

Since 2010, several additional sites with damaged deep-sea coral colonies have been discovered as far as 22 km away from the Macondo wellhead (Fisher et al. 2014b; Fisher et

al. 2016). Other research groups have found damage they attributed to this spill on mesophotic coral reefs (found at 30-150 meter [m] depths) as far away as 109 km north-east of the spill site (Silva et al. 2016; Etnoyer et al. 2016). Researchers have developed innovative sampling methods and data analyses for documenting impacts. High-resolution camera equipment mounted on submersibles was used to collect images of the corals, the analysis of which enabled researchers to quantify changes over time (Figure 1). Since 2010, over 350 spill-impacted coral colonies have been visited and photographed annually. Some corals have shown signs of recovery; others are not expected to survive the spill’s impacts. Corals in the deep sea grow very slowly and, ultimately, die slowly. The ultimate fate of the deep-sea corals is still unknown.

Lessons from the Coral Research

Spill Footprint and Role of Marine Snow: Studies of deep-sea corals after the DWH spill have allowed researchers not only to investigate impacts on the corals themselves, but also to draw conclusions about movement of DWH oil after the spill and the extent of the spill’s footprint on the seafloor, including estimating the extent of affected seafloor and depths at which impact was observed. In particular, the coral studies have improved understanding of the movement of the subsurface oil plume and the importance of marine oil snow (Fisher et al. 2014b; Fisher et al. 2016).

Role of Ophiuroids (Brittle Stars): A recent study uncovered new information about the role that ophiuroids (i.e. brittle stars) may have played in the extent of impact and recovery of a species of deep-sea coral (*Paramuricea*) after the spill (Girard et al. 2016). Ophiuroids, amongst other invertebrates, are known to associate with some deep-sea corals (Figure 2). Previous studies suggested that ophiuroids benefit from this association by getting better access to zooplankton and other suspended particles for nutrition. Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG, <http://ecogig.org>)

researchers found that corals also benefit from the ophiuroids. In this symbiotic relationship, ophiuroids not only help protect their coral hosts from deposition of material, but they also have a positive effect on recovery. This study is important not only in the context of the oil spill, but also when considering other impacts corals might be exposed to, such as natural or anthropogenic sedimentation events.



FIGURE 2. Brittle star (ophiuroid) living on deep-sea coral in the Gulf of Mexico. Courtesy of ECOGIG and Ocean Exploration Trust

FISH

Gulf fishes live in a variety of locations, from deep to shallow water. They may be bottom dwellers or surface feeders. They may travel broadly, linking separate parts of the ocean through the food web. Research since the oil spill has focused on assessing effects on individual fishes as a way of establishing damage that might affect full populations and on assessing actual damage to full populations. Research has included both field observations in affected areas and a variety of laboratory investigations.

Mortality Versus Sublethal Effects

Beginning with research following the *Exxon Valdez* oil spill in 1989 and continuing with research on the DWH oil spill, researchers have found that sublethal impacts (those that do not immediately kill the animal, but affect its feeding habits, navigation, gene expression, and/or reproduction) of oil and dispersant are important and, in some cases, can be significant (Peterson et al. 2003; Buskey et al. 2016). Understanding sublethal impacts provides critical insight about longer-term, population-level impacts of the spill on marine life. Several different types of sublethal effects are described here for fishes, and in later sections for other organisms.

Fishes exposed to high concentrations of oil frequently die, but lower concentrations of oil can cause injury, or sublethal effects (Peterson et al. 2003). For example, during the months after the DWH oil spill, fishermen across the northern Gulf reported seeing fish, such as red snapper, with skin lesions. The number of lesions observed was greatly reduced in subsequent years, which limited the scientists' ability to confirm the link between oil contamination and

lesions (Murawski et al. 2014). If exposure to oil did cause the lesions, it would be an example of a sublethal effect of the contamination. Rather than dying immediately, injured fish are more susceptible to death by predation, less efficient feeding, and reduced immunity to diseases. They may also have reduced ability to successfully reproduce. In addition, young fish (embryos, larvae, and juveniles) are extremely susceptible to sublethal impacts.

