PROSPECTS FOR GULF OF MEXICO ENVIRONMENTAL RECOVERY AND RESTORATION

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Great blue heron and boom along the Louisiana coast after the Deepwater Horizon oil spill. *Photo credit: Beckie Breeding-Mims, US National Park Service*

ABSTRACT. Previous oil spills provide clear evidence that ecosystem restoration efforts are challenging, and recovery can take decades. Similar to the Ixtoc 1 well blowout in 1979, the Deepwater Horizon (DWH) oil spill was enormous both in volume of oil spilled and duration, resulting in environmental impacts from the deep ocean to the Gulf of Mexico coastline. Data collected during the National Resource Damage Assessment showed significant damage to coastal areas (especially marshes), marine organisms, and deep-sea habitat. Previous spills have shown that disparate regions recover at different rates, with especially long-term effects in salt marshes and deep-sea habitat. Environmental recovery and restoration in the northern Gulf of Mexico are dependent upon fundamental knowledge of ecosystem processes in the region. Post-DWH research data provide a starting point for better understanding baselines and ecosystem processes. It is imperative to use the best science available to fully understand DWH environmental impacts and determine the appropriate means to ameliorate those impacts through restoration. Filling data gaps will be necessary to make better restoration decisions, and establishing new baselines will require long-term studies. Future research, especially via NOAA's RESTORE Science Program and the state-based Centers of Excellence, should provide a path to understanding the potential for restoration and recovery of this vital marine ecosystem.

INTRODUCTION

When a coastal ecosystem is damaged by oil, the system can recover gradually over time without intervention, although the new state of the ecosystem may not be equal to that before the damage. Generally, mitigation efforts that are undertaken to minimize the amount of oil reaching the coast include oil collection by skimmers, burning of the oil at sea, and the application of dispersants to reduce the oil to smaller droplets, thereby increasing oil surface area and allowing natural processes to more fully and quickly interact with the oil. When oil reaches the shore and causes damage to the coastal ecosystem, restoration efforts are often used to speed the recovery of the ecosystem. Mitigation efforts following the Deepwater Horizon (DWH) oil spill included those listed above as well as release of freshwater from the Mississippi River to hopefully keep the oil offshore, and even the building of berms to protect coastal areas. Restoration efforts included mechanically sifting the oil from beaches, cleaning marine animals, and eventually planting new marsh grasses to speed recovery. This article considers the prospects for environmental recovery based on what we know from previous oil spills and from the data on the coastal ecosystem of the Gulf of Mexico collected since the DWH oil spill.

LESSONS LEARNED FROM EARLIER SPILLS

The Ixtoc 1 oil blowout in the southern Gulf of Mexico in June 1979 had many similarities to the DWH oil spill. It was a well blowout that released massive amounts of crude oil (>3.4 million barrels) into a tropical marine environment; the well leaked for over nine months and reached all the way into Texas waters. Soto et al. (2014) reviewed the environmental legacy of the Ixtoc 1 blowout. Like DWH, the impacts of the Ixtoc 1 spill were initially mitigated by physical and chemical processes and the region's local hydrological and biological conditions. However, even today, Ixtoc 1 oil residues are measurable, especially in the sediments and on shore, and some scientists suggest that the collapse of important commercial shrimp species stocks are attributable to the spill, though there is disagreement about this. Soto et al. (2014) note that the lack of adequate pre-spill information precluded a robust assessment of the Ixtoc 1 spill's damage to the ecosystem. Intense research was conducted while the oil flowed; however, when Ixtoc 1 oil stopped flowing, many research efforts funded by US agencies ceased. As a result, the total extent of environmental damage from the Ixtoc 1 oil spill is not fully understood, while the official position of the Mexican federal agencies is that no environmental damage was caused by the Ixtoc 1 blowout (Soto et al., 2014).