Relationships of Effects of Cardiac Outcomes in Fish for Validation of Ecological Risk (RECOVER, <http://recoverconsortium.org>) scientists used laboratory experiments to study sublethal effects of oil on juvenile mahi-mahi. They explored the consequences of oil exposure using a swim tunnel (Incardona 2014). Cardiac function tests showed oil-exposed fish could not swim as fast or as long as healthy individuals. In vision experiments, oil-exposed fish became disoriented when following a moving target. The deficiencies resulting from oil exposure did not cause immediate death to the juvenile fish. However, affected fish were less able to evade predators, acquire food, spawn, migrate, and avoid oil (Figure 3; Mager et al. 2014; Stieglitz et al. 2016). All of these results reduce a fish's prospects for survival.

Population-level Impacts

Laboratory studies on individual organisms have consistently documented negative effects of oil (Fodrie et al. 2014). Researchers also anticipated a reduction in fish populations, which they inferred from surveys of species density (Fodrie et al. 2014). Post-spill studies in estuarine species of fish consistently showed damage to individuals, including sublethal abnormalities in development of individuals such as those described earlier for open water fishes (Dubansky et al. 2013). However, population-level damage had not



FIGURE 3. A mahi is loaded into a recovery tank after tagging. Courtesy of RECOVER

materialized by 2011 (Fodrie and Heck 2011). Coastal Waters Consortium (CWC, <http://cwc.lumcon.edu>) investigators explored this contradiction by reviewing past studies of oil spill impacts on coastal and estuarine Gulf fishes. They found that some factors conceal population-level responses while others reduce it (Fodrie et al. 2014). For example, closing an area to fishing might lead to an increase in survival of speckled trout that masks mortality related to the oil spill (Fodrie et al. 2014). On the other hand, flatfish swimming away from oil unharmed could make it appear that there are reduced population levels (Fodrie et al. 2014). From these results, researchers recommended that future research link population-level surveys with lab and field studies of individual animals (Fodrie et al. 2014).

OTHER LARGE MARINE VERTEBRATES

The body of literature documenting the toxicity and impacts of oil and, in some cases, chemical dispersant is large. In addition to GoMRI research publications, there are many resources to consult, the most comprehensive of which is the Natural Resources Damage Assessment document (NRDA 2016). The information presented here on birds, sea turtles, and marine mammals, less studied in the GoMRI program, is a subset of that body of work which summarizes results of hundreds of studies documenting specific impacts to as many habitats, organisms, and processes as possible following the DWH oil spill. The NRDA report was produced as a comprehensive description of oil spill impacts for the purpose of assessing a financial penalty to the responsible parties. Similarly, the Gulf of Mexico Sea Grant Oil Spill Science Outreach publications (see <https://gulfseagrant.org/oilspilloutreach/>) provide excellent sources of information about the impacts of the spill on a variety of species of interest.

Birds

In the northern Gulf of Mexico, birds live in a variety of habitats, including open water, island waterbird colonies, barrier islands, beaches, bays, and marshes (NRDA, 4-461). They were exposed to DWH oil in a variety of ways, including physical coating of their feathers and bodies, ingestion of contaminated prey, ingestion due to preening oiled feathers, and inhalation of oil vapors (NRDA, 4-461; 4-471). Emergency response activities to control and clean up the DWH spill may also have negatively impacted birds. Some clean-up activities disturbed birds while nesting or foraging, crushed nests and young birds, and in some cases intentionally scared birds away from heavily oiled areas using propane cannons and other methods (NRDA, 4-504). Burning and skimming operations may have fatally exposed birds to smoke (NRDA, 4-505) or fumes (NRDA, 4-471). Oiled booms retained oil on the water against bird colonies for several days and likely increased their exposure to oil (NRDA, 4-506).

Birds experienced a variety of adverse health impacts. A bird with oil-coated feathers loses its insulation as well as its ability to swim or float, causing the bird to expend more energy to swim or dive (NRDA, 4-471). Oil-coated feathers also impact a bird's ability to fly. The impacts of ingesting or inhaling oil are devastating to birds. Laboratory studies indicated a variety of problems from oil ingestion, including anemia, weight loss, hypothermia, heart and liver abnormalities, reproductive disruption (such as delayed egg laying, decreased eggshell thickness, etc.), gastrointestinal dysfunction, and death (NRDA, 4-461; 4-471).

More than 93 species of birds across all five Gulf states in a variety of habitat types were exposed to the oil (NRDA, 4-509). More than 8,500 dead and oil-impacted birds were collected after the DWH spill (NRDA, 4-479). Estimates of total bird loss vary widely and include not only bird deaths, but also birds not born as a result of the spill (NRDA, 4-509). Conservatively, it was estimated that 56,100 to 102,400 birds were lost in the first year after the spill (NRDA, 4-509); however, total injury is likely substantially higher, not only due to longer-term health effects, but also an acknowledgment that a significant amount of bird injury and loss in the first year after the spill was unquantified (NRDA, 4-509). Research models concluded that 800,000 coastal and 200,000 offshore birds died (Haney et al. 2014a, b). These numbers corresponded to losses estimated at 12% and 32% of the pre-spill populations of brown pelican and laughing gull, respectively (Haney et al. 2014b). Extensive restoration of bird habitat across the Gulf is a critical part of recovering from the spill.

Sea Turtles

Five of the world's seven sea turtle species live in the Gulf (Kemp's ridleys, loggerheads, hawksbills, leatherbacks, and green turtles), all of which are listed as threatened or endangered under the United States Endangered Species Act (NRDA, 4-516). All of the habitat types they occupy in the northern Gulf were impacted by the DWH spill, including open ocean, nearshore, and coastal areas. Turtles spend time at the water's surface to breathe, bask, rest, and feed, which put them at particular risk of exposure to DWH surface oil (NRDA, 4-517). Response activities were particularly disruptive for the turtles, including boat traffic, dredging, and clean-up activities on the beaches. Response personnel and vehicles on the beaches, equipment, and increased lighting disrupted nesting behavior and the nests themselves. Scientists estimate that almost 35,000 hatchlings were injured by response activities (NRDA, 4-518).



FIGURE 4. Dr. Brian Stacy, veterinarian with the National Oceanic and Atmospheric Administration (NOAA), prepares to clean an oiled Kemp's ridley turtle during the Deepwater Horizon oil spill. Courtesy of NOAA and Georgia Department of Natural Resources (CC by 2.0)



FIGURE 5. Striped dolphins (*Stenella coeruleoalba*) observed in emulsified oil on April 29, 2010. Courtesy of NOAA (CC by 2.0)

Sea turtles were exposed to oil by breathing oil droplets and oil vapors, ingesting oil-contaminated water and prey, and becoming coated in surface oil (Figure 4; NRDA, 4-516). Scientists concluded that the most acute adverse effects to turtles resulted from becoming coated in oil and getting bogged down or stuck in the surface oil (NRDA, 4-541). Turtles that became mired in the surface oil suffered from decreased mobility, exhaustion, dehydration, and overheating, all of which decreased their ability to feed and evade predators and, in many cases, the result was turtle death.

Due to the size of the surface oil slick, turtle surveys only covered less than 10% of the surface oil slick and did not include areas near the wellhead nor surveys conducted throughout the entire 87 days of the spill (NRDA, 4-517). Using knowledge of turtle behavior and statistical methods, scientists estimate that between 4,900 and 7,600 adult and large juveniles and between 55,000 and 160,000 small juvenile sea turtles were killed by the spill (NRDA, 4-518). These losses and reductions in reproduction potential cause challenges to recovery for turtle populations. Because turtles migrate around the world, damage to sea turtle populations is potentially global (Hale et al. 2017).