Before DWH, the largest oil spill in US waters came from the *Exxon Valdez* tanker accident in March 1989, where 257,000 barrels of North Slope crude oil was released into the cold, pristine waters of Prince William Sound, Alaska. The oil eventually affected 2,100 km of coastline, of which 320 km were heavily oiled. During the response, the carcasses of more than 35,000 birds and 1,000 sea otters were found, the herring fishery eventually collapsed, and two pods of killer whales have yet to recover. Mitigation techniques ranged from booms to keep the oil out of rivers and away from shorelines where salmon spawned to hot water cleaning of rocky beaches. The hot water made for great television, but it was eventually abandoned when it was realized that small coastal organisms were killed by the hot water. In the long term, fauna associated with hot water cleaned beaches recovered more slowly than those associated with beaches that were either left alone or treated by spraying nutrients on the rocky beach (Houghton, 1991). Peterson et al. (2003) concluded that because of persistence of oil in the ecosystem, the long-term population impacts are likely more important than the acute species mortality immediately following the spill. Even today, small amounts of oil can be found under rocks on the beaches of Prince William Sound (Nixon and Michel, 2018), and some species have not fully recovered. Esler et al. (2018) examined timelines for wildlife population recovery and found that for some species, the oil effects that persisted for decades had a large influence on population dynam-

ics. These chronic effects may have been more harmful than the acute toxic effects of the oil itself. Unlike for Ixtoc 1, a legacy of post-*Exxon Valdez* research is available, as long-term research funding was made available through federal agencies and the *Exxon Valdez* Oil Spill Trustee Council; the most recent effort is the Gulf Watch Alaska Program initiated in 2012 with a 20-year lifetime (Aderhold et al., 2018). Another outcome of the *Exxon Valdez* accident was passage of the Oil Pollution Act of 1990 that established how response to future oil spills would be managed and required the responsible parties to pay for the cleanup and restoration efforts.

DEEPWATER HORIZON IMPACTS

Detailed examination of impacts on various components of northern Gulf of Mexico habitats is beyond the scope of this paper. However, the following sections include a brief review of the status of several of the more prominent habitats and species impacted by the DWH oil spill, including wetlands and mortality of fish larvae, invertebrates, sea turtles, and cetaceans. (Please see other articles in this issue for further information.) In addition, we present a more detailed review of impacts on wetland fisheries and oyster restoration.

In accordance with the Oil Pollution Act of 1990 (OPA), an assessment of damage to the environment was conducted by scientists from NOAA and their contractors as part of the OPA-required National Resource Damage Assessment (NRDA; DHNRDAT, 2016).

In general, coastal habitats were fairly well buffered from the impact of the DWH oil spill, except for those of Louisiana. Much of that impact is documented elsewhere in this issue, but in general, NRDA-identified damages that relate to the coastal zone include the following.

The DWH oil spill resulted in the oiling of 2,113 km of coastline (Nixon et al., 2016), including 763 km of coastal marsh shoreline with 135 km heavily oiled, mainly in Louisiana (Michel, et al., 2013). Many acres of wetlands were damaged, and depending on the degree of oiling, it was estimated that marsh recovery would take from two to four years for intensely treated areas and eight years for those that were untreated (Michel and Rutherford, 2014; DHNRDAT, 2016). Some residual oil is still found in the Louisiana coastal sediment. Based on the degradation rates from oil spilled in Prince William Sound, continued degradation will be extremely slow, and oil will continue to surface through erosion for the next decade or more (Lindeberg et al., 2018). From previous studies, we also learned that marsh restoration can be enhanced by the planting of *Spartina* in salt marshes and *Juncus* in the freshwater marshes (Bergen et al., 2000; Mendelssohn et al., 2012). Some efforts to restore marshes are necessary, as Zengel et al. (2015) show that in the Louisiana marsh areas not treated after DWH, most ecological parameters had not improved two years after the spill. It follows that the benthic infauna will recover fairly quickly once native vegetation is restored.