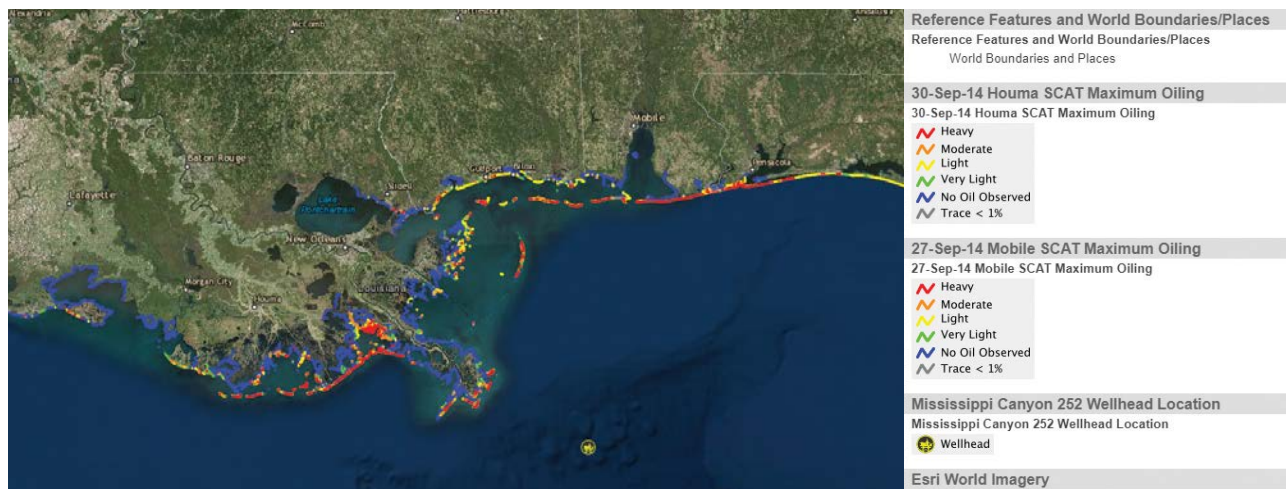
Marine Mammals: Dolphins

There are 22 species of marine mammals, including dolphins, whales, and the West Indian manatee, in the northern Gulf inhabiting open water, nearshore, and estuarine habitats (NRDA, 4-585). All of these habitat types were contaminated by DWH oil (NRDA, 4-598), and tens of thousands of marine mammals were exposed to the surface oil through inhalation, aspiration, ingestion, absorption, or skin exposure (NRDA, 4-584). The oil damaged their tissues and organs, which resulted in reproductive failure, adrenal disease, lung disease, liver failure, anemia, and in many cases, death. Marine mammals were also impacted by oil spill response activities, such as oil removal, dispersant use, and boat traffic, which exposed them to smoke and chemical dispersant, blocked access to habitats, increased vessel traffic, and noise from boats and response operations (NRDA, 4-606).

The DWH oil spill occurred after the start of an Unusual Mortality Event (UME). An UME is defined by the Marine Mammal Protection Act as an unusually large, unexpected marine mammal stranding event (NOAA[a]). Deaths attributed to the spill contributed to the largest and longest-lasting UME ever recorded for the Gulf (NRDA, 4-584). Between 2010 and 2014, 1141 mammals, mostly bottlenose dolphins, stranded along the northern Gulf shoreline, 95% of them dead. Of these, 89 stranded before the spill began (NOAA[b]). Dolphins that stranded in the Gulf had disease conditions consistent with oil exposure, unlike animals that stranded elsewhere (Venn-Watson 2015). Although the DWH spill began after the beginning of the UME, researchers concluded the spill was responsible for the persistent increase in deaths (NOAA[b]).