The number of fish killed was estimated during the NRDA process using biological data from NRDA-specific field studies, historical collections, NRDA toxicity testing studies, and published literature. Both direct kill and forgone production of fish and invertebrates exposed to DWH oil in the surface slick and the subsurface mixed zone were calculated. The exposure resulted in the death of between 2 trillion and 5 trillion fish larvae and between 37 trillion and 68 trillion planktonic invertebrates (DHNRDAT, 2016). Of these totals, 0.4–1 billion larval fish and 2–6 trillion invertebrates were killed in estuarine surface waters. The NRDA process also quantified the direct kill of fish and invertebrates exposed to DWH oil both in the rising cone of oil and in the deepwater plumes, as well as foregone production for a critical subset of these species. The exposure resulted in the death of between 86 million and 26 billion fish larvae and between 10 million and 7 billion planktonic invertebrates (DHNRDAT, 2016).

In general, the fish communities of the coastal Gulf of Mexico were found not to suffer long-term damage from the DWH oil spill (see below). Those communities have now recovered, and there has so far been no evidence of long-term sublethal impacts, showing the resilience of coastal fish communities (Patterson et al., 2015). As with the benthic community, once the habitat is restored, the organisms will follow.

The NRDA Trustees estimated that between 4,900 and 7,600 large juvenile and adult sea turtles and between 55,000 and 160,000 small juvenile sea turtles were killed by exposure to DWH oil. The Trustees also estimated that nearly 35,000 hatchling sea turtles were injured by response activities associated with the DWH oil spill. Likely, the most problematic impacts in the coastal zone were to higher-level vertebrates. Organisms such as birds, turtles, and marine mammals were unable to avoid the oil as it spread near the shore. Multiple recovery efforts were attempted during the spill to clean and release contaminated birds and turtles. Unfortunately, that was not possible with marine mammals. Mortalities of dolphins and turtles were documented during and immediately following the spill. Dolphin data collection funded during NRDA and continued by the Gulf of Mexico Research Initiative (GoMRI) documented dolphin fetal mortality, respiratory stress, and challenged immune responses. A variety of innovative studies conducted between 2010 and 2015 under the NRDA process documented that marine mammals experienced severe negative effects such as lung disease, reduced reproduction, and elevated death rates (see Barratclough et al., 2019). Unfortunately, restoration is not possible for this group of organisms, and it will simply take a long time for recovery to work through the system due to low reproductive success after the oil spill (Lane et al., 2015).

Eight-year study quantifies how oiling is a continuing stressor on the marsh ecosystem. Scientists measured changes in oil quantity and quality in 1,200+ samples collected over eight years at locations that Deepwater Horizon affected—the Gulf of Mexico continental shelf, estuarine waters, and marsh sediments. The concentrations in marsh sediments peaked in fall 2011 (1,000 times above May 2010 levels) then dropped to 10 times higher over eight years. The initial oiling at the marsh edge gradually affected the entire marsh within two years, suggesting that the total area oiled was larger than the visible initial oil distribution when the spill first occurred. The study authors estimated that marsh sediments will retain high levels throughout this century. *Photo credit: R. Eugene Turner, Louisiana State University*

ESTUARINE FISHERIES

The 2010 DWH oiling disaster challenged the integrity and long-term future of the Gulf of Mexico ecosystem at unprecedented scales. It led to immediate, but temporary, shutdown of fisheries harvesting and prompted serious concerns that there might be catastrophic injury to Gulf fishes and fisheries. However, nekton sampling at multiple, paired oiled and unoiled sites during 2012–2013 in Barataria and Terrebonne Bays, Louisiana, among the most heavily oiled salt marshes along the northern Gulf following the spill (DHNRDAT, 2016), documented no lasting differences in the densities, sizes, or assemblage structures of seven resident Cyprinodontiformes fishes (including the sentinel species, Gulf killifish, *Fundulus grandis*; Able et al., 2015). Similarly, catch rates of marsh-resident species, as well as overall community structure, were not different before (2009) versus after (2010–2011) oiling at impacted wetlands in Alabama (Moody et al., 2013). Likewise, settlement of blue crab, *Callinectes sapidus*, did not change in northern Gulf wetlands following the spill (Grey et al., 2015). Shrimp abundances in oil-impacted Louisiana embayments actually increased in the aftermath of the spill, perhaps due to delayed migration offshore and/or reduced harvest pressure (van der Ham and de Mutsert, 2014).