Amongst the best studied marine mammal populations were the stocks of bottlenose dolphins in Barataria Bay and Mississippi Sound (NRDA, 4-585). Scientists projected their populations were reduced by 51% and 62%, respectively

FIGURE 6. This figure shows areas where the shoreline was assessed for oil between the beginning of the spill and the end of September 2010. Red and orange marks show heavy and moderate oiling, respectively. Yellow, green, and blue marks represent areas where oiling was light, very light, or not observed. The oil well is located southeast of the mouth of the Mississippi River delta, shown here in yellow. Courtesy of NOAA's Environmental Response Management Application (ERMA), 2015



(NRDA, 4-585). Adrenal glands help an animal respond to environmental stress; in stranded and dead bottlenose dolphins from heavily oiled Barataria Bay, adrenal glands were unusually small (Schwacke et al. 2014; Venn-Watson et al. 2015; NRDA, 4-135). These dolphins experienced a relatively higher death rate and lower reproductive success (Lane et al. 2015). Only 20% of pregnant dolphins bore viable calves, compared to the 80% birth rate reported elsewhere.

Marine mammal populations in the Gulf have been declining in recent years due to a variety of human activities (NRDA, 4-585). In heavily oiled habitats after the DWH spill, the effects on marine mammals were devastating (Figure 5). With no recovery efforts, scientists predict that it would take Barataria and Mississippi Bay bottlenose dolphin stocks 40 to 50 years to fully recover (NRDA, 4-585). Whales and dolphins are long lived and slow to reach reproductive age; they only give birth to offspring every three to five years (NRDA, 4-637). Restoration efforts will include monitoring, analysis, and a scientifically-based management approach (NRDA, 4-637).

Understanding the effects of the oil spill on different animals is important; in particular, consumers at the higher trophic levels of the food web, such as birds, turtles, and marine mammals, can serve as good indicators of overall ecosystem health. During the spill, many animals perished immediately through direct contact when they swallowed or swam in oil or dispersant (Hale et al. 2017). Air-breathing animals like whales, sea turtles, and birds were also

susceptible to inhalation of DWH vapors and smoke (NRDA, 4-67). Indirect impacts from oil and dispersant also caused damage to individuals and populations through loss or degradation of habitat, and through disruption of social behaviors such as reproduction and rearing of young (Peterson et al. 2003). Many animals suffered sublethal effects of chemical exposure that caused them to be more susceptible to infection, organ and brain damage, and reproductive failure (NOAA[d]).

Oil spill response efforts themselves impacted some animals; turtle nesting activity, for example, was impacted by response activities on the beaches during and after the spill (NRDA, 4-516). Recovery efforts will focus on long-term population monitoring and habitat restoration for these important animals.

COASTAL HABITATS

Mats of weathered oil mixed with seawater reached the coastlines of all five of the Gulf states, impacting over 2,000 km of coastline, with Louisiana receiving the heaviest amount of oiling (Figure 6; Nixon et al. 2016). Just over half of the oiled shoreline was marshes.

Beaches

On sandy shorelines, oil mats that washed onto beaches or into shallow water were buried in sediment by wind, tide, and waves (Graham et al. 2015). Mats 100 km long and nearly 20 centimeters (cm) thick were found south of Louisiana beaches (Michel et al. 2013). These mats were

exposed and reburied, with parts breaking off and remaining on the beaches (Figure 7). The patchy distribution of the mats and the cycle of burial and exposure made it difficult to find and remove oil. Efforts to remove oil continued into 2013 in Mississippi, Alabama, and Florida, while a few miles of Louisiana beach were still subject to removal efforts into 2015 (Graham et al. 2015). As of 2014, oil saturated sand aggregates were still present on Alabama beaches, leaving researchers to predict beaches will continue to have oil aggregates beyond background, pre-spill levels for the foreseeable future (Hayworth et al. 2015). A new technique was developed to allow shoreline monitors to distinguish oil from the DWH spill from other anthropogenic sources and natural seeps (Han and Clement 2018).

Marshes

Marsh vegetation was completely lost up to 15 m from the edge of some of the most heavily oiled marshes, resulting in accelerated erosion (Michel et al. 2013). Marsh impact was directly related to the extent of oiling of the substrate (soil); heavily oiled marshes were devastated, and moderately oiled marshes were less impacted (Lin and Mendelssohn 2012). Some recovery of vegetation was documented during the first years after the spill (Lin and Mendelssohn 2012; Zengel et al. 2015; Silliman et al. 2012). However, the extent of marsh recovery as documented in different studies is variable (Rabalais and Turner 2016).