In addition to these spill-response patterns observed among marsh-associated nekton, similar patterns of stability in fish populations and communities have emerged post DWH in diverse northern Gulf settings such as seagrass-associated fishes (Fodrie and Heck, 2011), estuarine fishes throughout Mississippi Sound (Schaefer et al., 2016), and within the coastal population of Gulf menhaden, *Brevoortia patronus*, a key forage fish (Short et al., 2017).

The general resilience to unprecedented oiling exhibited by fishes, crabs, and shrimps at population levels has been surprising given what is known about the impacts of hydrocarbons on individuals within these marsh-associated taxa following DWH. In both lab experiments and field collections since 2010, individuals from these same taxa have shown negative responses to both oil constituents (e.g., polyaromatic hydrocarbons) and dispersants used to break down oil slicks. Indeed, a review of peer-reviewed studies demonstrated that in ~99% of cases (Fodrie et al., 2014), individual marsh-associated fishes exposed to even low concentrations (~1 ppb) of weathered Macondo oil and/or Corexit dispersants from the DWH oil spill demonstrated negative responses in terms of genomic expression, physiologic performance, morphological defects, and even mortality rate (Whitehead et al., 2012; Dubansky et al., 2013; Kuhl et al., 2013).

Several factors may help reconcile why these individual-level damages do not appear to manifest as losses at the population or community level for marsh-associated nekton. In addition to the fishery closures in 2010 that potentially reduced adult mortality and increased recruitment of summer/fall spawning species (Fodrie and Heck, 2011), many fishes, crabs, and shrimps may have relied on their mobility to detect and then evade oiling (Martin, 2017). In many estuaries, the distribution of oil was highly patchy and could have allowed for avoid-

Oyster populations in many areas of the north-central Gulf of Mexico were severely impacted. Researchers concluded impacts on oysters were primarily due to activities associated with response to the DWH oil spill. The summer release of large quantities of freshwater from the Mississippi River through the Caernarvon and Davis Pond diversion structures as the State of Louisiana moved to protect marsh ecosystems from the inflow of oil in 2010 resulted in the loss of 2–3 billion market-sized oysters from subtidal areas of Barataria Bay and Black Bay/Breton Sound estuaries (Grabowski et al., 2017; Powers et al., 2017b). (photo) Louisiana coastal oysters exposed at low tide. *Photo credit: Meagan Schrandt*

ance behaviors for highly mobile species, despite strong site fidelity at landscape scales (Jensen et al., 2019). Additionally, we know that many marine birds and mammals were impacted by Macondo oil, and reduced numbers of these predators might have also offset oil-related mortality on smaller fishes (Lane et al., 2015; Short et al., 2017). These are only a subset of the possible explanations that can be considered but are ultimately difficult to fully test as causal agents for observed patterns—which reinforces the complexity of ecosystem response(s) to broadscale oiling, as well as defining directions for future research. Additionally, other studies highlight the importance of identifying key taxa in the response of ecosystems to perturbations based on both their sensitivity to stressors (i.e., oiling) and their importance in the overall web of interactions (McCann et al., 2017).

OYSTER RESTORATION AND RECOVERY

Oyster populations in many areas of the north-central Gulf of Mexico were severely impacted, primarily due to activities associated with response to the DWH oil spill. During the injury assessment phase, the DWH NRDA Trustee Council directed significant resources to evaluating the impacts on oyster resources, including support of longer-term monitoring of many oyster habitats. The complexity of assessing the immediate and long-term effects of the DWH spill on oysters cannot be overstated: they were impacted both as direct consequences of oiling and response activities (e.g., freshwater diversion release, shoreline cleanup), and by the interaction of oiling and response activities. In addition, oyster resources in the Gulf region fluctuate naturally because recruitment changes in response to freshwater inflow patterns to estuaries, and because there is a legacy of different harvest regimes.

Studies in the aftermath of the DWH oil spill demonstrated that disturbances resulting from oiling and various response activities can have substantial impacts on oyster resources. The summer release of large quantities of freshwater from the Mississippi River through the Caernarvon and Davis Pond diversion structures as the State of Louisiana moved to protect marsh ecosystems from the inflow of oil in 2010 resulted in the loss of 2–3 billion market-sized oysters from subtidal areas of Barataria Bay and Black Bay/Breton Sound estuaries (Grabowski et al., 2017; Powers et al., 2017b). Mesocosm experiments funded by GoMRI indicated that exposing oysters to short periods of low salinity could help them combat oil contaminant effects; however, this must be balanced by heavy expected mortality resulting from extended periods at very low salinity (Schrandt et al., 2018). Oysters near the shoreline (fringing oyster reefs) suffered injury from direct oiling as well as from oil removal efforts (Powers et al., 2017a). While the magnitude of oysters killed in the nearshore was an order of magnitude less than in subtidal areas (34 million vs. 2–3 billion market-sized oysters), the loss of fringing oysters from the shoreline resulted in increased marsh erosion and additional loss of spawning stock biomass.

The combined effects of massive decreases in oysters in the subtidal and nearshore oyster areas likely contributed to the prolonged recovery seen in follow-up studies that were funded by GoMRI as a result of decreased oyster

recruitment (from the loss of spawning stock biomass). Recent research demonstrated that the longevity of oyster shell, which is necessary to support high settlement of oysters, is limited because of bioerosion and dissolution processes in the environment (Dunn et al., 2014). Consequently, recovery from natural and anthropogenic disturbances may not be adequate if natural recovery extends beyond the lifetimes of shell resources. In such instances, active restoration will be required to restore the oyster resources of the northern Gulf of Mexico.

INFORMING AND TRACKING GULF OF MEXICO RECOVERY

To promote the recovery of the Gulf of Mexico region following the DWH oil spill, the US Congress passed the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act of 2012 (known as the RESTORE Act). This law dedicated 80% of the Clean Water Act penalties paid by responsible parties in connection with the spill to the Gulf region to promoting ecological and economic recovery activities. Two of the programs established by the Act, the NOAA RESTORE Science Program and the Centers of Excellence Research Grants Program, focus on supporting research, observation, technology, and monitoring in the Gulf of Mexico. Each program is funded by roughly $138 million plus a portion of the interest from the penalty payments.

The NOAA RESTORE Science Program's mission considers the long-term sustainability of the Gulf of Mexico ecosystem, including its fish stocks, fish habitat, and fishing industries; its work is funded directly from the trust fund of Clean Water Act penalties established by the RESTORE Act. Working in partnership with the US Fish and Wildlife Service, the Science Program seeks to accomplish two equally important long-term outcomes. One is to improve understanding of the processes and connections within the Gulf of Mexico ecosystem. The other is to apply this integrated knowledge of the ecosystem to its sustainable management and restoration (NOAA, 2015). NOAA has laid the foundation to do so by building a program that connects the capacity of the research community to the information needs of resource managers in the Gulf region. By designing its funding opportunities around the needs of resource managers, using a competitive selection process, and working closely with their funded projects, the Science Program is supporting quality research and its application.

The Science Program recognizes the importance of making long-term investments. In the fall of 2019, the Science Program made its first set of long-term awards, which may provide up to 10 years of continuous funding to teams working on long-term trends in living coastal and marine resources in the Gulf of Mexico and the processes that drive them. Such long-term awards have the potential to be transformative by providing sustained funding to promising researcher and resource manager partnerships. To further explore the relationships between trends and processes in the ecosystem and lay the foundation for ecosystem-based management, the Science Program will also support a synthesis initiative that cuts across disciplines and seeks to gain new insights from existing data.