Scientists from the Alabama Center for Ecological Resilience (ACER, <http://acer.disl.org>) considered whether plant diversity may influence the effects of oil exposure on coastal vegetation. Some marsh plant species are resistant to the negative effects of oiling (Pezeshki et al. 2000). In post-spill lab experiments that considered black mangrove and smooth cordgrass separately, both species were harmed by oil. However, damage was reduced when both species were present together. Therefore, researchers conclude that greater species diversity may mitigate some of the negative effects of an oil impact (Hughes et al. 2018).

In both field observations and lab experiments, smooth cordgrass was less impacted and recovered to a greater extent than black needlerush (Lin and Mendelssohn 2012). The mixed black needlerush-smooth cordgrass community had shifted to a primarily smooth cordgrass marsh after two to three years, a loss of marsh plant diversity that may increase its vulnerability to future oiling (Figure 8).

Populations of some marsh invertebrates declined after marshes were oiled. Salt marsh periwinkle snail numbers were significantly reduced in marshes that were heavily oiled



FIGURE 7. Layers of weathered oil are seen in the cross section of this sediment sampling trench that researchers dug on Pensacola Beach shortly after the DWH oil spill. Courtesy of Deep-C and Markus Huettel



FIGURE 8. Students Jessica Diller (bottom) and Kamala Earl (top) prepare enclosed treatment plots in oiled marshes of Barataria Bay, Louisiana. Courtesy of Gabriel Kasozi

(Zengel et al. 2016). Greatly reduced numbers of sub-adult snails in 2011, in both heavily and less severely impacted marshes, were attributed to reproductive failure and adult mortality resulting from the oil (Pennings et al. 2016). The recovery of the snail population is expected to depend on the extent of recovery of marsh vegetation (Zengel et al. 2016).

The Gulf marshes exist in a delta where they are already experiencing a combination of human and natural processes, such as subsidence (compaction of sediments), canal dredging, and sea level rise. Coastal Louisiana marshes were eroding at high rates before the oil spill; nearly 4,833 square

kilometers (1,900 square miles) of marsh was lost between 1932 and 2016 (Couvillion et al. 2017). Heavy oiling of these marshes due to the DWH spill increased erosion rates and limited recovery of marsh vegetation (Silliman 2012; Turner et al. 2016).

As with the rest of the Gulf, coastal habitats experienced diverse impacts. Sandy beaches have been cleared of visible oil. However, oil from DWH and other sources remains in the environment where it may be exposed by a future storm. Already vulnerable marshes have been subject to vegetation loss and increased rates of erosion that may result in permanent loss of marshes and their residents.

CONCLUSIONS

Nearly a decade after the DWH oil spill, conclusive statements about how organisms and habitats fared are still difficult to make. This is how science works. It is slow and challenging, and sometimes it is inconclusive. Much of the work described in this paper will continue for years to come, as some of the impacts—and trajectories of recovery of impacted organisms—will be apparent only with long-term study. However, scientists are learning important lessons by studying the impacts of the largest accidental oil spill in history on marine life in the Gulf.

The oil spill enabled scientists to **further understand the unique deep-sea ecosystems** in the Gulf; in particular, cold seep communities and their microbial inhabitants, who were already conditioned to living in the presence of small amounts of seep hydrocarbons. Research into the impacts of the DWH spill on deep-sea corals provided not only information about impacts and recovery of these sentinel creatures, but also shed light on oil movement and the extent of the spill's footprint on the seafloor.

Microbes played a previously less-understood, yet important role in transferring oil and gas deeper into the water column and into the marine food web. While much of the oil and gas movement during and after the spill was driven by physical processes, scientists found that microbially-mediated **marine oil snow formation** was an important factor that transferred oil from the surface waters and subsurface plume deeper in the water column. Scientists also learned that microbial response to the spill was an important mechanism for transferring oil- and gas-derived carbon into the marine food web.