Since its inception, the Science Program has increasingly recognized the importance of investing in research and resource management partnerships. The program has begun to emphasize the use of co-production as one way to generate actionable science. The co-production of science involves iterative collaboration between a researcher and a resource manager in all phases of a research project, and it is often centered around reducing the uncertainties around a specific decision the manager has to make. In addition to conducting competitions to fund co-produced science, the Science Program is also exploring ways to increase the capacity for co-production of science in the Gulf of Mexico region by initiating workshops, seminars, and conference sessions.

Working with priorities set by the research and application needs of resource managers, the Science Program continues to seek opportunities to support monitoring and research that can inform restoration decisions and evaluate restoration outcomes as articulated by practitioners. The key to delivering relevant research findings and products is designing and conducting experiments, models, and monitoring networks tailored to the needs of restoration managers. Rigorous science and monitoring are critical, but it will only be utilized if it is delivered at the geographic and temporal scale of the restoration action and its utility is recognized by the resource manager—ideally even before it is produced.

THE CENTERS OF EXCELLENCE RESEARCH GRANTS PROGRAM

The Centers of Excellence Research Grants Program funds research, science, technology, and monitoring with administrative and civil penalties housed in the RESTORE Act Trust Fund from the DWH oil spill. The Centers of Excellence Program, with a budget of more than $138 million, is near the beginning of its 15-year tenure, with at least one Center of Excellence established in each Gulf Coast State. Centers of Excellence are required to focus on at least one of five disciplines in the Gulf of Mexico or Gulf Coast Region: (1) coastal and deltaic sustainability, (2) coastal fisheries and wildlife, (3) offshore energy development, (4) sustainable and resilient growth and economic development, and (5) observation, monitoring, and mapping. All Centers prioritize data discoverability, accessibility, and usability by other researchers over the long term, and most Centers are housing data at the Gulf of Mexico Research Initiative Information and Data Cooperative. Although the Centers are self-directed and operate in support of separate missions, they all follow the same guidelines and regulations stipulated by the US Department of Treasury, as administrator for the Centers

of Excellence Program, and funds for each Center are required to pass through a designated state entity.

Texas OneGulf Center of Excellence

Texas OneGulf is a consortium of nine top state institutions led by the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi. It has wide-ranging expertise in the environment, the economy, and human health. Texas OneGulf was established in 2015 with a mission to improve understanding of the Gulf of Mexico large marine ecosystem and its effects on human health and well-being for the betterment of both. In its initial years, Texas OneGulf supported seven research projects totaling nearly $3 million in RESTORE funding to tackle a variety of issues that directly impact Texas, the Gulf of Mexico, and its residents. These projects include establishing disaster research response infrastructure that can be deployed rapidly to assess the impacts of disasters along the Texas coast in real time, using underwater gliders to search the coast for hypoxic dead zones, and helping Texas communities build resilience and recover from Hurricane Harvey. The diversity and interdisciplinary nature of the projects helped OneGulf become a reliable source of information for Texas decision-makers and resource managers working to protect the Gulf and its coastal communities.

RESTORE Act Center of Excellence for Louisiana

The mission of the RESTORE Act Center of Excellence for Louisiana (LA-COE) is to fund research directly relevant to Louisiana's Comprehensive Master Plan for a Sustainable Coast by administering a competitive grants program and coordinating support to ensure that success metrics are tracked and achieved. The Coastal Master Plan is the guiding document for the Coastal Protection and Restoration Authority (CPRA) that was developed using the best available science and engineering to focus efforts and guide the actions needed to sustain Louisiana's coastal ecosystem, safeguard coastal populations, and protect vital economic and cultural resources. LA-COE is sponsored by CPRA and administered by The Water Institute of the Gulf. LA-COE began in 2014 and has been working with CPRA and various other advisory groups and scientists from The Water Institute of the Gulf to advance the LA-COE mission. In 2017, LA-COE granted universities nearly $3 million to support 13 research, collaborative, and graduate studentship awards. Research topics ranged from coastal restoration impacts to brown pelican nesting habitat, assessment of adaptive migration for coastal residents, and use of radar-based precipitation data sets for hydrology models.

Mississippi Based RESTORE Act Center of Excellence

The Mississippi Based RESTORE Act Center of Excellence (MBRACE) is a consortium of Mississippi's four research universities—Jackson State University, Mississippi State University, The University of Mississippi, and The University of Southern Mississippi (USM)—with USM serving as the lead institution. The mission of MBRACE is to seek sound comprehensive science- and technology-based understanding of the chronic and acute stressors on the dynamic and productive waters and ecosystems of the northern Gulf of Mexico, and to facilitate sustainable use of the Gulf's resources. Since its designation in 2016, MBRACE has dedicated more than $7 million to support oyster reef sustainability and water quality in Mississippi coastal waters, prioritizing research and modeling to inform management and restoration activities led by the Mississippi Department of Environmental Quality, the Center of Excellence pass-through entity in Mississippi, and the Mississippi Department of Marine Resources. The close partnership between MBRACE and state resource managers enables the Center to support research that both increases the state of knowledge and addresses critical management needs.

Alabama Center of Excellence

In the interest of being better prepared to respond to future disasters, the Alabama Center of Excellence (AL COE) will develop and implement a forward-looking competitive grant program that will fund up to 22 research grants and conduct hypothesis-driven, ecosystem-based monitoring focused on the development of data-driven predictions of impacts of future multi-stressors on the coastal and nearshore environments of the north central Gulf of Mexico. Lead scientists will be located at Alabama Marine Environmental Sciences Consortium's 23 member schools, and ecosystem-based monitoring will be led by resident faculty at the Dauphin Island Sea Lab. AL COE will also fund improvements to the Alabama Real-time Coastal Observing System (ARCOS), a core program administered by the Dauphin Island lab. ARCOS collects and disseminates quality-controlled hydrographic and meteorological data to a diverse and large array of stakeholders (e.g., US Coast Guard, National Weather Service, Alabama Department of Public Health) who depend on these data for a range of regulatory, commercial, and recreational activities. Partners in the evaluation of AL COE's work plan will include Mississippi-Alabama Sea Grant and the Mobile Bay National Estuary Program.

Florida RESTORE Act Centers of Excellence Program

In Florida, the RESTORE Act stipulated that the Florida Institute of Oceanography (FIO) serve as the Gulf Coast State Entity, responsible for conducting a competitive grant process to establish Florida's Centers of Excellence rather than serving as the Center of Excellence itself. FIO serves as the program headquarters for the Florida RESTORE Act Centers of Excellence Program (FLRACEP) and is responsible for administering the program's funds and evaluating the performance of each Florida Center of Excellence. Guided by the FLRACEP management team, the program seeks to engage, coordi-

Five-year study finds Deepwater Horizon negatively affected periwinkle snails. Scientists conducted a meta-analysis on marsh periwinkle snails using data spanning five years to investigate how the oil spill affected them over time. The researchers found that snails from heavily oiled sites exhibited decreased density and shell length. There were greater relative proportions of small adults and fewer large adults in heavily oiled sites compared to reference sites. These results suggest that the Deepwater Horizon spill suppressed periwinkle populations and that recovery was slowed or incomplete. (photo) Researchers sampling periwinkle snail density and size along a Louisiana marsh shoreline. *Photo credit: Scott Zengel*

nate, and establish collaborations with ocean and coastal research programs and to promote science and technology innovation among Florida's institutions of higher education, with emphasis on monitoring and supporting the health of the Gulf of Mexico and Florida's coastlines. Since 2015, FIO has established 10 Florida Centers of Excellence and allocated approximately $7 million toward the funding of 18 research projects that address multiple strategic goals identified by the FLRACEP management team.