The immediate and lethal impacts of the spill on individual, large vertebrates were reported extensively by the media. Quantifying **long-term impacts on animals with broad ranges**, like whales, dolphins, and turtles, has been

logistically challenging. Further questions about long-term impacts have taken longer to answer or have yet to be determined.

Sublethal impacts are important, and understanding them provides critical insight about longer-term, population-level impacts of the spill on marine life. Sublethal impacts do not immediately kill the animal, but affect its feeding habits, navigation, gene expression, development, and/or reproduction. Understanding sublethal impacts through data collection

DISPERSANTS

During the response efforts following the Deepwater Horizon (DWH) oil spill, commercial-grade dispersants called Corexit™ 9527A and Corexit™ 9500A (Corexit™) were applied to the surface oil slick, and for the first time, at the wellhead nearly 1500 meters below the sea surface (Lubchenco 2012). Approximately 1.8 million gallons of Corexit™ was used, 0.77 million gallons of which were injected directly into the wellhead on the seafloor (NRDA, 2-10). Dispersants are applied to oil spills to break the oil up into smaller droplets, similar to how liquid dish soap disperses grease. This process makes it easier for oil-degrading bacteria and organisms to break it down in the environment.

Dispersant is just one tool in the oil spill responders' toolbox that can be used as a resource in clean-up efforts. The Gulf of Mexico Research Initiative has funded many research projects aimed at understanding what impact the use of dispersant had during the DWH accident, and scientists are still learning where the dispersant ended up in the Gulf and how it affected the surrounding ecosystem and human health.

Understanding the impact of dispersants on ecosystems, coastlines, and local communities is essential. Therefore, it is important that scientists continue to study them so that if they are used again in response efforts, their use can be based on the best available science. Research into dispersants and how oil breaks down in the environment is helping scientists discover new technologies and techniques that can be added to the toolbox in responding to future oil spills.

and/or modeling allows scientists to figure out the mechanism by which the spill impacts the organisms and estimate how that impact is reflected in the **population-level impact** and trajectory of recovery.

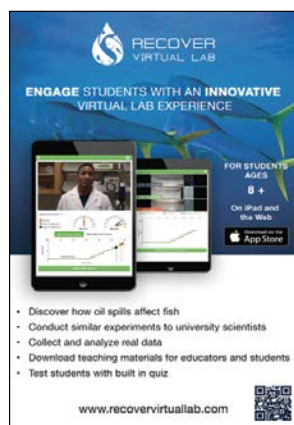
Coastal marshes were already experiencing changes and stress from human and natural processes prior to 2010. The DWH spill added insult to injury; marshes continue to erode from the edges inward, damaging their diverse associations of unique marsh vegetation, animals, and microbes.

Several scientists have pointed out that understanding the spill's impacts was impeded by **lack of baseline data**. Without sufficient baseline data, it is impossible to quantify and assign ecological importance to impacts resulting from the spill. One of the most valuable lessons from this accident has been that it is critically important to collect baseline data for ecosystems; in particular, those which are most at risk to be impacted by industrial activities. GoMRI research has contributed to establishing a baseline to inform future research and response efforts.

CLASSROOM ACTIVITY RESOURCE

The RECOVER Virtual Lab is available as a web application (<http://recovervirtuallab.com>) or a free app from the Apple App Store by searching for "Recover Virtual Lab." The RECOVER Virtual Lab takes teachers and students through a series of videos and simulations similar to laboratory-based experiments conducted by scientists to study oil impacts on mahi-mahi and red drum.

The simulations include a description of RECOVER's "fish treadmills" or swim tunnels. Students and educators can visualize the data, repeat experiments, and discuss findings. The Virtual Lab also includes transcripts, a teacher workbook that can serve as a classroom lesson guide, and a brief quiz to test users on what they've learned.



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