The Centers of Excellence described here represent a next phase of science and restoration funding across the Gulf of Mexico. Early accomplishments of the 15-year Centers of Excellence program include establishment of the Centers, development of science plans to define scopes and paths forward, and creation of connections and collaborations between the various Centers and other funding agencies. Although disparate in missions, the Centers of Excellence are all ultimately working toward a resilient Gulf of Mexico ecosystem, prioritizing research to inform restoration (e.g., oyster restoration and water quality sustainability in Mississippi and coastal ecosystem restoration in Louisiana), ecosystem monitoring (e.g., the Alabama Real-time Coastal Observing System and monitoring to support healthy coastal ecosystems in Florida), and healthy communities (e.g., hurricane recovery and resilience in Texas and protecting economic and cultural resources in Louisiana). The next 10 years will be critical for research, restoration, and recovery of the Gulf of Mexico following the DWH oil spill, and the Centers of Excellence will continue to support science, technology, and monitoring to meet the needs of their state entities and work toward a healthy, resilient, and productive Gulf of Mexico.

CONCLUSIONS

Oil spills are never good news, and the DWH oil spill was both tragic and environmentally harmful. The good news is that with lessons learned from previous oil spills and the ability of scientists to rapidly undertake field studies before the oil reached the shoreline, GoMRI-funded researchers added significantly to our understanding of ecosystem impacts and were able to continue those studies for a decade following the spill. Additionally, the creation of long-term research efforts like the NOAA RESTORE Science Program and the state-based Centers of Excellence will assure development of a better understanding of ecosystem science to inform restoration efforts and assess recovery.

As expected, recovery and restoration processes of habitats and species assemblages impacted by the DWH oil spill are varied and diverse. Nearshore species with short life cycles living in stable environments recover rapidly (i.e., the Cyprinodontiformes fishes in Barataria and Terrebonne Bays, Louisiana, described above). In contrast, cetaceans and other higher-level vertebrates have suffered multiple physiological impairments, and their recovery is slow and likely to extend for decades in populations severely impacted by the spill. Anthropogenic influence intended to enhance restoration and recovery, such as described for oysters, has risk-reward consequences yet to be evaluated.

In order to correctly determine the true pace of recovery, long-term continuing studies, including monitoring, are essential. Insufficient baseline research was available when the DWH

Study finds oil impacts on fiddler crabs may also affect broader marsh health. Scientists conducted mesocosm experiments to explore how crude oil affects marsh-dwelling fiddler crabs, classified as ecosystem engineers or bioturbators. The researchers tested impacts of various oil concentrations to mimic light to heavy oiling scenarios, with fiddler crabs experiencing more acute impacts at higher oil concentrations and less at lower concentrations. The study results suggest that oil impacts on fiddler crabs may have implications for other species that depend on them for food or ecological changes from their burrowing. (left) A male fiddler crab (*Uca panacea*) sits inside an experimental mesocosm that investigated crude oil impacts. *Photo credit: M.E. Franco, University of Louisiana, Lafayette.* (right) Fiddler crabs in a marsh. *Photo credit: CWC Consortium, LUMCON*

oil spill occurred, making comparison of impacts difficult. However, the GoMRI effort has provided many starting points for long-term studies. In addition, the RESTORE Science Program and the 30-year National Academies of Sciences Gulf Research Program (NRC, 2014) will enable researchers to continue assessments well into the future. Also, the Centers of Excellence Research Grants Program is designed to extend for many years, providing support for scientists to focus on regionally important long-term investigations.

A "new normal" for habitats and impacted ecosystems is often referenced as a possibility. Again, its determination requires extended studies. With the passage of time, as recovery progresses, and anthropogenic influence is included, a return to the previous, or some new, "normal" can be ascertained.

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